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Soil attribute changes along chronosequences of land use in the littoral wetlands of Lake Naivasha, Kenya

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Zusammenfassung

Lake Naivasha ist ein Süßwassersee im ostafrikanischen Rift Valley, dessen Wasserspiegel von 1980 bis 2011 stetig sank. Die dabei freigelegte, litorale Landfläche wurde von Pastoralisten und Kleinbauern kontinuierlich in Nutzung genommen, wobei Chronosequenzen der Landnutzung mit zunehmender Distanz zum Seeufer entstanden sind (space-for-time). Für diese Studie wurden Transekte mit einer Landnutzungsdauer von 1 bis 30 Jahren sowie Referenzflächen (keine, beziehungsweise erstmalige Landnutzung) auf Weide- und Ackerland vergleichend untersucht. Während Weidenutzung sowohl auf Alluvialböden als auch auf Böden mit lakustrinem Unterboden durchgeführt wurde, war eine Nutzung für den Anbau von Ackerkulturen auf lakustrinen Böden begrenzt. Änderungen der Bodenfeuchte sowie des Kohlenstoff- und Nährstoffgehaltes des Oberbodens wurden entlang der Chronosequenz zwischen November 2010 und Dezember 2011 ermittelt. Zusätzlich wurde ein Topfversuch mit Kikuyu Gras (dominante Art auf den Weideflächen) und mit Mais (Proxy für Ackerlandkulturen) in gesiebtem Oberboden unter kontrollierten Bedingungen durchgeführt. Der organische Kohlenstoff, der durch Kaliumpermanganat oxidierbare, und der nicht oxidierbare Kohlenstoff, sowie der Stickstoffgehalt nahmen exponentiell ($p < 0.05$) mit zunehmender Landnutzungsdauer ab. Auch der an Bodenpartikel gebundene Kohlenstoff, und damit die leicht wie auch die schwer mineralisierbaren organischen Bestandteile, gingen in allen Aggregatsgrößen-Klassen zurück. Die Geschwindigkeitskonstanten dieser Abnahme lagen beim organischen Kohlenstoff im Weideland bei -0.021 (15 jährige Zeitspanne) und im Ackerland bei -0.016 pro Jahr (30 jährige Zeitspanne). Im Fall des Bodenstickstoffs wurden Abnahmeraten von -0.019 auf Weideland und von -0.012 pro Jahr auf Ackerland ermittelt. Damit unterschieden sich die Verlustraten nicht oder nur gering zwischen den Bodentypen und Landnutzungsarten. Der Bodenwassergehalt verringerte sich signifikant ($p < 0,05$) mit der Landnutzungsdauer. Dies ist ein Indiz, dass vor allem die mit der Landnutzung einhergehende Drainage des Bodenprofils für die Verluste verantwortlich ist, während Bodentyp und Landnutzungsart geringen Einfluss hatten. Die oberen Bodenschichten (0 – 60 cm) trockneten ab einer Landnutzungsdauer ≥20 Jahre zeitweise aus, was auf die Absenkung des Grundwasserspiegels wie auch auf das Ausbleiben der Niederschläge zurückzuführen war. Dieser Bodenwassermangel wurde auf dem Ackerland durch zusätzliche Bewässerung der Flächen nur teilweise kompensiert. Die beobachteten Unterschiede in pflanzenverfügbarem Phosphor (Olsen P) waren nicht mit der Landnutzungsdauer gekoppelt. Nur der an Austauscherharze adsorbierte Phosphoranteil (auf den als Weideland bewirtschafteten lakustrinen Böden) verringerte sich signifikant mit zunehmender Landnutzungsdauer, und korrelierte mit dem Gehalt an organischem Kohlenstoff, sowie den Niederschlagsbeziehungsweise Bewässerungsmengen. Die beobachteten Trends konnten auch im Gefäßversuch bei konstantem Bodenwassergehalt bestätigt werden. So ging die Trockenmassebildung von Kikuyu Gras und von Mais mit steigender Landnutzungsdauer signifikant zurück, was mit der beobachteten Abnahme im Bodenstickstoffgehalt zusammenhing. Mit dem Rückgang von pflanzenverfügbarem Wasser und Nährstoffen im Bodenprofil bei fortschreitender landwirtschaftlicher Nutzung ist folglich ein Produktionsrückgang sowohl auf Weide- als auch auf Ackerlandflächen zu erwarten. Das Chronosequenz Modell erwies sich hierbei als geeigneter Ansatz, um edaphische und hydrologische Veränderungen und deren Einfluss auf die Pflanzenproduktion zu analysieren.

Summary

Lake Naivasha is a freshwater lake in the East African Rift Valley, which was affected by a continuously declining water level between 1980 and 2011. The newly exposed littoral area has been gradually put under agricultural land use by pastoralists and small-scale farmers, forming chronosequences of land use with distance to the lake shore (space-for-time approach). Transects representing land use durations of 1 to 30 years (as well as reference sites) were established, comprising soils of alluvial and lacustrine sediment origin in the pasture land and of lacustrine origin in the cropland. We assessed changes in soil moisture, carbon and nutrient content between November 2010 and December 2011. An additional greenhouse experiment studied the responses of kikuyu grass (proxy for pasture vegetation) and maize (proxy for crops) in potted topsoil. With increasing distance from the lake shore and duration of land use, we observed a exponential decline ($p < 0.05$) in soil organic carbon, potassium permanganate oxidized and non-oxidized carbon as well as N contents under both pasture and cropland uses. Additionally, carbon in particulate organic matter decreased in all size fractions, revealing that both the labile sand-bound and the stable silt- and clay-bound carbon were affected by the time of use. In the case of soil organic carbon, the rate constants of decline were -0.021 under pasture (15 years time span) and -0.016 per year under crops (30 year time span). In the case of soil N, the rate constants were -0.019 and -0.012 per year for pastures and cropland, respectively. Thus, carbon and nitrogen losses were similar on both soil types and land management systems. The soil water content decreased significantly ($p < 0.05$) with the duration of land use. Consequently, the associated change in soil aeration status is probably the key driver of the observed soil fertility decline, with soil type and land management having little influence. On chronosequence positions $\geq$20 years the upper soil layers (0 – 60 cm) dried up temporarily, owing to a drop in groundwater depth and insufficient rainfall. In croplands, this water deficit in the topsoil could only be partially compensated by supplementary irrigation. Observed changes in the plant-available Olsen-P fraction were not related to the duration of land use. Only the ion exchange resin-adsorbed P fraction decreased significantly with land use duration under pasture use (lacustrine soils), and was mainly associated with soil organic carbon and amount of rainfall and irrigation. The dry matter accumulation in potted soil of both kikuyu grass and maize declined with the duration of land use. As soil moisture was kept constant, this reduction with time of land use was primarily related to changes in soil nitrogen content. The reduction in plant available water and soil nutrients with continuous agricultural production is likely to entail the observed declining production potential on both, pastures and cropland. The chronosequence model provides a suitable tool to study edaphic and hydrological change processes and their impact on production and land productivity.

Deklaration

Ich versichere, dass ich diese Arbeit selbständig verfasst habe, keine anderen Quellen und Hilfsmaterialien als die angegebenen benutzt und die Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, kenntlich gemacht habe. Die Arbeit hat in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegen.

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List of Abbreviations

µg	Microgram
µmol	Micromole
θ_v	Volumetric water content
θ_a	Plant available water content
θ_{fc}	θ_v at field capacity
θ_G	Gravimetrically measured θ_v
θ_{pwp}	θ_v at permanent wilting point
θ_s	θ_v at saturation
a	Annum
ANOVA	Analysis of variance
BD	Bulk density
°C	Degree Celsius
C	Clay
C	Carbon
$CaCO_3$	Calcium carbonate
CH_4	Methane
Cl	Chlorine
CL	Clay loam
cm	Centimeter
cm^3	Cubic centimeter
CO_2	Carbon dioxide
CR	Crumbly
Cu	Copper
CV	Coefficient of variation
d	Day
DOC	Dissolved organic carbon
dS	Deci Siemens
DW	Dry weight
EC	Electric conductivity
ENSO	El Niño Southern Oscillation
ESP	Exchangeable sodium percentage
FDR	Frequency domain reflectometry
Fe	Iron
FW	Fresh weight
g	Gram
h	Hour
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
ha	Hectares
HC	Heavy clay
HCl	Hydrochloric acid
HCO_3^-	Bicarbonate
IC	Inorganic carbon
J	Joule
K	Potassium
k	Rate constant
K_2SO_4	Potassium sulfate
kg	Kilogram
km^2	Square kilometer
$KMnO_4$	Potassium permanganate
L	Loam
L	Liter
LS	Loamy sand
m	Meter
M	Molar
m^2	Square meter
MA	Massive
masl	Meters above sea level
Mg	Megagram (tons)
mg	Milligram
$MgCO_3$	Magnesium carbonate
Mha	Million hectares
ml	Milliliter
mm	Millimeter
mM	Millimolar
Mm^3	Million cubic meter
Mn	Manganese
MS	Medium sand
N	Nitrogen
n	Sample size
N_2	Nitrogen gas
N_2O	Nitrous oxide
Na	Sodium
Na_2CO_3	Sodium carbonate
$NaHCO_3$	Sodium bicarbonate
nd	No data
NH_4^+	Ammonium ion
NH_4-N	Ammonium nitrogen
nm	Nanometer
NO	Nitric oxide
NO_2^-	Nitrite

NO_3^-	Nitrate
NOC	Non-oxidized carbon
ns	Not significant
P	Phosphorus
p	Probability
PAW	Plant available water
pF	Water suction value
pH	Hydrogen ion concentration
POC	Permanganate oxidized carbon
POM	Particulate organic matter
PR	Prismatic
r	Correlation coefficient
r/Eo	Ratio between rainfall and evaporation
R^2	Coefficient of determination
RAQ	Resin adsorbed quantity
RGB	Reference soil groups
RI	Resistance Index
RMSE	Root-mean-square error
rpm	Rounds per minute
S	Sulfur
S	Sand
s	Second
SAR	Sodium Adsorption Ratio
SB	Subangular blocky
SC	Sandy clay
SCL	Sandy clay loam
SL	Sandy loam
SD	Standard deviation
Si	Silt
SiCl	Silty clay loam
SiL	Silt loam
SO_4^{2-}	Sulfate
SOC	Soil organic carbon
SPSS	Statistical Package for the Social Sciences
t	Time
VIF	Variance inflation factor
WE	Wedge shaped
WRB	World Reference Base for Soil Resources
Zn	Zinc

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1. Tropical wetlands and the littoral wetland of Lake Naivasha

1.1. Wetland definition, distribution and importance

Wetlands are transition zones between waterlogged (aquatic) and aerated (terrestrial) areas.[1] There have been numerous definitions for wetlands, but all define wetlands as areas (artificial, natural) with the presence (permanent or temporary) of water (fresh, salty) until a certain depth and with distinguishable flora, fauna, soils and biogeochemical processes. Wetlands have been distinguished according to soil properties, vegetation, hydrology or location within a certain landscape. Most important man-made wetlands are the rice production areas. The Ramsar Convention defines wetlands as "…areas *of 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 tide does not exceed six metres". W*etlands have also been defined as areas with "*at least one wet growing season per year, but may be dry, moist, or without surface water in other seasons*". We define wetlands for this study according to the location in landform, i.e. floodplains, inland valleys and tidal (littoral) wetlands, and as areas which have been inundated or groundwater-influenced permanently or periodically until today and/or during the past decades.

Tropical wetlands make up about the half of total wetlands worldwide, and inland wetlands in Kenya comprise 2.46 Mha [2]. Despite the small area covered by wetlands globally, they play an important role in global carbon cycle, water balance, biodiversity, wildlife and agricultural production. In East Africa, wetlands have multiple uses (e.g. fishery, building material, plant and forage production among others), especially for the poor rural populations. Kenya is a water scarce country, and under such circumstances communities are expected to increasingly rely on wetland resources.

1.2. Biogeochemistry of tropical wetland soils

The abundance of water is one of the most influential factors on the biogeochemistry of wetland soils[3]. Anaerobic processes start, when soil pores are water-filled > 60%. The soil submergence results in oxygen depletion and anaerobic processes coupled with chemical

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[1] Wetland definitions have been adapted from Krik (2004), Neue *et al.* (1997), Tiner (2006) and The Ramsar Convention on www.ramsar.org.

[2] Information on wetland distribution and importance in East Africa and Kenya have been adapted from Dixon and Wood (2003), Frenken (2005), MEMR (2012), Neue *et al.* (1997), Rebelo *et al.* (2010) and Schyut (2005).

[3] The chapter concerning biogeochemistry of tropical wetlands soils is based on the work of Kirk (2004), Köbel-Knabner *et al.* (2010), Neue *et al.* (1997) and Sahrawat (2003).

redox reactions eventually lead to chemical end products different to those under aerobic soil conditions.

In anaerobic respiration, microorganisms use inorganic oxidants (Mn(III, IV), Fe(III), NO_3^-, SO_4^{2-}) as electron acceptors, resulting in the chemical reduction of the mineral compounds (Mn(II), Fe(II), N_2/NH_4^+, H_2S). Nitrate (NO_3^-) either reduces to ammonium (NH_4^+) or more dominantly denitrifies to N_2 (stepwise with NO_2^-, NO, N_2O as intermediates). Manganese and iron are reduced by both, abiotic (via H_2S or organic acids) and biotic (i.e. by microorganism) processes. The reduction of iron changes the soil color from red/brown to grey/blue. Iron is highly mobile and may be relocated in the soil (illuviation and elluviation). Iron and manganese can thereafter re-oxidize forming red mottles and black concretions, the typical gleyic color pattern of hydromorphic soils.

Also organic substances serve as electron acceptors (i.e. fermentation). Fermenting bacteria decompose polysaccharides (among others), either totally to carbon dioxide (CO_2) (when inorganic electron acceptors are available), or to CO_2, hydrogen (H_2) and acetate. Proteins are decomposed to ammonium (NH_4^+), CO_2, H_2 and acetate during several steps of hydrolysis and oxidation. CO_2 reacts via several steps to bicarbonate (HCO_3^-), which buffers the pH near neutral. When inorganic electron acceptors are depleted or unavailable, microorganisms use CO_2 and reduce it to methane (CH_4), or produce CO_2 and CH_4 from acetate (methanogenesis). Especially easy mineralized organic substances contribute to methane production, and dissolved organic carbon (DOC) compounds (in a great share probably derived from fresh plant debris) are also linked to CO_2 and CH_4 production. The reduction of organic substances is probably also the reason for the increase of humified phenolic compounds in submerged soils.

Not surprisingly those chemical reactions do not occur in such a singular way, as it has been briefly described here. Different processes occur at the same time, are antagonistic or synergetic to each other at different steps of the reaction chain, or depend on certain environmental conditions. For example, anaerobic respiration processes are driven by the amount of H_2 and acetate formed during fermentation. The production of NH_4^+ depends on the amount of organic carbon (since organic material is the main nitrogen source in wetlands) and reducible iron (as the electron acceptor). DOC may also leach and accumulate in the subsoil and stabilize at the soil mineral matrix (with clay minerals, iron oxides and/or soil aggregates among others). Additionally, no wetland system is totally anaerobic under field conditions, and aerobic processes may still occur. Still not all biogeochemical soil processes from submerged soils are well understood.

Typically, organic material accumulates in tropical wetlands owing to the high net primary production and low mineralization rates under anaerobic conditions. However, the latter has been questioned: under specific circumstances mineralization rate in tropical wetlands can be similar to aerobic conditions. Also net primary production can be limited by iron toxicity and macro- (N, P, K, S) and micronutrient (Zn, Cu) deficienies. Depending on the type of wetland, sediment, debris and nutrient inputs from the surrounding catchment area as well as water driven losses by erosion, leaching or run-off affect the soil attributes. In general, permanently flooded undisturbed wetlands can be considered as carbon sinks, while drained wetlands are definetly a carbon source.

1.3. Agriculture driven soil attribute and hydrological changes

Natural wetlands have been diminished during the past 100 years, especially by soil drainage for agricultural land use (excluding anaerobic rice production and aquaculture)[4]. Agriculture has been hypothesized to be one of the main drivers of wetland degradation. The abstraction of irrigation water and the over-use of soil resources threaten the continuance of wetlands as production sites. In East Africa, natural wetland conversion to agricultural land has been increased during the past decades. Upland soil degradation and climate change based unpredictable rain patterns throughout the year has resulted in a shift to wetlands as agricultural production area, either seasonally or permanently. Especially the seasonally flooded wetland fringes are continuously claimed for crop production by building drainage canals and land clearing through slash and burn. That negatively affects soil water dynamics, and the subsequent drying of the topsoil combined with tillage operations enhances mineralization processes, while excessive grazing and the removal of natural vegetation additionally affect soil physical attributes. Already little aeration by land management can result in an increased mineralization of soil organic matter. In most severe cases the wetland desiccates, is weed infested and eventually abandonend.

