Kelebogile Botseo Mfundisi

Analysis of carbon pools and human impacts in the Yala Swamp (Western Kenya): A landscape approach

Zentrum für Entwicklungsforschung
Center for Development Research
University of Bonn

ZEF Bonn

Kelebogile Botseo Mfundisi

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This work is dedicated to my daughter Tswelelo Mfundisi for her support, understanding and patience

ABSTRACT

Soil and biomass carbon pools in the Yala Swamp of Western Kenya are analyzed using principles of landscape ecology through remote sensing techniques and geographic information system (GIS) tools. Two LANDSAT images are used to estimate land-use and land-cover change over the swamp between 1984 and 2001. It is found that 6 333 ha of the swamp have been drained for agricultural production. The time span of drainage of the areas varies from historic (20 to 40 years ago) to recent times (less than 20 years ago).

The impact of human activities on the carbon pools are assessed and carbon dioxide emissions in the area estimated based on the results obtained from processing satellite images and field data (during the annual cycle of 2002/2003). Soil samples collected from relatively undisturbed wetland and drained wetland areas are analyzed for SOC and total N. It is found that natural wetland areas contain higher SOC and total N than adjacent drained areas. The average SOC content in natural wetland topsoil (0-20 cm) is 5.63 ± 4.9%, while that for drained areas is 2.31± 1.61%. The total-N values for the two areas are 0.40 ± 0.3% and 0.22 ± 0.1%, respectively. Correlations between SOC and total N for the natural wetland and drained areas are 0.96 and 0.98, respectively. The SOC content for pairs covering natural wetland and recently drained areas (between 1984 and 2001) is 3.94 ± 1% and 2.29 ± 1%, respectively, i.e., a change in the SOC stock of 1.65 ± 1 kg C/m^2 in this part of the landscape. A comparison with the Nyando Swamp shows that the carbon stocks found in the two swamps are similar. Covering 15 267 ha, the Yala Swamp stores 1.2 Million tons of carbon in the top 20 cm alone. For the sum of all swamps around Lake Victoria, this amounts to 1.8 Million tons of carbon.

In addition to its effect on climate change, destruction of the carbon pools affects ecosystem productivity, the various functions of wetlands for biodiversity, and the regional carbon cycle. For the 6 333 ha converted to date, 104 494.5 tons of carbon have been lost from the top 20 cm of the soil. Unlimited access by farmers to the swamps around Lake Victoria for drainage and conversion to agricultural land could release 1.87 Million tons of carbon to the atmosphere. Meeting the human need for food in the area while sustaining the integrity of its biogeochemical cycles and swamp ecosystems is a challenge to farmers and policy makers alike.

KURZFASSUNG

Die Kohlenstoffsenken in Boden und Biomasse im Yala Sumpf von Western Kenya werden mit den Instrumenten der Landschaftsökologie Fernerkundung und geographische Informationssysteme (GIS) analysiert. Zur Ermittlung von Veränderungen in der Landnutzung und -bedeckung zwischen 1984 und 2001 werden zwei LANDSAT Satellitenbilder verwendet. Es wird festgestellt, dass 6.333 ha des Sumpfes für landwirtschaftliche Zwecke entwässert worden sind. Die Entwässerungsmaßnahmen wurden in den letzen 40 Jahren durchgeführt.

Die Wirkung von menschlichen Aktivitäten auf die Stickstoffsenken werden ermittelt und die Kohlendioxidemissionen im Untersuchungsgebiet auf der Grundlage der Ergebnisse der Satellitenbildauswertung und der Felderhebungen (während eines Jahres 2002/2003) ermittelt. Bodenproben aus relativ ungestörten bzw. entwässerten Feuchtlandgebieten werden auf bodenorganischem Material (SOC) und Gesamtstickstoff (N) analysiert. Die Ergebnisse zeigen, dass die natürlichen Feuchtgebiete einen höheren SOC-Anteil und Gesamt-N als danebenliegende entwässerte Bereiche enthalten. Der durchschnittliche SOC-Gehalt im Oberboden (0-20 cm) in natürlichen Feuchtgebieten beträgt 5.63 ± 4.9%, in entwässerten Bereichen beträgt dieser Wert 2.31± 1.61%. Die Gesamt-N-Werte für die beiden Bereiche betragen 0.40 ± 0.3% bzw. 0.22 ± 0.1%. Die Korrelation zwischen SOC und Gesamt-N für die natürlichen bzw. entwässerten Feuchtgebiete ist 0,96 bzw. 0,98. Der SOC-Gehalt für Wertepaare für natürliche Feuchtgebiete und Gebiete, die in den letzen 20 Jahren (von 1984 bis 2001) entwässert wurden, beträgt 3.94 ± 1% bzw. 2.29 ± 1%, d.h. eine Veränderung im SOC-Gehalt von 1.65 ± 1 kg C/m^2. Ein Vergleich mit dem Nyando Sumpf zeigt, dass die Kohlenstoffmengen in den beiden Sümpfen etwa gleich sind. Mit einer Fläche von 15.267 ha speichert der Yala Sumpf 1,2 Mio. Tonnen Kohlenstoff allein in den oberen 20 cm Boden. In Bezug auf alle Sümpfe um den Viktoria See beträgt die Summe 1,8 Mio. Tonnen.

Zusätzlich zu den Auswirkungen auf den Klimawandel beeinflusst die Vernichtung der Kohlenstoffsenken die Ökosystemproduktivität, die verschiedenen Funktionen der Feuchtgebiete hinsichtlich Biodiversität sowie den regionalen Kohlenstoffzyklus. Für die bisher umgewandelten 6.333 ha sind 104.494,5 Tonnen Kohlenstoff aus der oberen 20-cm Bodenschicht verloren gegangen. Durch einen unbeschränkten Zugang der Bauern zu den Sümpfen um den Viktoria See für Entwässerung und Umwandlung in landwirtschaftliche Flächen könnten 1,87 Mio. Tonnen Kohlenstoffe in die Atmosphäre entweichen. Den Bedarf der Menschen an Nahrungsmitteln zu erfüllen und gleichzeitig die Integrität der biogeochemischen Kreisläufe und Sumpfökosysteme zu erhalten, ist eine Herausforderung sowohl für die Bauern als auch für Entscheidungsträger und Politiker.

TABLE OF CONTENTS

1 GENERAL INTRODUCTION ... 1
1.1 Wetland ecosystems ... 1
1.1.1 Wetland types of Africa ... 2
1.1.2 Wetland soils ... 3
1.1.3 Decomposition of organic matter in wetlands ... 10
1.1.4 Oxidation –reduction sequence of inorganic substances ... 11
1.2 The effect of land-use and land-cover change on carbon pools ... 12
1.2.1 Land-use and land-cover change in tropical wetlands ... 15
1.2.2 Driving forces of land-cover change ... 17
1.2.3 Changing the global biogeochemical cycles ... 18

2 DESCRIPTION OF THE STUDY AREA AND OBJECTIVES ... 21
2.1 Summary ... 21
2.2 Geography ... 21
2.3 Climate ... 22
2.4 Soils of the Yala Swamp ... 23
2.5 Statement of research problem ... 25
2.6 Justification of the study ... 27
2.7 Objectives ... 27

3 MATERIALS AND METHODS ... 29
3.1 Satellite imagery ... 29
3.2 Processing and interpretation of satellite imagery ... 29
3.2.1 Change detection with digital imagery ... 30
3.3 Field surveys and sampling ... 31
3.3.1 Soil sampling ... 32
3.3.2 Vegetation sampling ... 33
3.4 Chemical analysis and green-house experiment ... 33
3.5 Spectral analysis ... 33
3.6 Statistical analysis ... 34

4 SPATIAL ANALYSIS OF LANDCOVER TYPES ... 35
4.1 Landscape characterization ... 35
4.1.1 Quantification of land cover change ... 39
4.2 Conclusion on land cover / land cover change ... 48

5 QUANTITATIVE AND QUALITATIVE CHARACTERIZATION OF SOIL CARBON POOLS ... 49
5.1 Summary ... 49
5.2 Introduction ... 50
5.3 Results and discussions ... 53
5.3.1 General descriptive statistics ... 53
5.3.2 Above-ground biomass C, N ... 56
5.3.3 C/N ratio ... 57

5.3.4 General correlations ... 58
5.4 Soil organic carbon (SOC) dynamics ... 60
5.4.1 Areas drained less than 20 years ago ... 60
5.4.2 Areas drained 20 to 40 years ago ... 60
5.4.3 Areas drained more than 40 years ago ... 61
5.5 SOC density ... 62
5.5.1 Carbon-dioxide emissions due to drainage in the Yala Swamp ... 64
5.6 The Nyando Swamp ... 66
5.6.1 Introduction ... 66
5.6.2 Results ... 68
5.6.3 Greenhouse gas emissions scenario for Yala and Nyando swamps ... 68
5.7 Conclusion ... 70

6 SOIL FERTILITY IN THE WETLAND AND RECLAIMED WETLAND SOILS USING PLANT PARAMETERS IN RELATION TO CHEMICAL ANALYSIS ... 71

6.1 Introduction ... 71
6.2 Observation and results ... 73
6.3 Conclusion ... 78

7 GENERAL CONCLUSIONS ... 79

7.1 Spatial analysis of the land cover ... 79
7.2 Quantitative and qualitative characterization of soil carbon pools ... 81
7.3 Soil fertility in the wetland and reclaimed wetland soils using plant parameters in relation to chemical analysis ... 83

8 REFERENCES ... 85

9 APPENDICES ... 93

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1 GENERAL INTRODUCTION

1.1 Wetland ecosystems

Wetlands comprise 6% of the Earth's surface (Williams, 1990). They are transitional between terrestrial and aquatic systems, and predominantly support hydrophytes, at least periodically. They occur in areas where soils are naturally or artificially inundated or saturated by water due to high groundwater or surface water during a part of or throughout the year. Wetlands are common in river deltas and estuaries, floodplains, tidal areas, and are widespread in riverbeds, depressions, foot slopes, and terraces of undulating landscapes. Wetland ecosystems may be discriminated on the basis of hydrology, soils, and vegetation and include swamps, marshes, bogs, fens, floodplains, and shallow lakes (Mitsch and Gosselink, 1993; Neue et al., 1997).

The Ramsar Convention defines wetland as marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceeds six meters (UNESCO, 1994). In agricultural ecosystems, wetlands may be defined as having free water at or near the surface for at least the majority of the growing season of arable crops, or for at least 2 months of the growing season of perennial crops, grassland, forest, or other vegetation. The water is shallow enough to allow growth of a crop or natural vegetation rooted in the soil. Free water may occur naturally or may be retained by: field bunds, puddled plow layers, traffic pans from rainfall run-off, or irrigation sources (Neue et al., 1997).

Tropical wetlands have at least one wet growing season per year but may be dry, moist or without water in other seasons. Wetland soils may therefore alternately support wetland and dryland plant species. Therefore, wetlands are ecotones. The boundary between wetland and dryland is often gradual, and may fluctuate from year to year depending on variations in precipitation. If water (drainage and irrigation) can be fully controlled it is within the farmer's discretion to establish either wet- or drylands. Despite that, the drainage capacities of most tropical wetlands are insufficient to prevent periodic soil submergence during the rainy season (Neue et al., 1997). This is due to lack of resources and understanding of the functioning of the wetland ecosystem.

Wetland aerial estimate is uncertain given the broad definition of wetlands (Mitra et al., 2003). Each country should formulate its definition based on the international definition. The Ramsar Convention requires all its parties to adopt and adapt the definition as is relevant to their territory. Each party is also required to make an inventory of wetlands within its territory and ensure the wise use of such wetlands. The contracting parties shall encourage research and the exchange of data and publications regarding wetlands and their flora and fauna. They shall also promote the training of personnel competent in the fields of wetland research, management and wardening (UNESCO, 1994).

1.1.1 Wetland types of Africa

The largest wetlands of Africa are the Sudd Swamp of Sudan, the Okavango Delta of Botswana, the Kafue/Bangweulu floodplains of Zambia, and the swamp forests of Zaire (Figure 1.1). East Africa contains wetlands that are smaller in size but nevertheless important in their ecological structure and functioning such as lowland valley swamps on the fringes of Lake Victoria (mostly in Uganda but a few on the eastern shores of Kenya) (Haper and Mavuti, 1996). Although wetlands of many types are found in Tropical Africa, the most distinct is perhaps the papyrus marsh (Williams, 1990). Papyrus (*Cyperus papyrus*) is a large sedge 3-5m in height but sometimes 10m (Jones and Humphries, 2002). It grows in dense stands along lake edges, most commonly in the vicinity of Lake Victoria. Papyrus marshes are absent in West Africa and the great riverine swamps of the Congo Basin.

Papyrus has a C4 photosynthetic pathway, an efficient mechanism found in most tropical grasses for fixing derivatives of atmospheric carbon-dioxide. Concentrations of nitrogen, phosphorus and other minerals are low in papyrus and other emergent macrophytes (Williams, 1990). However, papyrus concentrations of these elements are low within the macrophyte group, suggesting great efficiency in achieving growth under low nutrient conditions.

Papyrus also shares with other macrophytes the ability to extract minerals from infertile waters and sediments and to release, through decay and exudation, organic compounds that serve as energy sources for a variety of diverse consumer food chains, which in many places include humans.

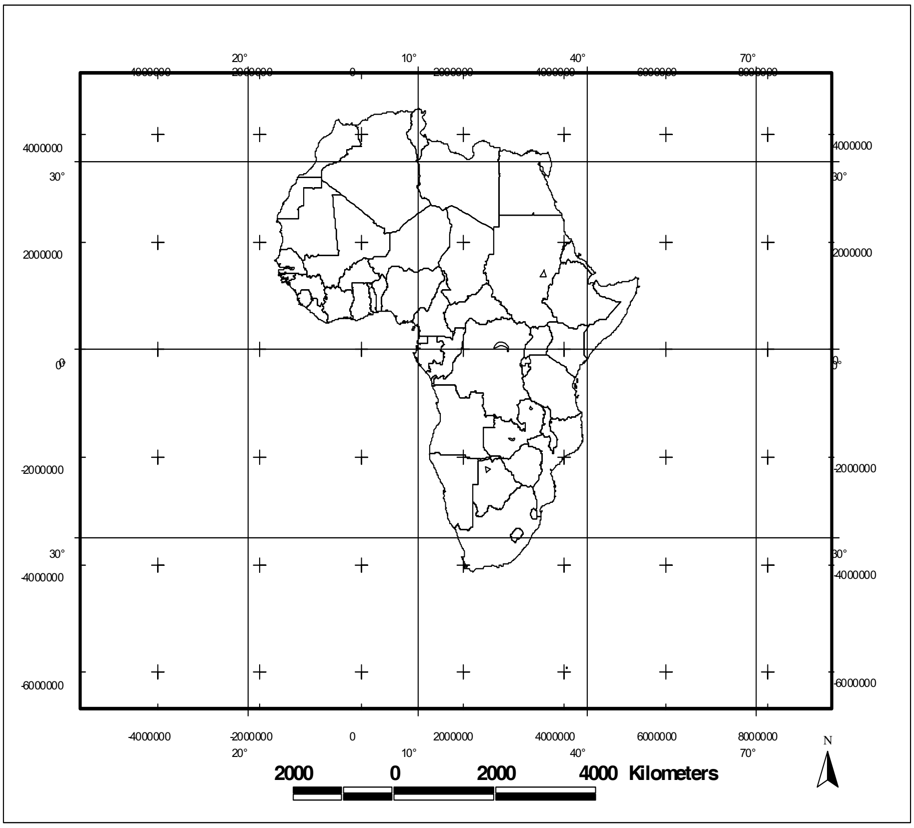


Figure 1.1: The largest wetlands of Africa (modified from Harper and Mavuti, 1996)

One of the major functions of wetlands is the enhancement of water quality by the trapping of suspended sediments in runoff from adjacent upland systems (Perison et al., 1997). Along Lake Victoria, well-developed papyrus marshes effectively remove sediments from water flowing in from adjacent savannahs, releasing high quality waters to the lake. Light intensity near the ground of the marsh is low. Therefore, efficiency of light capture by papyrus is high. Peat frequently develops beneath papyrus, sometimes accumulating to over 1m in depth. Peat accumulation is less obvious along lake edges and in open waters where papyrus forms a floating mat. In valley bottoms, papyrus peat is attractive for agriculture.

1.1.2 Wetland soils

The protection of wetland soils requires greater attention if soil C storage is to be increased in the humid tropics (van Noordwijk et al., 1997). Wetland soils are hydric soils, i.e. soils formed under conditions of saturation, flooding or ponding, long enough during the growing season to develop anaerobic conditions in the upper part (USDA, 1993). Hydric soils can be either organic or mineral soils. Organic soils formed in waterlogged situations, where decomposition is inhibited and plant debris slowly accumulates are called Histosols. All Histosols are hydric soils except Folists, which are freely drained soils occurring on dry slopes where excess litter accumulates over bedrock. Mineral hydric soils are those soils periodically saturated for sufficient duration to produce chemical and physical properties associated with a reducing or anaerobic environment.

Wetlands are complex ecosystems exhibiting considerable spatial variability. The soils there are physically unstable and in constant flux (Williams, 1990). A number of factors control the spatial relationships in these systems, making the separation of systematic from random soil components difficult. Systematic spatial relationships in wetland soils are the result of differences in parent material, elevation, erosional or depositional environment, frequency of flooding, vegetation, pedogenic effects, and hydrology (Stolt et al., 2001). Random effects are attributed to unrecognized differences in these parameters, as well as differences due to sampling and laboratory error. These random effects often obscure or confound soil-elevation, soil-vegetation, or soil-hydrology relationships. Therefore, to understand spatial relationships in wetland soils, random variability needs to be recognized and separated from systematic variability. A considerable difference in soil parameters can exist within a wetland area, even if the change in elevation is minimal (Stolt et al., 2001). For instance, significant differences in organic carbon and clay content occur between depressional wetland and a surrounding upland rim.

Wetland soil properties

Soil properties are strongly related to retention and movement of water within the soil system. Water serves as one of the primary energy sources for landscape processes, such as sequestration of organic carbon, erosion, colonization of vegetation, and distribution of soluble and mobile compounds (Reuter and Bell, 2001). The interaction between water level, sedimentation and decomposition is finely balanced, and within the soil there are biochemical processes at work such as energy flows through the ecosystem leading to the transformation and trapping of nutrients (William, 1990). The soil attributes that control nutrient availability in soils are organic matter content, soil moisture, pH, texture, sesquioxides content, and the type and amount of clay minerals (Iggy Litaor et al., 2002). Wetland soil development and properties are influenced by temporary or permanent saturation within the upper part of the pedon. If anaerobic conditions impose permanent characteristics on the soil, the term gley-phenomena or hydromorphic properties are commonly used (Neue et al., 1997). Gleyed soils develop when anaerobic soil conditions result in the pronounced chemical reduction of iron, manganese and other elements, thereby producing gray soil colors (USDA, 1993). Sulfidic material is present when mineral soils emit an odor of rotten eggs (hydrogen sulfide). Such odors are only detected in waterlogged soils that are permanently saturated and have sulfidic material within a few centimeters of the soil surface.

The correlation between water status, landscape and soil properties is well documented in pedologic studies (Reuter and Bell, 2001). Such studies indicate that correlation persists across land types and geographic locations. Landscape position and terrain attributes affect the distribution of soil properties such as A-horizon thickness and clay and organic carbon content. Also, a correlation exists between depth to water and soil color patterns in drainage basins. The relationships between duration and season of occurrence of soil saturation with soil color patterns are documented (Reuter and Bell, 2001). Trend surface analysis indicates significant relationships among elevation, vegetation, and soil chemical properties across a wetland (Stolt et al., 2001). A study by Brunet and Astin (1997) indicated that the vegetation strip on the flood zone of the Adour River accumulated large quantities of sediments with total nitrogen and carbon contents of 4mg/g and 30mg/g, respectively. The concentrations were found to vary as a function of topography and vegetation. The floodplains received less sediment but the observed concentrations of nitrogen and carbon were more variable and found in the range of 1-9 mg/g and 10-82 mg/g, respectively. The highest levels were found in wooded areas of the floodplain. A study by Davidson (1995) found that drainage class or soil wetness distinguished between C-rich and C-poor soils.

Spatial variability is important to consider when assessing the environmental and ecological functions of a wetland. Many wetland functions, such as floodwater storage, traps of sediments, and sinks of various non-point pollutants are difficult to measure directly. In lieu of direct measurements, soil and landscape properties can be recorded and then related to the potential of the wetland to function in one or more of these capacities (Stolt et al., 2001). The nature of the spatial variability must be considered to ensure that the full range of soil, landscape, and associated wetness conditions are described. Natural wetlands that are known to serve a number of functions are now used to serve as reference wetlands. Reference wetlands provide natural comparative sites for use as a marker of success or failure of adjacent wetlands.

Classification of wetland soils

Soil classifications do not deal with wetland soils but with hydromorphic soils, i.e. soils with defined long-lasting signs of periodically or permanently reducing soil conditions. Reducing conditions may not occur in soils or within wetland soils that contain considerable dissolved oxygen, lack decomposable organic matter in combination with high contents of calcium carbonates, or other factors that suppress the reducing activity of microorganisms (Neue et al., 1997). Many rice-growing countries have developed classification systems that discriminate between naturally wet and rice (paddy) soils (Sanchez and Buol, 1985). The only soil systems applicable worldwide are the Legend of the FAO-UNESCO Soil Map of the World (FAO, 1974) and the Soil Taxonomy (USDA, 1975).

In the FAO-UNESCO Legend for the Soil Map of the World (FAO, 1974), the Gleysols, Fluvisols, Planosols, and Histosols make up most of the wetland soils. Gleyic subunits of Acrisols, Luvisols, or Podzols are mostly wetland soils, too. Following the FAO nomenclature, a typical soil profile of a mineral wetland soil after weeks of flooding is as follows (Neue et al., 1997):

Horizon	Description
Afw	A layer of standing water (letter suffix 'fw' for floodwater) that becomes the habitat of bacteria, phytoplankton, macrophytes (submerged and floating weeds), zooplankton, and aquatic invertebrates and vertebrates. The chemical status of the floodwater depends on the source, soil, nature and biomass of aquatic fauna and flora, and cultural practices. The pH of the standing water is determined by the alkalinity of the rain or irrigation water,

soil pH, algal activity, and fertilization. As a result of algal growth and aquatic weeds, the pH and oxygen content undergo marked diurnal fluctuations. In the daytime, pH may reach above 10, and the standing water becomes over saturated with oxygen due to photosynthesis of the aquatic biomass. Standing water stabilizes the soil water regime, moderates the soil temperature regime and prevents soil erosion.

Aox A thin floodwater aerated soil interface (letter suffix 'ox' for oxidized) that receives sufficient oxygen from the floodwater to maintain pE + pH above the range where NH_4^+ becomes the most stable form of N. The thickness of the layer may range from several mm to several cm depending on pedoturbation by soil fauna and the percolation rate of water. Major processes are aerobic decomposition of organic matter, photodependent biological N_2^- fixation by algae and photosynthetic bacteria, nitrification by ammonium and nitrate oxidizers, and methane oxidation.

Ag A reduced layer (letter suffix 'g' for gleyic) that is characterized by the absence of free O_2 in the soil solution. The Eh of the soil solution is less than 300 mV, reduction processes predominate and the pE + pH is low enough to reduce iron oxides.

Ax This layer (letter suffix 'x' for deoxygenated) has increased bulk density, high mechanical strength, and low permeability. In cultivated soils it is frequently referred to as the plow pan or traffic pan. NH_4^+, Mn^{2+}, Fe^{2+} and, if the Eh is low enough, even sulfides and CH_4 are stable chemical forms.

B The characteristic of the B-horizon is highly dependent on the water regime. In epiaquic moisture regimes, the horizon generally remains oxidized, and redoximorphic features occur along cracks and in wide pores. In aquic moisture regimes, the whole horizon or at least the interior of soil peds remains reduced during most years.

Histosols (organic soils) are much less well defined. About 10% of the world's histosols are being farmed while only 5% of organic soils in the tropics may be used for rice farming and grazing. Clay minerals underlie most shallow histosols. These have considerable limitations for crop production because of their low bearing capacity and nutritional deficiency. Many of the shallow histosols have high levels of sulfur if the mineral is derived from marine sediments (Sanchez and Buol, 1985).

Organic soils within wetlands can be divided into two groups for agricultural production (mainly rice):

- Deep soils with the organic layer extending to a depth of 50 cm or more, and
- Shallow ones with a mineral horizon within 20 cm of the surface.

Attempts to grow rice in the deep organic soils have met with very limited success, while cultivation is possible in the shallow organics (Sanchez and Buol, 1985).

Biogeochemistry of wetland soils

Wetland biogeochemistry is controlled by flooding and the resulting status and pattern of oxidation and reductions (Mitsch and Gosselink, 1993). Wetland soils are different from most upland or aquatic soils and sediments because they often undergo intermittent flooding and draining, thus supporting both aerobic and anaerobic microbial communities that exploit a wide range of electron acceptors during respiration, such as O_2, NO^{3-}, Fe (III), SO_4^{2-} and CO_2 (D'Angelo and Reddy, 1999). Under favorable climatic, geomorphic and geologic conditions, wetlands in a watershed are capable of storing significant quantities of trace elements (Moldan and Cerny, 1994). The composition of terrestrial ecosystems within a watershed affects flooding pattern, groundwater level, water quality, sedimentation and erosion of wetlands (Mitsch and Gosselink, 1993). Irrigation, water harvesting, drainage, and cultivation practices influence agricultural wetland soil biogeochemistry. In order to evaluate the role of wetlands in moderating drainage water chemistry, as well as the effects of wetland disturbance on this important ecosystem function, the extent of trace metal storage and processes must be quantified.

Flooding a soil drastically changes its hydrosphere, atmosphere, biosphere, and biogeochemistry. Flooding decreases atmospheric oxygen diffusion to the soil by a factor of 10^5 and sets in motion a series of unique physical, chemical and biological processes not found in dryland soils (Neue et al., 1997) as described below. The nature, pattern, and extent of the processes depend on the chemical and physical properties of the soil, flooding duration, floodwater quality, soil and floodwater biosphere, management practices, plant growth, and climatic conditions.