1.4. Soil resistance and resilience

Soil resistance is defined as the capability to maintain soil functioning during a period of anthropological or natural event of disturbance[5]. Soil resilience is defined as the ability of soils to recover from such disturbances. Hence, resilient soils may have a low resistance and vice versa. Soil resistance and resilience has previously been applied in land management system studies with soil organic carbon and carbon fractions as indicator variables. Many

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[4] The chapter on agriculture driven soil attribute and hydrological changes is based on the work of Dam *et al.* (2013), Dixon and Wood (2003), Kamiri *et al.* (2013), Mitchell (2013), Neue *et al.* (1997) and Russi *et al.* (2012).

[5] The concept and definition of soil resistance and soil resilience is adapted from de Moraes Sá *et al.* (2014), Herrick and Wander (1998), Lal (1997) and Seybold *et al.* (1999), while the information on wetland disturbance is based on the work of Dixon and Wood (2003), Kamiri *et al.* (2013) and Neue *et al.* (1997).

wetlands have been reported to be fragile to man induced soil disturbances. Already small changes in climate, water supply or nutrients can disturb wetlands. Wetland resilience and resistance depends on soil properties, extent of land and water management and wetland type. The concept of soil resistance, defined as the capability to maintain soil functioning during a period of anthropological disturbance, will be applied in this study.

1.5. Statement of the problem

The conversion of natural wetlands to agricultural land can dramatically change chemical and physical soil properties as well as the hydrological soil status, which eventually will affect plant production. Many wetlands have already been heavily degraded due to unsustainable land management (Dixon and Wood, 2003), and especially the rural poor in East Africa depend on wetlands as production sites (Schyut, 2005). While effects of intensified or extended land use on soil chemical and physical attributes are well-described for tropical upland soils (Lepers *et al.*, 2005; Hartemink, 2006), little information exists on such trends in wetlands other than paddy rice fields (Roth *et al.*, 2011; Wissing *et al.*, 2011), East African swamps and floodplains (Kamiri *et al.*, 2013). There is also a lack of information on soil water dynamics in agriculturally used East African tropical wetlands other than small inland valleys (Böhme *et al.*, 2013). Since wetland resilience and resistance depend on the type of wetland (Kamiri *et al.*, 2013), there is a need to study the impact of anthropological disturbances on tropical littoral wetlands. Especially the longer-term dynamics of soil chemical and physical attributes as well as the soil water dynamics and the effect on plant production in agriculturally used tropical littoral wetlands are widely unknown. Additionally, the impact of other factors influencing wetland resilience and resistance, such as soil type, land and water management (Kamiri *et al.*, 2013) have not yet been studied for tropical littoral wetlands. The analysis of soil attribute dynamics and impact on plant production may thus help for the sustainable use of tropical littoral wetlands.

1.6. The chronosequence model at Lake Naivasha, Kenya

Lake Naivasha is located in the semi-arid zone of Kenya, and is one of two freshwater lakes in the Kenyan Rift Valley. The lake and the surrounding littoral wetland (comprising 30,000 ha) are protected as Ramsar site since 1995 (MEMR, 2012). The lake water keeps fresh owing to the main water inflow from Malewa River and groundwater inflow in the Northeastern lake shore, and a subterranean outflow in the south (Gaudet and Melack, 1981). The presence of freshwater in a semi-arid environment combined with easy access and physical infrastructure made the littoral wetlands of Lake Naivasha a hotspot of diverse agricultural activities, including horti- and floricultural agro-industry, small-scale crop production and pastoralism. While the lake level has been strongly fluctuating during the past centuries (Verschuren *et al.,* 2000), an accelerated and continuous decline has been observed between 1980 and 2010, which was ascribed to water abstraction for agricultural irrigation and domestic purposes (Becht and Harper, 2002; Mekonnen *et al.*, 2012). Especially from the year 2000 a rapid lake level decline of 33 cm a^{-1} has been reported with annual lake area shrinkage of 1.41 km^2 (Awange *et al.*, 2013). During this period, the land in the littoral wetland zone, that has been newly exposed by the recession of the lake, was constantly put under agricultural use, creating chronosequences or transects of increasing land use duration with distance from the lake shore (space-for-time substitution). Those chronosequences at Lake Naivasha may thus serve as model to analyze soil attribute changes and effect on plant production in a littoral wetland. The Naivasha case provides the additional advantage of different land uses, such as crop farming and pastures, and soil types (alluvial deposits and lacustrine sediments).

1.7. Hypothesis and Objectives

We hypothesize that the identified chronosequence in the littoral region of Lake Naivasha provides a suitable framework to assess effects of land use and land use duration on soil attributes and crop productivity. To test this hypothesis, the following objectives were enumerated:

1. A detailed description and classification of the littoral wetland soils of Lake Naivasha and the evaluation of the area for its suitability in a chronosequence study.
2. The analysis of soil attributes on different land use systems (pasture, cropland) and soil type (alluvial and lacustrine sediments) along a chronosequence of land use.
3. The analysis of biomass accumulation response on soil attribute changes on different land use systems (pasture, cropland) and soil type (alluvial and lacustrine sediments) along a chronosequence of land use.
4. The analysis of soil moisture content dynamics on different land use systems (pasture, cropland) and soil type (alluvial and lacustrine sediments) along a chronosequence of land use.

2. General material and methods

This section gives a general overview of the experimental setup, which was applied for the whole study. Further, the study area is described with climate, topography, hydrology, vegetation and agricultural activities. The following chapters will focus on the in-depth methods and analysis.

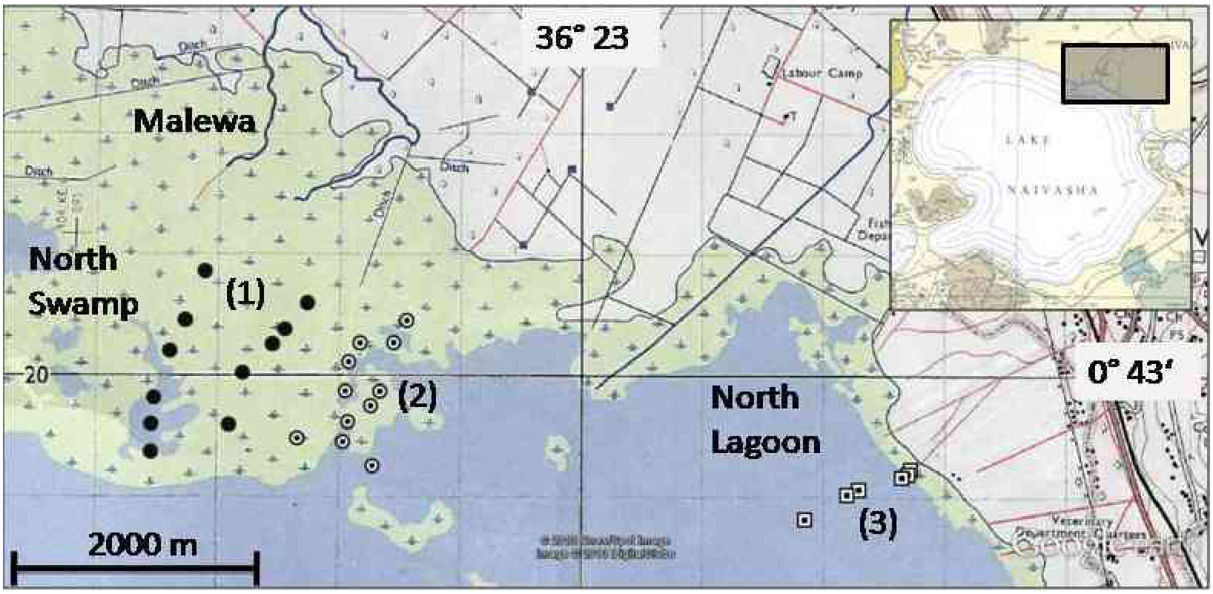


Figure 1. Map of the Lake Naivasha area with Malewa River, former North Swamp, former North Lagoon area, and two chronosequence transects on alluvial pasture (1), two on lacustrine pasture (2) and one on lacustrine cropland (3), respectively. Overlay of satellite picture (Google Earth 2012) and topographic Lake Naivasha map (Kenya Government, 1975, Sheet 133/2, 1: 50,000), additional inlay map of Lake Naivasha (Geological map from the Naivasha area, Kenya Survey, 1963, Sheet 133, 1:125,000), changed.

2.1. Experimental set-up

The field study was conducted in the littoral wetland zone of Lake Naivasha on both pasture and cropland between November 2010 and December 2011 (Figure 1). From 1980 to 2011, the newly exposed land areas have been gradually put under agricultural uses by both pastoralists and small-scale farmers. The pastures in the study area were continuously grazed by wildlife and cattle, while the cropland was continuously used for crop production (mainly maize and diverse vegetables). Based on detailed lake level records since 1980 (Figure 2), we identified the ideal position of the lake shore in 1980, 1985, 1990 and 1995 using geodetic GPS Leica 500 coupled with a Nikon AP-7 Automatic Level in November 2010. That represented ideal land use duration of 30, 25, 20 and 15 years, respectively. After further lake recession in 2011, we identified the 1 year position and reference sites (0 years) (Table 1, Figure 3).

The positions were either unused (reference site) or grazed and cultivated for one growing season (1 year) since last exposure and at time of sampling. That led to some discontinuity between actual years of exposure and duration of land use (Table 1, Figure 2). The parent material of the study area consists of either lacustrine or alluvial sediments (Clarke *et al.*, 1990). The pasture land was differentiated based on the parent material into "lacustrine pastures" and "alluvial pastures", while the cropland was only located on the lacustrine sediments (referred to as "lacustrine cropland"). For further soil information see chapter 3.

Table 1. Altitude, duration of land use, number of years of land exposure to aerobic conditions, and time and duration of last inundation of five chronosequence transects from November 1980 to May 2011. Data presents means and the standard deviation in brackets.

Altitude (masl)	Land use duration (years)	Land exposure (years)	Last inundation (years)	Duration of inundation (months)
1886.0 (0)	0	4 (1)	0/1	11 (1)
1886.8 (0.1)	1	15 (1)	11*	30 (0)*
1887.2 (0.1)	15	19 (1)	11**	28 (0)**
1887.5 (0)	20	21 (0)	11	26 (0)
1888.0 (0.1)	25	24 (0)	12	19 (3)
1888.5 (0.3)	30	26 (1)	12/28	15 (4)

* sites additionally inundated in May 2003 to January 2004 for 4 (3) months, from May 2004 to August 2004 for 2 (2) months, from September 2007 to December 2007 for 4 (1) months and from October 2010 to January 2011 for 2 (1) months; ** site additionally inundated for 1 month in October2007.

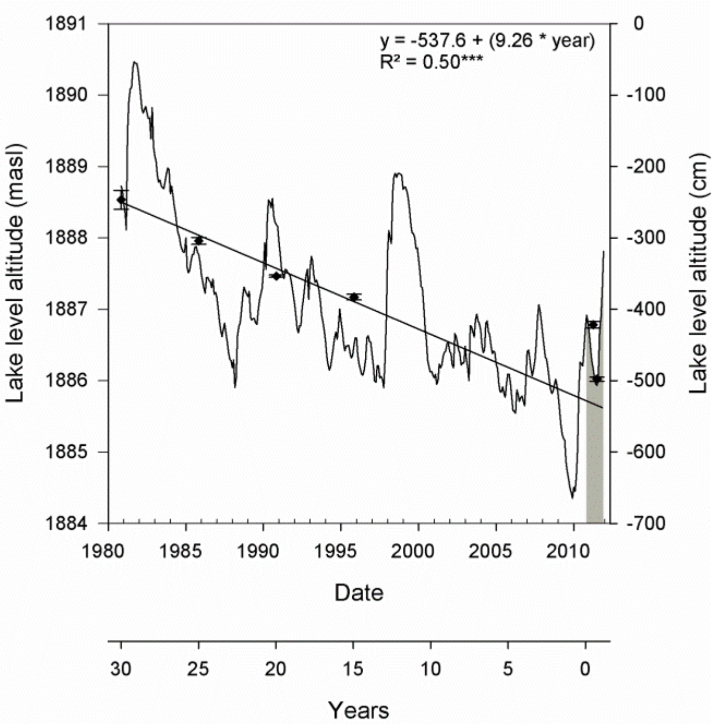


Figure 2. Mean monthly lake level from November 1980 to December 2011 (Homegrown Ltd.). Linear regression between number of years and mean monthly difference in lake level altitude between 1891 and 1884 masl (in cm) (n = 374). Points and error bars represent mean altitude and standard deviation of ideal chronosequence position in 1980, 1985, 1990, 1995, 2010 (n = 5) and 2011 (n = 3), respectively. The grey area indicates the lake level fluctuation during the studied period.

In each of the three land use situations, transects were established, representing chronosequence positions (durations of land use) of 0, 1, 15, 20, 25 and 30 years. In total five transects of 1 to 30 years of land use were established, one on the lacustrine cropland and two each on lacustrine and alluvial pasture, respectively. One reference site (0 years) each was additionally established on lacustrine pasture, alluvial pasture and lacustrine cropland, respectively (total: 11 lacustrine pasture, 11 alluvial pasture and 6 lacustrine cropland positions) (Figure 3). The identified chronosequences were used for an analysis of the effects of land use duration on soil attributes and plant production.

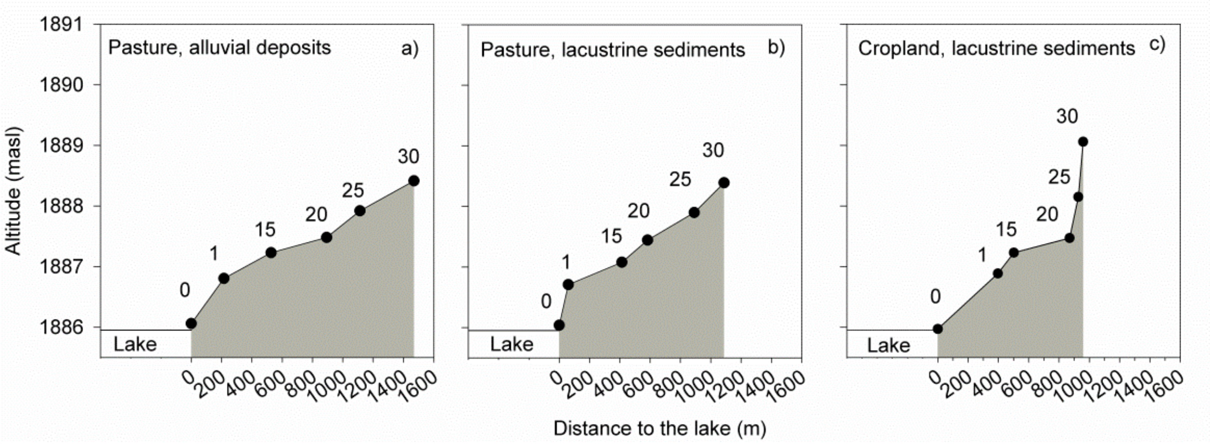


Figure 3. Catenae of five chronosequence transects on alluvial pasture (n = 2) (a), lacustrine pasture (n = 2) (b) and lacustrine cropland (n = 1) (c) and mean lake level in June 2011 (0 years), respectively. Chronosequence position 30, 25, 20, 15, 1 and 0 years of land use represent ideal lake level altitude in the years 1980, 1985, 1990, 1995, 2010 and 2011, respectively.

2.2. Study area

Lake Naivasha lies in the lower highlands of the Kenyan Rift Valley (0° 45’ S; 36° 21’ E) at about 1890 masl (Sombroek *et al.*, 1982). The study site is located in the flat plains (concave slope of 0.9 mm m^{-1}) of the littoral wetland at the north to northeast lake shore line. The study area included pastureland located at the former North Swamp papyrus stand, near to the inflow of Malewa River on the premises of the Kenya Agriculture Research Institute - KARI (0° 43' S, 36° 22' E), and cropland at the former “North Lagoon” (Gaudet, 1977) in the small-scale farmers’ area at Kihoto on the Northeastern lake shore (0° 44' S, 36° 24' E) (Figure 1). Soils in the north to northeastern shore line derive either from alluvial deposits or lacustrine sediments (Clarke *et al.*, 1990) (for details on soil characteristics see also chapter 3).

2.3. Climate and topography

The climate is cool temperate and semi-arid with mean temperature between 16 – 20°C, mean annual rainfall of 620 mm and a ratio between rainfall and evapotranspiration (r/Eo) of

25% – 40%. According to the Agro-Ecological Zones classification, this corresponds to a length of growing period of 75 – 180 days (Sombroek *et al.*, 1982; Clarke *et al.*, 1990). Highest evaporation is in January and February. Typically, there are two rainy seasons with little rain in November and main rainfall in April to May. However, precipitation in the Naivasha area is locally unequal distributed and rainfall is irregular (Gaudet and Melack, 1981). Total rainfall was 891 mm on the pasture area from December 2010 until November 2011 and 466 mm on cropland from December 2010 until end September 2011 (Figure 4).

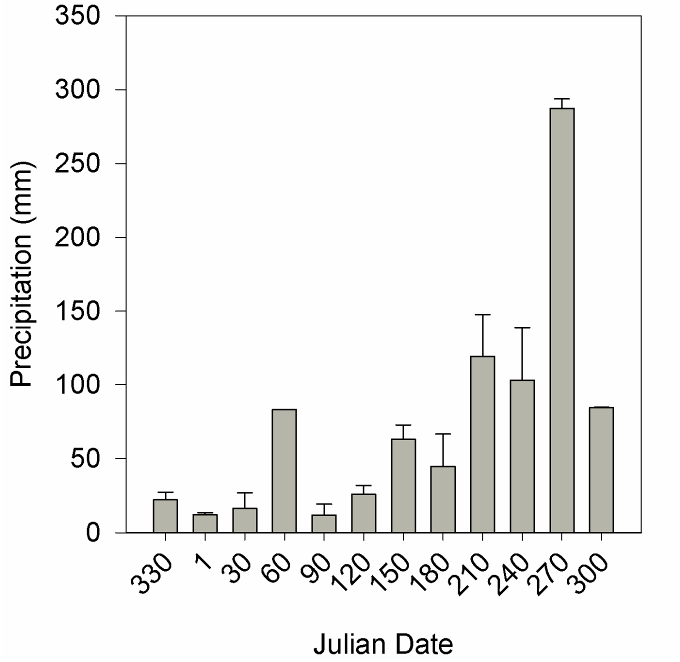


Figure 4. Mean monthly rainfall (mm) on the study area (based on three rain gauges readings) from December 2010 to November 2011. Bars represent the mean and error bars the standard deviation.

2.4. Hydrology and bathymetry of Lake Naivasha

Lake Naivasha is mostly shallow with 6 m water depth (Verschuren, 1999), and the lake comprised an area of 126 km² in 2010 (Awange *et al.*, 2013). The deepest point lies in the Crater Lake, an old volcano crater at the Eastern lake side. The crater fringe forms a peninsula known as Crescent Island. Nearby Lake Naivasha, there exist two satellite lakes: Oloidien and Sonachi, at the Southwestern and Western lake side, respectively. Both lakes are saline due to the lack of a subterranean outflow. Oloidien is separated from Lake Naivasha by a small land area, which is inundated at high lake level. Then Oloidien is a bay of Lake Naivasha and the water is fresh (Verschuren, 1999).

Three rivers, Gilgil, Malewa and Karati, circulate to Lake Naivasha, of which Malewa provides permanent inflow with highest water contribution. Previously, Malewa and Gilgil entered the lake through a papyrus swamp at the northern lake shore, known as the North

Swamp (Gaudet and Melack, 1981). Malewa has now a fixed riverbed after the die-back and decline of the papyrus swamp (Harper and Mavuti, 2004). The lake has a subterranean in- and outflow which keeps the water fresh with EC = 0.2 – 0.5 dS m^{-1} (Verschuren, 1999) and pH = 8.6 (Gaudet and Melack, 1981). Natural lake level fluctuation is a common phenomenon, which is mainly driven by evaporation and rainfall. Typically, the lake has its annual maximum level in September and October (Gaudet and Melack, 1981). Since East African rainfall pattern is influenced by the El Niño Southern Oscillation (ENSO) (Indeje *et al.,* 2000), the lake level has also been fluctuating during past ENSO years, in recent years most pronounced in November 1997 (Becht and Harper, 2002) (Figure 2).

While these natural lake level fluctuations occurred during the past centuries (Verschuren *et al.,* 2000), an accelerated and continuous decline has been observed between 1980 and 2010, which was ascribed to water abstraction for agricultural irrigation and domestic purposes (Becht and Harper, 2002; Mekonnen *et al.*, 2012), and an observed overall precipitation decrease during the past decades (Awange *et al.,* 2013). From November 1980 to December 2011 the rate of lake level decline was 9.26 cm a^{-1} (Figure 2). While the lake level kept relatively stable from 1989 until 2006, there was a rapid decline from 2006 to 2010 with a lake level decline rate of 10.2 cm a^{-1} between 2000 and 2006 (Awange *et al.,* 2013). The lake level decreased during this study from 1886.94 to 1885.90 masl from November 2010 until 9 August 2011 and barely any strong rain events occurred. Thereafter, strong rains started and the lake level rose again (Figure 2, Figure 4).

2.5. Natural vegetation and agriculture

The water supply from Lake Naivasha and the catchment is an important resource for agriculture in this region. Small-holder and commercial irrigated agricultural area in the Kenyan Rift Valley comprise 11,000 and 5,000 ha, respectively (in 2003) (Frenken, 2005). Thereby, flower production is one of the most important irrigated crops with countrywide > 3,000 ha (in 2003) (Frenken, 2005). Horticulture industry at Lake Naivasha started in the early 1980s (MEMR, 2012), and vegetable and flower production for export are the main irrigated crops with 1824 and 1911 ha in 2006, respectively (Mekonnen *et al.*, 2012). The water consumption for the production of one rose was estimated to 7 – 13 liters with total virtual water consumption of 16 Mm^3 a^{-1} from 1996 to 2005 at Lake Naivasha (Mekonnen *et al.*, 2012). Further, there exist small-scale cropland areas (mean farm size 0.4 – 0.9 ha) with mainly irrigated maize and vegetable production, of which the Kihoto cropland area at the north east lake shore has been cultivated since the 1970s (Schneider, 2010). Water use efficiency from small-scale farmers located in the Lake Naivasha basin has reportedly been low (Njiraini and Guthiga, 2013). In addition, nomadic pastoralists frequently use the littoral wetland area for cattle grazing and watering, especially in drought periods (Schneider, 2010).

The natural vegetation along the lake shore line was formerly dominated by papyrus (*Cyperus papyrus*). Lake level decline, land clearing for agriculture and horticulture connected with papyrus harvest for fodder has steadily decreased the papyrus stands (Harper and Mavuti, 2004). Land reclamation for agriculture was still on-going during this study. Especially the North Swamp area was affected with formerly 11.7 km² of papyrus vegetation, which surrounded the Malewa river mouth (Harper, 1992; Gaudet, 1979; Gaudet and Melack, 1981). The swamp area declined beginning from 1983, and the area was claimed for agricultural use right after (Harper, 1992). Although the swamp could recover from 1988 after heavy rains (Harper, 1992), only fragments exist at the lake fringes today. Further lake level decline connected with Malewa riverbed cavity after storm events had lowered the groundwater, which enhanced papyrus dieback (Harper and Mavuti, 2004). That made the area easy accessible for large grazers, such as buffaloes (*Syncerrus cafer*) or zebras (*Equus burchelli*) among others, which destroyed the swamp structure and grazed on new evolving papyrus shoots (in 1980s to 1990s) (Harper and Mavuti, 2004). Eventually, grasses (e.g. Kikuyu grass) and other terrestrial plants evolved and overgrew the papyrus mounds (Harper and Mavuti, 2004). Grasses and shrubs were still the dominating vegetation on the pasture area during the study.

2.6. Thesis Outline

- Chapter 1 comprises the overall statement of the problem, hypothesis and objectives.
- Chapter 2 gives a general description of the experimental setup and the study area.
- Chapter 3 comprises the detailed soil description of the study area and evaluates the suitability of Naivasha littoral wetland soils for the chronosequence study.
- Chapter 4 comprehends the soil water dynamics along a chronosequence of land use in a littoral wetland area with special focus on plant available water.
- Chapter 5 compasses soil organic carbon and carbon fraction kinetics along a chronosequence of land use in a littoral wetland area.
- Chapter 6 comprises soil chemical attribute changes along a chronosequence of land use in a littoral wetland and the effect on plant biomass production.
- Chapter 7 comprises resin adsorbed soil phosphorus changes along a chronosequence of land use
- Chapter 8 gives an overall discussion with respect to the presented results, and a general conclusion.

3. Soil characterization along chronosequences of agricultural land use

3.1. Introduction

Lake Naivasha is a freshwater lake in the Kenyan rift valley. The lake has been fluctuating throughout the last centuries (Verschuren *et al.*, 2000), and a substantial lake level decrease has been recognized since the past decades owing to water abstraction for agriculture and domestic water use (Becht and Harper, 2002), and precipitation decline (Awange *et al.*, 2013). Thereby, the exposed land area has been frequently put under agricultural use, giving the opportunity to study changes in soil chemical and physical attributes along a (topo-) chronosequence of land use (space-for-time approach). The space-for-time approach is a widely used method to analyze physical and chemical soil attribute kinetics. Especially long term studies are not feasible, as they would require unrealistic sampling periods (Hartemink, 2006; Walker *et al.*, 2010). Such approach had successfully been applied in previous chronosequence studies, including paddy soils (Cheng *et al.*, 2009) and small agriculturally used wetlands in East Africa (Kamiri *et al.*, 2013). One precondition of the space-for-time approach is that soils have underlain the same soil formation processes or anthropogenic influences (Hartemink, 2006). However, wetlands can be highly dynamic areas, and soils can therefore be distinct. In particular, soils of the Lake Naivasha littoral wetland area have been influenced by parent material (Clarke *et al.*, 1990), vegetation (Gaudet and Melack, 1981), water (Urassa, 1999, Ranatunga, 2001) or land management among others. The parent material of Lake Naivasha wetland fringes is dominated by lacustrine sediments, which derived from erosion of volcanic material from the surroundings (Urassa, 1999). It is composed of silt and gravel sized volcanic ash and pyroclastic material (Siderius and Muchena, 1977; Clarke *et al.,* 1990). Thereby, volcanic sodium rich material dominates with 70% trachytes, tuffs, and welded tuffs, 10% rhyolites and obsidians, and 15% strongly and mildly alkaline lavas (Saggerson, 1970; Gaudet and Melack, 1981). The clay fraction comprises mainly amorphous material with traces of kaolinite (Siderius and Muchena, 1977), and partly with vermiculite and chlorite (Gaudet and Melack, 1981).

Lacustrine material (grayish brown diatomaceous silts and sands with underlying gravel) was deposited in a 3 m layer in old Holocene, overlain by grayish brown silt sized material of 3 m thickness, deposited in the Middle Holocene. The most recent deposits consist of silt and clay which largely occur at the northern and north-eastern lake shores (Thompson and Dodson, 1963). In addition, lacustrine sediments were mixed or overlain with alluvial deposits of grayish brown silt, some reddish brown ferruginous coarse sand, or granule gravel (Clarke *et al.*, 1990). Such alluvial material is located at the Malewa river mouth and in the former North Swamp area. River sediments dominantly consist of material from upriver catchment

(Tarras-Wahlberg *et al.*, 2002). Additional detritus, sediments and solute nutrients were trapped in the former papyrus swamp delta. Carbon and soil nutrients accumulated, and below the floating papyrus mats a peat layer developed (Gaudet, 1979). The clays are mostly amorphous, with traces of poorly crystallized Montmorillonite (Gaudet and Melack, 1981).

The dominating soil reference group (RGB) has been defined as undifferentiated Solonetz (saline phase) on a macro scale (1:1,000,000) (Sombroek *et al.*, 1982). However, there have been other RGBs been identified on a micro-scale along the north to north east littoral wetland fringes including calcaric Fluvisols, ochric Gleysols (Ranatunga, 2001), fibric Histosols and eutric Cambisols (Urassa, 1999) (Figure 5). While most soils were identified at the north east, east and south east shores, no such soil description exists to our knowledge for alluvial sediment soils from the former North Swamp area other than information about sedimentation processes and chemical analysis of selected soil material (Gaudet, 1979; Clarke *et al.,* 1990; Boar and Harper, 2002; Tarras-Wahlberg *et al.*, 2002).

We assessed a soil chemical and physical attribute analysis and description of Lake Naivasha littoral wetland soils derived from two parent material (alluvial deposits and lacustrine sediments) and under distinct land management (pasture and cropland) along chronosequence transects of 0 - 30 years of land use for its suitability in a chronosequence study.

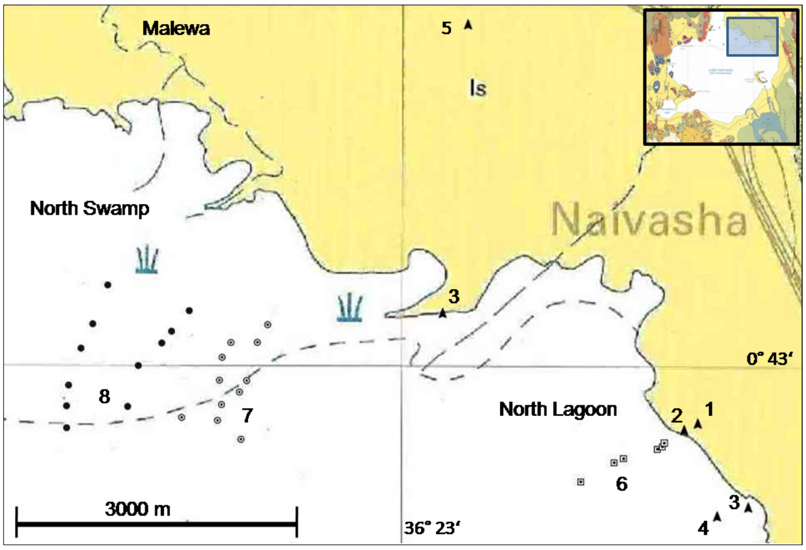


Figure 5. Lake Naivasha study area with former North Swamp and North Lagoon, and previous soil descriptions: (1) ochric Gleysols (Ranatunga, 2001), (2) calcareous Fluvisols (Ranatunga, 2001), (3) eutric Cambisols (Urassa, 1999), (4) fibric Histosols (sodic phase) (Urassa, 1999), (5) orthic Solonetz and calcic Cambisols (sodic phase) (Siderius and Muchena, 1977), (6) lacustrine cropland soils, (7) lacustrine pasture soils, (8) alluvial pasture soils. Overlay of Google Earth (2012) and geological map (1:100,000) of the Naivasha region with parent material (ls: lacustrine sediments) (*Clarke et al.,* 1990), changed.

3.2. Material and Methods

3.2.1. Soil description and analysis

We assessed a soil field description of Lake Naivasha littoral wetland soils in January, April and June 2011, and thereafter analyzed selected physical and chemical soil attributes. Therefore, soil pits of 100 cm depth were opened at chronosequence positions 1 to 30 years, (total: 25) in January and April 2011 (Figure 5). Only the reference sites (0 years) were not sampled for a detailed soil description. Soil horizons were identified according to soil color (moist), structure, texture (feel method), depth, horizon boundaries, and mottling. Additionally, water status and reaction to hydrochloric acid as a measure of soil carbonate content were evaluated in field (FAO, 2006). Three core samples from each horizon were taken, dried at 105 °C, and bulk density (BD) estimated. Thereafter, one bulk core sample from each horizon were sieved (< 2 mm) and stored for laboratory analysis. Soil samples of two lacustrine pasture positions (15 and 20 years) got lost, and no chemical analyses are available. Soil pH and electrical conductivity (EC) was determined in a soil water suspension of 1:2.5 ratio. The inorganic carbon and carbonate content was measured according to the Scheibler method. Ground subsamples were analyzed for total C and N with CNS Elemental Analyzer (EuroEA 3000; Euro Vector SpA, Milan, Italy). Thereafter, soil organic carbon content (SOC) was estimated as the difference between total C and inorganic C. SOC was multiplied with BD (g cm^{-3}), and thereafter a first order exponential model was established for each chronosequence position with SOC (g cm^{-3}) as dependent variable and the corresponding mean soil depth (cm) as independent variable. Eventually, SOC (Mg ha^{-1}) in 0 – 100 cm soil depth was estimated as the area below the regression line according to the trapezoidal rule (in steps of 5 cm; i.e. n = 20 calculations):

$$\mathrm{SOC} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\frac{(x_i - x_{i-1}) * [f(x_i) + f(x_{i-1})]}{2}\right) \qquad (1)$$

whereby: SOC = soil organic carbon content (Mg ha^{-1}) in 0 – 100 cm soil depth; x_i = soil depth (cm) at step i; $f(x_i)$ = SOC stock according to exponential model at x_i; n = number of calculations (20).

Thereafter, soils were classified in soil reference groups (RGB) according to the World Reference Base for Soil Resources (WRB) (IUSS, 2006).

Additionally, mini-pits of 60 cm soil depth were opened in April 2011 on six selected chronosequence positions (1 and 30 years) on lacustrine pasture, alluvial pasture and lacustrine cropland, respectively. One disturbed soil sample was taken in fix depths of 10 – 15 and 50 – 55 cm, air-dried, sieved (< 2 mm) and clay minerals determined with X-ray diffractometer method (D8 ADVANCE, Bruker AXS, Billerica, MA, USA). Furthermore, topsoil samples (0 – 15 cm) were taken as composites (n = 5) at all observation points (1 to 30 years of land use + reference sites, n = 28) in November 2010 (position 15 to 30 years), April 2011 (1 year), and June 2011 (reference sites). All samples were air-dried, sieved to < 2 mm, and soil texture was determined with laser diffraction (Retsch LA-950 V2 Horiba, Haan, Germany).

3.2.2. Statistical analysis

The first order exponential decay model for SOC calculation and all graphs were established with SigmaPlot 11.0 software package.