After oxygen is depleted by aerobic respiration, facultative and obligate anaerobic organisms progressively use oxidized soil substrate as electron acceptors for their respiration. Denitrifying bacteria use nitrate as an alternative electron acceptor for oxidation of organic matter below a redox potential of +240 mV at pH 7. When nitrate is depleted, Mn (IV) reduction begins below +400 mV, followed by the reduction of Fe (III) at +180 mV. Various bacteria that use fermentation to obtain energy, with Mn (IV) and Fe (III) acting indirectly as electron acceptors, catalyze these reactions. This is coupled by the oxidation of simple organic substances. Obligate anaerobes reduce sulfate when the redox falls below –215 mV and methane is formed at –244 mV. Sulfate reducing bacteria produce a variety of sulfur gases, including hydrogen sulfide (H_2S) and dimethyl sulfide [$(CH_3)_2S$] (Mitsch and Gosselink, 1993; Neue et al. 1997). Once formed, hydrogen sulfide will readily react with Fe^{2+} or other heavy metal ions and precipitate or form carbon-bonded sulfur that accumulates in peat sediments. Large amounts of H_2S are formed within organic soils low in Fe^{2+} and high in SO_4^{2-}. Salinization of peat soils low in Fe increases H_2S production especially when aerated and reflooded. Prior to industrial emissions, the release of wetland biogenic gases was the dominant source of methane and sulfur gases into the atmosphere (IPCC, 1997).

Although reduction processes in flooded soils proceed stepwise through a thermodynamic sequence, oxidation-reduction reactions are only partially applicable to field conditions where redox potentials of a given redox reaction span a fairly wide range. Mineral phases present within soils are not pure and chemical reactions that are favored thermodynamically may not necessarily be kinetically favored. The equilibrium depends strongly on microbial growth and behavior and on the degree to which reacting products diffuse and mix. Nitrate and manganese reduction may occur at the same time, while sulfate reduction does not occur in the presence of O_2, NO_3^- or NO_2^-. Given the heterogeneous nature of soil systems with its spatial and temporal variability, different reduction processes may well occur simultaneously at separate locations.

The magnitude and strength of soil reduction is controlled by the amount of easily degradable organic matter, its rate of decomposition, and the amount and kinds of reducible nitrates, manganese, iron oxides, sulfates and organic substrates. The most important redox buffers in wetland soil are Fe (III)/Fe (II) and organic compounds because they are mostly present in large amounts. The C/N ratio of decomposable organic matter influences the soil reduction rate upon wetting, whereas the active iron content defines the reduction capacity of the soil. Soils low in active iron but high in degradable organic matter may attain redox values of less than -200 mV within two weeks after submergence. In soils high in both organic matter and reducible iron, the redox potential may rapidly fall to –50 mV and slowly decline further for weeks before leveling off (Neue et al., 1997).

1.1.3 Decomposition of organic matter in wetlands

Decomposition of organic matter can determine productivity and water quality within wetlands (McLatchey and Reddy, 1998). It influences the flow of nutrients within the systems. Carbon flow through the organic matter of soil is important to the functioning of the terrestrial ecosystems (Manjaiah et al., 2000). The release of nutrients during decomposition depends on the composition of substrates, temperature, Eh and pH, hydrologic regime, quantity and type of clay minerals, microbial activity and supply of electron acceptors, e.g. O_2, NO_3^-, SO_4^{2-} (Manjaiah et al., 2000; McLatchey and Reddy, 1998). In tropical and subtropical climatic conditions, in addition to the above parameters, the type of vegetation or crop and land-use management practice clearly affects soil organic C and N stocks and their storage profiles (Manjaiah et al., 2000). Most of the organic matter in wetlands comprises plant-derived complex polysaccharides such as cellulose and lignin, which are broken down into simple monomers by the action of extracellular enzymes (McLatchey and Reddy, 1998).

Many transformations in wetlands are directly mediated by diverse groups of aerobic and anaerobic microorganisms in the soil (D'Angelo and Reddy, 1999). Microbial activities also indirectly influence redox potential and pH-sensitive processes, such as trace metal and phosphorus solubility, precipitation, sorption and hence mobility. Flooding a soil considerably alters micro- and macro-faunal communities and activities. Bacterial anaerobic fermentation of organic matter predominates and actenomycetes, fungi, and yeast are less active in the soil. Anaerobic fermentation, however, does play an important role in the decomposition of reduced carbon. It comprises the breakdown of complex substrates prior to oxidation, resulting in an array of substances, many of them transitory and not found in well-aerated soils (Neue et al., 1997). Although many wetlands receive inputs of C and nutrients from adjacent watersheds and urban areas, which affect water quality and stimulate growth of water vegetation, a significant portion of the nutrient release occurs as a result of organic matter decomposition (McLatchey and Reddy, 1998).

Short-term H_2 evolution immediately follows the disappearance of O_2 in the first days after flooding. Thereafter, CO_2 production increases and, finally, with decreasing CO_2, CH_4 formation increases. At high temperatures, the formation of CO_2 and CH_4 occurs earlier and stronger, while that of organic acids is also earlier but smaller in amount (Neue et al., 1997). Organic matter decomposition in the absence of free oxygen, as found for wetland soils, relies on the re-oxidation of intracellular electron acceptors produced by catabolic reactions. The two general mechanisms of re-oxidation are fermentation and anaerobic respiration. Fermentation alone does not result in carbon mineralization (except for some conversions from acetate to methane and carbon dioxide) because it does not involve externally supplied electron acceptors. Instead, it uses organic acceptors that are intracellularly generated.

1.1.4 Oxidation–reduction sequence of inorganic substances

1. Disappearance of O_2	$O2 + 4H + 4e \rightarrow$	$2H_2O$
↓		
2. Disappearance of NO_3^-	$NO_3^- + 2H + 2e \rightarrow$	$NO_2^- + H_2O$
↓		
3. Disappearance of NO_2^-	$4NO_2^- + 12H + 8\ e \rightarrow$	$2\ N_2O + 6H_2O$
↓		
4. Formation of Mn^{2+}	$MnO_2 + 4H + 2e \rightarrow$	$Mn^{2+} + 2H_2O$
↓		
5. Reduction of Fe^{3+} to Fe^{2+}	$Fe\ (OH)_3 + 3H + e \rightarrow$	$Fe^{2+} + 3H_2O$
↓		
6. Formation of H_2S	$SO_4^{2-} + 10H + 8e \rightarrow$	$H_2S + 4H_2O$
↓		
7. Formation of CH_4	$CO_2 + 8H + 8e \rightarrow$	$CH_4 + 4H_2O$

Waterlogging can greatly retard organic matter decomposition, leading to accumulation of organic matter, as it is evident for peat soils. Decomposition is retarded in flooded soils with low and imbalanced nutrient supply, and low biological diversity and activity. Accumulation of organic matter requires continuous flooding and low redox potentials, high soil acidity and inhibitory effects of protonated organic acids in addition to flooding, and a relatively high net primary production of organic matter. If waterlogging causes an incomplete anaerobic decomposition, wetlands become sinks for carbon and nutrients. Evidence of this exists in temperate wetlands. However, not all wetlands, even if waterlogged, accumulate carbon. The balance between organic matter inputs and decomposition is the primary determinant (Neue et al., 1997).

A diversity of biological, chemical and physical mechanisms is known to selectively protect different pools of soil organic matter from decomposition by soil micro-organisms. These are associated with the amount of protected C pools. Chemical inhibition of decomposer organisms is often the result of chemical attributes that protect the live plant tissues from disease and pest attack. Intimate chemical bonding between organics and minerals also limits substrate accessibility to decomposers. Physical barriers to decomposition result from occlusion by clay minerals and exclusion of organisms from certain pore size classes. Particulate organic materials that would otherwise be subject to rapid decomposition are bound within soil aggregates, resulting in their stabilization (van Noordwijk et al., 1997).

1.2 The effect of land-use and land-cover change on carbon pools

The pace, magnitude and spatial reach of human alterations of the Earth's land surface are unprecedented (Lambin et al., 2001). Changes in land use or land cover impact soil organic carbon (Lantz et al., 2001; Houghton, 2002). They explain a large part of the carbon sink in northern mid-latitudes and indicate a large source in the tropics. The better these fluxes or emissions from land-use change are defined in terms of their magnitude, location, temporal pattern, and mechanisms, the more predictable the behavior of future emissions (Houghton, 2002). Land cover is defined as the layer of soil and biomass, including natural vegetation, crops and human structures, which cover the land surface (Dolman et al., 2003). Land-use refers to the way in which humans exploit the land cover (Lambin et al., 2001). Land-use and resource policies will both affect and be affected by changes in the atmosphere (United Nations Conference on Environment and Development, 1992). Land-cover change is the complete replacement of one cover type by another, while land-use changes also include the modification of land-cover types, e.g. intensification of agricultural use, without changing its overall classification. Land cover change may be the most significant agent of global change. For instance, it has an important influence on the hydrology, climate, and global biogeochemical cycles. And it is an important input variable to other areas of global change research. It is also an issue with far reaching policy implications, internationally, nationally and locally. Indeed land cover change is linked to policy and sustainable development as it is to basic research issues (Skole et al., 1997).

Natural and sensitive areas such as evergreen forests, flooded forests, deltaic systems, mangrove forests and wetlands, among others, constitute ecosystems of particular importance. This is not only because of their physical support to a vast variety of animal and vegetal species, but also because of their intervention in climatic and hydrologic local or regional events (Gomez and Medina, 1998). Wetlands are sensitive ecosystems that are subject to stress from human activities (van den Bergh et al., 2001). This includes changes in land use, resource extraction and drainage. Wetlands accumulate organic materials and have properties of water retention. Therefore, they have a global impact on the cycling of carbon and of water (Moore, 2002). They are also valuable for the conservation of biodiversity. The Yala Swamp, along Lake Victoria, in Western Kenya, the subject of this study, is already under pressure from agriculture (Gichuki, 2001).

The individual human activities that lead to land-use change are meant to meet locally defined needs and goals, but aggregated they have an impact on the regional and global environment (Dolman et al., 2003). They may affect biodiversity, water and radiation budgets, trace gas emissions and other processes that, cumulatively, affect global climate and biosphere (IPCC, 1997). Change in land-use typically results in differing rates of erosion, aggregation formation, biological activity, and drainage, which all have a significant impact on SOC accumulation and CO_2 evolution (Lantz et al., 2001). Table 1.1 shows the estimated size of global carbon pools and changes since 1800.

Table 1.1: Estimated size of global carbon pools and changes since 1800 (Boyle and Lavkulich, 1997)

Reservoir	Carbon Pg	%	Change since 1800 (%)
Ocean			
Intermediate and deep	35 000	72	<1
Surface	900	2	<1
Fossil Fuel	10 000	21	- 2
Atmosphere	755	2	27
Soil	1 200	2	- 2
Biota	550	1	- 27

Land-use change is linked to the theme of transition to a sustainable world. As reported in the Brundtland report and in Agenda 21, the overarching concern is achieving sustainability in a warmer, more crowded, and more resource-demanding world characterized by unexpected and extreme events (Dolman et al., 2003). Land-cover change alters ecosystem services, and affects the ability of biological systems to support human needs (Lambin et al., 2001).

A better understanding of land-use change is essential to assess and predict its effect on ecosystems and society (Lantz et al., 2001). This will allow for effective land-use policy that can be implemented to curtail the rate of carbon dioxide emissions specifically from wetlands to the atmosphere. The inventory of greenhouse gas emissions and the reduction objectives need to include changes in emissions caused by land- use change. Rates and patterns of land-use change need to be understood to design appropriate biodiversity management. Areas of rapid land-use change need to be identified to focus land-use planning on the appropriate regions (Dolman et al., 2003).

There are many methods of investigating land-cover and land-use change, ranging from the micro, macro, to the multi-scale. Rooted in the natural rather than in the social sciences, geographers and ecologists have focused on land-cover and land-use at the macro-scale, spatially explicit through remote sensing and GIS, and using macro properties of social organization to identify social factors connected to the macro-scale pattern (Dolman et al., 2003). This is the case in this study.

1.2.1 Land-use and land-cover change in tropical wetlands

In the past, wetlands were considered to be wastelands and worthless, and change and transformation were predominant themes when considering them (Williams, 1990). Many of the world's remaining wetlands are in poor countries, or in the poorest regions of the rich countries (Maltby, 1986). They have survived because they are in places that have discouraged developmental processes and agricultural production due to drainage problems, low fertility, risk of diseases (e.g., malaria) and inaccessibility (Food and Agriculture Organization of the United Nations (FAO), 1988). These wetlands have now become increasingly attractive options for agricultural expansion and intensification in developing and often hungry countries (Maltby, 1986).

In recent decades, wetlands have assumed a new attraction and value. On the one hand they are still reduced in size, as modern draining techniques make them even more attractive as potential agricultural land, and their flatness, coastal location and perceived worthlessness still make them obvious locations for large plants, harbors and waste disposal. Therefore, wetlands are truly threatened landscapes. On the other hand, they have become more appreciated and valued as their hydrological-physical, chemical, biological functions and socioeconomic benefits are recognized. In addition wetlands are increasingly perceived as an environment where air, water and land, and their fauna and flora meet in an attractive and delicate way. This has excited scientific and popular imagination (Williams, 1990).

There are a number of major landscapes that have caught the attention of many scholars as a focus for their studies. For example, tropical rainforests and savannas, arid lands, tundra lands, polar lands, and Mediterranean lands have all at some time or another been studied by people from different disciplines from their varying points of view. Wetlands are another such major landscape, but it is only since the 1960's that they have attracted the attention of a range of scholars in an effort to understand their variety and complexity (Williams, 1990). They are one of the most fruitful areas of archaeological research, and they are an ideal setting in which to study the interactions between physical processes and human actions that encapsulate and exemplify many of the themes of mankind's impact on his environment. Also, the newfound beneficial functions of wetlands seem to be in danger due to drainage and infilling.

There is a growing tendency towards reclaiming swamps by drainage as is the case in Kalimantan and Sumatra (Indonesia), which have 26 million ha of swamps, in the Sudd (Sudan) with permanent swamps of 13 million ha, and in the Patanal (Brazil) with 17 million ha of swamps (Neue et al., 1997). Conversion of natural ecosystem to agriculture in the tropics leads to the immediate removal of aboveground biomass, and gradual subsequent reduction in soil organic carbon (van Noordwijk et al., 1997). The special character of wetland landscapes and the underlying soils is often not recognized, and reclamation follows the same pattern as for mineral soils (FAO, 1988). A variety of drainage systems is used in agriculture, such as ditch drains, mole drains, pipe drains and drainage wells. These may increase transport not only of water but also of agrochemicals and nutrients to watercourses or groundwater. In wetlands, the effects of drainage can be an increase in rate of nitrogen mineralization, sulphur oxidation and substrate decomposition. This results in a release of, in particular, ammonia, nitrate, sulphate and organic acids. This increased anion mobilization results in increased leaching of cations such as calcium and magnesium in nutrient-rich soils or protons and aluminium in nutrient-poor acid soils (Moldan and Cerny, 1994). In contrast, gaseous emissions such as N_2O and CH_4 are reduced due to an increase in aeration.

The urgent need to feed people is a very convincing argument, but it tends to treat the goal of local increase in food production in isolation. Draining wetland may increase local yields over the short term, but may cause large reductions in yields everywhere in the ecosystem, or reduce the entire ecosystem's ability to sustain harvests over the long term (Maltby, 1986). Draining of marshes that develop upon marine clays often leads to formation of highly acid -rich soils (e.g. cat clays), which become so highly acidic as to be toxic to plants, resulting in barren land (Williams, 1990).

The United Nations Framework Convention on Climate Change (UNFCCC) is committed to promote sustainable management, cooperation in the conservation and enhancement of sinks and reservoirs of all greenhouse gases not controlled by the Montreal protocol, including biomass in forests and oceans as well as in other terrestrial ecosystems such as wetlands (UNEP, 1998). Through the Kyoto protocol the net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under Article 3 of each Party included in Annex I. The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner and reviewed in accordance with Articles 7 and 8. There is no doubt that wetlands are among the most important sources and sinks of greenhouse gas emissions.

The parties included in Annex I under the Kyoto protocol should cooperate in the promotion of effective modalities for the development, application and diffusion of, and take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies, know-how, practices and processes pertinent to climate change, in particular to developing countries. The exploitation of wetland resources in developing countries should be based on expert knowledge to minimize emissions of greenhouse gases.

1.2.2 Driving forces of land-cover change

Land-use and land-cover change is driven by a combination of:

- Biophysical factors which determine the capability of land use;
- Technological and economic considerations which determine the socioeconomic feasibility of land use, and
- Institutional and political arrangements that determine the acceptability of land use.

The complexity of land-use and land-cover change is manifested in the multifunctionality of land: climate change policies interact with several other policy issues such as food production, forestry, recreation and biodiversity conservation.

In the tropics, demand for agricultural land continues to be one of the main driving forces of land-cover changes such as deforestation of the tropical rainforests, drainage of wetlands, and cultivation of marginal lands (Dolman et al., 2003). Wetland drainage for agriculture results in loss of carbon to the atmosphere, adding to the greenhouse effect (Moore, 2002). An excess of decomposition caused by draining leads to wetlands becoming a carbon source (Chimner et al., 2002).

Land-use and land-cover change are the result of many interacting processes. Each of these processes operates over a range of scales in space and time (Dolman et al., 2003). Often, the range of spatial scales over which the driving factors and associated land-use change processes act corresponds with levels of organization in a hierarchically organized system characterized by their rank ordering. Examples of levels include organism or individual, ecosystem, landscape and national or global political institution. Changes that occur in the Yala Swamp are directed from the individual level to the global political level. Individuals are eking out a living from the goods and services provided by the natural resources from the swamp. In the 1970s, the Kenya Government initiated a drainage project funded by a global organization, the World Bank, to increase food production in the area. The project was not successful, but recently, a private organization from the USA, started planning to utilize the drained area for intensive agricultural production.

1.2.3 Changing the global biogeochemical cycles

Globally, the land surface is a non-negligible factor in the carbon (Figure 1.2) and nitrogen cycles. Table 1.2 shows that 20% of the current atmospheric CO_2 concentration can be attributed to emissions due to land use change, which remained almost constant between the 1980s and 1990s. Land-use thus plays an important part in the biogeochemical cycles.

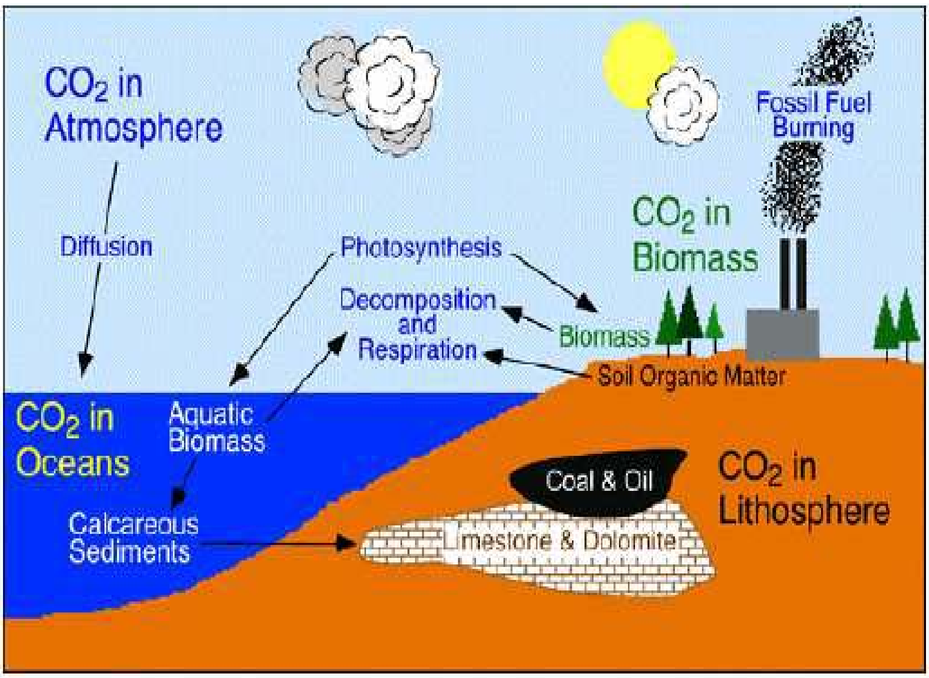


Figure 1.2: The Carbon cycle (Source: NASA)

At the earth's surface, vegetation and soil interact with the atmosphere to produce complex flows and exchange of water, nutrients and heat. Carbon and nitrogen change from fast rotating pools and atmospheric storage to more slowly rotating pools, and may eventually get locked up in long-term, very slowly changing pools (Dolman et al., 2003).

Table 1.2: Global carbon balance for the 1980s and 1990s (Source: Schimel et al., 2001; IPCC, 2000)

	1980s (Gt C yr-1)	1990s (Gt C yr-1)
Emissions (fossil fuel burning and cement manufacture)	5.4 ± 0.3	6.3 ± 0.4
Atmospheric increase	3.3 ± 0.1	3.2 ± 0.1
Ocean-atmosphere flux	-1.9 ± 0.5	-1.7 ± 0.5
Land-atmosphere flux	-0.2 ± 0.7	-1.4 ± 0.7
Emissions due to land-use change	1.7 ± 0.8	1.6 ± 0.8
Residual terrestrial sink	-1.9 ± 1.3	-2.3 ± 1.3

Table 1.3: Increase in the three main greenhouse gases (GHG), their global warming potential (compared to CO_2) contribution to radiative forcing (Source: IPCC Third Assessment Report)

GHG	Period 1000-1750	Present	Global Warming Potential	Increase in RF (W/m^2)
CO_2	280 ± 6 (ppm)	368 (ppm)	1	1.5
CH_4	750 ± 60 (ppb)	1750 (ppb)	21	0.5
N_2O	270 ± 10 (ppb)	316 (ppb)	310	0.15

Table 1.3 shows the impact of three major greenhouse gases on the radiative forcing of the atmosphere. A change in the net radiative energy available to the global Earth-atmosphere system is referred to as radiative forcing (IPCC, 1994). All three gases are formed or taken up at the earth surface (Figure 1.2). The increase of these gases has occurred since the industrial revolution.

The increase is considerable, but in the short term, a considerable reduction in the global warming may be obtained if the emissions of CH_4 and N_2O are curbed. In the longer term, CO_2 emissions have of course to be reduced by introducing new energy sources and improving energy efficiency. Emissions of CH_4 and N_2O are mainly caused by agricultural practices. Agricultural practices increase the amount of CH_4 and N_2O

released, but also of CO_2, mainly because humans manipulate the carbon and nitrogen cycles to produce food.

CO_2 remains the most important greenhouse gas (Dolmann et al., 2003). The political significance of the land surface increased significantly, since the Kyoto protocol recognizes the potential of the land to sequester carbon. At the third conference of the parties in Kyoto, for the first time, the parties of the industrialized world agreed to limit their emissions of greenhouse gases by a fixed amount (Dolmann et al., 2003). To achieve these reductions, the protocol included the possibility of using the terrestrial biosphere to sequester carbon. This is found in paragraphs 3.3 and 3.4 of the protocol.

Land management and changes in land-cover, however, can also be used to mitigate the effects of climate change (Vlek et al., 2003). The major ways in which these could be achieved relate to stopping or slowing down current deforestation and drainage of wetlands. Restoration efforts in the tropics, such as creation of wetlands, should also be undertaken for carbon sequestration.

2 DESCRIPTION OF THE STUDY AREA AND OBJECTIVES

2.1 Summary

Wetlands perform a variety of ecological and hydrological functions that benefit humans (Mitsch and Gosselink, 1993). Kenya's wetlands are among the country's most important natural resources for socio-cultural and economic development. The Yala Swamp occurs in a densely populated area dominated by small-scale farming, where its ecosystem services and products are highly needed. Local communities depend much on the wetland for their livelihood.

The dominant vegetation of the Yala Swamp is primarily *Cyperus papyrus* with swamp grasses along the edge of most inundated places, and *Phragmites mauritianus* on the drier and higher ground. Further inland, the swamp has a dense mixture of *Phragmites* and *papyrus* reeds. In open water, common macrophytes include *Potamogeton pectinatus*, *Ceratophyllum demersum*, *Typha latifolia*, *Phragmites mauritianus*, *Echinocloa* sp. and *Polygonum* sp. (Mavuti, 1992). Therefore, a gradient can be easily identified in the wetland environment.

2.2 Geography

The Yala Swamp is a deltaic wetland along Lake Victoria (LV) in Western Kenya (Figure 2. 1), dominated by *Cyperus papyrus* vegetation. It is located between rivers Yala and Nzoia, 0° 07’ N – 0° 01’ S / 33° 58’ – 34° 15’ E and was formed as a result of backflow of water from LV (Hughes and Hughes, 1992). The swamp is separated from the LV shore by a 5 km sandbar. It encompasses the Nzoia Delta, the entire lakeshore south to Ugowe Bay, and the entire land east to Lake Kanyaboli. The Nzoia River, with an average discharge of 115.3 m^3s^{-1} into LV, enters the swamp from the northern side, while the Yala River with an average discharge of 37.6m^3s^{-1} into LV, which has been canalized to some extent, enters from the southern end (East African Community). The swamp covers a total area of 30 000 ha including Lake Kanyaboli (1 500 ha) and stretches 25 km west-east direction and 15 km north-south (Hughes and Hughes, 1992). Several minor lakes are included in this system, e.g., the lakes Sare and Nambeyo (Mavuti, 1992; Hughes and Hughes, 1992). The swamp is shared between the Siaya and Busia districts.