3.3. Results

3.3.1. Soil description

Lacustrine pasture soils

Lacustrine pasture soils belong to the following RGBs: gleyic Fluvisols (calcaric) (1 year of land use), haplic and gleyic Vertisols (15, 20, 25 and 30 years of land use) (Table 2). The A Horizon depth varied from 2 – 18 cm (Figure 9), with brownish black (black, olive black, olive brown; hue: 2.5Y, 5 – 10YR; value: 2 – 4; chroma: 1 – 3) soil color, crumbly to subangular blocky structure, and silt loam (sandy loam, loam) texture. Mean SOC is 4.7% ± 2.6%, and pH ranges from 6.5 – 8.4. The Fluvisols C Horizon has a gleyic color pattern and consists of fluvic material with varying SOC content. Also, the B and C Horizons of chronosequence positions ≥15 years have partly a gleyic color pattern and soil color is (dark) brown, brownish black, (dull) yellowish brown, dark grayish yellow, grayish brown, grayish olive, or (dark) olive brown (hue: 2.5 – 7.5Y; 7.5 – 10YR, value: 2 – 5, chroma: 1 – 4). The B Horizon has a subangular blocky, angular wedge shaped or prismatic structure, with a texture of clay, sandy clay, clay loam, sandy clay loam, silty clay loam or clay rich silt loam. Slickensides and cracks (when dry) are present (vertic properties). Electric conductivity (EC) is below 2 dS m^{-1} at all positions. Secondary carbonates accumulated in the subsoil in form of light gray hard concretions. Subsoil (B and C horizon) pH reaches a maximum of 9.9, indicating ultra-basic soil conditions. For detailed soil description see Appendix.

Alluvial pasture soils

Alluvial pasture soils belong to the following reference soil groups (RGB): gleyic Fluvisols (1 and 15 years of land use), haplic Gleysols (15 and 20 years), haplic and gleyic Vertisols (20, 25 and 30 years) (Table 3). Soil organic carbon is 8.2% ± 2.6% and 1.1% ± 1.0% in the A and B/C Horizon, respectively. EC ranges from 0.7 – 2.1 dS m^{-1} on sites near to the lake shore (1 and 15 years), and a very fine salt crust bloomed out during soil desiccation. Otherwise, soils have an EC <2 dS m^{-1}. The pH ranges from 4.9 to 8.0 and carbonate content is low. All soils have an A Horizon of 2 – 15 cm depth (Figure 9), black, brownish black or dark brown soil color (hue: 5 – 10YR; value: 2 – 3; chroma: 1 – 3) with mainly crumbly to subangular blocky soil structure and silt loam (clay poor) texture. On older chronosequence positions (≥ 15 years) a B Horizon with prismatic, subangular blocky or wedge shaped soil structure has developed and slickensides and cracks are present (vertic soil properties). Soil texture is silt clay, clay, clay loam or heavy clay. On three chronosequence positions (15, 25 and 30 years) a buried black colored A Horizon has been identified. C Horizons of Fluvisols consisted of sandy or loamy fluvic material, and SOC content alternated with soil depth. Both, B and C Horizons have a pronounced gleyic color pattern and soil color differs between brownish black, olive black, grayish brown, dark brown, brownish gray, yellowish gray, dark olive brown and dark reddish brown (hue: 2.5 – 5Y, 2.5 – 10YR, value: 2 – 4; chroma: 1 – 6). For detailed soil description see Appendix.

Lacustrine cropland soils

Lacustrine cropland soils belong to the following reference soil groups (RGB): mollic Fluvisols (1 and 15 years of land use), and haplic Cambisols (calcaric) (20, 25 and 30 years) (Table 4). The A Horizon ranges from 5 – 38 cm depth (Figure 9) with crumbly soil structure, silt to silty clay texture, brown to olive black soil color (hue: 2.5 – 5Y, 10YR, value: 3 – 4, chroma: 2 – 4) and light gray concretions (secondary carbonates) at all chronosequence positions. EC values are below 2 dS m^{-1}. Soil pH on the 15-year position and partly on the 1-year position was ultrabasic (pH > 8.7). The 1 and 15 year C Horizon consists of 50% - 90% fine gravel of brownish black to olive black color (hue: 10YR, 5Y; value: 3; chroma: 1 – 2). The subsoil on position 20 and 25 years are similar, but the 30 year haplic Cambisols has higher carbonate content with 6.0%. The subsoil is very hard when dry, which is also most pronounced on the 30-year position (highest BD = 1.4 g cm^{-3}). The pH on position ≥20 years was 7.0 – 8.5, indicating non-ultrabasic soils. For detailed soil description see Appendix.

3.3.2. Selected soil chemical and physical attributes

Soil organic carbon content (SOC) (Mg ha^{-1}) in 0 – 100 cm soil depth on alluvial pasture, lacustrine pasture and lacustrine cropland ranged from 100 – 303, 36 – 120 and 54 – 106 Mg ha^{-1} (Figure 6, Figure 7). Standard error of the mean was high on alluvial pasture soils, compared to the lacustrine pasture soils (Figure 7). Topsoil sand content on pastureland (0 and 1 year) ranged from 19% – 43%. Sand and clay content on pasture positions ≥15 years ranged from 2% – 17% and 4% – 16%, respectively. On lacustrine cropland (0 – 30 years), sand and clay content ranged from 12% – 25% and 3% – 8%, respectively (Figure 8). All soils belong to the FAO textural class of silt and silt loam (clay poor and clay rich). X-ray diffraction revealed little (not quantifiable) amounts of crystallized clay minerals at all three land use situations. The crystallized clays comprise Illite-Montmorillonite, Illite/Muscovite, and Kaolinite, respectively.

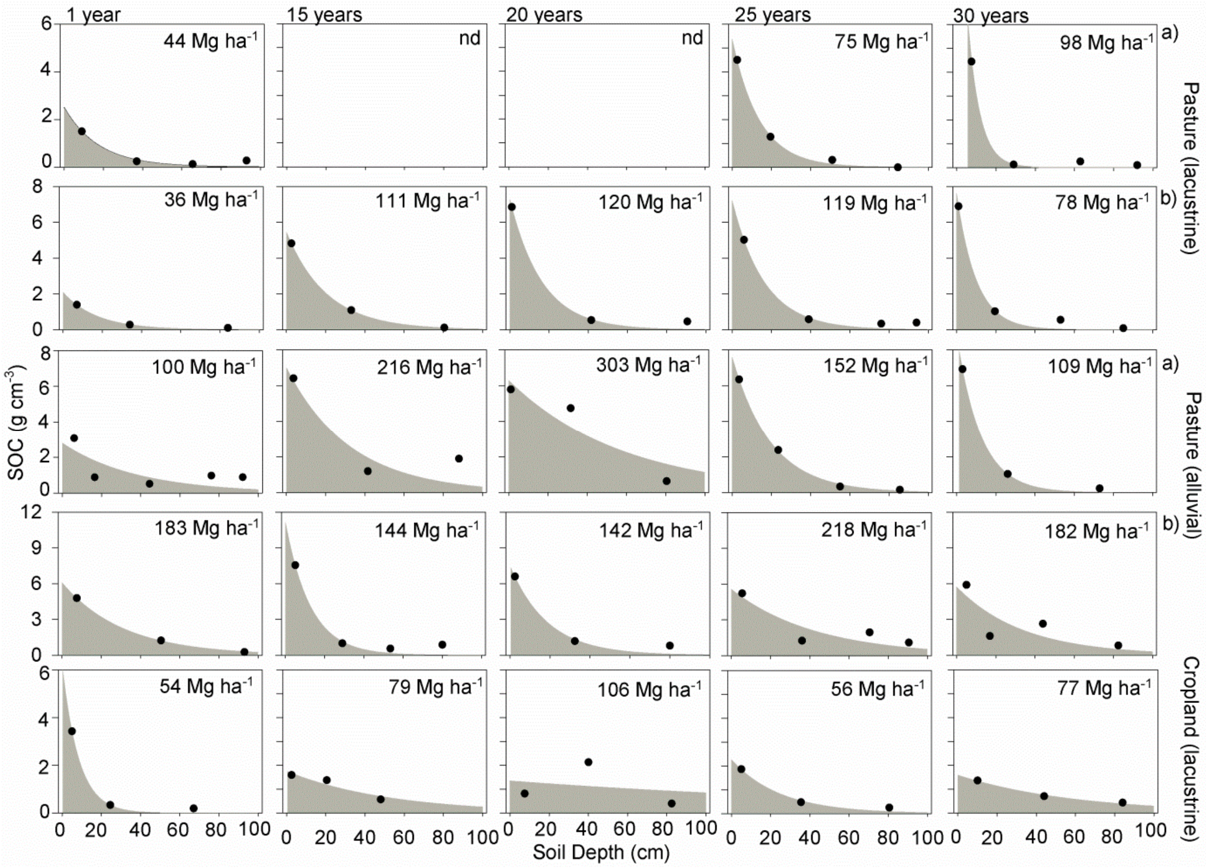


Figure 6. Soil organic carbon (SOC) (Mg ha^{-1}) in 0 – 100 cm soil depth on chronosequence positions 1 to 30 years on alluvial pasture, lacustrine pasture and lacustrine cropland, respectively. Points represent measured soil organic carbon (g cm^{-3}) and mean soil depth (cm). The grey area represents the estimated soil organic carbon pool (Mg ha^{-1}) below the regression line of the first order exponential decay model according to the trapezoidal rule.

3.4. Discussion

3.4.1. *Soils at Lake Naivasha*

Soils in the studied area are dominantly hydromorphic (Fluvisols, Gleysols, gleyic Vertisols and gleyic colour pattern on other chronosequence positions), and especially lacustrine sediment soils match with previous soil descriptions: The A-Horizon on lacustrine cropland was comparable to eutric Cambisols and ochric Gleysols (Urassa, 1999; Ranatunga, 2001) identified in the same area, especially in color (hue: 2.5Y, 10YR; value: 2.5 – 4; chroma: 1 – 2), depth (20 – 25 cm), texture (sandy loam to clay loam), and pH (6.8 – 8.1) (Figure 5). Also the subsoil (eutric Cambisols and ochric Gleysols) was similar on position ≥20 years with Bwg or Bw horizons of similar color (hue: 2.5Y, 10YR, value 2.5 – 4, chroma 1 – 3), structure (subangular blocky), and pH (7.3 – 8.7) (Urassa, 1999; Ranatunga, 2001). The positions 1 and 15 years are similar to the calcaric Fluvisols with fine sandy loam to loam texture, olive grey to dark grey color, and pH 8 – 10 (Ranatunga, 2001). Parent material of fine to coarse gravel at 20 – 40 cm soil depth had previously been reported nearby the cropland area (Urassa, 1999), similar to the 1 and 15 year site.

Soils formed below the former North Swamp area have not yet been described to our knowledge. However, there has been much research concerning sedimentation processes in that area (Gaudet, 1979; Taras-Wahlberg *et al.,* 2002; Boar and Harper, 2002). Alluvial and lacustrine pasture soils have probably been influenced by sediment input from Malewa River, either by sediment trapping in the former papyrus swamp (Gaudet, 1979), or, after an substantial papyrus die-back, by silt and clay deposition at the north to northeastern lake shore (Boar and Harper, 2002). Vertisols have developed on both land use situations (lacustrine and alluvial sediments) with pronounced large cracks and slickensides. The susceptibility of wetland fringe soils to cracking soon after lake recession have previously been reported (Gaudet, 1977), and soils have a high shrink-swell potential (Ranatunga, 2001). That is probably connected to shrink-swelling clays (Vermiculite, Montmorillonite) and the dominance of amorphous clays (Gaudet and Melack, 1981; Siderius and Muchena, 1977). Also the x-ray diffraction in this study showed little amounts of crystallized clays on all three land use situations. Amorphous clays (Wan *et al.,* 2002) and allophanes (Gray and Albrook, 2002) have reportedly a high shrink-swell potential, which could explain the vertic soil properties on lacustrine and alluvial pasture soils. Still, both soil types differed from each other with increasing soil depth, mainly in pH, carbonate accumulation, SOC content and mottling. Probably alluvial sediment inflow from Malewa River brought iron-enriched soil material and detritus dominantly into the alluvial pasture area, while the sedimentation fainted in direction to the lacustrine pasture sites (Taras-Wahlberg *et al.,* 2002; Boar and Harper, 2002). Additionally, papyrus vegetation and peat accumulation (Gaudet, 1979) might have been denser around Malewa River (Figure 5) with more influence on present alluvial pasture soils. Eventually soil pH decreased and SOC and N content increased (Gaudet, 1979) with distinct red to orange mottles on alluvial pasture soils, while the parent material is probably dominated by reworked volcanic material (Gaudet and Melack, 1981) on the lacustrine pasture area.

It also appears that younger chronosequence positions (1 and partly the 15 year positions) have been less influenced by alluvial sedimentation or papyrus swamp vegetation, since the parent material is somewhat distinct. The lacustrine and alluvial pasture soils (1 year) have not established profound soils having a shallow A-Horizon and lacking a B-Horizon. Sedimentation from Malewa River is strongest at the river mouth and decreases with increasing off shore distance (Boar and Harper, 2002). Wave movement transports the sediments to other parts of the lake (Taras-Wahlberg *et al.,* 2002). The 1 and 15 year soils may also be located at the former papyrus swamp fringe (Figure 5) with less influence of the former vegetation, although that is not much than speculation since only historical macro-scaled maps are available. Nevertheless, under such highly dynamic conditions, different influences on soil development within the chronosequence transects can be suspected.

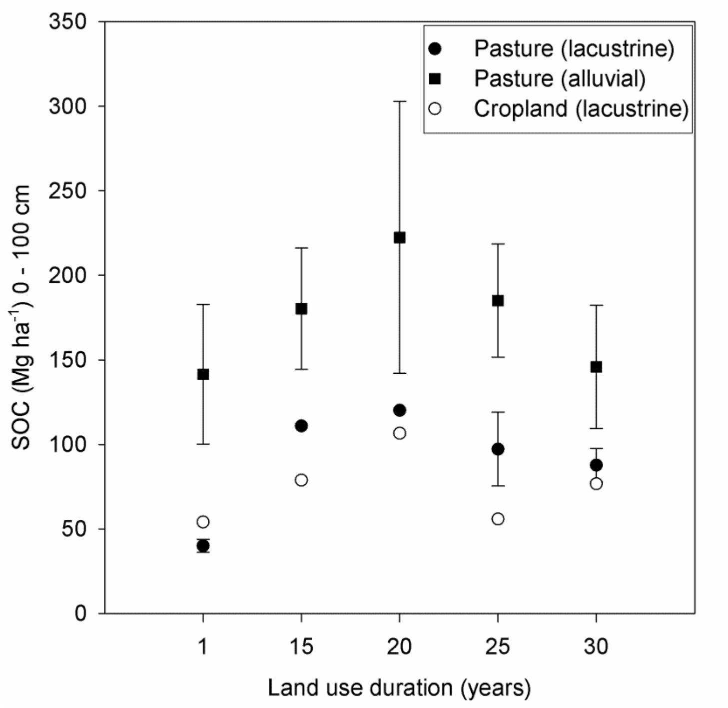


Figure 7. Mean soil organic carbon (SOC) (Mg ha^{-1}) in 0 – 100 cm soil depth on chronosequence position 1 – 30 years of land use on alluvial pasture, lacustrine pasture and lacustrine cropland, respectively. Error bars represent standard error of the mean.

3.4.2. Sodic soil conditions on lacustrine sediment soils

Soils around Lake Naivasha have been identified as Solonetz on the macro scale (Sombroek *et al.,* 1982), and soil descriptions from the Naivasha area reportedly identified sodic soil conditions on orthic Solonetz, Calcic Cambisols (sodic phase) (Siderius and Muchena, 1977) or fibric Histosols (sodic phase) (Urassa, 1999) (Figure 5). Thereby, the Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) has been used to describe the sodic soil nature (IUSS, 2006), and was previously applied on East African soda lake soils (Mugai, 2004). Natric soil horizons have and ESP >15% (IUSS, 2006). Alternatively, field identification of natric horizons comprises a pH measurement >8.5 (IUSS, 2006). Thereby, a pH >8.7 indicates the presence of Na_2CO_3 and $MgCO_3$ rather than $CaCO_3$ (IUSS, 2006). Lacustrine pasture (positions ≥15 years) and lacustrine cropland sites (1 and 15 year position) reached pH values up to 9.9 in the subsoil. For comparison, the subsoil of calcic Cambisols (sodic phase) had a pH of 7.6 – 8.9, and an ESP from 3% – 11%. An identified

Solonetz subsoil had a pH of 8 – 10, and an ESP from 5% – 43% and 58% – 76%, respectively (Siderius and Muchena, 1977) (Figure 5).

Sodium accumulation in semi-arid regions can derive by ascendant flow or after a drop of the groundwater table (Zech and Hintermaier-Erhard, 2002). Lake Naivasha lacustrine sediments have reportedly sodium-enriched volcanic material (Saggerson, 1970, Mugai, 2004) and lake recession has decreased groundwater table (see chapter 4). Under such conditions, the presence of sodium-rich parent material or the sodium accumulation by ascendant flow can be expected. Possible agricultural limitations could be Cl, Na and bicarbonate toxicity. The high pH could immobilize P, Fe, Zn and Mn. Clays disperse when moist but shrink when dry, resulting in soil cracks which damage plant roots. Crusts can develop, which decreases permeability and drainage, and root growth may be hindered (Mugai, 2004). According to informal farmer interviews, the 15-year lacustrine cropland position was frequently abandoned from agriculture, probably owing to the ultra-basic soil conditions leading to crop failure or limitations. However, further soil analysis beyond the scope of this study is needed to verify the sodic nature of these soils, including SAR and ESP measurements.

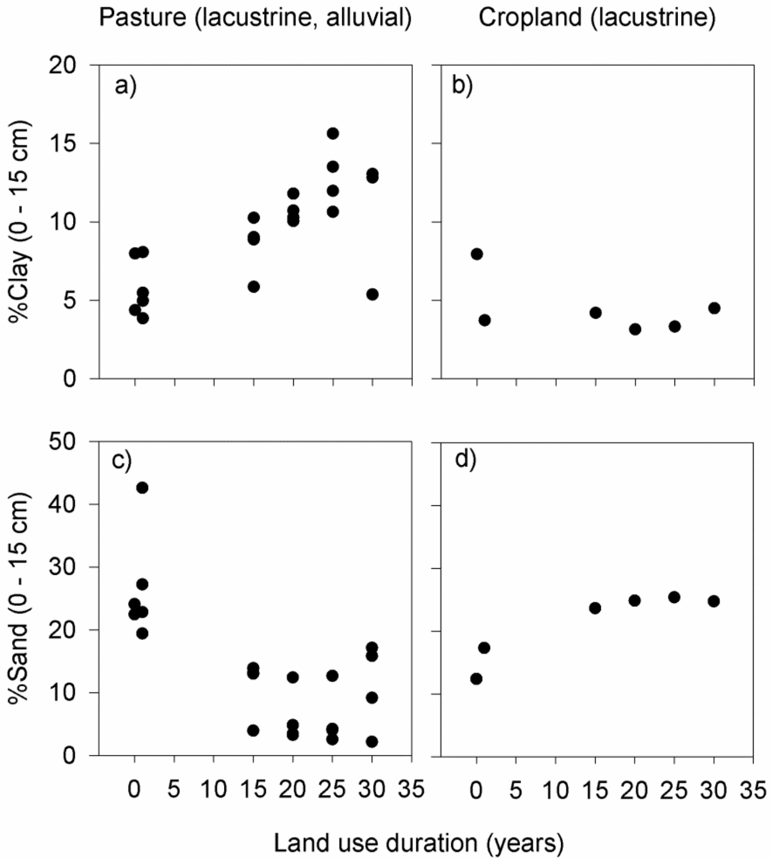


Figure 8. Sand and clay content in 0 – 15 cm soil depth from chronosequence position 1 to 30 years of land use on lacustrine and alluvial pasture (a, c) and lacustrine cropland (b, d), respectively.

3.4.3. The space for time approach

The space for time approach is a common method to analyze changes of chemical or physical soil attributes over time (Hartemink, 2006). It is an indirect method to analyze temporal changes of soil and vegetation (Walker *et al.,* 2010). The assumption is that changes among sites are only influenced by one factor, which requires equal soil properties as precondition. Typical errors include poor soil quality or unknown land use history of single sites, and soil variability (soil depth or clay content) along the chronosequence (Hartemink, 2006). There are concerns that other influencing factors can lead to misinterpretations, but information on such factors (e.g. floods, field abandonment) can improve the chronosequence approach (Walker *et al.,* 2010). The Naivasha study area is highly dynamic. The lake level fluctuated substantially from 1980 until 2011, which required the definition of land use duration as an ideal chronosequence position (see chapter 2). Soils at the Lake Naivasha northern wetland fringes are influenced by river sedimentation and re-suspension processes in the lake (Tarras-Wahlberg *et al.,* 2002), and soil textural changes have been reported previously at other lake positions (Gaudet, 1977). Soil variability increased in deeper soil layers within the chronosequence transects (e.g. buried A Horizons on alluvial pasture soils), and especially the pasture reference sites and 1-year pastures showed substantial differences in soil chemical and physical attributes compared to older positions. That includes soil textural changes (Figure 8) and SOC variations along the soil profile (Figure 6). Additionally, poor land quality (i.e. pH > 9 until soil surface) led to land abandonment of the 15-year lacustrine cropland position.

Thus, only the topsoil of selected positions appeared to be adequate in a chronosequence study. All topsoil samples (0 – 15 cm) included the A Horizon and top B Horizon (Figure 9) with similar soil properties (depth, color, texture, structure) on positions ≥15 years on pastureland and from 0 – 30 years on cropland. The lacustrine and alluvial pasture reference sites and 1-year positions have been excluded from further chemical (i.e. carbon, nutrients) and plant production analysis (distinct soil texture, soil depth, and salt crust evolvement). Also the 15-year lacustrine cropland position was excluded owing to the ultrabasic soil conditions and land abandonment.

3.5. Conclusion

Lake Naivasha soils are dominantly influenced by the lake water, sediment inflow, parent material and former papyrus vegetation in the studied area. Soils differed greatly between alluvial pasture, lacustrine pasture and lacustrine cropland, especially in pH, carbonate accumulation and soil organic carbon. Soil chemical and physical attributes differed also within the chronosequence transects, and the space for time approach is only suitable for the topsoil from selected chronosequence positions.

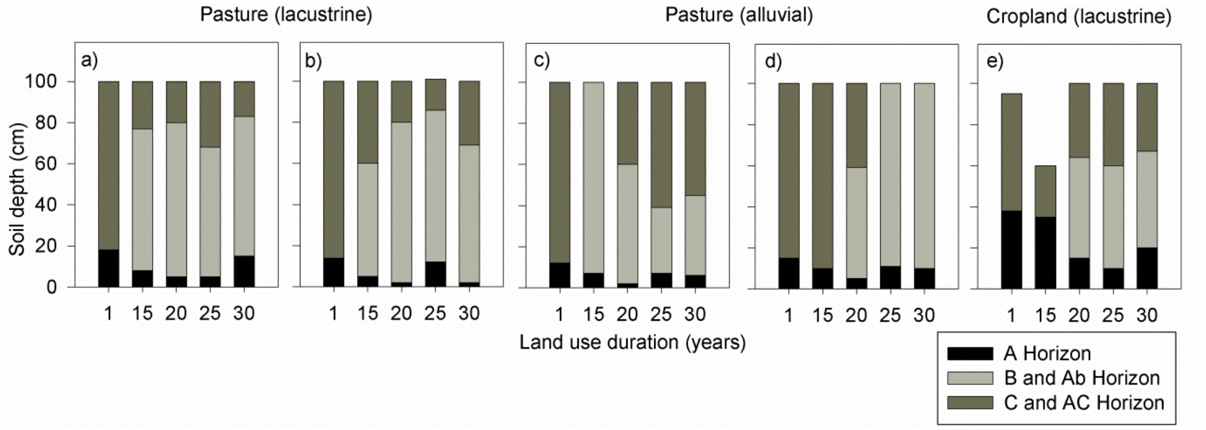


Figure 9. Soil horizons and soil depth (cm) from five chronosequence transects with 1 to 30 years of land use on lacustrine pasture (a, b), alluvial pasture (c, d) and lacustrine cropland (e), respectively.

Table 2. Soil description of lacustrine pasture soils (a, b) (1 to 30 years of land use, 0 – 100 cm depth) according to the World Reference Base (FAO, 2006; IUSS, 2006) with horizon, depth, color, mottles, texture, structure, bulk density (BD), pH, electrical conductivity (EC), soil organic carbon content (SOC), carbonate and total nitrogen.

Soil	Year	Soil No.	Horizon	Depth (cm)	Color	Mottles	Texture	BD (g cm^{-3})	Structure	pH$_{H2O}$	EC (dS m^{-1})	%SOC	% Carbonate	%N
gleyic Fluvisols (calcaric)	1	a)	Ahk	0-18	2.5Y 4/4	10YR 8/1	C	1.2	CR	8.0	0.3	1.3	2.8	0.1
			ACg	18-55	2.5Y 4/3	7.5R 2/2; 7.5Y 3/1	SL$_{\text{clay-poor}}$	1.2	MA/SB	8.2	0.2	0.2	0.6	0
			1C	55-75	2.5Y 4/4	2.5Y 8/1	CL	1.0	MA	8.5	0.2	0.1	1.4	0
			2Ck	75-110	10YR 3/3	10YR 8/1	CL	1.1	MA	8.4	0.2	0.3	2.5	0
gleyic Fluvisols (calcaric)		b)	Ahk	0–14	10YR 2/2	10YR 8/1	SiL$_{\text{clay-rich}}$	1.1	CR	8.4	0.3	1.2	3.4	0.1
			1C	14-53	5Y 4/2	-	LS	1.2	MA	8.0	0.2	0.2	1.1	0
			2Cgk	53-114	10YR 4/3	10YR 4/1; 10YR 8/1	CL	1.1	MA	8.3	0.2	0.1	4.3	0
haplic Vertisols	15	a)	Ah	0-8	5YR 2/1	-	SiL$_{\text{clay-poor}}$	1.0	CR	nd	nd	nd	nd	nd
			Bik	8-77	2.5Y 3/1	2.5Y 8/1; 7.5YR 6/8	C	1.1	PR/WE	nd	nd	nd	nd	nd
			C	77-110	10YR 4/4	2.5Y 8/1	SiCL	1.1	MA	8.9	0.2	nd	nd	nd
gleyic Vertisols		b)	Ah	0-5	7.5Y 3/2	-	SiL$_{\text{clay-poor}}$	0.8	CR	6.8	0.1	6.2	0	0.5
			Bi	5-60	5Y 2/1	5Y 8/1	C	1.1	PR/WE	7.7	0.4	1.0	0	0.1
			Cg	60-100	2.5Y 3/3	10Y 5/1	CL	1.2	MA	9.2	0.1	0.1	0.5	0
haplic Vertisols	20	a)	Ah	0-5 (10)	7.5YR 2/1	-	SiL$_{\text{clay-rich}}$	0.9	CR	7.0	0.7	nd	nd	nd
			Bi	5-38	10YR 4/3	-	SiL$_{\text{clay-rich}}$	1.3	PR/WE	nd	nd	nd	nd	nd
			Bik	38-80	10YR 4/3	10YR 8/1	C	1.2	PR/WE	nd	nd	nd	nd	nd
			C	80-100	10YR 5/4	-	SiL$_{\text{clay-poor}}$	1.1	MA	8.8	0.5	nd	nd	nd
haplic Vertisols		b)	Ah	0-2	5YR 2/1	-	SiL$_{\text{clay-rich}}$	0.9	CR	6.5	0.5	7.8	0	0.7
			Bi	2-80	10YR 3/2	10YR 1.7/1	SiCL	1.2	SB/WE	8.9	0.5	0.5	0.5	0
			C	80-100	10YR 4/2	-	C	1.3	MA	9.4	0.4	0.4	1.7	0
haplic Vertisols	25	a)	Ah	0-5	10YR 2/3	-	SiL$_{\text{clay-poor}}$	0.8	CR	6.9	0.5	5.5	0	0.5
			Bi	5-33	10YR 2/2	10YR 8/1; 5YR 6/8	CL	1.0	SB/WE	7.8	0.4	1.2	0	0.1
			Bigk	33-68	2.5Y 4/2	2.5Y 8/1; 2.5Y 2/1	SC	1.4	PR/WE	9.6	0.6	0.2	4.6	0
			Ck	68-100	10YR 3/4	10YR 1.7/1; 10YR 8/1	C	1.1	MA	9.6	0.3	0	2.0	0
haplic Vertisols		b)	Ah	0-12	10YR 2/3	-	L	1.1	CR	6.6	0.4	4.5	0	0.4
			Bik1	12-65	10YR 3/3	10YR 8/1	C	1.0	SB/WE	9.1	0.5	0.6	0.6	0
			Bik2	65-85	2.5Y 3/3	2.5Y 8/1	SC	1.3	PR/WE	9.9	0.8	0.3	2.1	0
			Cgk	85-100	2.5Y 4/2	2.5Y 8/1; 2.5Y 2/1	SC	1.2	MA	9.7	0.4	0.3	1.6	0
gleyic Vertisols	30	a)	Ah	0-15	2.5Y 3/3	-	SiL$_{\text{clay-rich}}$	1.2	CR/SB	7.6	0.3	3.6	0.3	0.3
			Bigk1	15-42	5Y 4/2	5Y 8/1; 5Y 2/1	CL	1.4	PR/WE	8.9	0.3	0.1	0.4	0
			Bigk2	42-83	2.5Y 3/2	5Y 8/1; 5Y 2/1	SC	1.2	PR/WE	9.5	0.4	0.2	3.2	0
			Ck	83-100	7.5YR 4/4	7.5YR 8/1; 7.5YR 2/1	CL	1.1	MA	9.6	0.2	0.1	1.4	0
haplic Vertisols		b)	Ah	0-2	10YR 2/3	-	SL$_{\text{clay-rich}}$	0.9	CR	6.5	0.6	7.7	0	0.7
			Bi	2-36	2.5Y 3/3	7.5YR 5/8	SCL	1.3	PR/WE	8.7	0.7	0.8	0.4	0
			Bik	36-69	2.5Y 4/1	10YR 8/1; 10YR 1.7/1	SCL	1.4	PR/WE	9.6	0.8	0.4	3.3	0
			Ck	69-100	7.5Y 4/3	10YR 8/2; 10YR 1.7/1	CL	1.2	MA	9.8	0.3	0.1	3.7	0

Texture: MS = medium sand, S = sand, LS = loamy sand, L = loam, SL = sandy loam, CL = clay loam, SiCL = silty clay loam, SC = sandy clay, SCL = sandy clay loam, C = clay, HC = heavy clay, Structure: CR = crumbly, SB = subangular blocky, PR = prismatic, MA = massive, WE = wedge shaped, BD = bulk density, EC = electrical conductivity, SOC = soil organic carbon, N = total nitrogen, nd = no data

Table 3. Soil description of alluvial pasture soils (a, b) (1 to 30 years of land use, 0 – 100 cm depth) according to the World Reference Base (FAO, 2006; IUSS, 2006) with horizon, depth, color, mottles, texture, structure, bulk density (BD), pH, electrical conductivity (EC), soil organic carbon content (SOC), carbonate and total nitrogen.