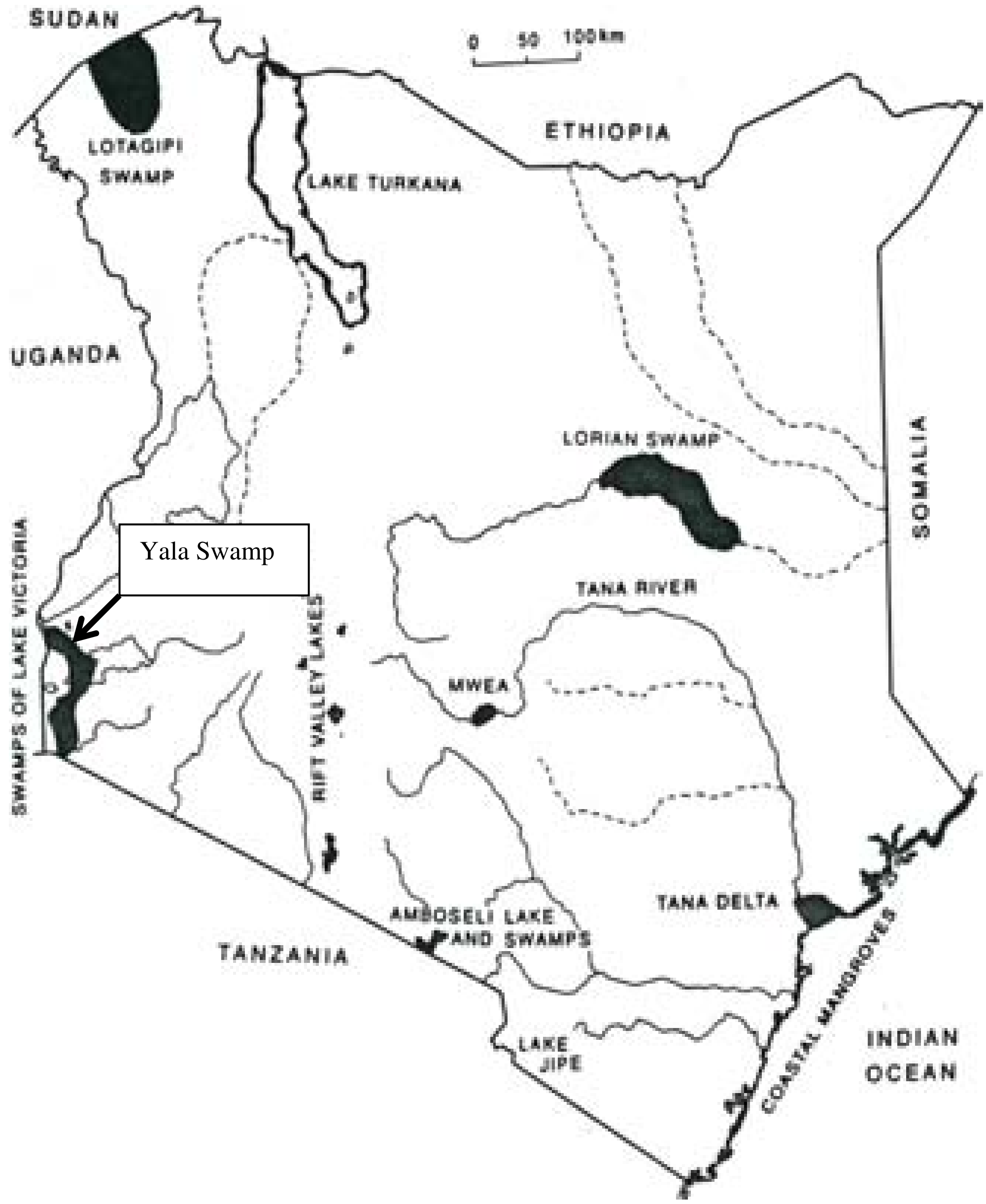


Figure 2.1: Map of major wetlands of Kenya (Source: Howard, 1992)

2.3 Climate

The Yala Swamp falls in the Lake Victoria region and has no real pronounced dry season. The region has a variable rainfall pattern, but generally it increases from the lake shoreline to the hinterland (Ekirapa and Kinyanjui, 1987). The mean annual rainfall in this part of Kenya ranges from 1055-1157 mm (Figure 2.2) and is bi-modal. Long rains occur in the March-May period, and short rains in the October-December period. The long rains and short rains contribute 44% and 25% of the total mean annual rainfall

(TMAR), respectively. January-February and June-September contribute 11% and 20% of TMAR, respectively.

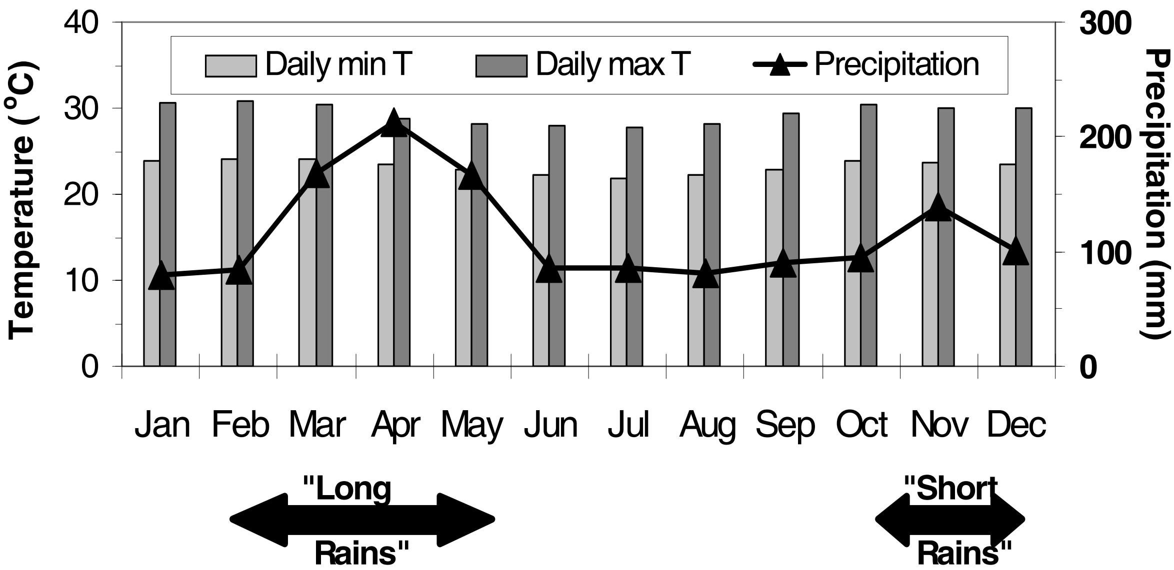


Figure 2.2 Weather in Kisumu / Western Kenya

The mean annual daily maximum and minimum temperatures are 28.9°C and 15.9°C, respectively. Therefore, the mean annual temperature is 22.4°C.

2.4 Soils of the Yala Swamp

Soils in the Yala Swamp consist of eutric Fluvisols, dystric Histosols and humic Gleysols (Sombroek et al., 1982). Fluvisols are soils showing fluvic properties and having no diagnostic horizons other than ochric, mollic, or umbric A-horizons, or histic H-horizon or sulphuric horizon, or sulfidic material within 125 cm of the surface (FAO-UNESCO, 1990). The eutric Fluvisols are a complex of well-drained to imperfectly drained, very deep, dark grayish brown to dark reddish brown, stratified soils of varying consistencies and textures (Sombroek et al., 1982). These occur along the Yala River and drainage area (Figure 2.3). Histosols are soils having 40 cm or more organic soil materials either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rock or on fragmented material in which the interstices are filled with organic matter (FAO-UNESCO, 1990). The dystric Histosols are very poorly drained, very deep, dark grey to black, firm clay with acid humic topsoil and in many places peaty, permanent swamps (Sombroek et al., 1982). Gleysols are soils formed from unconsolidated materials, exclusive of course-textured materials and alluvial deposits which show fluvic properties, which are gleyic within 50 cm of the surface and have no diagnostic horizons other than the A horizon, a histic H horizon, a cambic B horizon, and a sulfuric, calcic or gypsic horizon (FAO-UNESCO, 1990). The humic Gleysols are very poorly drained, very deep, very dark grey to black firm cracking clay, with an acid humic topsoil typically found in the northern part of the wetland.

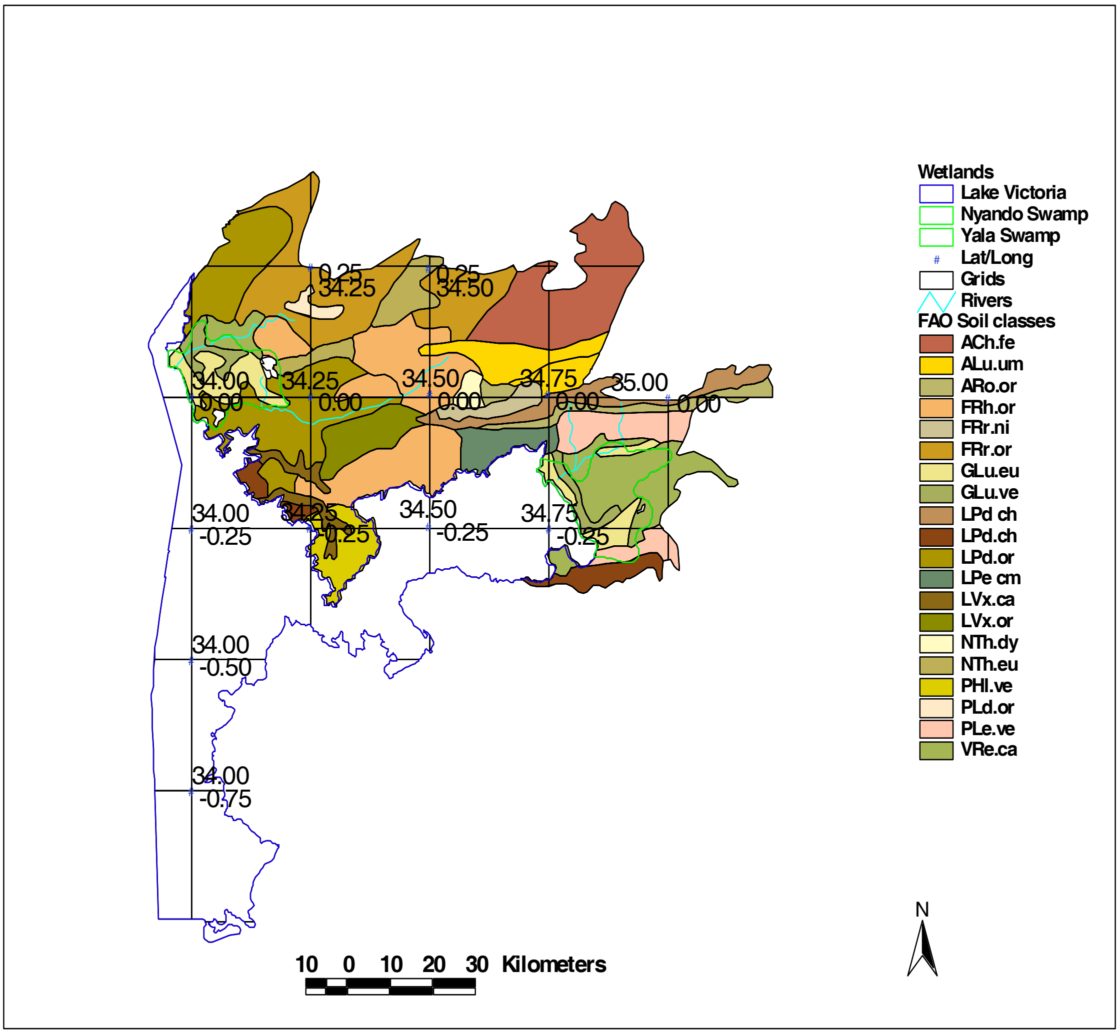


Figure 2.3: Soils of Western Kenya (Source: World Agroforestry Centre).

2.5 Statement of research problem

Africa south of the Sahara is the only remaining region of the world where per capita food production has remained stagnant over the past 40 years (Sanchez, 2002). About 180 million Africans do not have access to sufficient food to lead healthy and productive lives, making them more susceptible to the ravages of malaria, HIV and tuberculosis. Absolute poverty characterized by incomes of less than $1 per person per day is coupled with increased damage to the natural resource base such as wetlands. Western Kenya is a region where the majority of the population are rural poor, and where malaria and HIV are rampant.

The Yala Swamp is located along Lake Victoria, where there is a rapid increase in the human population. Average population density for the Luo people, who inhabit the swamp area, rose to 150 people per km^2 by 1970 (Mango, 1999). The population density in the area almost doubled between 1969 and 1998, with the average population density reaching 250 people/km^2. The growing population in the Lake Victoria basin has accelerated changes in land use, resulting in increased run-off of sediments and nutrients (Beeton, 2002). Clearing of riparian vegetation has led to erosion and loss of vegetation that acted as filters. Land clearances in the area accelerated in the 1960s (Beeton, 2002). Intense population growth and unsustainable exploitation of natural resources in and around the lake are eroding the livelihoods of people (Swedish International Development cooperation (SIDA), 2000). Environmental deterioration is increasing poverty, and poverty is exacerbating environmental degradation.

The Yala Swamp is located in a relatively high-potential agricultural area in Kenya, i.e., western Kenya; this acts partly as a driving force for its exploitation in agricultural development. Communities living near this wetland ecosystem use it as a source of food items, medicine, building materials and grazing among others. For example, phragmites plant materials are used by the local people for making fish traps, while papyrus reeds are used for making baskets, mats and thatching. However, with the increasing population pressure, the wetland is currently perceived more as an alternative fertile farming area.

From 1965-70, the swamp was partly reclaimed by the Kenya Ministry of Agriculture (Figure 2.4). The swamp was separated from Lake Kanyaboli by a dyke, which later collapsed. River Yala used to flow into the swamp, but was canalized over a length of 7km. The result was drainage of part of the swamp and formation of the Yala Farm covering about 2 300 ha (Ekirapa and Kinyanjui, 1987). The crops envisaged to be grown in the Yala farm were maize, beans, sorghum, rice, coffee, citrus fruits, cabbages, kales, tomatoes, sugarcane, and various orchard crops. Currently, the Lake Basin Development Authority (LBDA) manages a small portion of the farm, and free holder farmers, who in addition to growing the afore-mentioned crops, also grow cassava and bananas, manage the rest.

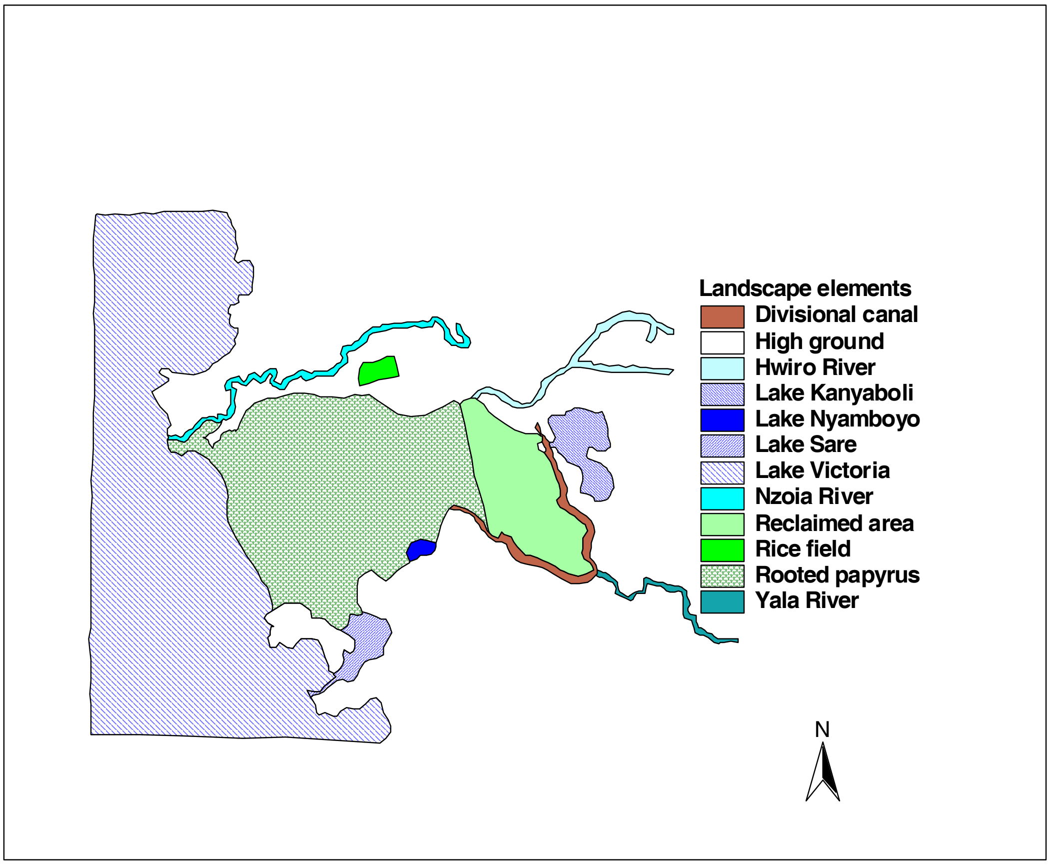


Figure 2.4: Map of the Yala Swamp showing drained area (modified from Mavuti, 1992)

Drainage of the swamp still continues, as small-scale farmers, who do not have access to the Yala farm, drain the margins of the swamp. Smallholder farmers in the area are forced to engage in increasingly desperate and unsustainable use of natural resources. This includes cultivation of marginal and fragile areas such as wetlands

(SIDA, 2000). Drainage of wetlands does not follow the Ramsar Convention's wetlands 'Wise Use' concept. In Kenya, the problem is compounded further by lack of information for farmers who regard swamps as high-potential agricultural areas like floodplain and forest riverine wetlands. An understanding of the biogeochemical cycles of the Yala wetland and other wetlands is important in case of an emerging carbon market under the Kyoto protocol. This can help in promoting sustainable utilization of the wetland, and meeting the wise use concept of the Ramsar convention by local communities, the Government of Kenya, countries in the Lake Victoria region and in Africa. This study aims at analyzing carbon pools on natural and managed areas in the Yala swamp along wetland disturbance and environmental gradients.

2.6 Justification of the study

Wetlands of tropical areas when compared with those found in temperate regions are insufficiently studied (FAO, 1988). Most wetlands' research in Kenya has been concentrated in the large lacustrine wetlands of the Rift Valley formation, e.g., Lake Naivasha and Lake Victoria. Other studies were carried out on riverine wetlands including flood plains such as the Tana River, which are important especially for the ecosystem services they provide such as water supply, floodplain farming and grazing areas. The swamp areas are not well understood, but at the same time the importance of their structural components and ecosystem functions cannot be overlooked. The carbon pools of wetland systems in Kenya have not yet been studied. Numerous studies have been carried out on carbon pools in terrestrial environments but most focused on forest ecosystems (Follett and Stewart, 1998). Therefore, this study will help fill this existing gap on available information, and assess the human impact on carbon pools. Also, there is shortage of people with expertise on wetlands in Africa.

2.7 Objectives

The objectives of this study can be grouped into three clusters. The first cluster is aimed at a spatially explicit characterization of landscape components and land-use changes:

A. Develop a GIS-based framework on topography, soils and landscape components (water bodies, vegetation cover and agricultural land) derived from maps.

B. Supplement geographic information on the different landscape components through remote sensing analysis in combination with ground-truthing.

C. Compile a time series of vegetation cover over the last two decades and quantify the area affected by land-use change.

The second cluster of objectives covers analyses of carbon pools to derive emission estimates:

D. Analyze present carbon content in soils and vegetation along wetland disturbance and environmental gradients.

E. Combine data on land-use change (see C) and carbon pools (see D) to quantify C emissions involved.

F. Design different development scenarios (using policy assumptions, landscape map, etc.) and quantify carbon emissions involved.

The third cluster of objectives sets the results obtained through this case study into a broader context:

G. Extrapolate carbon emissions to similar wetlands in the Lake Victoria Basin for up-scaling the regional source strength of wetlands.

3 MATERIALS AND METHODS

3.1 Satellite imagery

Recent research has shown that remote sensing data can provide a synoptic and repeatable source of information to overcome difficulties in multitemporal characterization of wetlands, which arise from their size and the complexity within such landscapes (Munro and Touron, 1997; Lilisend and Keifer, 1987). Remote sensing data sets (image subsets) of the Yala Swamp were obtained from DLR for this study. These were a Landsat TM image acquired on 31 December 1984, and a Landsat ETM image of 02 February 2001. TM bands 3, 4, 5 that correspond to the green, red, and near-infrared part of the image reflectance spectra, respectively, were selected to characterize changes in the distribution of marshland. Landsat ETM spectral bands 2, 3 and 4 were chosen for this study based on the proven suitability of these bands for wetland studies (Harvey and Hill 2001; Seto et al., 2002). Other bands from the images were also used to detect changes in moisture level and vegetation health in the wetland and its vicinity.

3.2 Processing and interpretation of satellite imagery

The acquired images were processed and classified in the ENVI digital image processing software to produce landscape structure (land cover) maps. The distribution of marshland was assessed by mapping of water and vegetation, identified by their different spectral signatures in remote sensing data. First, unsupervised classification was performed, followed by supervised classification. Unsupervised classification is preferred in most wetland studies because of difficulties in selection of training sites due to the heterogeneous arrangement of cover types (Harvey and Hill 2001; Wang et al. 2002). However, supervised classification was deemed important after ground-truthing. Ground control points were selected from the Landsat ETM subset for truthing using Aster images acquired in February 2002. Aster images have a higher spatial resolution of 15 m as compared to 30 m for Landsat (EROS Data Center). Training areas covering water, marsh vegetation and agricultural land were selected to train an image classification algorithm of the chosen bands. Selection of the training areas relies very much on visual interpretation of color composite images and as such is able to take account of object shape and spatial context (Munro and Touron, 1997; Lilesend and Keifer, 1987).

Arc View GIS 3.2a was used to overlay the GIS coverages obtained from the World Agroforestry Center. The coverages used were data sets on soils, climate, vegetation and topographic maps of Western Kenya. The GIS is important for displaying maps and for the landscape structure analysis. The maps were used to complement the landscape structure maps in selection of sampling units from different parts of the landscape. It was expected that each part of the landscape (landscape element) had a different carbon level; each part was sampled separately (Lal et al., 2001).

3.2.1 Change detection with digital imagery

Multiple date imageries are used to ensure reliable mapping of baseline conditions and change trends (Lyon and McCarthy, 1995; Sharma et al., 2001). Change detection is performed through comparison between two classified images that depict both the changed area location and the nature of the change (Lyon and McCarthy, 1995). During the dry season, the wetland system stands out from the surrounding upland because it alone still has dense green vegetation (Munyati, 2000). This minimizes confusion of the wetland vegetation with that of the surrounding upland. However, the wetland system is also much stressed in the dry season and it is expected that any long-term trend in wetland size and quality would be easily detected with dry season images. Furthermore, dry season images are largely cloud free (Munyati, 2000).

The two image data sets used, Landsat TM 1984 and ETM 2001, were acquired during dry periods. The change detection method used involved an image differencing technique, and the use of indices derived from Tasselled Cap transformation. In the difference approach, remote sensing is used to monitor changes in land cover associated with deforestation, or forest harvest and C flux is estimated as the difference in total C storage over the landscape at two points in time divided by the interval between image acquisitions (Turner et al., 2000). In this study, the differencing method was used to estimate changes in wetland areal extent due to drainage. The result was then used to estimate emissions derived from drainage of the wetland between 1984 and 2001.

The Landsat Thematic Mapper Tasselled Cap transformation is a useful tool in vegetation change detection over large areas and reasonably long, decadal time periods (Crist et al., 1986; Franklin et al., 2002). A multi-date Tasseled Cap transformation was used to detect changes in Landsat TM 1984 and ETM 2001 image data. This method employs fixed coefficients that can be applied to any scene across dates. The transformation rotates the image data and creates three planes: Brightness (B), Greenness (G), and Wetness (W). The BGW bands are directly associated with physical scene and attributes and, therefore, easily interpreted (Seto et al., 2002). The number of channels to be considered are reduced and a more direct association between signal response and physical processes on the ground are provided. Also, the particular types of information of greatest interest to the user are highlighted (Crist et al., 1986). The brightness band is a weighted sum of all the six reflected bands and can be interpreted as the albedo at the surface. The greenness band primarily measures the contrast between the visible and near-infrared bands and is similar to the vegetation index (NDVI). The wetness band measures the difference between the weighted sum of the visible and near- infrared bands and the mid-infrared bands. This can be interpreted as the measure of soil and vegetation moisture (Seto et al., 2002, Franklin et al., 2002). No literature was found where this method was applied to study changes in wetland ecosystems.

3.3 Field surveys and sampling

The study area was surveyed for ground truthing of the classification result and field sampling. Three selected ground control points were visited in the field. It was difficult to identify more control points in the area because of limited places with intersections. A Global Positioning System (GPS) was used to collect coordinates of the control points. Flight surveys were carried out on February 2003 for inaccessible areas and photos taken to help in truthing of the identified classes. Existing soil, topographic and vegetation maps were also used to support ground truthing.

3.3.1 Soil sampling

Samples were collected during the 2002/2003 short-rain season. Transects were placed along the gradient of the study area, and soil samples collected at each landscape component along the transect. Paired plots covering wetland and agricultural land were sampled (Figure 3.1). In each plot, three samples were collected along a 30m transect at 5 m, 15 m and 25 m. Soil samples were taken at 0-20 cm, 20-50 cm using a wetland corer and an auger for the wetland and agricultural land, respectively. A 50 mm diameter ring was used to collect soils for bulk density analysis. Bulk density was determined for the agricultural land soil samples. Sampling was limited to the top 20cm in the agricultural field, as most arable agricultural practices occur up-to this depth, since farmers use hand tools such as hoes to till the land. Location of each sample site was determined by a GPS (Geo-Explore III). Soil samples were sun-dried, crushed, passed through a 2-mm sieve and packaged for spectral and chemical analysis.