Soil	Year	Soil No.	Horizon	Depth (cm)	Color	Mottles	Texture	BD (g cm^{-3})	Structure	pH$_{H2O}$	EC (dS m^{-1})	%SOC	% Carbonate	%N
gleyic Fluvisols	1	a)	Ah	0-12	7.5 YR 2/2	10R 4/6; 7.5R 8/1	SiL$_{\text{clay-poor}}$	1.0	CR/SB	7.3	1.7	3.0	0.2	0.3
			1Cg1	12-20	10YR 3/3	10R 4/8; 10YR 1.7/1	S	1.0	MA	7.3	0.7	0.9	0.1	0.1
			2Cg2	20-68	10YR 3/1	10YR 1.7/1; 10R 3/4	C	0.9	MA	7.4	0.4	0.6	0	0.1
			2Cg3	68-83	10YR 3/1	5YR 4/8; 10YR 1.7/1	C, CL	1.1	MA	7.6	0.2	0.9	0	0.1
			3Cg4	83-100	2.5Y 3/1	10R 4/8; 2.5YR 1.7/1	C	1.0	MA	7.3	0.2	0.9	0	0.1
gleyic Fluvisols		b)	Ahg	0-15	7.5YR 3/3	10R 4/4	SCL	1.0	CR/SB	7.6	2.1	4.7	0.2	0.5
			ACg	15-85	10YR 3/2	10R 4/6; 10R 2/2	C	1.1	MA	7.7	0.4	1.2	0.7	0.1
			2Cg	85-100	2.5YR 3/2	10R 3/1; 10R 2/1	S	1.2	MA	6.7	0.1	0.2	0	0
haplic Gleysols	15	a)	Ah	0-7	10YR 2/2	-	CL	0.7	CR	5.7	0.7	9.5	0	0.9
			Bg	7-75	5Y 3/1	10R 5/8; 5Y 2/1	C	1.0	PR/SB	6.3	0.2	1.2	0	0.1
			2Abg	75-100	2.5Y 3/2	5Y 2/1	HC	1.0	PR/SB	6.1	0.3	1.9	0	0.2
gleyic Fluvisols		b)	Ah	0-10	10YR 2/3	10R 6/8	SiL$_{\text{clay rich}}$	0.8	SB	6.6	1.3	9.9	0	0.9
			1Cg1	10-47	10YR 3/4	10YR 1.7/1, 10R 4/8	C	1.2	MA	8.0	0.5	0.9	0.1	0.1
			2Cg2	47-59	7.5YR 3/4	5YR 1.7/1; 5R 5/8	L	1.3	MA	7.2	0.2	0.4	0	0.1
			3Cg3	59-100	10YR 4/1	5YR 4/8; 5YR 2/1	C	1.1	MA	7.9	0.1	0.8	0	0.1
gleyic Vertisols	20	a)	Ah	0-2	10YR 2/3	-	SiL$_{\text{clay-poor}}$	0.7	SB	6.0	0.6	8.7	0	0.7
			Big	2-60	10YR 2/2	2.5YR 4/8; 5YR 6/8; 10YR 8/1	SiCL	1.0	SB/WE	5.9	0.3	4.8	0	0.4
			Cg	60-100	2.5Y 3/3	5YR 6/8; 10YR 1.7/1; 10YR 8/1	CL	1.3	MA	7.3	0.1	0.5	0	0.1
haplic Gleysols		b)	Ah	0-5	5YR 3/1	-	L	0.5	SB	6.2	0.7	12.3	0	1.0
			Bg	5-59	5YR 4/1	5YR 7/8; 5YR 5/8; 5YR 1.7/1	C	1.1	PR/SB	6.5	0.2	1.1	0	0.1
			Cg	59-100	7.5YR 4/2	10R 3/6; 5YR 5/8; 5YR 1.7/1	C	1.0	MA	6.0	0.3	0.8	0	0.1
gleyic Vertisols	25	a)	Ah	0-3 (7)	10YR 2/2	-	SiL$_{\text{clay-poor}}$	0.8	SB	6.0	0.5	7.5	0	0.6
			Big	3-39	10YR 3/2	5YR 6/8	C	1.1	SB/WE	6.2	0.2	2.1	0	0.2
			1Cg	39-70	2.5Y 4/1	5YR 6/8	SiC	1.3	MA	7.0	0.1	0.3	0	0
			2C	70-100	10YR 4/6	10YR .7/1; 2.5Y 8/1	SiL$_{\text{clay rich}}$	1.2	MA	7.6	0.2	0.1	0.9	0
gleyic Vertisols		b)	Ah	0-11	7.5YR 2/2	-	SiL$_{\text{clay-poor}}$	0.7	SB	6.1	0.5	7.6	0	0.7
			Big	11-60	7.5YR 4/2	2.5YR 3/6; 7.5YR 2/1	HC	1.0	PR/WE	4.9	0.2	1.3	0	0.1
			2Abg	60-80	10YR 2/1	5YR 5/8; 10YR 8/1; 10YR 1.7/1	HC	1.0	PR	5.3	0.3	2.0	0	0.2
			2Big	80-100	10YR 3/2	10YR 1.7/1; 10R 5/8; 10YR 8/1	HC	1.1	PR/WE	5.5	0.2	1.0	0	0.1
gleyic Vertisols	30	a)	Ah	0-6	7.5YR 2/1	-	SiL$_{\text{clay-poor}}$	0.6	CR	5.6	0.4	10.9	0	0.9
			Big	6-45	10YR 3/3	2.5YR 4/8; 2.5YR 2/2	C	1.1	PR/WE	6.2	0.1	1.0	0	0.1
			C	45-100	10YR 4/4	10R 4/8; 2.5YR 2/1	C	1.1	MA	6.8	0.1	0.2	0	0
gleyic Vertisols		b)	Ah	0-10	7.5YR 2/2	-	SiL$_{\text{clay-poor}}$	0.7	CR/SB	5.8	0.5	8.1	0	0.7
			Big	10-23	10YR 4/2	5YR 5/8; 5YR 8/1	SiC	1.1	PR/WE	5.4	0.1	1.5	0	0.2
			2Abg	23-64	5YR 3/2	5YR 5/8; 5YR 1.7/1	C	0.9	PR/SB	5.5	0.2	2.8	0	0.2
			2Big	64-100	5YR 4/1	7.5YR 7/8; 7.5YR 1.7/1	C	1.3	PR/WE	6.3	0.1	0.7	0	0.1

Texture: MS = medium sand, S = sand, LS = loamy sand, L = loam, SL = sandy loam, CL = clay loam, SiCL = silty clay loam, SC = sandy clay, SCL = sandy clay loam, C = clay, HC = heavy clay, Structure: CR = crumbly, SB = subangular blocky, PR = prismatic, MA = massive, WE = wedge shaped, BD = bulk density, EC = electrical conductivity, SOC = soil organic carbon, N = total nitrogen, nd = no data

Table 4. Soil description of lacustrine cropland soils (1 to 30 years of land use, 0 – 100 cm depth) according to the World Reference Base (FAO, 2006; IUSS, 2006) with horizon, depth, color, mottles, texture, structure, bulk density (BD), pH, electrical conductivity (EC), soil organic carbon content (SOC), carbonate and total nitrogen.

Cropland (lacustrine)	Year	Soil No.	Horizon	Depth (cm)	Color	Mottles	Texture	BD (g cm^{-3})	Structure	pH$_{H2O}$	EC (dS m^{-1})	%SOC	%Carbonate	%N
mollic	1	---	Apk	0-10	5Y 3/2	5Y 8/4	SiC	0.9	CR	7.6	0.7	3.7	1.7	0.4
Fluvisols			Ak	10-38	5Y 3/2	5Y 8/3	SC	1.3	SB	8.9	0.3	0.3	3.3	0.1
			Cgk	38-95	5Y 3/2	5Y 8/1	MS	0.8	MA	8.9	0.2	0.2	1.1	0
mollic	15	---	Apk	0-5	2.5Y 3/2	-	L	0.9	CR	9.1	0.6	1.8	2.7	0.2
Fluvisols			Ak	5-35	2.5Y 3/3	2.5Y 8/1; 2.5Y 6/6	CL	1.3	SB	9.4	0.4	1.1	2.0	0.1
			Ck	35-60	10YR 3/1	2.5Y 8/1; 10YR 6/4	SL$_{\text{clay rich}}$	1.0	MA	9.2	0.4	0.6	2.2	0.1
haplic	20	---	Apk	0-15	10YR 4/4	10Y 8/1	Si	0.9	CR	7.6	0.2	0.9	0.0	0.1
Cambisols			Bwk	15-64	7.5YR 3/2	5YR 7/8; 5YR 8/1	Si	1.1	SB	7.0	0.3	2.0	0.0	0.3
(calcaric)			Cgk	64-100	10YR 3/3	10YR 8/6; 10Y 8/1	SiL$_{\text{clay rich}}$	1.2	MA	8.1	0.1	0.3	1.2	0
haplic	25	---	Ap	0-10	2.5Y 3/2	-	SiL$_{\text{clay rich}}$	1.0	CR	7.6	0.3	1.8	0.1	0.2
Cambisols			Bwk	10-60	2.5Y 3/2	2.5Y 7/8; 7.5Y 7/1	SiL$_{\text{clay rich}}$	1.3	SB	8.5	0.1	0.4	0.2	0.1
(calcaric)			Ck	60-100	2.5Y 3/3	2.5Y 3/2; 5YR 5/8; 10Y 8/1	SiL$_{\text{clay poor}}$	1.2	MA	8.0	0.1	0.2	4.4	0
haplic	30	---	Apk	0-20	10YR 3/3	10GY 7/1	L	1.0	CR	8.0	0.3	1.4	1.8	0.2
Cambisols			Bwk	20-67	10YR 3/4	10GY 7/1; 7.5YR 5/6	CL	1.4	SB	8.4	0.3	0.5	6.0	0.1
(calcaric)			C	67-100	7.5YR 4/4	10GY 7/1	SCL	1.3	MA	8.4	0.2	0.3	1.8	0

Texture: MS = medium sand, S = sand, LS = loamy sand, L = loam, SL = sandy loam, CL = clay loam, SiCL = silty clay loam, SC = sandy clay, SCL = sandy clay loam, C = clay, HC = heavy clay, Structure: CR = crumbly, SB = subangular blocky, PR = prismatic, MA = massive, WE = wedge shaped, BD = bulk density, EC = electrical conductivity, SOC = soil organic carbon, N = total nitrogen, nd = no data

4. Soil moisture dynamics along chronosequences of agricultural land use

4.1. Introduction

In East Africa, wetlands have been increasingly converted to agricultural land during the last decades (Dixon and Wood, 2003). Upland soil degradation and the unpredictability of rainfall patterns have accelerated the shift of cultivation from the uplands towards the lowlands with sufficient water supply. However, the conversion of natural wetlands is often connected with soil drainage and tillage activities (Dam *et al.*, 2013), and the subsequent soil desiccation negatively affects soil hydrology, mineralization processes, crop production and wetland productivity. Published research on soil water dynamics in agriculturally-used tropical wetlands focused mostly on inland valleys (Böhme *et al.*, 2013), largely ignoring the littoral area of lakes.

Lake Naivasha is a freshwater lake in the East African rift valley. The lake level has been declining and the lake surface shrinking between 1980 and 2011, which has been ascribed to increased water abstraction for irrigation as well as for domestic uses (Becht and Harper, 2002; Mekonnen *et al.*, 2012), and declining rainfalls (Awange *et al.*, 2013). Especially from the year 2000 onward, the lake level reduction has accelerated. Decline rates of 33 cm a^{-1} have been reported with concomitant annual lake area shrinkage of 1.41 km^2 (Awange *et al.*, 2013). The newly exposed land area along the wetland fringes has been continuously converted to agricultural land (grazing pastures as well as cropland), resulting in chronosequences of land use from 1980 to 2011. Along these chronosequences, a gradient of declining soil moisture can be expected, and deduced amounts of plant-available water are likely to negatively impact on crop production. To date, most research focused on the bathymetry of Lake Naivasha (Ramírez-Hernández*,* 2000; van Oel *et al.*, 2013; Yihdego and Becht, 2013), largely ignoring the dynamics of soil moisture and plant available water for crops or pasture vegetation. Due to exceptionally heavy rains, the lake water level increased again starting 2011, providing the additional opportunity to study the water dynamics during periods of both lake level decline and increase. We assessed the dynamics of soil moisture and plant-available water along chronosequences of 1 to 30 years of land use in different land use systems (cropland, pasture) and on two different parent materials (alluvial, lacustrine sediments) in the littoral zone of Lake Naivasha.

4.2. Material and Methods

4.2.1. Site description and experimental set-up

The study area is located at 0° 43 'S and 36° 22' E in the Kenyan Rift valley at an altitude of about 1890 masl. The climate is semi-arid with mean temperature of 16 – 20° C, the r/Eo of 25% - 40% (Sombroek *et al.*, 1982), and mean annual precipitation of 620 mm (Clarke *et al.*, 1990). Typically, rainfall is bimodal with long rains in April to May and short rains in November. However, precipitation tends to be patchy and irregular (Gaudet and Melack, 1981).

The studied pasture area is located at the northern lake fringe, near the inflow of Malewa River into Lake Naivasha, and is being grazed by game and cattle. The cropland is located along the eastern lake shore and is cultivated with irrigated vegetable and maize. The parent material consists of lacustrine sediments with mixture of volcanic ash or pyroclastic material (Siderius and Muchena, 1977). At the fringes of Malewa River, this parent material is overlain by alluvial deposits (Clarke *et al.*, 1990). While the pasture land was located on alluvial deposits and lacustrine sediments, the cropland was situated on lacustrine parent material. Based on these differences in the parent material and land use, the sites will thereafter be referred to either “alluvial pasture”, “lacustrine pasture” or “lacustrine cropland”. Soils were identified as Fluvisols and Cambisols on the lacustrine cropland, as Fluvisols and Vertisols on lacustrine pasture and as Vertisols, Gleysols and Fluvisols on alluvial pasture (IUSS, 2006) (chapter 3).

With continued lake level declines between 1980 and 2011, the gradually exposed land areas have been used by both pastoralists and small-scale farmers. Based on detailed lake level records, we identified the positions of the lake shore in 1980, 1985, 1990, 1995 and 2010 using a geodetic GPS (Leica 500 coupled with a Nikon AP-7 Automatic Level) in each of the three land use situations (lacustrine cropland, lacustrine and alluvial pasture) representing transects of chronosequence positions (durations of land use) of 1, 15, 20, 25 and 30 years (space for time substitution). Five such chronosequence transects were established, two each on lacustrine and alluvial pasture, and one on lacustrine cropland.

4.2.2. Volumetric soil moisture content

Soil pits of 100 cm depth were opened at position 15 to 30 years at all three land use situations (total: 20 pits) in January 2011. Soil horizons were identified (FAO, 2006) and three core samples were taken from each soil horizon. The core samples were weighed fresh, then oven-dried at 105 °C for 24 h, weighed again, and mean values of fresh weight, dry weight and bulk density calculated. Mean gravimetrical measured volumetric soil water content (θ_G) (0 – 100 cm soil depth) was calculated as:

$$\theta_G = \frac{\sum_i^n \left[\frac{(FW_i - DW_i)}{DW_i * BD_i}\right]}{n} \qquad (2)$$

whereby: θ_G = initial volumetric soil water content (cm^3 cm^{-3}), FW_i = core sample fresh weight (g) *ith* horizon; DW_i = core sample dry weight *ith* horizon (g), BD = bulk density *ith* horizon (g cm^{-3}), n = number of soil horizons.

Permanently installed FDR soil moisture sensors (EC-5 sensor, EM-5b datalogger, Decagon Inc., Pullman, WA, USA) took hourly measurements of volumetric soil water content (θ_v) from November 2010 to December 2011 (total: 42 sensors). The sensors were installed along three transects (one each on alluvial pasture, lacustrine pasture, and lacustrine cropland) at soil depths of 10, 30 and 50 cm, representing θ_v in 0 – 20, 20 – 40 and 40 – 60 cm soil depth, respectively. No sensors were installed at 50 cm depth at position 20, 25 and 30 years lacustrine pasture, because the very hard soil layer did not allow sensor installation. Sensor outputs were calibrated according to the manufacturer's instructions (Cobos, 2009) with soil samples of 10 – 15 cm depth. Thereafter, θ_v was calculated using a three parameter sigmoid model (Figure 10a):

$$\theta_v = \theta_s / (1 + \exp(- (x - x_0) / b)) \qquad (3)$$

whereby: θ_v = volumetric soil water content (cm^3 cm^{-3}), θ_s = upper asymptote, saturated soil water content at pF 0.1 (cm^3 cm^{-3}), x = raw counts, b = lower asymptote, fitting parameter, x_0 = fitting parameter.

The upper asymptote was changed according to the site and depth-specific saturated soil water content (θ_s). Volumetric soil water content at saturation (θ_s, pF 0.1), field capacity (θ_{fc}, pF 1.8) and permanent wilting point (θ_{pwp}, pF 4.2) was determined from site and depth specific moisture retention curves. Moisture retention curves were calculated from soil organic carbon (SOC), bulk density (BD) and soil texture using the pedotransfer function of Vereecken *et al.* (1989) (Table 5). Therefore, additional mini-pits were opened at the same positions and depths about 10 m from the sensor station. Soil weights and bulk density were determined from three undisturbed samples (taken with 100 cm^3 metal cans), and soil moisture content (θ_{G2}) gravimetrically measured (with equation 2). Disturbed samples were taken, air-dried, sieved to <2 mm, and stored until analysis. Thereafter, soil texture was determined by hydrometric method. The inorganic carbon content was measured by Scheibler method. Subsamples were fine-ground with a swing mill (Retsch GmbH, Germany), and total carbon content was measured with CNS Elemental Analyzer (EuroEA

3000; Euro Vector SpA, Milan, Italy). The SOC was calculated as the difference of total and inorganic carbon content.

We validated the volumetric water content (θ_v) with gravimetrically-measured water content (θ_{G2}) using linear regression, and both were significantly related with RMSE = 0.13 cm^3 cm^{-3} ($p < 0.05$) (Figure 10b). That indicates a low accuracy of sensor calibration. FDR sensor calibration for East African tropical wetland soils has been reported with RMSE of 0.07 cm^3 cm^{-3} (Böhme *et al.*, 2013). However, lateral soil moisture changes and irregular irrigation pattern have to be considered in this study, as field samples were taken at distances as far as 10 m from the installed sensors.

The prevailing soil conditions of wetland soils (high organic carbon content, water saturated soils) require a calibration of water sensors to field conditions (Böhme *et al.*, 2013). The manufacturer calibration settings of EC-5 sensors have been verified for soils with a wide textural range and salt concentrations (Campbell *et al.*, 2009). A linear model was proposed (Campbell *et al.*, 2009), which is certainly sufficient for most mineral soils. However, it did not match the requirements for wetland soils in this study. A linear model would theoretically imply water contents above saturation level. Indeed, the raw counts from the EC-5 sensors have yielded volumetric water contents > 100% under saturated conditions using a linear model in this study (not shown). Raw counts reached a maximum of 1309 counts on sites directly located at the lake shore, while manufacturer´s calibration only considered counts < 1000 (Campbell *et al.*, 2009). We therefore proposed a three parameter sigmoid model with the upper asymptote being adjusted to saturated water content (θ_s). That considered the specific soil conditions (bulk density, organic carbon content, and soil texture) by using the Vereecken pedotransfer function. McLaughlin *et al.* (2012) found a highly significant relation between measured and calculated moisture retention curves (derived from the van Genuchten pedotransfer function, which is similar to the Vereecken approach) for sandy and clay soils in a wetland transition zone, Florida, U.S.A. Prior to this study, Wendel *et al.* (2011) proposed a polynomial model for EC-5 calibration, measuring volumetric water content in a Canadian peat bog. The advantage of our model was the overall cap of volumetric water content at θ_s. Such procedure may be necessary where *in-situ* plant available water measurements are required and soil water conditions reach saturation during a certain period of time.