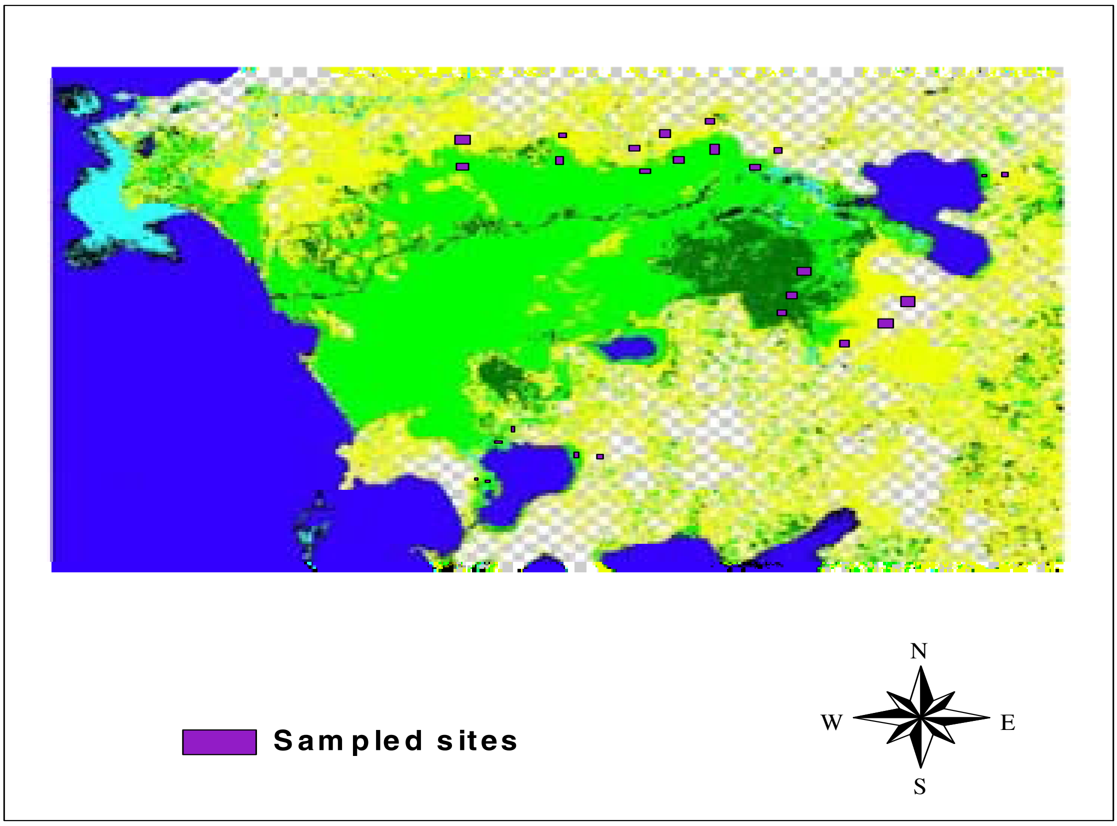


Figure 3.1: Landscape structure map of the Yala Swamp showing location of sampled sites

3.3.2 Vegetation sampling

Half-meter (50 cm) quadrates were placed along the same transects as in soil sampling, and a destructive method used to collect vegetation samples. First, the species composition and percentage land cover in each quadrate were identified. The vegetation was then cut and placed inside plastic bags for biomass measurements. The samples were sun dried followed by oven drying at 60°C for 24 hours. Dry weights for samples were measured followed by grinding with a mill to prepare for chemical analysis.

3.4 Chemical analysis and green-house experiment

The soil and plant samples were analyzed for total organic carbon and nitrogen using a Carlo Erba CNS analyzer. Additionally, the soils were analyzed for pH and bulk density. The pH was determined using the soil to water ratio of 1: 2.5.

A greenhouse experiment was conducted using all collected topsoils (450 samples) to evaluate the soil fertility status of wetland soils as compared to surrounding agricultural soils. Maize seeds of the same genotype *(Zea mays L.)* were planted in potted soils.

The research was established in a completely random design with 450 soil samples. The size of the pots used is shown in Appendix 1. About 100 g of dry soils were used for potting. First, the soils were watered for 48 hours before the seeds were planted. The seeds were then weighed and one seed was planted in each pot. No chemicals were used for the soils and plants. The soils were watered every morning with about 50 ml water.

The plants were harvested 14 days after sowing. First, the whole plants (roots and shoots) were gently removed from the soil media and washed with tap water followed by distilled water. It was ensured that all the soil particles were washed out, especially from the roots, and no roots were lost. The shoot and roots were separated and their fresh weight determined using a 4 digit balance. The roots and shoots were then dried at 65 °C for 48 hours and their dry weight determined.

3.5 Spectral analysis

All the collected soil and plant samples were analyzed for relative reflectance through a Near Infrared Spectrometer in the World Agroforestry Center. Soil NIR spectra were evaluated for their relationship with carbon content in the wetland soil. A near infrared scanning spectrometer (model 6500, NIRSystems Incl., Silver Spring, MD, U.S.A.) was used to obtain soil absorption spectra at 2nm wavelengths intervals from 350 to 2500 nm. Each spectrum was the average of 30 scans of a standard sample cell with a quartz front containing approximately 10 g of soil. Each sample was scanned in duplicate and the spectra averaged. NIR calibrations were performed by partial least squares (PLS) regression using the 'Unscrambler' Version 7.01.

PLS is a multivariate linear calibration technique that produces projections in a few dimensions of a data matrix with many variables. Thus a very large number of variables are reduced to a few latent variables (components). These orthogonal components are used in the regression and problems with the otherwise strong dependence between wavelengths are avoided (Russell et al., 2002; Shepherd and Walsh, 2002; Russell, 2003).

The PLS models were validated using full cross validation. With this technique, models were created leaving one sample out each time and then the models were tested on the omitted samples. These were repeated until all the samples had been tested once. The number of components to use in the PLS model is selected according to maximum explained variance in the cross-validated samples. In this case 20 principal components were use.

The calibrations were evaluated for their standard errors of cross-validation and correlation coefficient r between measured and calculated values. The r-values provide a comparison of the NIR calibrations with the chemical soil test. There was no correlation between the result from the spectral analysis and the carbon content in the soil samples. Therefore, the results will not be discussed.

3.6 Statistical analysis

Shape metrics was calculated using remote sensing software (ENVI) for landscape structure analysis. T-test and ANOVA were used for statistical analysis of chemical data.

4 SPATIAL ANALYSIS OF LANDCOVER TYPES

4.1 Landscape characterization

Landscape characterization is based on the landscape structure of the study area. Landscape structure refers to the types and patterns of elements (or patches). Taking into account the processes within and between landscape elements, viz. exchange of energy, matter (dead or living), is a prerequisite to a true landscape-ecological approach (Turner, 1990; Canters et al., 1991). The Yala Swamp consists of a combination of patches and corridors (Figure 4.1). A corridor is a strip of a particular patch type that differs from the adjacent land on both sides (Forman, 1997). Corridors have several important functions, acting as conduits, barriers and habitats. There are two corridors in the Yala Swamp: the Yala River and the Nyando River. The main corridor in the Yala Swamp is the Yala River, which has a major influence on the structure and functioning of the ecosystem. The Yala River corridor enters the swamp at the southern end and the Nyando River on the northern (Figure 4.2). Landscape processes that occur in the Yala Swamp are movement of water, nutrients and sediment materials, as well as animals. The structure of the Yala Swamp landscape is influenced by the quantity and quality of water and sediments carried by the Yala River and by disturbance patterns due to human activities. There is evidence of emergence of a new corridor, which divides the swamp along Lake Victoria into two areas (Figure 4.2).

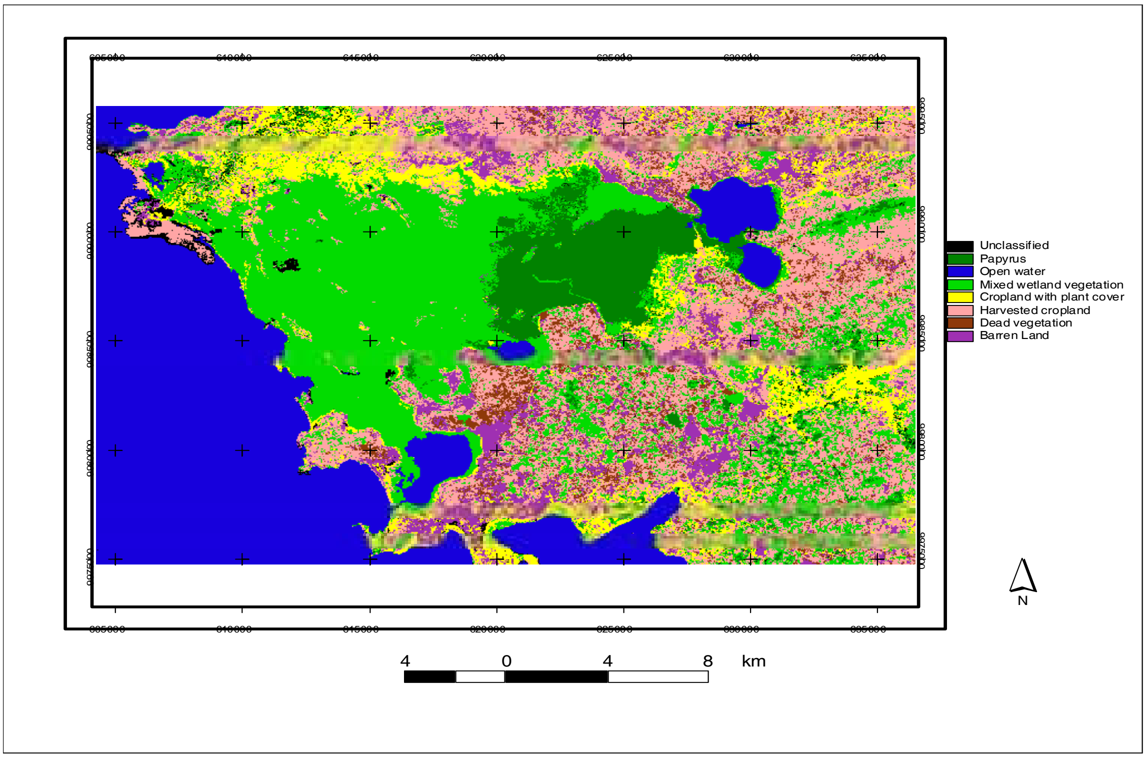


Figure 4.1: Landscape structure of Yala Swamp (Landsat TM 1984)

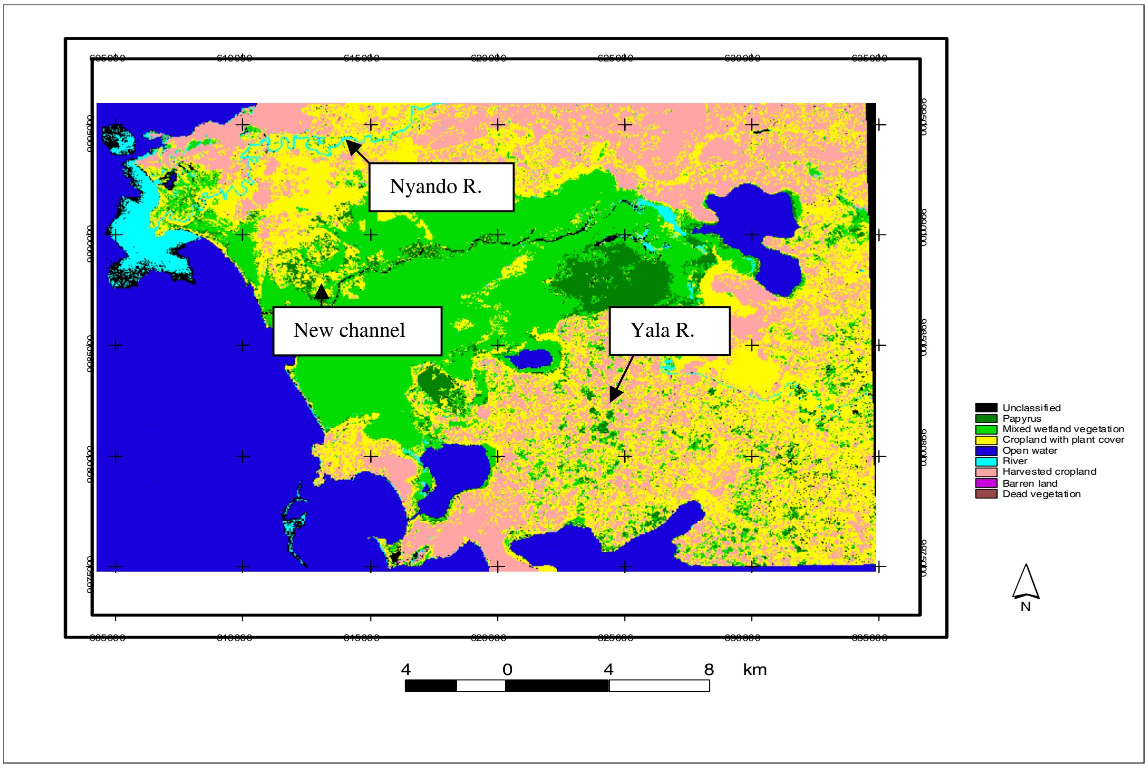


Figure 4.2 Landscape structure of Yala Swamp (Landsat ETM 2001)

The swamp lies in a depression, with upland areas raised above the wetland ecosystem (personal observations). Agricultural lands occurr in the proximity of the swamp (Figure 4.1, 4.2). Also, there are agricultural activities on the swamp edge. An edge is the portion of an ecosystem near its perimeter, where environmental conditions prevent development of interior characteristics (Forman, 1997). An edge effect was observed along the perimeter of the swamp environment. Edge effect refers to distinctive species composition or abundance in this transitional area between patches, which result from a combination of biotic and abiotic factors that alter environmental conditions along patch edges compared to patch interiors (Collinge, 1997). Therefore, the area of an edge effect is important in quantification of the interior patch areas over time. The potential area and impact of edge effects are also important in projecting changes of interior patches. The fields near the swamp exerted edge effects onto the marsh vegetation by creating a microclimatic change at the edge of the swamp, including increase in temperature and light intensity, and wind speed. Sun and wind are overriding controls on edge microclimate, because they both desiccate leaves and increase evapotranspiration, thereby determining which plants survive and thrive in an edge. This also has an impact on soils, insects and other organisms on the edge. An edge effect is evident in the landscape structure map of the Yala Swamp (Figure 4.1). The contrasting patches around the boundary of the swamp environment represent the edge species that occurr due to clearance of the marsh vegetation for agricultural activities, and bare agricultural-lands. The encroachment of the edge species into the marsh is evident from the two landscape structure maps. This is especially pronounced at the northern end of the swamp area (Figure 4.2). Table 4.1 summarizes the landscape elements of the Yala Swamp and its proximity.

Table 4.1: Percentage cover of landscape elements in the Yala Swamp for 1984 and 2001

Landscape element	Proportions for 1984 (%)	Proportions for 2001 (%)
Papyrus	6.7	4.2
Mixed wetland vegetation	25.1	19.1
River	2.3	2.3
Open water	24.3	25
Agricultural-land	33.6	48.2
Barren land	4.9	0
Dead vegetation	2.0	0
Unclassified	1.1	1.2
Total	100	100

Agricultural-land covers harvested cropland and cropland with plant cover

There are three main patch types in the swamp environment interior: papyrus (*Cyperus papyrus*) plants (deep water emergent), a patch of mixed wetland vegetation (shallow water emergents), and open water (Figure 4.2). The papyrus plants occur as a monoculture in relatively deep waters. Generally, papyrus is rooted in peat submerged below the level of permanent flooding (Ellery et al., 1995). In situations where papyrus occurs on the margins of open water, shoots (rhizomes) extend from the peat into the area of open water. It is therefore able to colonize areas of open water as a floating mat of entangled rhizomes, culms and umbels. In cases where it colonizes floating water, mats of floating papyrus may be broken off from the fringe, to form floating rafts. Mobile islands of floating papyrus plants occurred on Lake Kanyaboli at certain times of the day in relation to wind direction (personal observations). The aerial extent of papyrus vegetation decreased between 1984 and 2001 (Table 4.1, Figure 4.1 and 4.2). The change was accounted for by the appearance of a channel within the swamp, which transferred water into Lake Victoria. The channel was not detected in the 1984 image (Figure 4.1). Channel blockage and abandonment were reported to have happened in deltaic wetlands with papyrus vegetation such as the Okavango Delta of Botswana. Resulting shifts in the location of a marsh are common in the Rift Valley zone of Kenya (Lambin and Mertens, 2001). Therefore, the appearance of a relatively new channel in the Yala Swamp needs to be further investigated.

The matrix in the Yala landscape is a patch of mixed wetland vegetation that connects the swamp area to Lake Victoria (Figure 4.2). A matrix is the background ecosystem or patch type in a mosaic/landscape, characterized by extensive cover, high connectivity, and or major control over the dynamics of the landscape (Forman, 1997). The size of the Yala swamp is largely determined by the size and inundation of the matrix patch (papyrus plus other swamp vegetation). Therefore, to maintain the integrity of this landscape, the most extensive part of the swamp should be kept integral. It is within the matrix where human activities are directed such as drainage for agricultural production.

The water bodies in the Yala landscape are Lake Kanyaboli in the north of the swamp, Lake Nyameyo in the east, Lake Sare near the outlet of the Yala River, and Lake Victoria (Figure 4.1 and 4.2). All these water bodies had an influence on the integrity of the Yala Swamp. Reductions in the water levels of the water bodies, especially the three lakes in the wetland, could seriously impact the structure and functioning of the Yala Swamp. The three water bodies act as a complex of recharge-discharge zones for groundwater beneath the wetland environment, resulting in the buffering of the wetland against dramatic seasonal changes. It is documented that wetlands influenced by groundwater are buffered against dramatic seasonal changes (Mitsch and Gosselink, 1993). In fact, the Yala Swamp is capable of withstanding rather dry periods as is evident from the data obtained from the drought year image of 1984 (Figure 4.1) as compared to 2001. Generally, the more homogeneous the environment has been in both space and time, the more likely the system is to have low fluctuations and low resistance to disturbance (Hansson and Angelstam, 1991). The Yala Swamp has been able to withstand natural disturbances such as drought periods, but that does not guarantee that it could survive drainage if modern techniques are used. The area that was drained in the 1960s never returned to its original state, even though it was occasionally inundated. Therefore, the Yala Swamp is truly a threatened landscape.

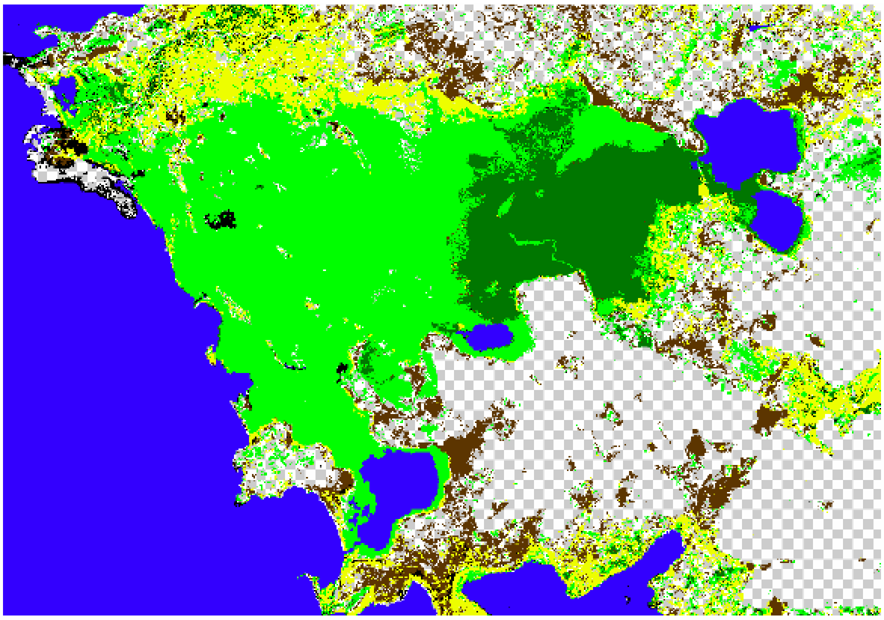
4.1.1 Quantification of land cover change

Change detection is useful for determining and evaluating differences in a variety of surface phenomenon over time (Jusoff and Senthavy, 2003). Land cover change for the study area was quantified through estimation of the area of marsh vegetation present in the 1984 and 2001 images, followed by differencing of the vegetation cover for the two years. Changes in surface albedo, moisture and vegetation health were also used to depict relative land cover change over the area. Table 4.2 shows the areal coverage in pixels for the marsh vegetation over the two periods.

Table 4.2: Estimated wetland area and drained area between 1984 and 2001 in the Yala Swamp

Landscape element type	Total area (1984) in pixels (30 m x 30 m)	Total area (2001) in pixels (30 m x 30 m)
Papyrus	50 439	31 462
Mixed wetland vegetation	189 560	138 175
Total marsh area	239 999	169 637
Drained area since 1984	0	70 362

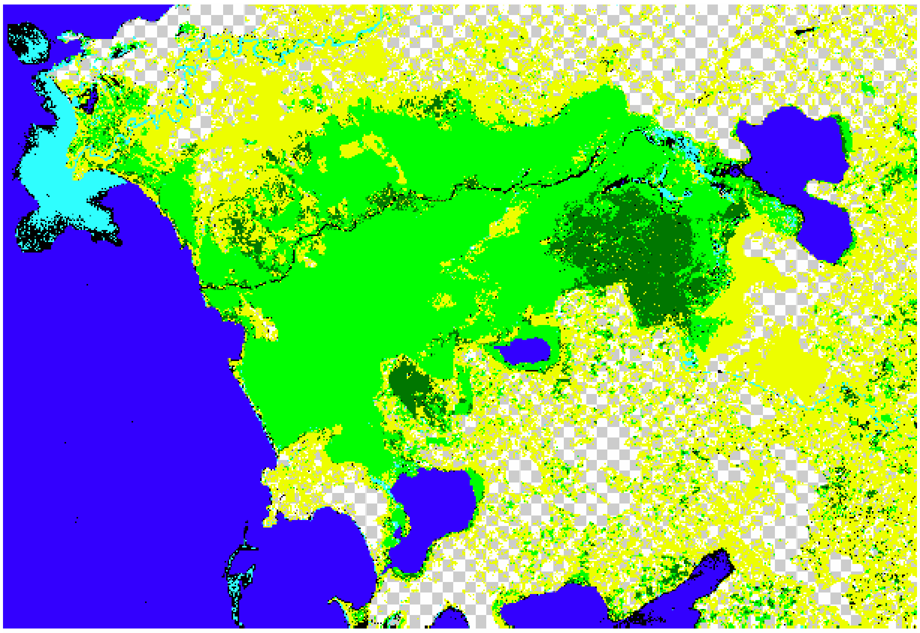
Based on the total marsh area for the years 1984 and 2001, it was possible to estimate the amount of drained or converted area. The total marsh area in 1984 was 239 999 pixels, which equals 21 600 ha (Figure 4.3). In 2001, the total marsh area was 169 637 pixels amounting 15 267 ha (Figure 4.4). Therefore, the total drained area (using 1984 as a reference year) was estimated at 70 362 pixels, which amounts to 6 333 ha. Over the 17-year period, the rate of marsh area converted to agricultural land stood at 372.5ha/yr. That was a considerable amount of land, given that in Western Kenya the average farm size is less than 1ha. This also supports the findings by Lambin and Mertens (2001) who reported that the proportion of households that practice some form of cultivation drastically increased over the last few decades around the Shompole swamp area within the ecological zone of the Rift Valley in Kenya. However, the areal extent of the land converted to agricultural land in Shompole swamp was not reported.



Legend

- Bare soil
- Mixed wetland vegetation
- Papyrus
- Agricultural –land
- Water body
- Dryland

Figure 4.3: Total marsh area for 1984 image data



Legend

- Bare soil
- Mixed wetland vegetation
- Papyrus
- Agricultural –land
- Water body
- Dryland

Figure 4.4: Total marsh area for 2001 image data

Figure 4.5 (a) shows the relative surface albedo (brightness) for the year 1984. The albedo figures ranged from 52 to 565. The lesser values for brightness occurred over the water bodies and the highest was over cloud cover. The relative surface albedo over the marsh area ranged between 116 and 373.

In 2001 (Figure 4.5(b)), the relative surface albedo ranged from 69 to 271. The water bodies had a lowest relative surface albedo of 69 which is high compared to 52 in 1984. The relative surface albedo over the marsh area ranged from 107 to 170. Generally, the relative surface albedo over the marsh area was higher in 1984 than in 2001. That suggests a much healthier vegetation for 1984 compared to 2001.

It is important to consider changes in relative surface albedo for the water bodies in this study, because they could easily be used to depict changes in the flow of energy and materials such as sediments and nutrients in the region. The surface albedo for water bodies was 52 and 69 for 1984 and 2001, respectively. Therefore, the year 1984 had relatively clearer waters than 2001 based on the surface albedo for water bodies over the two years. Suspended sediments increase the radiance emergent from surface waters in the visible and near infrared portion of the electromagnetic spectrum (Schultz and Engman, 2000). Surface water radiance is affected by sediment type, texture, and color, sensor view and sun angles, and water depth. Most researchers have concluded that surface suspended sediments can be mapped and monitored in large water bodies using sensors available on current satellites.

The remote sensing findings suggest that 1984 was drier than 2001. According to meteorological data from Kenya, 1984 was indeed a drought year. In particular, surface albedo was of major interest in the Sahel drought problem, because an increase in surface albedo was positively correlated with reduced rainfall (Ba et al., 2001).