Table 5. Soil texture, bulk density (BD), soil organic carbon content (SOC), volumetric water content at saturation (θ_s), field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) (0 - 60 cm soil depth) from lacustrine pasture, alluvial pasture and lacustrine cropland at position 1 to 30 years of continuous land use.

Site	Land use duration (years)	Soil depth (cm)	%S	%Si	%C	BD (g cm^{-3})	%SOC	θ_s (cm^3 cm^{-3})	θ_{fc} (cm^3 cm^{-3})	θ_{pwp} (cm^3 cm^{-3})
Pasture (alluvial)	1	0 – 20	34	61	5	1.0	1.6	0.52	0.39	0.07
		20 – 40	15	57	28	1.1	1.0	0.53	0.50	0.20
		40 – 60	17	58	25	1.1	1.0	0.53	0.49	0.18
	15	0 – 20	11	55	34	0.8	3.2	0.62	0.60	0.27
		20 – 40	5	61	34	1.0	0.9	0.58	0.55	0.23
		40 – 60	18	74	8	0.9	0.9	0.56	0.41	0.07
	20	0 – 20	12	60	28	0.7	4.8	0.66	0.62	0.26
		20 – 40	2	70	28	0.9	1.7	0.60	0.55	0.21
		40 – 60	2	48	50	0.9	1.6	0.63	0.61	0.34
	25	0 – 20	2	51	47	0.8	3.4	0.66	0.64	0.36
		20 – 40	2	47	51	0.9	1.2	0.62	0.60	0.35
		40 – 60	2	57	41	0.9	1.0	0.62	0.58	0.28
	30	0 – 20	2	43	55	0.8	5.0	0.66	0.66	0.45
		20 – 40	2	37	60	1.0	1.9	0.62	0.61	0.42
		40 – 60	3	25	73	1.0	1.3	0.63	0.62	0.48
Pasture (lacustrine)	1	0 – 20	20	63	17	1.1	1.2	0.51	0.46	0.14
		20 – 40	8	76	15	1.0	0.3	0.54	0.46	0.11
		40 – 60	20	74	7	1.1	0.1	0.49	0.38	0.06
	15	0 – 20	4	62	34	0.8	8.1	0.63	0.63	0.40
		20 – 40	5	37	58	1.0	2.7	0.61	0.61	0.42
		40 – 60	12	46	42	1.1	0.4	0.55	0.53	0.28
	20	0 – 20	14	40	46	0.8	4.0	0.63	0.62	0.37
		20 – 40	19	51	31	1.2	0.7	0.50	0.48	0.21
	25	0 – 20	10	38	52	1.0	2.8	0.60	0.59	0.38
		20 – 40	24	37	39	1.0	0.6	0.57	0.53	0.26
	30	0 – 20	15	40	45	1.1	1.8	0.57	0.55	0.32
		20 – 40	26	51	23	1.3	0.4	0.48	0.44	0.16
Cropland (lacustrine)	1	0 – 20	30	64	6	1.0	1.8	0.52	0.42	0.08
		20 - 40	22	50	27	1.1	0.5	0.52	0.48	0.19
		40 - 60	19	53	28	0.8	0.5	0.62	0.51	0.18
	15	0 - 20	29	39	32	1.2	1.2	0.51	0.48	0.22
		20 - 40	23	47	30	1.0	0.3	0.55	0.50	0.20
		40 - 60	28	49	23	1.0	0.3	0.57	0.46	0.15
	20	0 - 20	29	56	14	1.1	2.4	0.53	0.47	0.15
		20 - 40	9	55	36	1.1	1.2	0.56	0.53	0.26
		40 - 60	9	58	33	1.1	0.7	0.55	0.52	0.23
	25	0 - 20	31	63	5	1.1	1.7	0.49	0.40	0.07
		20 - 40	3	50	47	1.3	0.7	0.51	0.50	0.31
		40 - 60	33	60	6	1.1	0.7	0.49	0.37	0.06
	30	0 - 20	32	52	16	1.2	2.1	0.50	0.45	0.15
		20 - 40	35	49	16	1.4	0.4	0.44	0.39	0.12
		40 - 60	26	68	6	1.1	0.13	0.51	0.37	0.05

%S = % sand content, %Si = % silt content, %C = % clay content, SOC = soil organic carbon, BD = bulk density, θ_s = volumetric water content at saturation (pF 0.1), θ_{fc} = volumetric water content at field capacity (pF 1.8), θ_{pwp} = volumetric water content at permanent wilting point (pF 4.2).

4.2.3. Plant available water

Mean daily plant available water relative to the potential plant available water (PAW) was calculated separately for each soil depth as (*Allen* et al., 1998):

$$PAW = [(\theta_v - \theta_{pwp}) / (\theta_{fc} - \theta_{pwp})] * 100 \qquad (4)$$

whereby: PAW = mean daily plant available water, θ_v = mean daily volumetric soil water content ($cm^3\ cm^{-3}$), θ_{pwp} = volumetric soil water content at permanent wilting point ($cm^3\ cm^{-3}$), θ_{fc} = volumetric soil water content at field capacity ($cm^3\ cm^{-3}$).

Additionally, mean daily plant available water (θ_a) (mm) was calculated for the upper soil layer of 0 – 60 cm (*Rowell*, 1997):

$$\theta_a = [\Sigma(\theta_v - \theta_{pwp}) / n] * d \qquad (5)$$

whereby: θ_a = mean daily plant available water (mm), θ_v = mean daily volumetric soil water content ($cm^3\ cm^{-3}$) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth, θ_{pwp} = volumetric soil water content at permanent wilting point ($cm^3\ cm^{-3}$) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth, n = number of samples (soil layers); d = effective rooting depth (600 mm).

Despite no sensors were installed on position 20, 25 and 30 years of land use on lacustrine pasture (40 – 60 cm soil depth), θ_a was calculated until 60 cm.

4.2.4. Rainfall, irrigation, groundwater and capillary rise

Rainfall was measured with rain gauges, installed at each of the three land use situations, and amount of irrigation water was recorded on cropland. Total rainfall from December 2010 until November 2011 was 891 mm on the pasture area. Supplementary irrigation on the cropland area was 709 mm (later referred to as minimum irrigation) and rainfall was 466 mm from December 2010 until October 2011. Groundwater depth was measured in weekly intervals in boreholes of 6 cm diameter at the 1 and 15 year positions from April to December 2011. No groundwater was detected within 100 cm depth beginning from position > 15 years (until August 2011). Capillary rise (mm d^{-1}) was determined according to AD-HOC-AG (2000) using soil texture and bulk density data (mini-pits) and groundwater readings.

4.2.1. Statistical analyses and data preparation

Daily and monthly plant available water (PAW) and volumetric water content (θ_v) were calculated from hourly measurements. Sensor output was checked for data plausibility (Bogena *et al.*, 2010) by crosschecks to rainfall and groundwater. Poor sensor data was discarded resulting in total loss of sensor output on position 15 (0 – 20 cm soil depth), 25 (20 – 40 cm) and 30 years (20 – 40 cm) of land use on lacustrine pasture soils. For those positions plant available water (θ_a) (mm) was extrapolated until 60 cm soil depth using equation (5). Additionally, θ_a (mm) was estimated for the period from 10 April to 8 August 2012, which reduced sample size variation due to temporary sensor blackout (n = 121, in two cases n = 119 and n = 55). Additional water supply by capillary rise was not considered for θ_a (mm), and capillary rise was estimated until an upper limit of 5 mm d^{-1}. Effective rooting depth was set to 60 cm soil depth (deepest sensor installation), despite that it exceeded that value in all cases. Mean values, standard deviation, median, range and percentiles were estimated for percent plant available water (PAW). The relation between land use duration and PAW mean and standard deviation was analyzed with Pearson correlation. The relation between groundwater, lake level and θ_v was analyzed with Pearson correlation. Plant available water (θ_a) and initial water content in 0 – 100 cm soil depth (θ_G) were analyzed with a first order exponential model. For all rainfall/irrigation periods (defined as daily rain/irrigation events with only one consecutive non-rainy/irrigation day) the correspondent $d\theta_v$ (0 – 20, 20 – 40 and 40 – 60 cm) was estimated. In three cases $d\theta_v$ period was prolonged by 2 days due to delayed sensor response. Thereafter, mean $d\theta_v$ was calculated from all three land use situations (excluding sites with possible groundwater influence, i.e. 1-year and 15-year sites), and categorized according to amounts of precipitation/irrigation (categories in steps ≥ 10 mm). Relation between categorized rainfall/irrigation events and $d\theta_v$ was analyzed with Spearman Rank Order correlation. Statistical analysis and plotting was done using the SigmaPlot 11.0 software package.

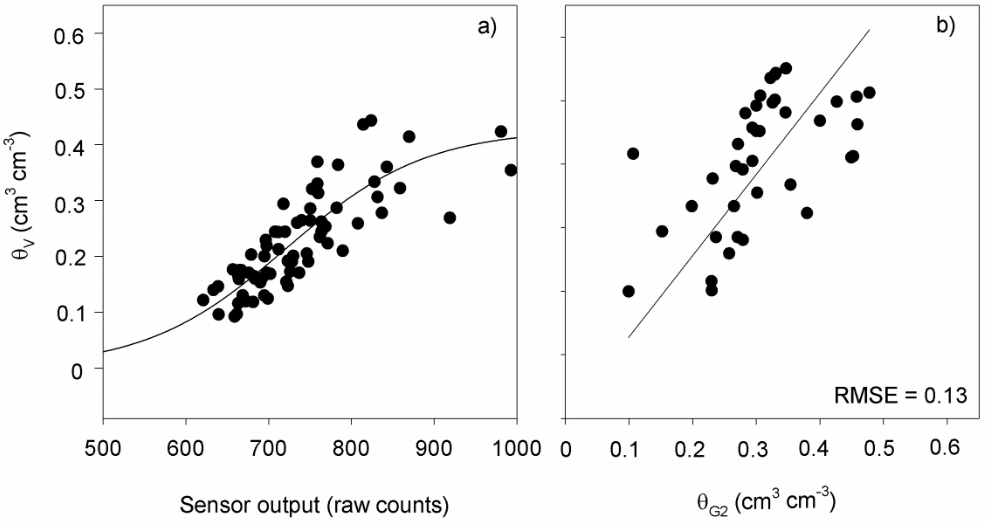


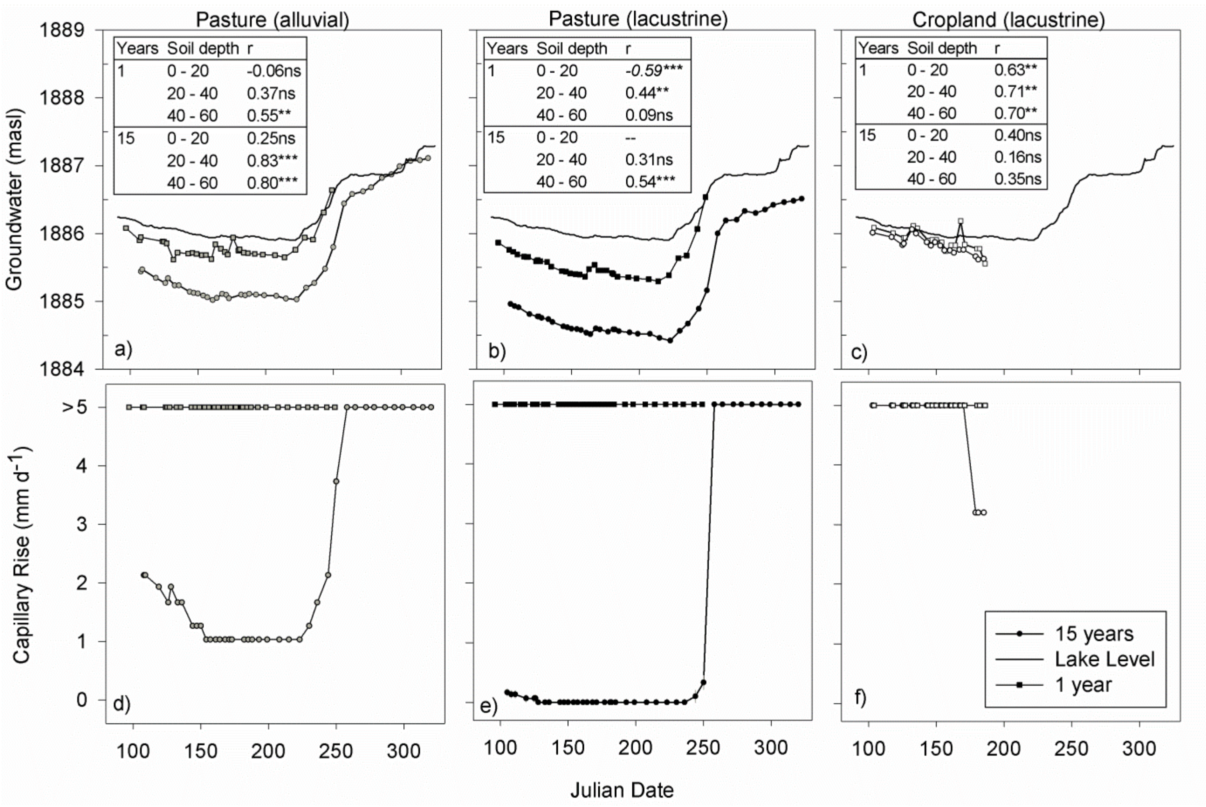
Figure 10. a) Sensor calibration to field conditions. Data was fitted to a three parameter sigmoid model with the upper asymptote being volumetric water content at saturation (θ_s) (here: all sites included) b) Linear regression analysis (y = a*x) between volumetric water content (θ_v) from sensor readings and gravimetrically measured volumetric water content (θ_{G2}) (mini-pits) in 0 – 20, 20 – 40 and 40 – 60 cm of lacustrine pasture, alluvial pasture and lacustrine cropland soils on position 1 - 30 years of continuous land use (n = 39).

4.3. Results

4.3.1. Soil water dynamics

The estimated volumetric water content at saturation (θ_s), field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) (0 – 60 cm soil depth) ranged from 0.06 – 0.63 (lacustrine pasture), 0.07 – 0.66 (alluvial pasture) and 0.05 – 0.62 $cm^3\ cm^{-3}$ (cropland) (Table 5).

Groundwater depth and lake level were significant and positively correlated at lower chronosequence positions (15-year position: r = 0.57***, n = 85; 1-year position: r = 0.69***; n = 85). The groundwater level declined even below the lake level on the pasture area, while on cropland it corresponded to the absolute altitude of the lake level (Figure 11a - c). Groundwater depth also affected daily volumetric soil water content (θ_v) by capillary rise processes (Figure 11d - f) at the lower chronosequence positions (land use of 1 - 15 years) and at all three land use situations (Figure 11a - c). This resulted in a change of the soil moisture regimes along the chronosequence (with distance from the lake shore) from aquic (seasonally flooded or saturated) to aridic (permanently aerobic). Mean volumetric water content (θ_v) decreased between the 1 and 30 year position (0 – 60 cm) from 0.46 (0.03) to 0.29 (0.09) $cm^3\ cm^{-3}$ on alluvial pasture, from 0.51 to 0.36 (0.09) $cm^3\ cm^{-3}$ on lacustrine pasture, and from 0.49 (0.05) to 0.35 (0.05) $cm^3\ cm^{-3}$, on the cropland (Figure 12). The reduction of soil moisture (θ_G) was significant following a first order exponential model with decay constants (k) of -0.061 and -0.033 a^{-1} on lacustrine and alluvial pasture, respectively. The observed decline in soil moisture was not significant in the cropland area (Figure 15d - f). Thus, the impact of the lake water level on the soil water content was most apparent under pasture use (no irrigation): Monthly θ_v on the 15-year alluvial pasture position (close to the lake shore) changed by -0.20, -0.02 and 0 $cm^3\ cm^{-3}$ in 0 – 20, 20 – 40, and 40 – 60 cm soil depth, respectively between November 2010 and May 2011 (Figure 12a, d, g). During the same period, the lake level decreased from 1886.8 to 1886.0 masl (Figure 11a - c). Thereafter (July to November 2011), the lake level increased again to 1886.9 masl (Figure 11a – c) with monthly change rates of θ_v by 0.18, 0.03 and 0.01 $cm^3\ cm^{-3}$ (Figure 12a, d, g). Lower positions (more recently used) were flooded until the end of the observation period in December 2011.