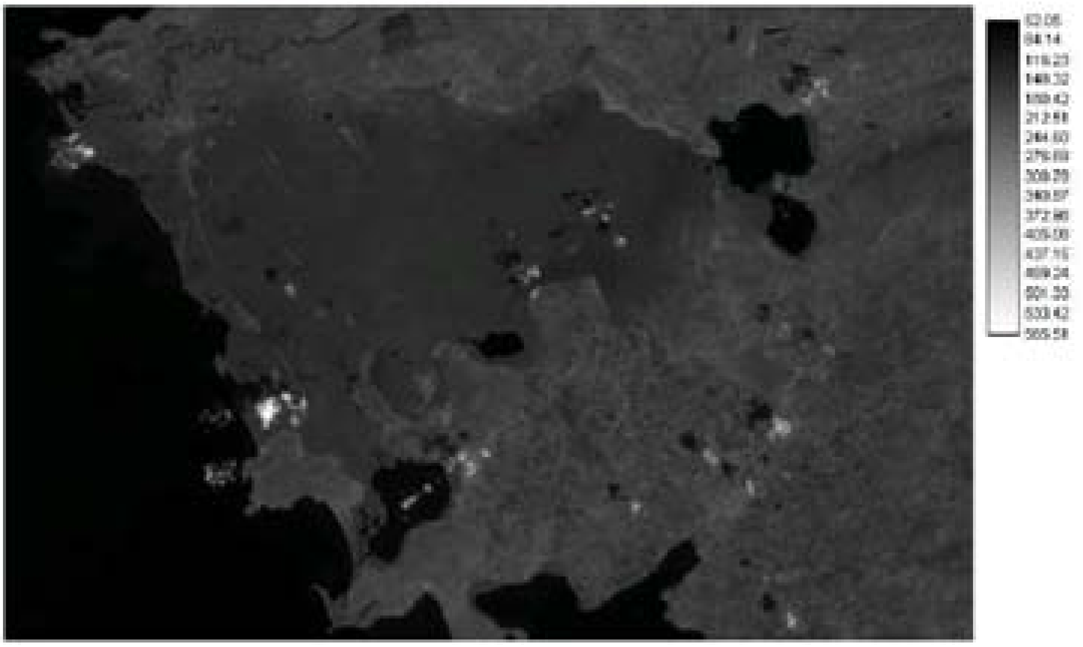


Figure 4.5 (a): Tasseled Cap transformation brightness index: 1984

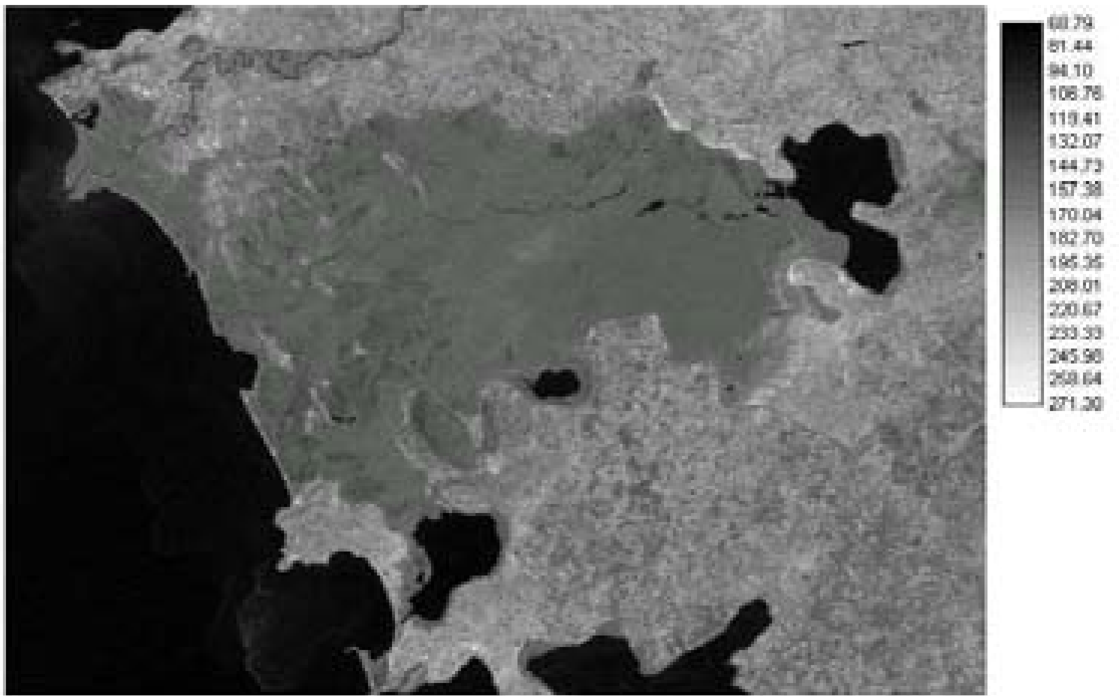


Figure 4.5 (b): Tasseled Cap transformation brightness index: 2001

The other measure used to quantify land cover change was the Tasseled Cap Greenness band that is similar to NDVI. Greenness is a contrast between near-infrared and visible reflectance and is thus a measure of the presence and density of green vegetation (Crist et al., 1986). The NDVI is based on the spectral properties of green vegetation contrasting with its soil background. This index provides a strong vegetation signal and good spectral contrast from most background materials (Eastwood et al., 1997; Oindo and Skidmore, 2002). NDVI also strongly reduces the impact of varying illumination conditions and shadowing effects caused by variations in solar and viewing angle. NDVI is a measure derived by dividing the difference between near-infrared and red reflectance measurements by their sum:

$$NDVI = (NIR - R)/ (NIR + R)$$

where NIR = near infrared measurements and R = visible red measurements. High positive values of NDVI correspond to dense vegetation cover that is actively growing, whereas negative values are usually associated with bare soil, snow, clouds or non-vegetated surfaces (Lillesend and Kiefer, 1987).

Figure 4.6 (a) shows the greenness/vegetation index (VI) values for 1984 over the Yala Swamp. The values range from -133 to 76. The maximum values occurred in marsh vegetation and the minimum values in areas covered by clouds. The positive values ranged from 10.5 to 75.6 depicting relatively healthy vegetation. Figure 4.6 (b) shows the greenness values for 2001. The values range from -79 to 27. The highest values represent marsh vegetation and the lowest sedimentation in Lake Victoria at the mouth of the Nzoia River. The positive values for the vegetation index ranged from 0.77 to 27 depicting relatively unhealthy vegetation as compared to that in 1984. A number of studies showed that the vegetation index provides an effective measure of photosynthetically active biomass (Oindo and Skidmore, 2002). The vegetation index correlates with climate variables including rainfall and evapotranspiration over a wide range of environmental conditions. The vegetation index may therefore be considered to represent the integration of climatic variables at a given location and time (Anyamba and Eastman, 1996). The year 1984 was a relatively dry year in Kenya, but the 2001 image fell under the 2000 drought period since it was recorded at the beginning of the year. Therefore, both images represent similar climatic conditions. Despite that, there are significant differences in greenness values, which may be accounted for by other environmental factors such as nutrient depletion or attacks by diseases and pests. Further investigations are needed in this regard.

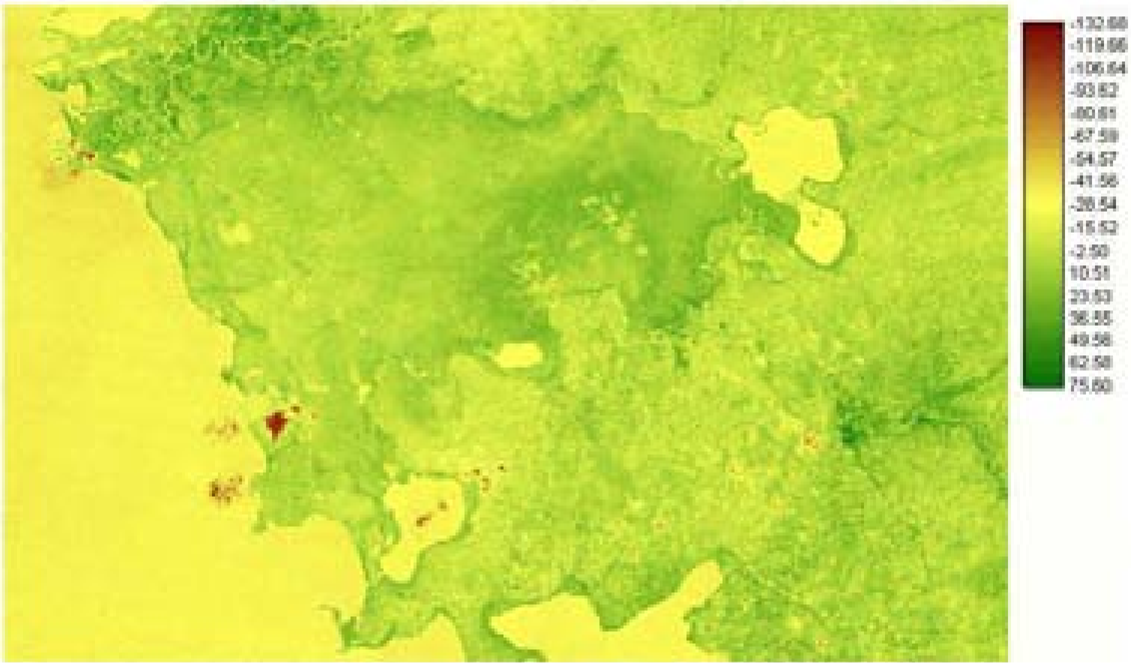


Figure 4.6 (a): Tasseled Cap transformation greenness (vegetation) index: 1984

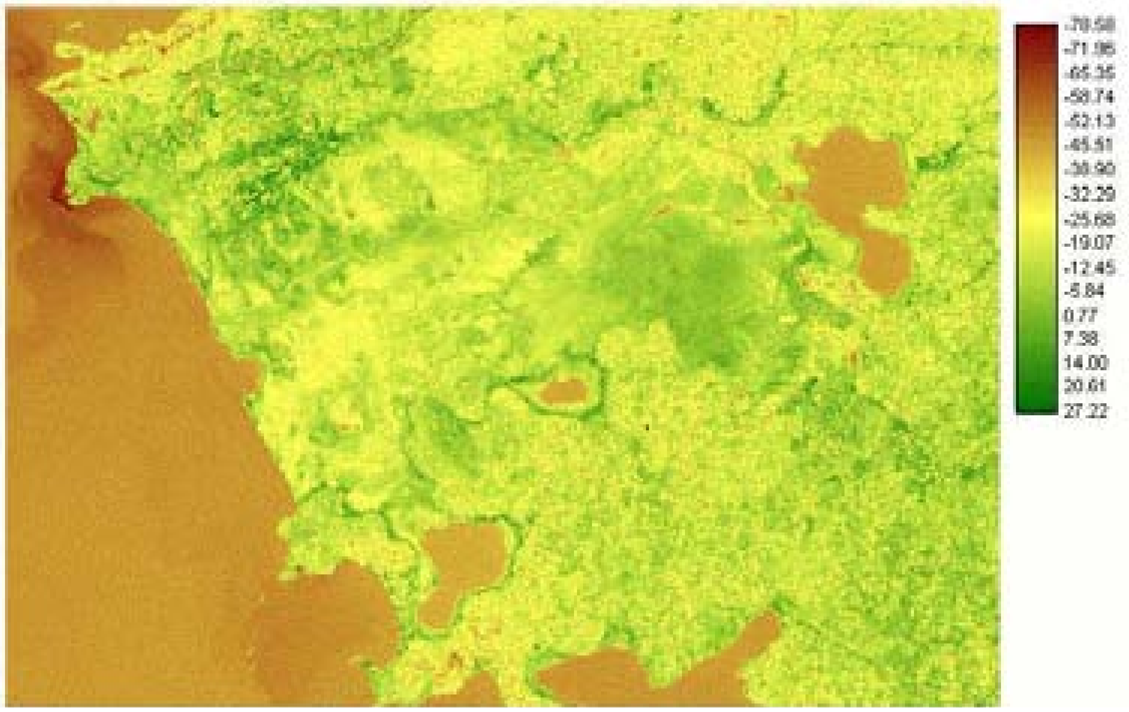


Figure 4.6 (b): Tasseled Cap transformation greenness (vegetation) index: 2001

Relative changes in soil moisture were also used to assess changes over the Yala Swamp environment. Soil moisture is an environmental descriptor that integrates much of the land surface hydrology and is the interface between the solid earth surface and the atmosphere (Schultz and Engman, 2000). Figure 4.7 (a) shows soil moisture variations over the Yala Swamp region in 1984. The moisture contents varied between -87.8 and 70.4. The highest moisture contents, ranging from 44.1 to 70.4, represent the water bodies (continuous green) followed by the wetland area (yellowish green) ranging from -34.9 to 44.1. Agricultural land (red) had a relatively low moisture level between -87.8 and -34.9.

Figure 4.7 (b) shows the moisture level over the swamp for 2001. The moisture level ranges from -90.2 to 74.3. The highest moisture values, ranging from 46.9 to 74.3, were found for water bodies followed by wetland area ranging from -35.3 to 46.9. Agricultural-lands had the least moisture, varying from -90.2 to -35.3. On average, the moisture levels for 2001 do not differ much from those of 1984, even though the images were recorded almost 20 years apart. This shows that the moisture level over the swamp environment remained stable for a prolonged period of time. It is also important to recognize that in 2001 most of the agricultural land had a high moisture content as compared to 1984. Therefore, it appears that the moisture deficit in agricultural-lands was greater in 1984 than in 2001.

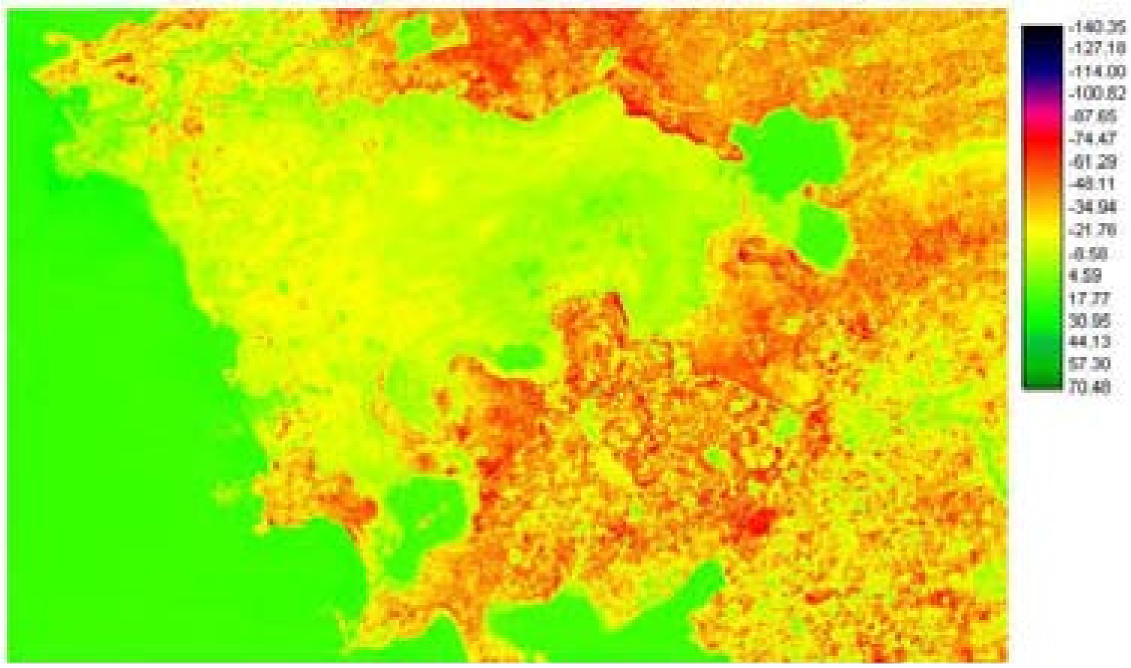


Figure 4.7 (a): Tasseled Cap transformation wetness index: 1984

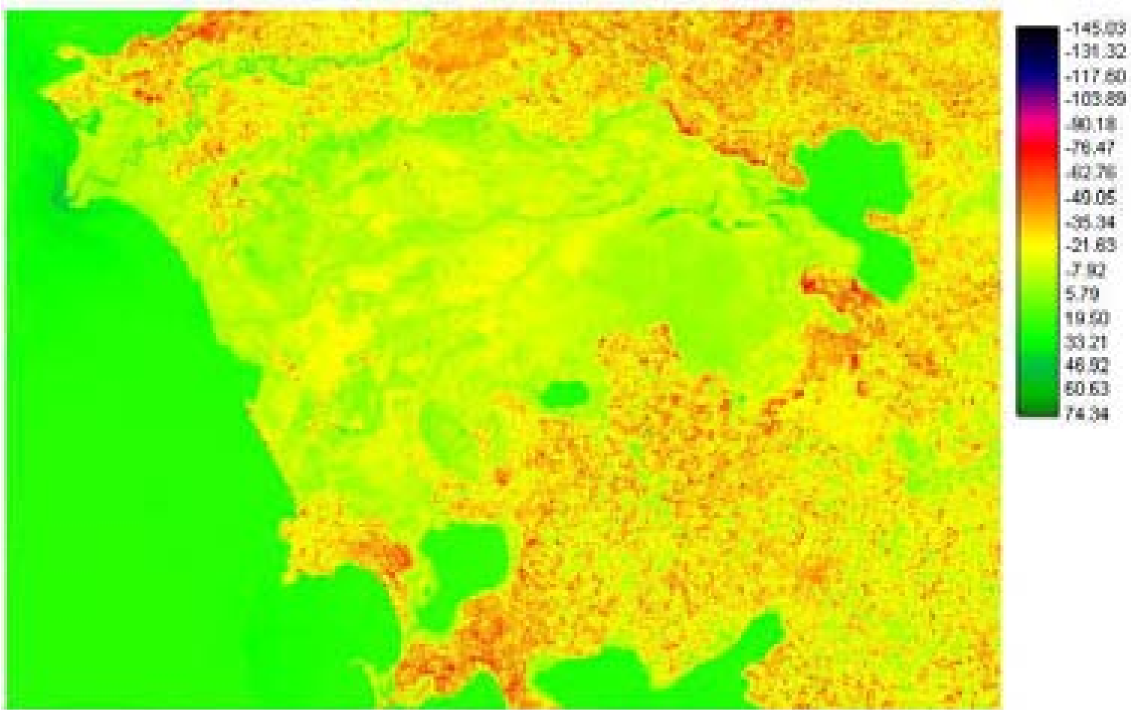


Figure 4.7 (b): Tasseled Cap transformation wetness index: 2001

4.2 Conclusion on land cover / land cover change

Before the interaction between landscape structure and landscape processes can be understood, landscape patterns must be identified and quantified in a meaningful way. Based on the results obtained from image classification and Tasselled Cap transformation, it is concluded that land cover changes have occurred in the Yala Swamp over the past 17 years (almost 2 decades). Changes in the areal extent of the marsh were brought about through drainage of wetland areas for agricultural production. These changes have been caused mainly by the desperate small-scale farmers who are struggling to meet their food security need. The total area and status of tropical wetlands are still unknown, but the results from this study suggest that the pattern of wetland conversion in tropical countries may have been similar to that of developed countries in the past, particularly in the United States. The United States has lost 54 % (87 million hectares) of its original wetlands, of which 87 % have been lost to agricultural development (Pearce et al., 1991).

Other changes occurred in the health status of the vegetation over the swamp as can be seen from the reduced greenness values between 1984 and 2001. Sedimentation load into open water patches, particularly Lake Victoria, has also increased as explained by the increased surface albedo over the past 17 years, all of which suggest a degradation of the resource base. In contrast, the wetness or soil moisture content in the wetland has not significantly changed over the 17 years. The Tasselled Cap transformation is a useful tool in wetland moisture and vegetation change detection over reasonably long time periods.

5 QUANTITATIVE AND QUALITATIVE CHARACTERIZATION OF SOIL CARBON POOLS

5.1 Summary

Carbon pools are reservoirs. They are systems that have the capacity to accumulate or release carbon. Three systems that contain carbon pools are terrestrial, marine, and the atmosphere. The units are mass, e.g., tC (IPCC 2000). The terrestrial pool comprises C stocks in biota, wetlands, and soils (German Advisory Council on Global Changes (WBGU), 1998) Terrestrial carbon dynamics is an issue of political and scientific importance (Kahle et al., 2002). The biota pool (Figure 5.1) contained largely in above-ground and below-ground biomass in forests (live and dead) is labile depending on the use of forest products (Lal, 2002). The soil organic carbon (SOC) pool is highly reactive. Furthermore, it is the seat of action of most pedological and edaphological processes and is sensitive to natural and anthropogenic perturbations (Lal, 2003). Carbon pools in wetlands are not well understood. This chapter examines carbon pools in plants and soils in tropical wetlands.

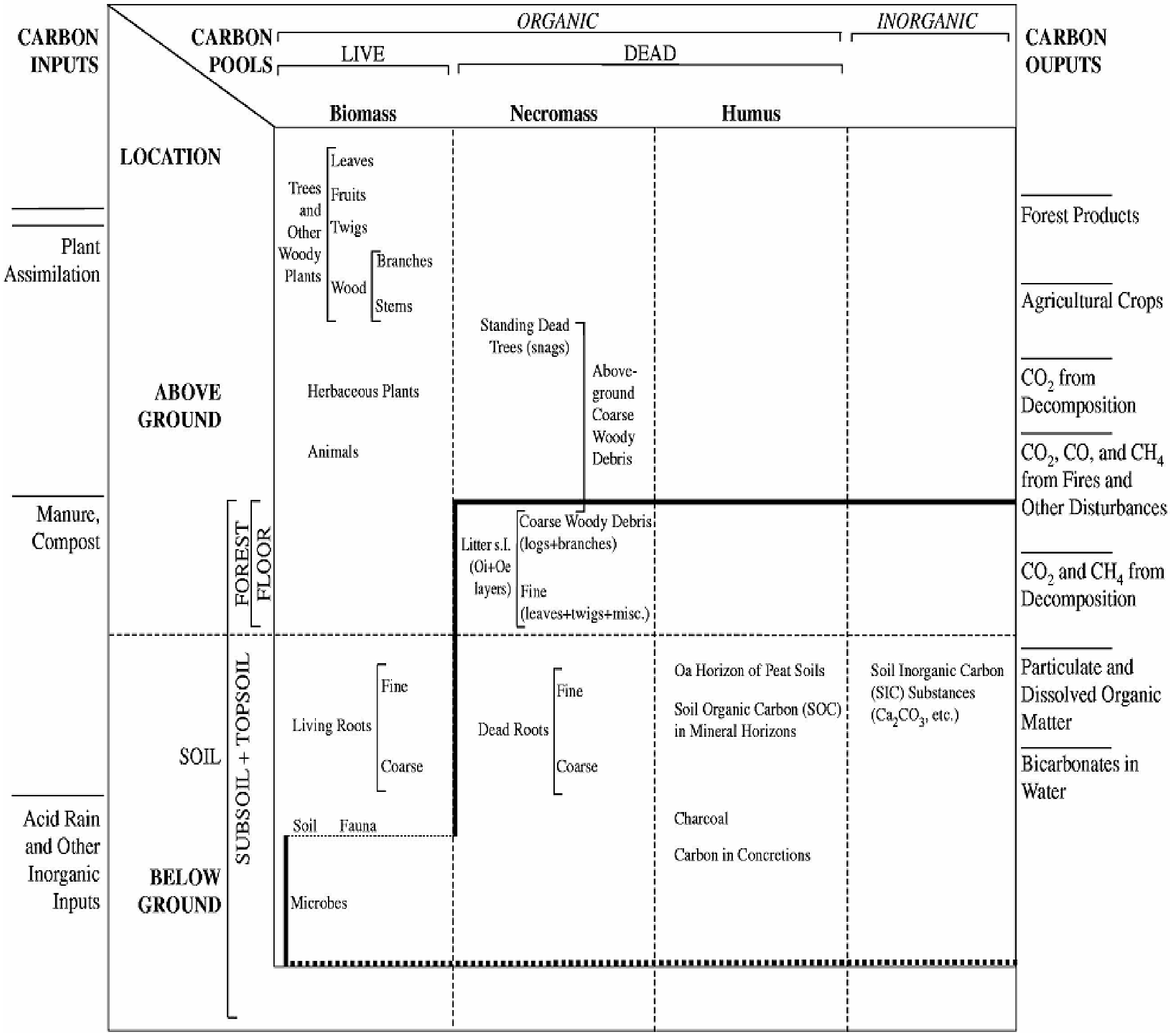


Figure 5.1: Plant and soil carbon pools (Source: IPCC, 2000)

5.2 Introduction

The carbon balance examines the movement of carbon among reservoirs or pools in the atmosphere, oceans, animals, soils, vegetation, and in large deposits such as peat, oil or coal (Boyle and Lavkulich, 1997). Human activities have made such a balance more complex and changed the carbon pools through the burning of fossil fuels, destruction of large areas of forests, and agricultural effects upon soil carbon. Destruction of carbon pools in wetlands occurs through the drainage of these areas for agricultural production.

Carbon pools in wetlands consist of the plant and soil pools (Chimner et al., 2002). Plant pools consist of below-ground and above-ground materials. These are partitioned into structural and metabolic pools based on the lignin and nitrogen content. The greater the lignin concentration, the greater the partitioning into the structural pool, and the slower the turnover rate compared with a strictly metabolic pool. The surface microbial pool consists of dead microbes and microbial residues that result from decomposing plant litter and have a very fast turnover time.

Soil organic carbon pools are active, slow and passive. The active pool consists of microbes and microbial by-products associated with soil organic matter decomposition, which has a turnover time of less than one year. The slow pool includes plant and microbial products that are biologically resistant to decomposition and has a turnover time in the tens of years. The passive pool is very resistant to decomposition and includes stabilized biological products that are chemically recalcitrant or physically protected, with a turnover time of hundreds to thousands of years. The turnover time is a function of the abiotic decomposition factor, which is controlled by temperature, nutrients and water availability, and anoxic conditions (Chimner et al., 2002).

The response of ecosystems to regionally heterogeneous stimuli such as historical land use and its effect on carbon pools and fluxes is not predictable from global averages (Schimel et al., 2001). Soil organic matter, the largest pool of terrestrial carbon, can act either as a sink or a source of C in response to climate, land-use changes and the rising atmospheric CO_2 levels (Ganuza and Almendros, 2003). To gain an understanding of the dynamics of carbon pools after land-use change at a landscape level, measurement techniques are needed that can discriminate between different pools (van Noordwijk et al., 1997; The Royal Society, 2001). This could be achieved through quantification of spatial variation with time in soil organic carbon and biomass carbon in natural and managed areas. The advantage of spatio-temporal variation analysis over other approaches is that it considers both the amount of carbon at a specific location and the emissions due to changes in land use and land covers. It is based on the fact that most uses of land affect the amount of carbon held in the vegetation and soil (The Royal Society, 2001). The history of the place under consideration is important for documentation of previous land cover and land use upon it (Houghton, 1999). This complements the use of remote sensing for identification of past and present land use and land cover.

Another important factor is the quality and degradability status of the soil organic matter (Wichern et al., 2004). Common quality indices are C/N ratio or the lignin content. The decomposition of materials is regulated in part by this ratio, so in agricultural practices, materials with different C/N ratios are usually mixed to improve decomposition rate in composting. The C/N ratio for optimal biological activity is about 30:1 in farm manure, with higher values being nitrogen limited and lower values being carbon limited (Brady, 1990).

In this study, soil and plant samples were collected from paired plots covering relatively undisturbed wetland areas and drained wetland areas used for agricultural production as discussed under the chapter on materials and methods. The history of the place was documented through interviewing farmers and key informants. The integration of data from chemical analysis of the samples, remote sensing and history of land use over the study area is presented below.

The agricultural land was further divided into three categories based on the land-use history. Those included: areas drained more than 40 years ago, areas drained 20 to 40 years ago and areas drained less than 20 years ago. The remote-sensing images data used allowed for estimation of land-use change for areas drained less than 20 years (1984-2001). Under climate change deliberations, the years considered important for global carbon balance estimates are the 1980s and 1990s (Houghton, 1999; Schimel et al., 2001), which were covered by the analyzed images data. It is assumed that both decades had the same rate of land-cover or land-use changes, as reported estimates of carbon fluxes by terrestrial ecosystems due to land-use change for the 1980s and 1990s were not significantly different (Schimel et al., 2001). Table 5.1 shows the global carbon stocks in vegetation and soil carbon pools for the world biomes including wetlands. Although wetlands cover the lowest areal extent on the earth, they contribute a disproportionate amount to the global carbon stocks.

Table 5.1: Global carbon stocks in vegetation and soil carbon pools down to a depth of 1m (Source: IPCC, 2000)

Biome	**Area (10^9ha)**	**Vegetation Gt C**	**Soil Gt C**	**Total Gt C**
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas	2.25	66	264	330
Temperate grasslands	1.25	9	295	304
Deserts and semi-deserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Croplands	1.60	3	128	131
Total	15.12	466	2011	2477

5.3 Results and discussions

5.3.1 General descriptive statistics

The average pH for soils in wetland was 5.43 ± 0.8 and that for agricultural land was 6.19 ± 1.1. The median for pH values in wetland and agricultural land soils were 5.2 and 6.1, respectively. Bulk density measurements were estimated for agricultural land soils and ranged from 0.6 gcm^{-3} to 1.3 gcm^{-3} with an average of 0.93 ± 0.2 gcm^{-3}. The median for bulk density was 0.92 gcm^{-3}.

Table 5.2 shows the summary statistics for percentage soil organic carbon and total nitrogen content in soils of wetlands and agricultural lands. In the wetland, two depths were covered 0-20 cm (topsoil) and 20-50 cm (subsoil). The average soil organic carbon (SOC) content in wetland topsoil and subsoil were 5.63 ± 4.9 % and 2.31 ± 1.6 %, respectively. That for agricultural-land topsoil (0-20 cm) was 2.48 ±1.2 %, which was significantly lower than in the wetlands. The median for SOC in wetland topsoil and subsoil were 3.85 % and 1.81 %, respectively, and that for agricultural-land topsoil was 2.46 %. The amount found by Ekirapa and Kinyanjui (1987) on poorly drained humic Fluvisols/Gleysols along the Yala farm were within the range of the carbon and nitrogen content found in the wetland in this study. They found that the wetland topsoil had an average pH value of 5.6 and SOC of 4.31 %; the subsoil had an average SOC of 1.89 %. The parent material for the soils they studied was alluvial deposit, which occurs in most deltaic wetlands including the Yala Swamp.

Table 5.2: SOC (%) and total N (%) in wetland and agricultural-land topsoil (0-20 cm) and subsoil (20-50 cm).

Descriptive Statistics	Wetland topsoil		Wetland subsoil		Agricultural-land topsoil	
	N (%)	SOC (%)	N (%)	SOC (%)	N (%)	SOC (%)
Min	0.097	1.34	0.020	0.530	0.038	0.457
1st Qu	0.221	2.794	0.127	1.451	0.153	1.664
Mean	0.399	5.633	0.189	2.308	0.222	2.482
Median	0.304	3.832	0.158	1.823	0.224	2.464
3rd Qu	0.456	5.860	0.213	2.693	0.294	3.252
Max	1.436	21.620	0.882	9.752	0.539	6.643
Total N	71	71	71	71	71	71
Std Dev.	0.285	4.860	0.131	1.624	0.105	1.211

The average total N content for wetland topsoil and subsoil, and agricultural-land soils was 0.40 ± 0.29 %, 0.19 ± 0.13% and 0.22 ± 0.11%, respectively. The medians for the three categories, respectively, were 0.30 %, 0.16 % and 0.22 %. Erikapa and Kinyanjui (1987) found an average total N of 0.47% in humic Fluvisols topsoil, which was within the range of the amount found in this study. Mitsch and Gosselink (1993) reported total sediment N between 0.35 and 0.66 % in the freshwater marsh of the Atchafalaya Delta.

The SOC of the wetland soil population had a skewed distribution (Figure 5.2), whereas that for the agricultural-land soil was relatively normal (Figure 5.3). The standard deviations measure the dispersion of the population around the mean (Voelkl and Gerber, 1999). The overall structural and functional integrity of a landscape can be understood and evaluated in terms of both pattern and scale (Dramstad et al., 1996). The skewed distribution in the wetland soil population is due to the complexity in the structure of the system, which results in different processes at micro and macro scales yielding rather high levels in some areas. The shape of the wetland was complex as opposed to regular shapes often found in fields, i.e., square and rectangular. That may have resulted in complex flows of matter in the wetland mosaic of corridors and patches of high carbon content, patterns that are eliminated in agricultural-land patches, possibly by avoiding patches of extremely high carbon content. Elimination of the extreme highs automatically yields more normal distributions.

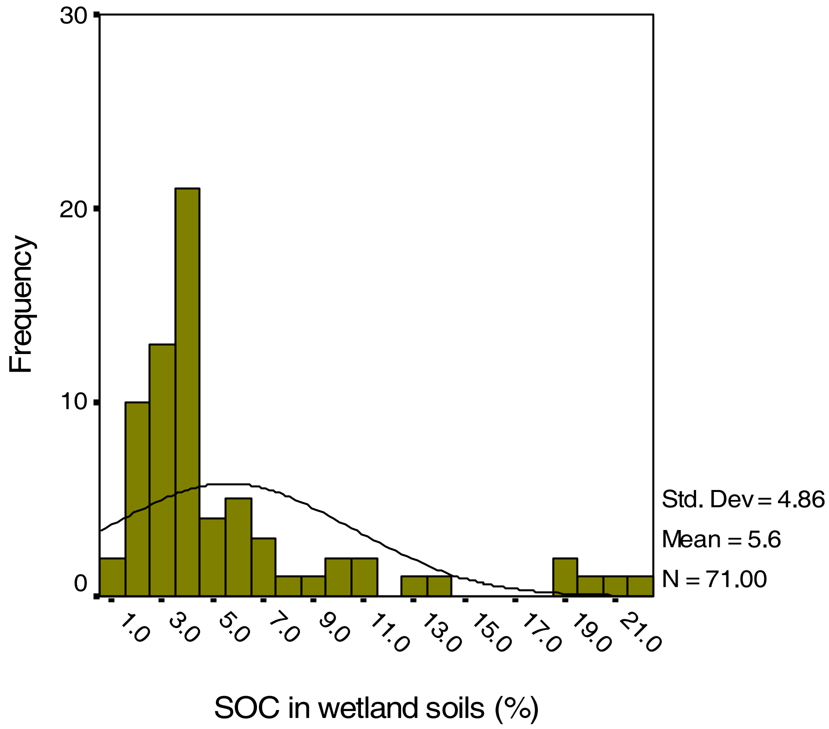


Figure 5.2: Frequency distribution for SOC in wetland soils

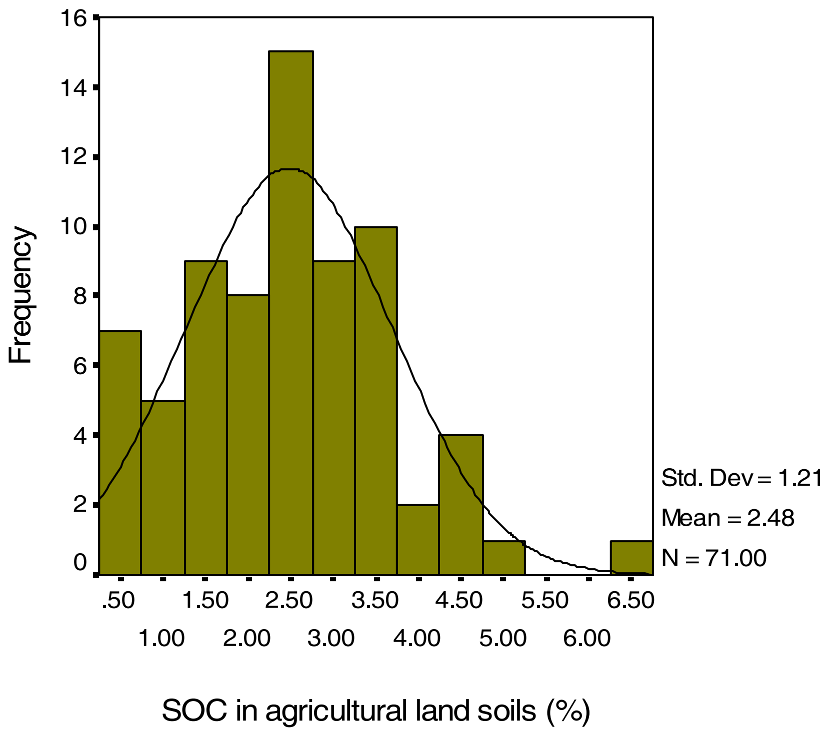


Figure 5.3: Frequency distribution for SOC in agricultural land soils

5.3.2 Above-ground biomass C, N

Biomass carbon content for the wetland vegetation was determined and had an average of 41 ± 2.4 %; the median was 41.7 %. Therefore, wetland plants stored a larger amount of carbon than soils. However, most of the carbon was readily decomposed as was indicated by the low amount of SOC in wetland soils. Clearing of marsh vegetation for agricultural production released a large amount of biomass carbon into the atmosphere in addition to that lost from the soil as discussed below. Most of the carbon in wetlands is stored in dead vegetation and peat, which if burned, release carbon dioxide to the atmosphere.

The average above-ground biomass for wetland plants was 566.7 ± 230 g/m2, or about 5.7 t/ha. This amounts to 86 411.2 t, based on the 2001 areal estimate of the entire swamp; and the carbon held in the biomass was estimated at 0.035 Million (M) tC. This is proportional to 2.3 tC/ha. Moore et al. (2002) reported above-ground biomass ranging from 327 to 587 g/m2 in a Canadian bog. The amount of carbon released from above-ground biomass by drainage of the Yala Swamp in the 20 years between 1984 and 2001 was estimated at 0.015 MtC, and the carbon released during drainage 20-40 years ago, over a total area of 2 300 ha, was 5 375 tC. The amount released due to drainage more than 40 years ago could not be estimated, as it was not possible to determine areal extent using satellite images, and no secondary data was available. Boyle and Lavkulich (1997) reported that a reduction in wetland biomass from 91.4 Mt to 10.6 Mt between 1827 and 1990 in the Lower Fraser Basin, if burned would have released 148 Mt of carbon dioxide to the atmosphere. In the tropics, the drainage procedure for agriculture culminates in the burning of dried wetlands plants (Appendix 2), which is a common phenomenon even in tropical forest ecosystems. For example, when forests are cleared for croplands, the carbon initially held in vegetation is released to the atmosphere rapidly when trees are burned and more slowly as dead plant material decays (Houghton, 2002).

The average total N content for wetland plants was 1.32 ± 0.6 %. The amount of total N held in the biomass (based on the 2001 areal estimate of the entire swamp) was 1 140.6 tC. There was a negative correlation (r = -0.45) between N and C in wetland plants. This was due to the fact that as N was re-used rather than newly taken up from the soils, plant-tissue C accumulated to build structural (lignin) components.

The amount of N released from the biomass as a result of drainage of the swamp 0 to 20 years ago was 476.5 tN; and the amount released from drainage activities 20 to 40 years ago was 173 tN.

5.3.3 C/N ratio

The average C/N ratios for wetland topsoil and agricultural-land soils were 13.5 and 11.2, respectively. Plant productivity is determined by several nutrients simultaneously, including macronutrients (mainly N, P, and K) and micronutrients. Their availability in ionic forms rather than their total content in the soil controls plant growth (Begon et al., 1996). Each can be incorporated into complex carbon compounds in biomass. However, ultimately when the carbon compounds are metabolized to CO_2, the mineral nutrients are released again in a simple inorganic form. In wetland soils, the decomposition process was not complete as is indicated by the higher C/N ratio.

The speed of decomposition of organic material depends on its C/N ratio (i.e., Corg/N), since microorganisms responsible for decomposition need N for their protein synthesis. Plant productivity is low in soils with C/N ratios > 20, because decomposition (i.e., the transformation of organic N into plant available N) is N-limited and microorganisms compete for inorganic N from the soil and make it unavailable for the plants (Tanneberger and Hahne, 2003). However, both wetland and agricultural-land soils had C/N ratios < 20, which was indicative of high plant productivity and nutrient availability.

The three natural trophic levels are oligotrophic (C/N > 33), mesotrophic ($20 <$ C/N ≤ 30), and eutrophic ($10 <$C/N ≤ 20) (Tanneberger and Hahne, 2003). Therefore, the Yala wetland can be considered eutrophic. Agriculture has introduced nutrients into Lake Victoria resulting in eutrophication as evidenced by the invasion of the lake by water weed (Salvinia molesta). Under further anthropogenic influence (e.g., fertilization and drainage) polytrophic conditions may eventually occur (C/N ≤ 10). Drained areas around the Yala swamp (agricultural lands) had an average C/N ratio of 11, indeed not far from the reported value for polytrophic conditions.

5.3.4 General correlations

The correlations between SOC and total N values, bulk density and SOC were calculated in order to determine if there is any association between these parameters in the study area. Correlation between SOC in wetland topsoil and subsoil was also determined.

The correlation coefficient (r) between SOC and total N was 0.96 for wetland topsoil and 0.98 for topsoil of the agricultural land (Figure 5.4); the coefficient for wetland subsoil was 0.93 (Figure 5.5). Correlation also existed in carbon content with depth. A correlation coefficient of 0.43 occurred between wetland topsoil and subsoil, reflecting the soil-inherent properties of subsoil organic matter in relation to the layers above it. There was no correlation between SOC in wetland and the paired samples from the nearby agricultural-land soil. The correlation coefficient was 0.03. Apparently, the spatial variability of SOC in the swamp is too high. The correlation between bulk density and SOC in agricultural soils was -0.68 (Figure 5.6), and that between total N and bulk density was -0.67.

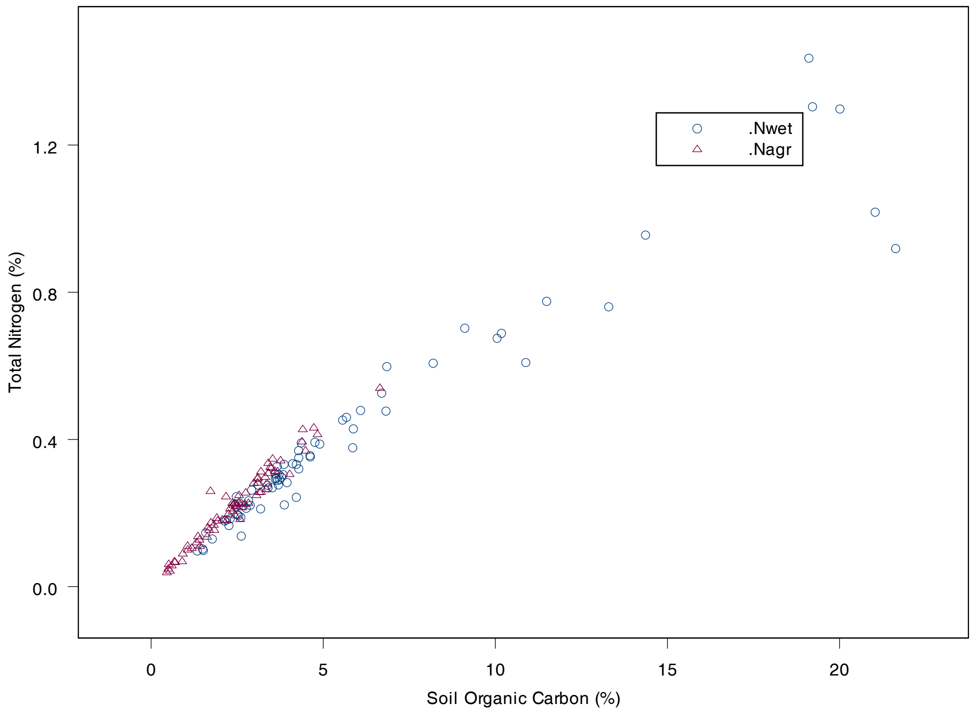


Figure 5.4: SOC (%) against total N (%) in wetland soils (wet) and agricultural-land soils (agr)

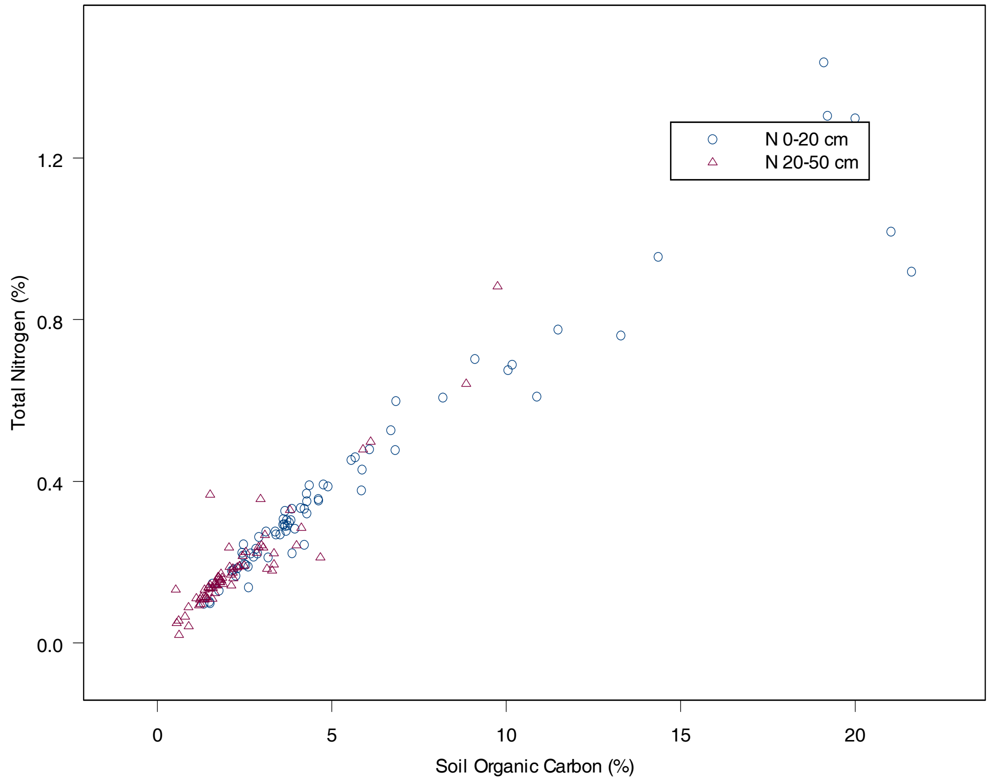


Figure 5.5: SOC (%) against total N in wetland topsoil (0-20 cm) and subsoil (20-50 cm)

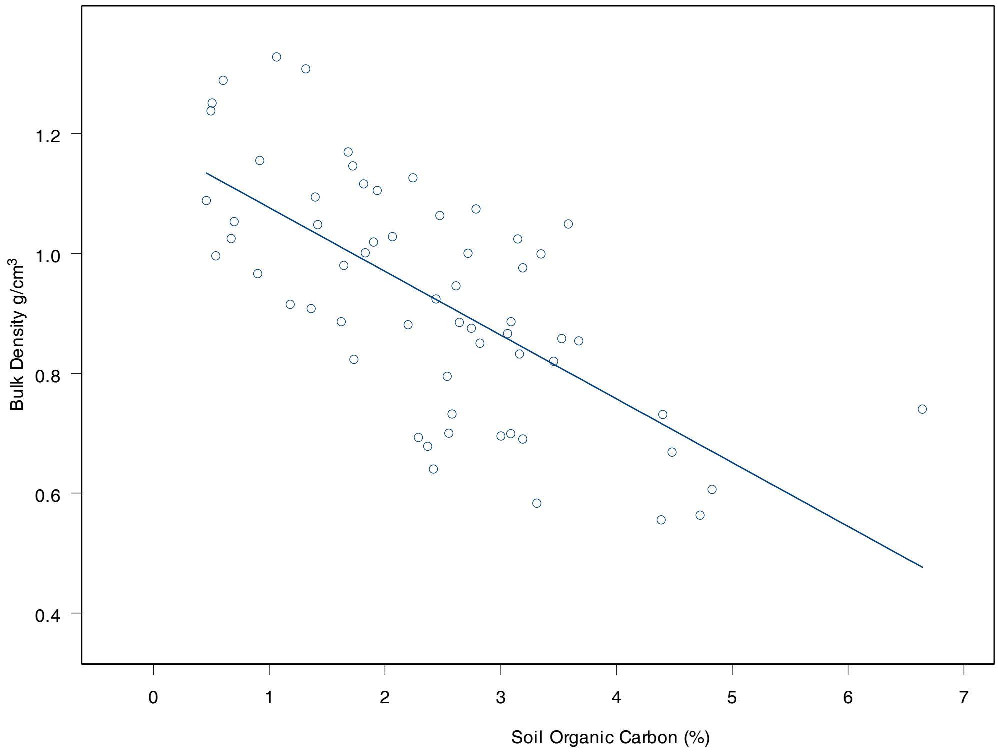


Figure 5.6: SOC (%) against bulk density (g/cm^3) in agricultural-land soils

5.4 Soil organic carbon (SOC) dynamics

5.4.1 Areas drained less than 20 years ago

In areas drained less than 20 years ago, the average SOC for wetland and agricultural-land were 3.94 ± 0.99 % and 2.29 ± 1.27 %, respectively, with medians of 3.73 % and 2.42 %. The results from the t-test (P = 0.04) show that at 0.05 significance level and 95% confidence interval, there was a significant difference in the carbon content of the wetland soils compared to that in adjacent agricultural-land soils converted less than 20 years ago. The results from ANOVA (P = 0.253) show that the variation in the amount of carbon in the soils of agricultural-land could not be explained by that in wetland soils. The reason for the loss of carbon following drainage is likely of an increased decomposition rate under aerobic conditions due to drainage.

The variation in the SOC content in the cropped areas is higher than in the wetland area. Contrary to conventional drainage procedures, flood waters still reached the drained areas during long rains because of poor drainage facilities. The flood waters remained in the area for about three months of rainfall and immediately receded thereafter (personal observations). Farmers dug drainage ditches to control water, which often get blocked when it rains. However, instead of remaining in the fields, much of the water was retained in drainage ditches that never get blocked. The heterogeneity of the drainage effectiveness likely caused differential aerobic conditions in the fields and enhanced the variability in SOC. A study by Minkkinen (1999) reported a drop in the water table because of drainage ditches in forestry drainage areas of peatlands in Finland. This was associated with a decrease in peat C. The study also reported that drainage ditches often get blocked resulting in great variability in peat C values. Another study by Lantz et al. (2001) accounted for the large differences in the SOC pool between forested and pasture site of Hoytville to close vicinity of a drainage ditch alongside the pasture site.

5.4.2 Areas drained 20 to 40 years ago

In areas drained 20 to 40 years ago (the Yala farm), the average SOC for wetland and agricultural-land were 3.04 ± 0.75 % and 3.08 ± 0.57 %, respectively; the medians were 2.88 % and 3.10 %, respectively. The results from the t-test (P = 0.14) show that there was no significant difference in the carbon content in wetland soils to that in adjacent agricultural-land soils converted 20 to 40 years ago. The amount found by Erikapa and Kinyanjui (1987) for SOC in agricultural land managed by the LBDA ranged between 2.29 % and 2.45 %. Though the SOC content was lower, here again there was no significant difference between the ecosystems. The SOC levels are likely to be location-specific.

The drainage facilities for the Yala farm project did not totally exclude water from agricultural land, which is typical of drainage measures in developing countries. Therefore, the area was seasonally flooded more than three months and the conditions resembled those in seasonal wetlands. During the flood periods, no farming activities occurred. Also, the slope in the Yala area is flat, which allows for flooding during the long rains and occasional deposition of sediments. This may have diluted the SOC concentration in these predominantly sandy loams in the drained area (Table 5.3).

Also, there was spatial dependence among the wetland soils data. For example, flood waters entered the swamp adjacent to the drained segment causing continuous oxidation of the soil due to flux of water and therefore decreased SOC accumulations. Studies by Trettin et al. (1996) reported increased soil oxidation depth in upstream segments of the wetland as compared to interior and downstream wetland segments. According to the key informants interviewed, the part of the wetland along the Yala River was also heavily disturbed by the El-Nino rains of 1987, and successional processes occurred thereafter.

Table 5.3: Soil texture for agricultural land adjacent to the Yala Swamp

Soil particle size	Particle size designations (FAO)	Average (%)	Standard deviation
Gravel	>2mm	3.07	2.97
Sand	53µm -2mm	66.59	10.74
Silt	2µm – 53µm	16.44	6.92
Clay	<2µm	10.82	4.35

5.4.3 Areas drained more than 40 years ago

In areas drained more than 40 years ago, the average SOC in wetland and agricultural land were 8.07 ± 6.55% and 2.19 ± 1.02%, respectively. The medians for wetland soils and agricultural-land soils were 4.49 and 2.07, respectively. The results from the t-test ($P<0.000$) show that there was a significant difference in carbon content between wetland soils and adjacent agricultural-land soils drained more than 40 years ago. Also, the results from ANOVA ($P = 0.438$) show that the variance in wetland soils could not be used to explain that in agricultural land soils. The amount of carbon found in agricultural land drained more than 40 years was not significantly different from that in soils drained less than 20 years ago. On the other hand, the amount of SOC in wetland segment adjacent to agricultural-land drained less than 20 years ago was more than that in wetland segment adjacent to agricultural land drained 20 to 40 years ago and less than that in wetland segment adjacent to agricultural land drained more than 40 years ago.

The differences in SOC in wetland segments might be due to differences in the spatial arrangement of landscape elements and the effect of disturbance patterns on the wetland. Deltaic ecosystems are complex owing to the transport and transformation of nutrients and different paths of water movement through the landscape. For instance, the two wetland segments adjacent to agricultural land drained less than 20 years ago and more than 40 years ago occurred in the northern portion of the Yala Swamp. They did not have a direct connection to the Yala River. Wang et al. (2002) reported that the spatially structured variance in the forest (the variance due to the location of sampling sites) accounted for a 68 % of the sample variance for SOC. Also, the wetland segment adjacent to agricultural land drained more than 40 years ago accumulated more SOC as compared to the other segments because the human disturbance pattern there was minimal. The main use of the wetland segment was harvesting of the vegetation instead of drainage for agricultural production. The effect of harvesting marsh vegetation on SOC needs to be further investigated.

5.5 SOC density

Analytical values for SOC were recalculated using the weight per volume basis of 0.5 gcm^{-3} for both wetland and agricultural-land soils. The weight per volume was derived from the measured weights and volumes for soil samples analyzed in the CN analyzer. Table 5.4 shows the SOC in gm^{-2} and t/ha for the topsoil (0-20 cm) in the study area.

Table 5.4: SOC density in the Yala Swamp and adjacent agricultural-lands for the topsoil (0-20 cm)

Drainage period	Wetland soil		Agricultural-land soil	
	gCm^{-2}	tC/ha	gCm^{-2}	tC/ha
Topsoil (0-20 cm)	5630	56.3	2480	24.8
A (0-20 years ago)	3940	39.4*	2290	22.9*
B (20-40 years ago)	3040	30.4**	3080	30.8**
C (> 40 years ago)	8070	80.7*	2190	21.9*

A corresponds to pairs covering wetland and agricultural-land drained 0-20 years ago, B to pairs covering wetland and agricultural-land drained 20-40 years ago, and C to pairs covering wetland and agricultural-land drained more than 40 years ago.
* Significant difference at 0.05 SL
**No significant difference at 0.05 SL

On average, the top 0-20 cm soil layer had 56.3 tC/ha (5.6 kgC/m^2) of SOC in the wetland and 24.8 tC/ha (2.48 kgC/m^2) in agricultural-land. In areas drained 0-20 years ago, the average SOC was 39.4 tC/ha (3.94 kgC/m^2) and 22.9 tC/ha (2.29 kgC/m^2) for wetland and agricultural-land, respectively. For areas drained 20-40 years ago, the SOC in the two categories was 30.4 tC/ha (3.04 kgC/m^2) and 30.8 tC/ha (3.08 kgC/m^2); for areas drained more than 40 years ago, the average SOC for wetland and agricultural-land was 80.7tC/ha (8.07 kgC/m^2) and 21.9 tC/ha (2.19 kgC/m^2), respectively. Figure 5.7 shows the carbon density distribution map for the whole world. The carbon density content obtained for the wetland in this study agrees with that reported for the Lake Victoria region in the map, i.e., 4- 8 kgC/m^2.

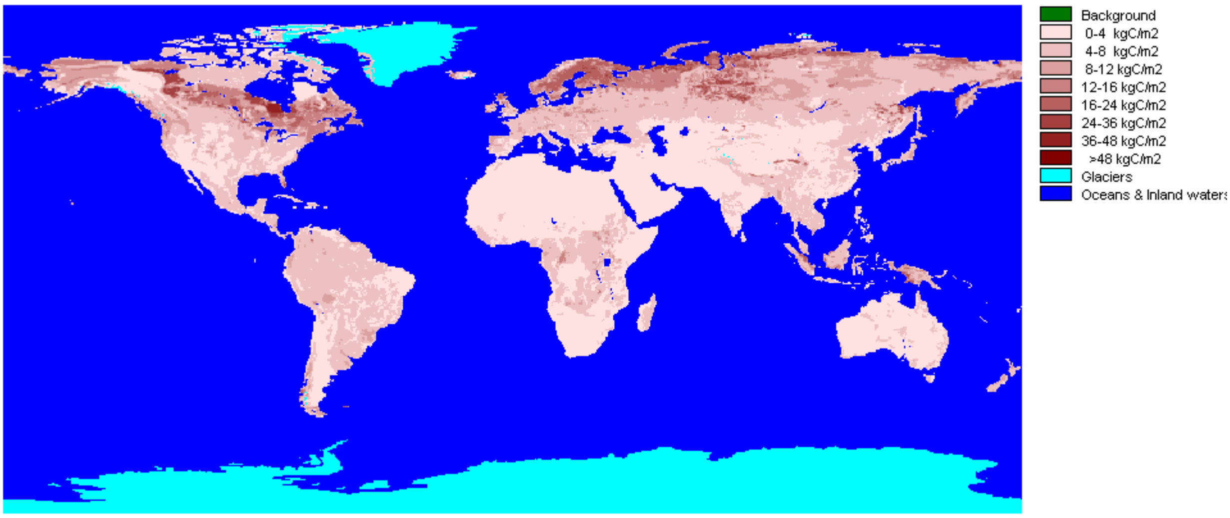


Figure 5.7: Global soil organic carbon distribution in the 0-0.3m soil layer (Source: Mitra et al., 2003).

5.5.1 Carbon-dioxide emissions due to drainage in the Yala Swamp

Generally, the amount of carbon emitted due to drainage in the Yala wetland was 31.5 t/ha, equivalent to 55.9 % of the SOC. Losses of SOC of as much as 50% in surface soils (20 cm) have been observed after conversion of natural vegetation to agricultural-land for 30 to 50 years (Post and Kwon, 2000). In areas converted 0-20 years ago, the carbon emitted was 16.5 t/ha (1 tC/ha/yr), equivalent to 41.9 % of the SOC, in areas converted 20-40 years ago, the carbon emitted was insignificant (-0.4 t/ha). In areas drained more than 40 years ago, the emitted carbon averaged 58.8 t/ha, equivalent to 72.9 % of the SOC. Therefore, the amount of carbon emitted from areas drained 0-20 years ago gave a good indicator of recent carbon emissions following drainage of wetlands in the tropics. The emissions from areas drained for longer than 40 years exemplified the scenario under which drainage in the area totally excludes water from the agricultural-land, i.e., complete conversion of wetland soils to mineral or upland soils.

If peat-forming wetlands are drained and converted to utilized areas, the mineralization stocks generate high carbon flux densities. The losses could be as high as 10 tC/ha/yr in the initial years. In Great Britain, losses resulting from converting bogs to cultivation are estimated at 5 tC/ha/yr. For Finland, the loss rate is 2.5 tC/ha/yr after drainage (WGBU, 1998). At 1 tC/ha/yr, the Yala Swamp lost a relatively low amount of

SOC through drainage in comparison to reported losses in temperate wetlands. This might be because there is less peat formation in the Yala Swamp.

Based on the areal extent of areas converted 17 years ago, which averaged 372.5 ha/year, the amount of emissions was estimated at 104 494.5 tC. Assuming a constant rate of land-cover change over the past 20 years, the amount of carbon emissions was estimated at 122 925 tC (6 146 tC/yr). The equation used to estimate carbondioxide emissions from carbon emissions is:

1 ton carbon = 3.67 (tCO_2) (IPCC, 2000) (5.1)

Using equation 5.1 to estimate carbon dioxide emissions in the area over the past 20 years, the amount derived was 451 134.7 tCO_2 (22 555.8 tCO_2/yr). The global estimate for carbon emissions due to land-use change between 1980 and 2000 was 1.7 G tC/yr. Therefore, the changes that occurred in the Yala Swamp soils over the same period accounted for 0.0003 % of the global carbon emissions estimate. There were no emissions in areas converted 20-40 years ago. As discussed earlier, there was no gain or loss of carbon dioxide on agricultural-land converted 20-40 years ago as compared to the adjacent wetland segment. The two systems appeared at equilibrium with each other.

Worldwide, wetland soils contribute 225 GtC to the carbon stock (IPCC, 2000). Based on the results from the Yala Swamp spatial analysis for 1984 and the average SOC amount, the amount of carbon held in the soil was estimated at 1.2 MtC, which equals 0.0005 % of the carbon stock held in wetland biomes globally. In agreement with the IPCC (2000) report, a larger proportion of the carbon was held in the soil than the above ground biomass. The Yala Swamp is relatively small as compared to other wetlands in Africa such as the Okavango Delta, which covers a total area of 68 640 km^2 (Ramsar Archives), and the Sudd with a total area of 179 700 km^2 (World Wildlife Fund). Therefore, more studies are needed covering other wetlands in the Lake Victoria region and Africa before concluding that the amount of SOC held in papyrus wetlands is insignificant as compared to the global stocks.

5.6 The Nyando Swamp

5.6.1 Introduction

Lake Victoria shores are fringed by extensive papyrus-dominated wetlands, and dense forest patches of tropical rain forests characterize many of its islands. The lake and its adjacent swamps were formed during the Miocene period (about 20 million years ago) as a result of the vertical upwarping of the African surface and the resultant sagging of the great ridge center (Bugenyi, 2001). Much of the forest cover and wetlands have been severely degraded through excessive resource use by a rapidly growing human population (Lung'ayia et al., 2001). In Kenya, wetlands are threatened as a result of policies that emphasize their exploitation rather than management. The Nyando Swamp is a deltaic wetland along Lake Victoria at 0°11'-0°19'S/34°47'-34°57'E, covering about 10 000 ha (Wandiga and Makopa, 2001). According to the 1999 census, the population of the Nyando district stood at 299 930 with a population density of 270 persons per km^2 (Mugo et al.,?). The geology, vegetation and soils of the Nyando Swamp resemble those of the Yala Swamp (Figure 5.8). For example, the rivers that drain into the Yala and Nyando swamps rise from the highlands of Kenya and flow into Lake Victoria. Particularly, the Yala River drains the central highlands west of the Rift Valley, as does the Nyando River (Wandiga and Makopa, 2001).

The Nyando Swamp was reclaimed for agricultural production during the 1940s, long before the Yala Swamp was drained. The land remained under intensive agricultural activities for 15-20 years before the prolonged rains of 1963 (Uhuru rains) that caused floods due to overflow of the Nyando River. All the agricultural activities were then abandoned due to the floods. Currently, small-scale farmers use the area especially during the dry season between November and February. It used to be a rice and sorghum growing area, but now agricultural activities cover growing of vegetables, beans, cowpeas, pigeon peas, sorghum and sometimes maize along the swamp margins. The average farm size ranges from 0.3 to 1.6 ha.

The swamp vegetation has been heavily disturbed by human activities due to harvesting of papyrus for subsistence and commercial purposes (personal observations). Papyrus is used for making mats, baskets and thatching houses. Swamp grass is also cut for feeding cattle. Previous comparative studies done around the Lake Victoria region have not addressed carbon pools per se. A study by Gichuki et al. (2001) involved the use of stable carbon isotopes to trace ecosystem functioning in two contrasting wetland ecosystems of Lake Victoria. In this study, it was considered imperative to carry out a comparative assessment of the soil carbon pools, using the same sampling and analytic procedures, in the Yala and the Nyando swamp. This would allow an assessment of the possibility to extrapolate the results from the former to the whole Lake Victoria region.

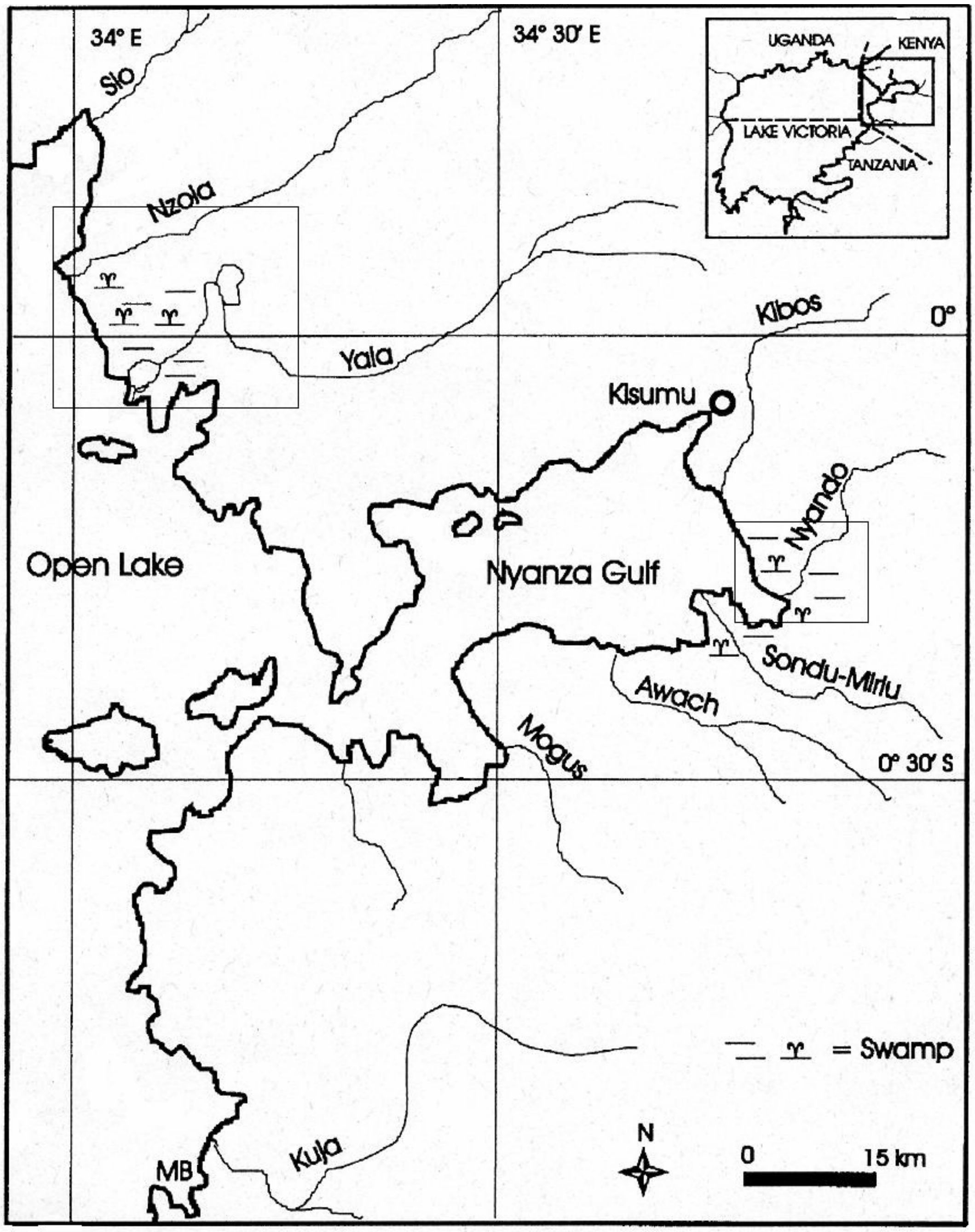


Figure 5.8: Geologic situations of the Yala and Nyando swamps (modified from Lung'ayia et al., 2001).

5.6.2 Results

Soil organic carbon (SOC) and total N for topsoil, 0-20cm depth, from the two wetlands were statistically analyzed. A random selection (37) of the samples from the Yala Swamp was taken to match the number taken in Nyando so as to allow for comparative statistical analysis of the two sites with an equal number of samples. Table 5.5 gives summary statistics for SOC in the two wetlands.

Table 5.5: Descriptive statistics for SOC (%) in the Yala and Nyando Swamp topsoils (0-20cm)

Descriptive statistics	Yala Swamp SOC (%)	Nyando Swamp SOC (%)
Minimum	1.51	1.47
Mean	5.57	4.90
Median	3.69	3.80
Maximum	21.6	19.8
Standard deviation	5.27	3.97
Total N	37	37

The average SOC for the Yala and Nyando Swamp was 5.57 ± 5% and 4.9 ± 4%, respectively. The SOC levels did not differ significantly from each other ($P = 0.54$). Total N for the Nyando wetland was 0.36 ± 0.2% and for the Yala wetland 0.40 ± 0.3%; these values were also not significantly different. Correlation between SOC and total N in the Nyando Swamp was 0.99 (Figure 5.9), which was also the case in the Yala Swamp as discussed before. The result from an ANOVA ($P = 0.000$) shows that the variation in SOC contents in soils from the Nyando Swamp cannot be used to explain that in the Yala Swamp. The two swamps represent two different entities.

5.6.3 Greenhouse gas emissions scenario for Yala and Nyando swamps

Greenhouse gas emissions are the product of very complex dynamic systems, determined by driving forces such as demographic and socio-economic development, and technological change (IPCC, 2000). The rapidly growing population, socio-economic development (such as market integration), and adoption of new drainage techniques are foreseen as factors that will influence future greenhouse gas emissions around Lake Victoria.

Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties (IPCC, 2000). In this case, the scenario under investigation is: complete conversion of the two wetland areas into agricultural-land. The two wetlands cover a total area of 31 600 ha. The content of carbon each holds, as already discussed before, does not significantly differ. Based on the estimated amount of SOC and biomass C for the Yala Swamp, which was 56.3 tC/ha and 2.3 tC/ha, respectively, the total amount of carbon held in the two systems is 1.87 MtC (1.8 Mt SOC and 0.07 Mt above-ground biomass C). Therefore, using the estimated emission rates over the Yala Swamp for recent conversions, the amount of C to be released as a result of drainage of the swamps is 0.82 MtC (41.9 % of SOC + 0.07 MtC). This is equivalent to 3.01 $MtCO_2$, and 0.05 % of the global estimate for emissions due to land-use change between 1980 and 2000, which is significant considering the size of the two swamps. Also, the sub-soil C was not estimated for this study. Losses through conversion of wetlands to agricultural-lands in temperate and tropical regions are 0.063-0.085 GtC/yr and 0.053-0.114 GtC/yr, respectively (WBGU, 1998). Therefore, conversion of wetlands around Lake Victoria contributes proportionally to carbon losses through wetland conversion in the tropics.

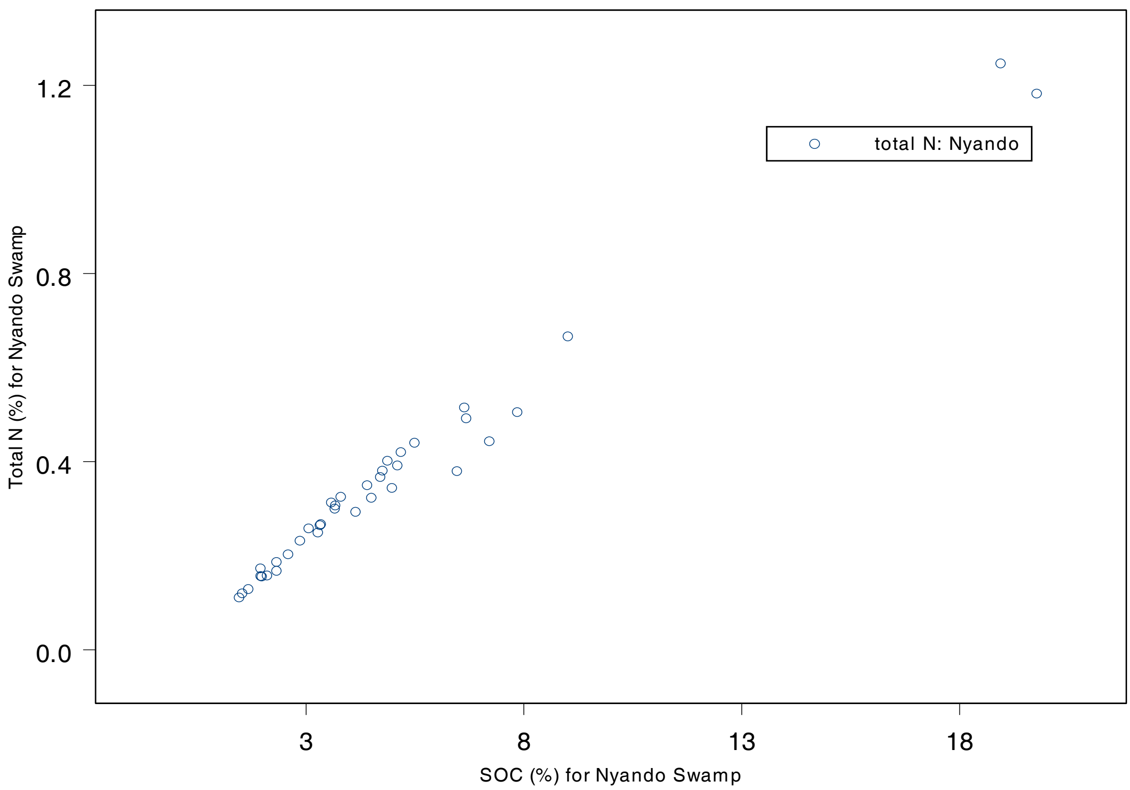


Figure 5.9: SOC (%) versus Total N (%) for soils in the Nyando Swamp

5.7 Conclusion

SOC in the wetland soils was more than those of the agricultural-land. The land-use history of agricultural land, the crops grown on them, their spatial location and flooding patterns influenced the amount of SOC. Agricultural lands that were flooded for a prolonged period maintained higher levels of SOC as compared to those flooded for a short time or not flooded at all. The landscape position of agricultural land was also of great influence on the SOC. For example, the carbon content in agricultural land drained less than 20 years ago and more than 40 years ago in the northern part of the study area was not significantly different. The agricultural-land drained 20-40 years ago, in the southern part of the study area had the same SOC content as the adjacent wetland segment due to prolonged flooding over the area during and after the long rains; this area had the highest SOC content amongst the agricultural land studied. The main agricultural crop in the area was maize, which according to several studies increases the SOC.

The SOC in wetland segments was also influenced by their spatial location in relation to the Yala River and by their disturbance pattern. The wetland segment at the entrance of the Yala River had the lowest SOC content due to increased influx of water and materials in this part. Natural disturbances such as the heavy El-Nino rains of 1987 resulted in successional processes in this wetland segment. The other segments were not directly connected to the Yala River, and the disturbance pattern was mainly harvesting of papyrus vegetation.

The results from the Yala Swamp can be used to extrapolate for SOC in natural wetlands around Lake Victoria. The spatial location and land-use history of the Nyando Swamp in relation to the Yala Swamp did not significantly impact on the SOC of the former in comparison to the latter. Harvesting of papyrus vegetation which is a common practice in the Nyando Swamp also did not seem to have a major impact on the SOC levels. More research is needed to study the impact of papyrus harvesting on wetlands SOC. A scenario under which the two swamps would be drained contributes a significant amount to the global emission estimate based on the 1980-2000 emission rates due to land-use change, and proportionally to losses through wetland conversions in the tropics.

6 SOIL FERTILITY IN THE WETLAND AND RECLAIMED WETLAND SOILS USING PLANT PARAMETERS IN RELATION TO CHEMICAL ANALYSIS

6.1 Introduction

The productivity of the soil is largely determined by its fertility, which in turn is dependent on the root development zone (topsoil) depth and the nutrients stored in its mineral and organic constituents (Vlek et al., 1997). Food security is a pressing concern for the world today especially in sub-Saharan Africa. Increased and sustained production in tropical Africa requires appropriate soil management practices (Nandwa et al., 1994). While developed countries face eutrophication problems due to the excessive application of animal manure and fertilizers, in sub-Saharan Africa soil fertility decline is a major problem affecting crop production (Vlek, 1993; Nziguheba et al., 2000). Maize is sown in areas typified by infertile soils. Farmers squeeze meager harvests out of holdings which have shrunk and lost productivity; fallows have been abandoned in favor of intensive, multiple cropping the year round. Increasing pressure on agricultural-land and the subsequent abandonment of many traditional maintenance strategies for soil fertility have resulted in negative nutrient balances (Kaizzi and Wortmann, 2001). The relegation of maize to ever more marginal and fragile cropping areas represents a continual hardship for millions of farmers (Reeves, 1996). In well-drained tropical soils, continuous maize cultivation on recently cleared land depletes nitrogen and may cause erosion (Moser et al., 1996). The result is increasing pressure on virgin lands such as the wetlands.

In Western Kenya, wetlands are perceived as fertile land for production of maize and other agricultural products. The farming system has evolved from shifting cultivation via fallow-based farming, to permanent agriculture mainly due to increasing population pressure and market integration (Mango, 1999). In the Yala Swamp, nitrogen content is highly correlated to carbon content. Therefore, reductions in nitrogen content directly impact carbon (C) content in the soil.

Maize and other grasses are often used as indicators of nutrient status in organic soils as long as the nutrient under investigation is not a micro-nutrient (FAO, 1988). A maize seed caries a limited amount of nutritive tissue that must suffice to support development of the seedling until such a time that the seedling is established in light and photosynthesis takes over supply of energy and carbon (Hopkins, 1995). The presence of plant roots has significant effects on the soil microbial population, and hence soil mineralization, because conditions for microbial growth are favorable in the rhizosphere (Sanchez et al., 2002). For example, the soil microflora is heavily influenced by C sources derived from rhizodeposition. Rhizodeposits are easily decomposable substrates translocated from the aboveground parts of the plants to the roots and subsequently transferred into the surrounding soil as root exudates, mucilage, and sloughed cells and tissues (Qian et al., 1997).

Nitrogen (N) mineralization is defined as the process by which soil organic N is transformed into the inorganic forms, ammonia (NH_3) or ammonium (NH_4^+), by microorganisms (Brady, 1990; Bashkin, 2002). If the environmental conditions are not limiting, the NH_4^+ is oxidized to nitrate (NO_3^-) almost as rapidly as it is formed (Ma et al., 1999). This process is retarded in cold, acid or anaerobic soil conditions. Thus nitrate nitrogen (NO_3^- -N) is usually the dominant form of plant available N in most arid and semi-arid areas. Bioenergetic considerations revealed that the assimilation of nitrate nitrogen by plants requires more energy than the assimilation of ammonium nitrogen (Schortemeyer et al., 1993). Thus, feeding plants with ammonium could be an interesting alternative to nitrate-based nutrition. However, even when ammonium is provided as fertilizer, nitrate is the dominant nitrogen source for plants in most arable areas.

The process in which inorganic N is transformed into organic N is defined as N immobilization. If new N inputs (less than 5 years) are incorporated into stable organic matter, then retained N will be susceptible to repeated microbial mineralization and associated leaching and gaseous N loses. In contrast, if some N inputs are quickly transferred into stable organic matter that is not readily susceptible to microbial mineralization, soils could sequester N for years to decades without significant loss from the ecosystem (Kaye et al., 2002). The aim of agricultural N management is to enhance net N mineralization at times when plants need N and to synchronize soil N mineralization (N release) with uptake by the plant. The objective of this study was to quickly assess whether the loss of soil carbon upon drainage impacted the soil fertility status of wetland soils as compared to drained wetland (agricultural-land) soils using maize growth and root to shoot ratio indices in relation to chemical (C, N) analysis. Without some knowledge of the nature and properties of soils, it is not possible to predict soil quality in a given area and to know how soils should be managed and conserved (Brady, 1990). The details of the experiment were provided in the Materials and Methods section.

6.2 Observation and results

Observations were made during the 14 days of the experiment. It was observed that plants grown on wetland soils experienced some burning of leaves during the initial stages of growth. Overall, plants grown on soils from agricultural land appeared healthier than those on wetland soils. Waterlogging may have stunted the growth of plants grown on wetland soils as compared to those on reclaimed wetland (agricultural-land) soils. A study by Manske and Vlek (2002) associated poor soil drainage with increases in soil CO_2 and ethylene content, which have detrimental effects on root and shoot growth of wheat. These may also apply to maize plants.

Table 6.1 shows the descriptive statistics for maize-seedling roots and shoots after harvesting and drying. The average total biomass for maize grown on wetland and agricultural-land soils were 0.47 ± 0.1 g and 0.55 ± 0.1 g, respectively. The medians for the two categories were 0.47 g and 0.54 g. Though differences are small, they are significant due to the large sample size (216) and probably reflect the more hospitable conditions in drained soils with more readily available nutrients.

The average root to shoot ratios (R:S) for the maize grown on wetland and agricultural-land soils were 1.67 ± 1 and 1.21 ± 1, respectively, and the medians for the two categories were 1.46 and 1.0. There was a significant difference in the average R:S for maize grown on wetland and agricultural-land soils. A study by de Toledo Machado and Furlani (2004) reported that high dry matter yield in maize plants correlates positively with accumulation of more dry mater on shoots rather than on roots. Annuals generally use small amounts of photosynthate to support root growth, whereas species with perennial roots and rhizomes such as papyrus, often have root: shoot ratios well in excess of 1 (Mitsch and Gosselink, 1993). However, early in their development most plants invest heavily in root establishment, and more so if soil conditions are unfavorable (Reich, 2002). According to the optimality theory, there should be a functional balance among root and shoot systems, and this balance should vary with resource supply and among species in relation to life history traits and /or habitat affinities (Reich, 2002) Indeed, it was found that R:S ratio decreased when total biomass increased so that less photosynthate was invested below ground as plants grew (r = -0.2 for both substrates). The maize grown on wetland soils invested more in root development than that on agricultural-land soils, again suggesting that agricultural-land soils provide more hospitable grounds for plant growth.

Table 6.1: Total biomass (dry matter) and root to shoot ratios for maize seedlings grown on wetland and reclaimed wetland (agricultural-land) soils

Descriptive statistics	Maize grown on wetland soils Total biomass (g)	R:S ratio	Maize grown on agric. land soils Total biomass (g)	R:S ratio
Mean	0.47	1.67	0.55	1.21
Median	0.47	1.46	0.54	1.0
Sample size	216	216	216	216
Std Dev.	0.1	1.4	0.1	1.2

Dry matter partitioning between shoots and roots depends on several external factors in the root and shoot environment (Engels, 1994). The root to shoot ratio is often increased by soil factors which reduce specific root activity (i.e., nutrient and water uptake) such as low water potentials and low availability of phosphorus or nitrogen (Chapin et al., 1988), and by environmental factors that increase specific shoot activity (i.e., photosynthetic rate) such as high light intensity (Mahall et al., 1981) or CO_2 concentration (Larigauderie et al., 1988). The ambient environmental factors were constant for the experiment as it was carried out under controlled conditions in a screenhouse. However, edaphic factors were different due to differences in the aeration of the soils.

Waterlogging was imposed in pots filled with wetland soils thus simulating conditions under poorly drained wetland soils. White and Reddy (2001) reported higher rates of N mineralization under aerobic conditions than under anaerobic conditions in the Everglades soils. Since the agricultural-land soils had been under aerobic conditions, the mineralization level was supposedly higher than that for wetland soils. Also, the average pH for wetland soils (5.4) was outside the suggested pH range for better growth of maize, whereas that for agricultural-land soils (6.1), was within the range. In fact, an increase in wetland soils pH resulted in a decrease in the R:S ratio, thereby increasing the shoot biomass (r = -0.2), reflecting a more favorable rooting environment. The opposite is true for agricultural soils (r = 0.2), suggesting that the current pH for soils in agricultural land is near-optimal for maize growth.

For the purpose of this study, nitrogen was considered more important than phosphorus (P), because maize plants largely rely on seed reserves of organic P during early plant growth (Hopkins, 1995). As the plant matures, available inorganic phosphorus (Pi) is liberated by an enzyme group, phosphatases, which occur scattered in all tissue cells of plant organs. Root-secreted phosphatase activity is related to plant ability to make soil P available for absorption (de Toledo Machado and Furlani, 2004). Thus, N is the most limiting nutrient for early maize growth. The average total N uptake for maize grown on wetland and agricultural-land soils was 3.5 ± 0.7 % and 3.6 ± 0.6 %, respectively. Both categories had the same population distribution curves (Figure 6.1a and 6.1b). The medians for the two categories were 3.41 % and 3.45 %. There was no significant difference (P = 0.67) in the total N content for maize grown on wetland and agricultural-land soils. The total N amounts were calculated using the total N contents and total biomass for maize plants in each category. The average amount of total N uptake for maize grown on wetland and agricultural-land soils was 16.4 ± 3 mg and 19.7 ± 3 mg, respectively. The average content of biomass carbon accumulated on the plants over the 14 days was 81 ± 2% (Figure 6.2 a) and 79 ± 2 % (Figure 6.2 b) for plants grown on wetland and agricultural-land soils, respectively. The average amounts for the two categories were 376 ± 9 mg and 440 ± 11 mg, respectively. There was a significant difference (P = 0.007) in the average amount of biomass carbon accumulated in maize plants grown on wetland and agricultural-land soils.

Though wetland soils had more total N than agricultural-land soils, the greenhouse findings suggest that organic matter in wetlands does not mineralize as readily as in soils drained for longer periods. Also, when total N increased the R:S ratio decreased thus favoring shoot growth, but less so in wetland soil (r = -0.1) than in agricultural soil (r = -0.2). Most of the nitrogen in wetlands is in organic form, whereas some quantities of nitrate are usually present in drained wetland soils in which organic materials oxidize rapidly (FAO, 1988). In fact, the C/N ratios indicate poor nutrient quality in wetland soils as compared to agricultural-land soils, which is consistent with the result of the greenhouse experiment. The lower the C/N ratio, the more readily is the organic N released (Alef and Kleiner, 1986).

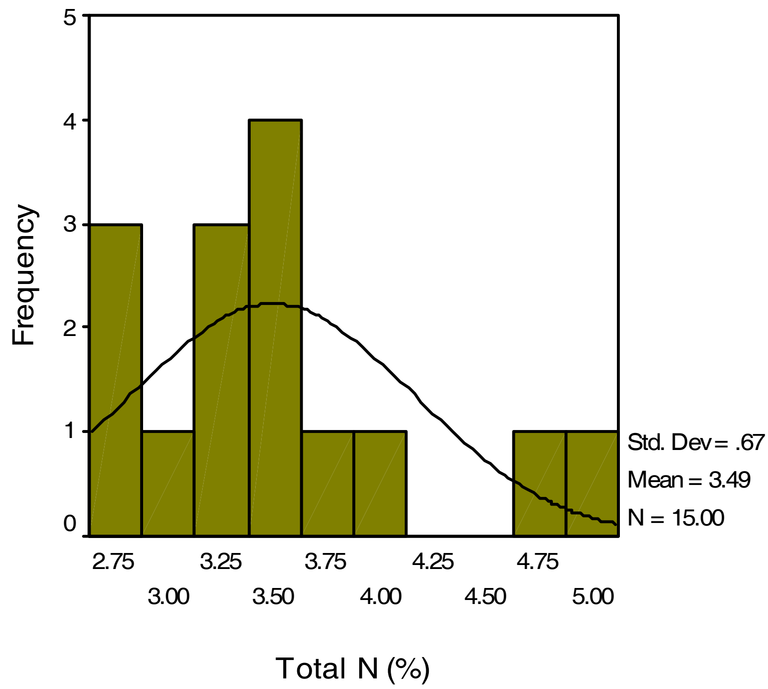


Figure 6.1 (a): Frequency distribution for total N (%) in maize grown on wetland topsoils

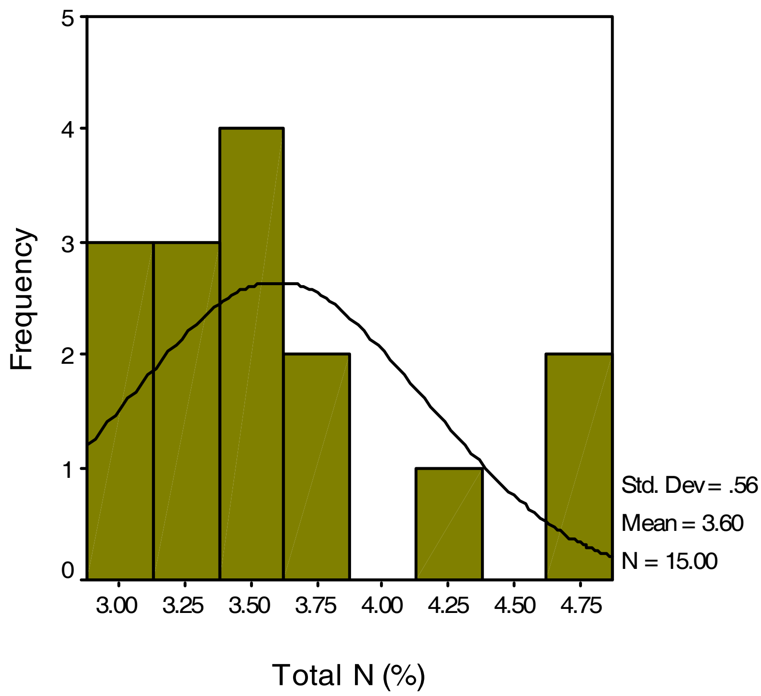


Figure 6.1 (b): Frequency distribution for total N (%) in maize grown on agricultural-land topsoils

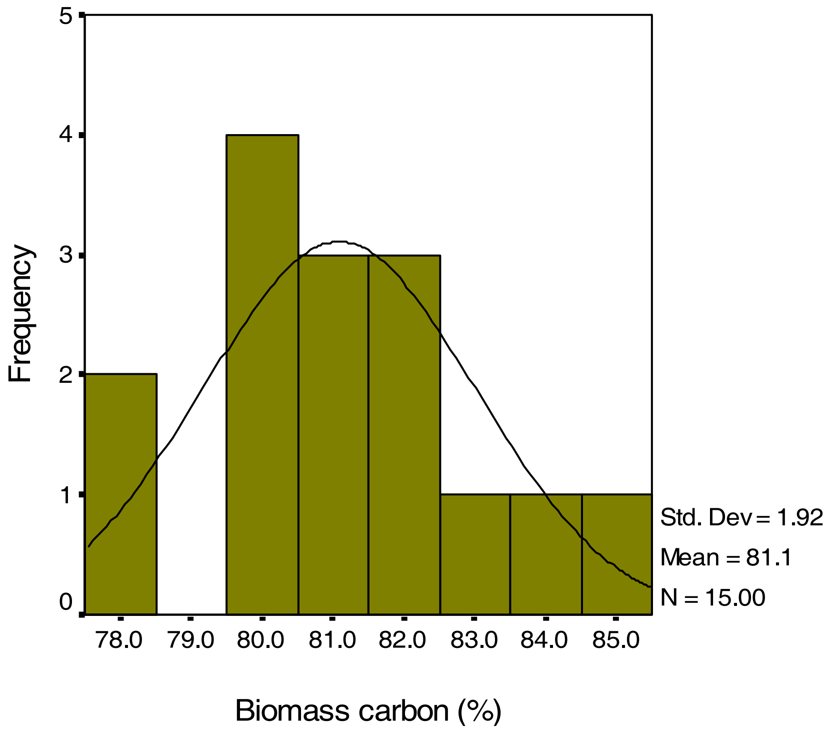


Figure 6.2 (a): Frequency distribution for biomass carbon in maize plants grown on wetland topsoils

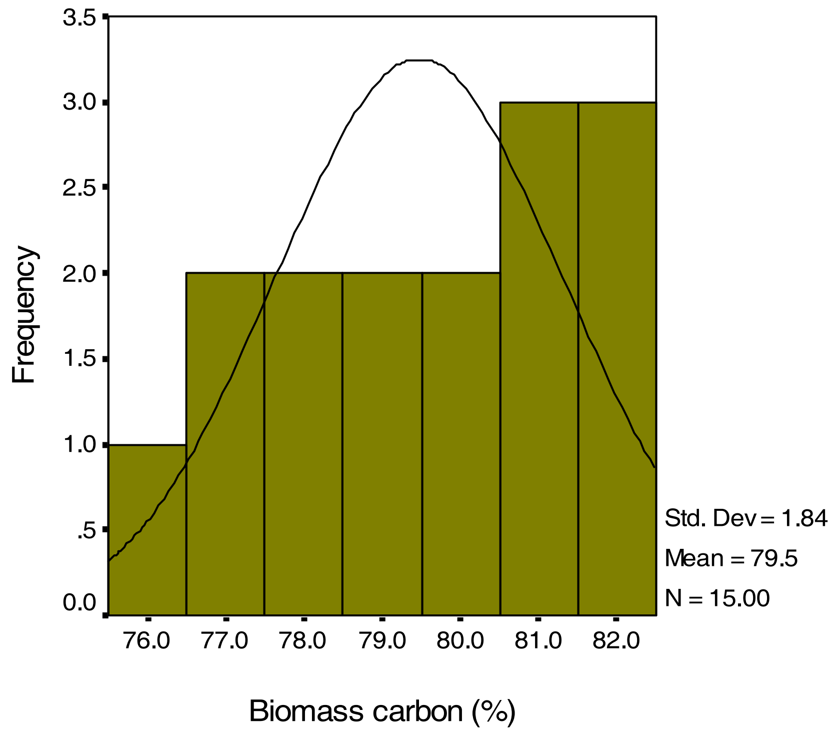


Figure 6.2 (b): Frequency distribution for biomass carbon in maize plants grown on agricultural-land topsoils

6.3 Conclusion

The results from the experiment clearly show that nitrogen availability in wetland soils after drainage does not correlate with total N. Even though the wetland soils had more total N as compared to agricultural land soils, the latter had higher biomass and lower root to shoot ratios than the former. Also, the N uptake was not significantly different for the two categories. Wetland soils also had more acidic pH values, which impede the development of the maize and shift the partitioning towards the roots. The experiment successfully shows that wetlands following drainage are not less fertile even though they have lost a significant fraction of their organic carbon.

7 GENERAL CONCLUSIONS

This study analyzed the impact of wetland drainage on soil and plant carbon pools in the Yala Swamp, a tropical wetland along Lake Victoria. Remote sensing techniques and geographic information system tools were adequately used to identify the landscape elements over the study site, and to estimate the areal extent of the drainage between 1984 and 2001. Soil organic carbon (SOC) and above-ground biomass carbon contents and amounts were analyzed and estimated for the soil and plant samples collected in the Yala Swamp during the short-rain season. The result obtained from analysis of the Yala Swamp soils was compared to that in the Nyando Swamp (another major wetland along the lake) to assess for the possibility of extrapolating the result from the former to all swamps around Lake Victoria. A scenario under which all the wetland areas would be converted to agricultural-land was investigated and convincing results were obtained. And comparative assessment of soil fertility in relatively natural wetland to that in drained wetland areas (agricultural-land) reveals that high content and amount of nutrients do not guarantee high nutrient uptake by plants.

7.1 Spatial analysis of the land cover

When addressing land use, land use change and forestry sinks in the context of potential additional activities that may be included in the Kyoto protocol, it immediately comes to mind that wetlands, a significant reservoir and potentially a sink for carbon, would be further protected if they are included in the agreement (Environment Canada, 1998). This could only be done if the land-cover dynamics over the wetlands are well understood. Therefore, before the interaction between landscape structure and landscape processes can be understood, landscape patterns must be identified and quantified in a meaningful way. Remote sensing techniques and geographic information systems tool were adequately used to analyze the land cover over the Yala Swamp. The main landscape elements over the swamp are papyrus vegetation, mixed wetland vegetation and water bodies. If wetlands processes are to be fully understood, studies on wetlands must go beyond the wetland boundary. Therefore, the main landscape element in the proximity of the swamp is agricultural-land which covers croplands with plant cover and harvested croplands. Based on the results obtained from image classification and

Tasselled Cap transformation, it is concluded that land cover changes occurred in the Yala Swamp over the past 17 years (almost 2 decades). An area of about 6 333 ha (372.5 ha/yr) was drained. Changes in areal extent of the marsh were brought about through drainage of wetland areas for agricultural production. These changes have been caused by the desperate small-scale farmers who are struggling to meet their food security need. High population densities coupled with poverty exert land-use pressure on wetlands. This results with conversion of wetland areas to agricultural-land. The phenomenon of conversion of wetland to agricultural-land has a short history in Africa, whereas, in developed countries a long history of wetland drainage exists. For example, in Kenya, conversion of the Yala Swamp started in the 1960s, whereas in the United States of America, drainage of the Mississippi River bottomland hardwood wetlands started in 1893 (USDA and NRCS, 2002). While the functions or ecological services provided by wetlands are becoming recognized as important environmental and economic components of the agricultural landscapes in developed countries, wetlands are perceived as fertile land for agricultural production in the tropics. In Kenya, the government policies support exploitation of wetlands as opposed to their conservation. The total area and status of tropical wetlands are still unknown, but the results from this study suggest that the pattern of wetland conversion in tropical countries may have been similar to that of developed countries in the past, particularly in the United States. The United States has lost 54 % (87 million hectares) of its original wetlands, of which 87 % have been lost to agricultural development (Pearce et al., 1991).

Other changes occurred in the health status of the vegetation over the swamp as can be seen from the reduced greenness values between 1984 and 2001. Sedimentation load into open water patches, particularly Lake Victoria, has also increased as explained by the increased surface albedo over the past 17 years, all of which suggest a degradation of the resource base. In contrast, the wetness or soil moisture content in the wetland has not significantly changed over the 17 years. The Tasselled Cap transformation is a useful tool in wetland moisture and vegetation change detection over reasonably long time periods.

7.2 Quantitative and qualitative characterization of soil carbon pools

Soil organic carbon in the wetland soils was more than that in those of the agricultural-land. About 55 % SOC was lost due to drainage of the wetland for agricultural production. Agricultural-lands were divided into three categories (0-20 years, 20-40 years and more than 40 years of drainage/conversion) based on their drainage history. The land-use history of agricultural-land, their spatial location and flooding patterns influenced the amount of SOC. Agricultural-lands that were flooded for prolonged period maintained higher levels of SOC as compared to those flooded for a short time or not flooded at all. The landscape position of agricultural-land was also of great influence on the SOC. For example, the carbon content in agricultural-land drained less than 20 years ago and more than 40 years ago in the northern part of the study area was not significantly different. The agricultural-land drained 20-40 years ago in the southern part of the study area had the same SOC content as the adjacent wetland segment due to prolonged flooding over the area during and after the long rains; this area had the highest SOC amongst the agricultural-land studied. The main agricultural crop in the area is maize, which according to several studies increases the SOC.

The SOC in wetland segments was also influenced by their spatial location in relation to the Yala River and by their disturbance pattern. The wetland segment at the entrance of the Yala River had the lowest SOC content due to increased influx of water and materials in this part. Natural disturbances such as the heavy El-Nino rains of 1987 resulted in successional processes in this wetland segment. The other segments were not directly connected to the Yala River, and the disturbance pattern was mainly harvesting of papyrus vegetation.

In the deliberations under the Kyoto protocol, the 1980s and 1990s are considered important years for reporting of greenhouse gas emissions. Therefore, in this study the pair of samples covering wetland and agricultural-land converted 0-20 years ago is chosen as a representative of the study area for estimation of carbon dioxide emissions due to drainage of the wetland. The emission estimation result convincingly reveals that 1 tC/ha/yr was lost due to drainage between 1984 and 2001.This is indeed not too far from the emission estimates for Finland, which is 2.5 tC/ha/yr. The main difference may be because there is less peat formation in tropical wetlands as compared to temperate wetlands due to high temperatures and increased decomposition in the former.

This study successfully showed that the results from the Yala Swamp can be used to extrapolate for SOC in natural wetlands around Lake Victoria. The spatial location and land use history of the Nyando Swamp in relation to the Yala Swamp did not significantly impact on the SOC of the former in comparison to the latter. Harvesting of papyrus vegetation, which is a common practice in the Nyando Swamp, also did not seem to have a major impact on the SOC levels. More research is needed to study the impact of papyrus harvesting on wetlands SOC. A scenario under which the two swamps are drained shows how land-use changes will influence the carbondioxide global emission rates; contributes proportionally to emissions by wetland conversions in the tropics. The two wetlands cover an area of 31 600 ha. The carbon content of these wetlands as already discussed before does not significantly differ. Based on the estimated amount of SOC and biomass C for the Yala Swamp, which were 56.3 tC/ha and 2.3 tC/ha, respectively, the total amount of carbon held in the two systems is 1.87 MtC (1.8 Mt SOC and 0.07 Mt above-ground biomass C). Therefore, using the estimated emission rates over the Yala Swamp for recent conversions (0-20 years ago), the amount of C to be released as a result of drainage of the swamps is 0.82 MtC (41.9 % of SOC + 0.07 MtC). This is equivalent to 3.01 $MtCO_2$, and 0.05 % of the global estimate for emissions due to land-use change between 1980 and 2000, which is significant considering the size of the two swamps. Also, the sub-soil C was not estimated for this study.

Losses through conversion of wetlands to agricultural-lands in temperate and tropical regions are 0.063-0.085 GtC/yr and 0.053-0.114 GtC/yr, respectively (WBGU, 1998). Therefore, conversion of wetlands around Lake Victoria contributes proportionally to carbon losses through wetlands conversion in the tropics. It is hoped that this findings will be disseminated to policy makers in Kenya and in Africa as a whole, as a plight to follow the wise use concept of the Ramsar Convention. This will help to conserve the remaining wetlands in the tropics, which could also contribute to the clean development mechanism of the Kyoto protocol under the emerging carbon trade.

7.3 Soil fertility in the wetland and reclaimed wetland soils using plant parameters in relation to chemical analysis

Soil fertility is a major problem hindering crop production in the tropics, especially in sub-Saharan Africa. Majority of people in the tropics have to manage their soils to get good yields and to meet their food security need. In highly populated places like western Kenya, the problem is compounded by shortage of land. Farmers are forced to engage in desperate activities such as farming of marginal and fragile land such as wetlands. This poses a serious problem because farmers perceive wetland as fertile land and do not have a proper understanding of the properties of wetland soils. The special character of wetland landscapes and the underlying soils is often not recognized, and reclamation follows the same pattern as for mineral soils (FAO, 1988). A greenhouse experiment was carried out using soils from wetland and agricultural-land topsoil. Maize was used as it is the staple crop in western Kenya. The result from the experiment clearly showed that Nitrogen availability in wetland soils after drainage does not correlate with total N. Even though the wetland soils had more total N as compared to agricultural-land soils, maize plants from the latter had higher biomass and lower root to shoot ratios (R:S) than the former. However, there was no significant difference in the total biomass for the two soil categories. Also the N uptake was not significantly different for the two categories. Wetland soils also had more acidic pH values than agricultural-land soils, which impede the development of the maize and shift the partitioning towards the roots.

Though wetland soils had more total N than agricultural-land soils, the greenhouse findings suggest that organic matter in wetlands does not mineralize as readily as in soils drained for longer periods. Also, when total N increased the R:S ratio decreased thus favoring shoot growth, but less so in wetland soil ($r = -0.1$) than in agricultural soil ($r = -0.2$). Most of the nitrogen in wetlands is in organic form whereas some quantities of nitrate usually are present in drained wetland soils in which organic materials oxidize rapidly (FAO, 1988). In fact, the C/N ratios indicated poor nutrient quality in wetland soils as compared to agricultural-land soils, which is consistent with the result of the greenhouse experiment. The lower the C/N ratio the more readily the organic N is released (Alef and Kleiner, 1986)

Waterlogging was imposed in pots filled with wetland soils thus simulating conditions under poorly drained wetland soils. White and Reddy (2001) reported higher rates of N mineralization under aerobic conditions than under anaerobic conditions in the Everglades soils. Since the agricultural-land soils had been under aerobic conditions, the mineralization level was supposedly higher than that for wetland soils. Also the average pH for wetland soils, at 5.4, was outside the suggested pH range for better growth of maize, whereas that for agricultural-land soils, at 6.1, was within the range. In fact, an increase in wetland soils pH resulted in a decrease in the R:S ratio thereby increasing the shoot biomass ($r = -0.2$), reflecting a more favorable rooting environment. The opposite is true for agricultural-land soils ($r = 0.2$), suggesting that the current pH for soils in agricultural-land is near-optimal for maize growth.

The experiment successfully showed that wetlands following drainage are not less fertile even though they have lost a significant fraction of their organic carbon. Some amendment is needed such as liming to increase the pH of the wetland soils after drainage. Amendments are also needed to counteract the waterlogging capacity of the soils. It is hoped that this information would be made available to farmers to improve their understanding of wetland systems.

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9 APPENDICES

Appendix 1

Figure 9.1: A green house with maize plants ready to harvest

Figure 9.2: Preparing plants for harvesting

Appendix 2:

Figure 9.3: Burning of vegetation in drained wetland area around Lake Victoria (Photo by Dr Wassmann in Feb 2003)

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