Pasture (alluvial)

Years	Soil depth	r
1	0 - 20	-0.06ns
	20 - 40	0.37ns
	40 - 60	0.55**
15	0 - 20	0.25ns
	20 - 40	0.83***
	40 - 60	0.80***

Pasture (lacustrine)

Years	Soil depth	r
1	0 - 20	-0.59***
	20 - 40	0.44**
	40 - 60	0.09ns
15	0 - 20	--
	20 - 40	0.31ns
	40 - 60	0.54***

Cropland (lacustrine)

Years	Soil depth	r
1	0 - 20	0.63**
	20 - 40	0.71**
	40 - 60	0.70**
15	0 - 20	0.40ns
	20 - 40	0.16ns
	40 - 60	0.35ns

Figure 11. Groundwater level (a, b, c) and mean capillary rise (d, e, f) in relation to lake level on alluvial pasture, lacustrine pasture and lacustrine cropland (1 and 15 years) from April to December 2011, respectively. Pearson correlation (Tables in a, b, c) between daily volumetric water content (θ_v) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth and groundwater table on alluvial pasture (n = 30/33), lacustrine pasture (n = 27/31) and lacustrine cropland (n = 18/10) (1 and 15 year position) with correlation coefficient r being significant at: * = p < 0.05, ** = p < 0.01, *** = p < 0.001, ns = not significant.

Also rainfall and irrigation influenced the moisture regime of the upper soil layers, particularly at the (intermittently irrigated) cropland site. Precipitation and irrigation were significant and positively related to mean $d\theta_v$ in the topsoil (0 - 20 cm: r = 0.79***, n = 23; 20 - 40 cm: r = 0.48*, n = 19), but not in the subsoil (40 - 60 cm). The largest recorded rainfall event of 280 – 320 mm increased mean $d\theta_v$ by 0.18 (0 - 20 cm), 0.07 (20 - 40 cm) and 0.03 cm^3 cm^{-3} (40 – 60 cm soil depth) (Figure 13a - c). Between November 2010 and 9 August 2011 (period of lake level decline), we observed twenty-three rainfall or irrigation events, none of those exceeding 32 mm. In the observation period thereafter (period of lake level increase), six events with ≤ 30 mm, three events with 50 – 100 mm and one event with 280 – 300 mm were recorded.

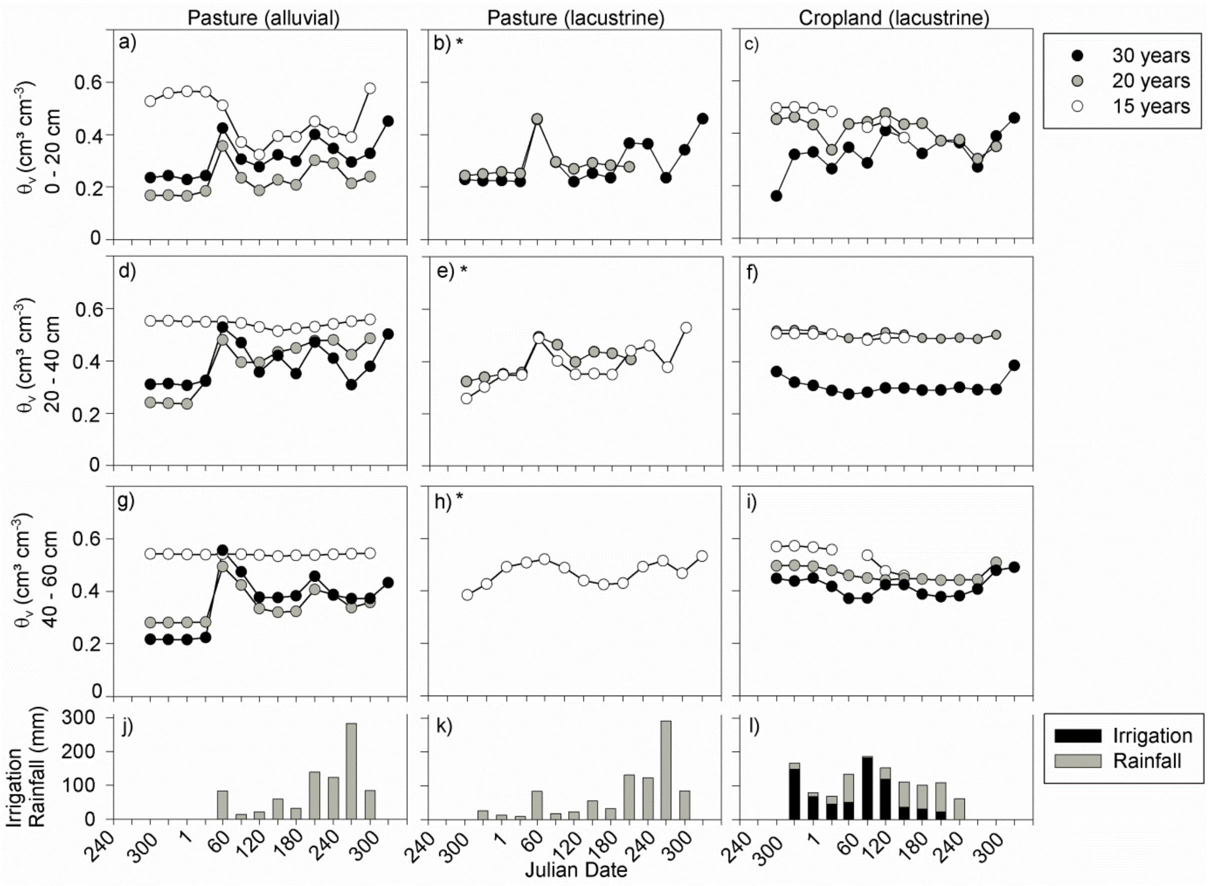


Figure 12. Mean monthly volumetric water content (θ_v) (cm^3 cm^{-3}) on alluvial pasture (a, d, g) lacustrine pasture (b, e, h) and lacustrine cropland (c, f, i) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth after 15, 20 and 30 years of continuous land use, and total monthly rainfall and irrigation (j, k, l) in the period of November 2010 to December 2011.* = missing data (sensor blackout, bad readings) or no data

4.3.2. Plant available water

The soil water dynamics affected also the amount of plant available water on pastureland and cropland. Mean daily plant available water (PAW) was negatively (r = -0.64***, n = 39) and daily PAW standard deviation (r = 0.48***, n = 39) positively related to land use duration. Plant available water (θ_a) decreased on pastureland (lacustrine and alluvial soils) from 216 and 228 mm (1 year) to 0 mm (30 years) in the upper 60 cm soil layer. That reduction was significant, following a first order exponential model with a rate constant (k) of -0.061 a^{-1} on alluvial soils and -0.087 a^{-1} on lacustrine pasture soils (Figure 15a - b). Especially the upper soil layer was affected (0 – 20 cm): The amount of the potential plant available water (PAW) on alluvial pastureland decreased from 133% (1 year) to 1% (30 year position) (Figure 14a). On irrigated cropland mean plant available water (PAW) decreased in the upper 20 cm soil layer from 105% (1 year) to 64% (30 years) (Figure 14c). In the whole soil horizon (0 – 60 cm) plant available water (θ_a) decreased exponentially ($p < 0.05$) from 221 mm (1 year) to 93 mm (30 years) with a rate constant (k) of -0.016 a^{-1} (Figure 15c). Rainfall, irrigation and lake level rise increased the amount of plant available water. From July to December 2011 (period of heavy rains and lake level increase) monthly plant available water (PAW) increased by 9% (0 – 20 cm), 44% (20 – 40 cm) and 10% (40 – 60 cm) on alluvial pasture (30 year position) (Figure 14a, d, g). During the same period, monthly PAW increased by 28% (0 – 20 cm), 34% (20 – 40 cm) and 36% (40 – 60 cm) on lacustrine cropland (30 year position) (Figure 14c, f, i).

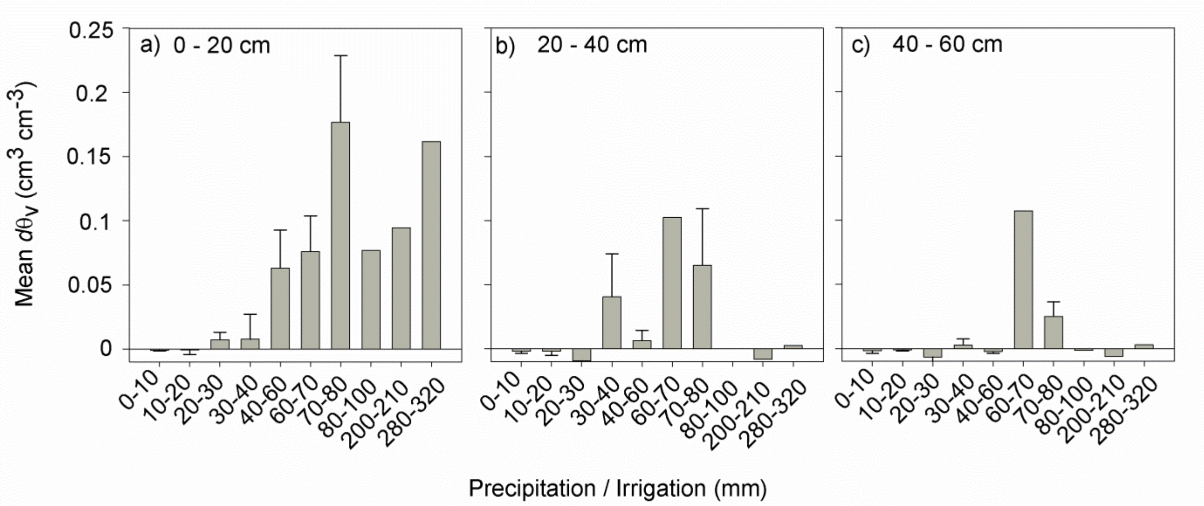


Figure 13. Mean change of volumetric water content ($d\theta_v$) (average of lacustrine pasture, alluvial pasture and lacustrine cropland area, n = 3) in relation to rainfall/irrigation periods (in categories) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth, respectively. Presented are the mean (bars) and standard error (error bars).

4.4. Discussion

4.4.1. Soil water dynamics

The relation between groundwater and lake water level at Lake Naivasha has previously been investigated (Ojiambo *et al.*, 2001, van Oel *et al.*, 2013), and was also confirmed in this study. Additionally, groundwater influenced the soil moisture regime of the littoral wetland, which is in accordance to other wetland types (McLaughlin *et al.*, 2012; Böhme *et al.*, 2013) and on global scale (Fan *et al.*, 2013). Soil water content (θ_G) (0 – 100 cm soil depth) decreased exponentially with increasing land use duration (distance to the lake). While the upper soil layer (0 – 60 cm) of the 1-year positions kept mostly water saturated, the 30-year positions desiccated without irrigation. Capillary rise decreased to a minimum on pastureland (15-year position) until August 2011. We therefore suspect that, groundwater could not supply the upper soil layers from positions ≥ 20 years. That would correspond to a distance to the lake ≥ 745 (163) m (June 2011).

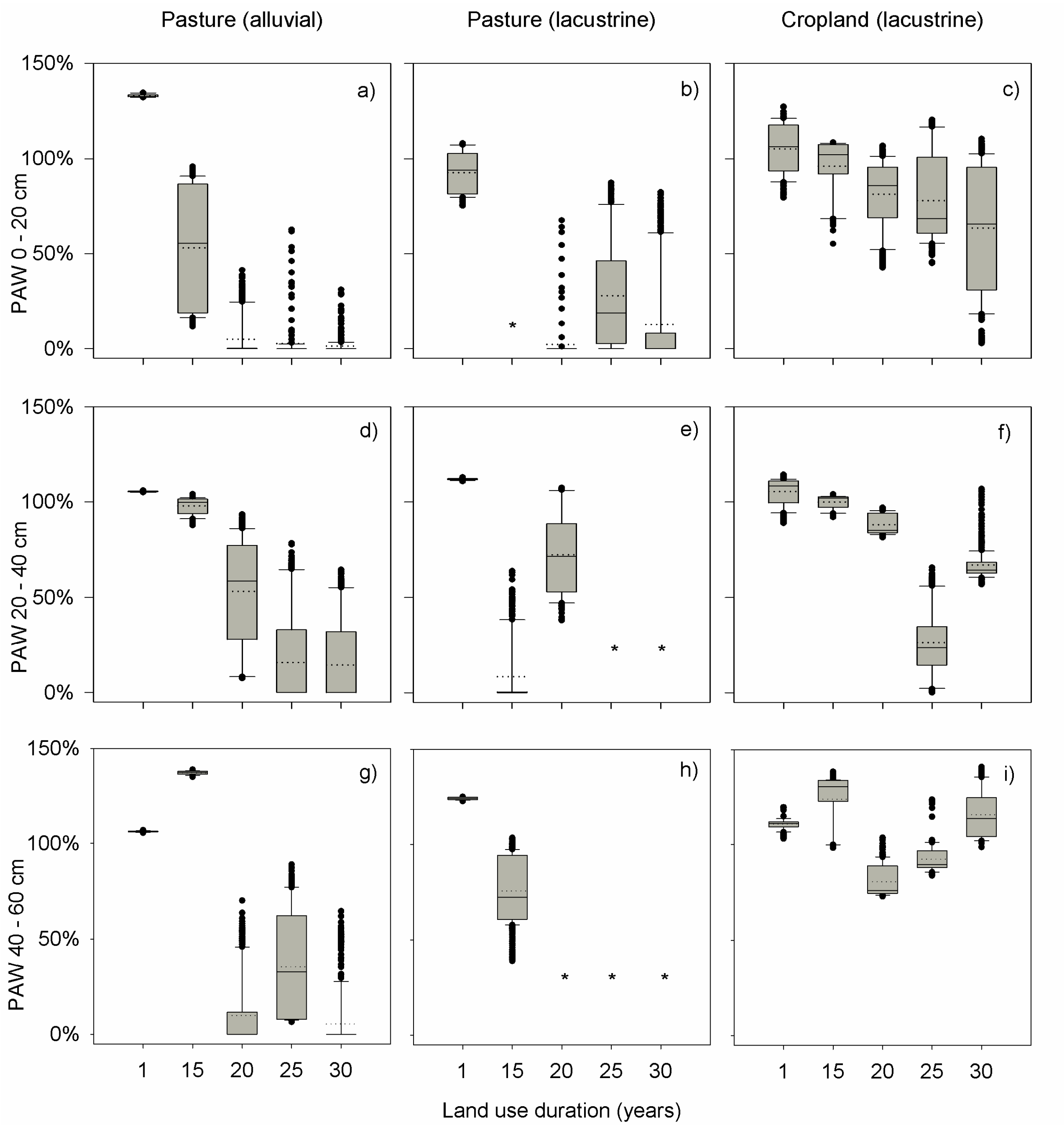


Figure 14. Percent plant available water (PAW) in 0 – 20, 20 – 40 and 40 – 60 cm soil depth and chronosequence position 1 to 30 years on alluvial pasture (a, d, g), lacustrine pasture (b, e, h) and lacustrine cropland (c, f, i) from November 2010 to December 2011. Boxplot present mean (dotted line), median (straight line), 25%/75%-percentiles (box), 10%-/90%-percentiles (error bars) and outliers (dots) (n = 163 – 356). * missing data (sensor blackout, bad readings) or no data

Where soils had no groundwater contact, irrigation or rainfall were the main sources of water supply. A substantial θ_v increase (i.e. ≥ 0.05 cm³ cm^{-3}) in the first 20 cm soil layer would require an amount > 40 mm of precipitation (Figure 13). That is similar to previous findings from a semi-arid Australian floodplain, where 30 – 40 mm rainfall was required to increase θ_v in the first 15 cm by 0.05 cm³ cm^{-3} (Baldwin *et al.*, 2012). However, there was no rainfall period until August 2011, which could have provided such amount of precipitation. That shows the increased dependency on irrigation for plant production. In fact, volumetric water content on lacustrine cropland was higher with less variability under minimum irrigation than on the pasture sites (Figure 12). Water is also the main driver of the wetland biogeochemistry (Sahrawat, 2003). The reduction of volumetric water content affects soil aeration, and thus indirectly influences mineralization processes (Kader *et al.,* 2010). The drainage of wetlands enhances soil mineralization and eventually reduces the amount of soil organic matter (Neue *et al.*, 1997) (see also chapter 5). The nitrogen mineralization is also affected by the water content (Paul *et al.,* 2003), and the remoistening of dry soils increases nitrogen mineralization (Hassink, 1992) (see chapter 6). The rate of nitrogen mineralization reportedly decreased at a water filled pore space > 65% (Sleutel *et al.*, 2008). Such soil water conditions were mainly present at the lake shore (1 year position), in deeper soil layers (partly 15 and 20 year position), and on irrigated sites (data not shown). Older chronosequence positions mostly had a water filled pore space < 65% in all soil layers, and were also exposed for a longer period (see chapter 2), both optimal conditions for enhanced nitrogen and soil organic matter mineralization. The drop of groundwater table and the absence of rain reduced the soil water content of the upper soil layers, and formerly well saturated littoral wetland fringes desiccated. That probably has influenced the biogeochemistry of wetland soils, and influenced plant production.

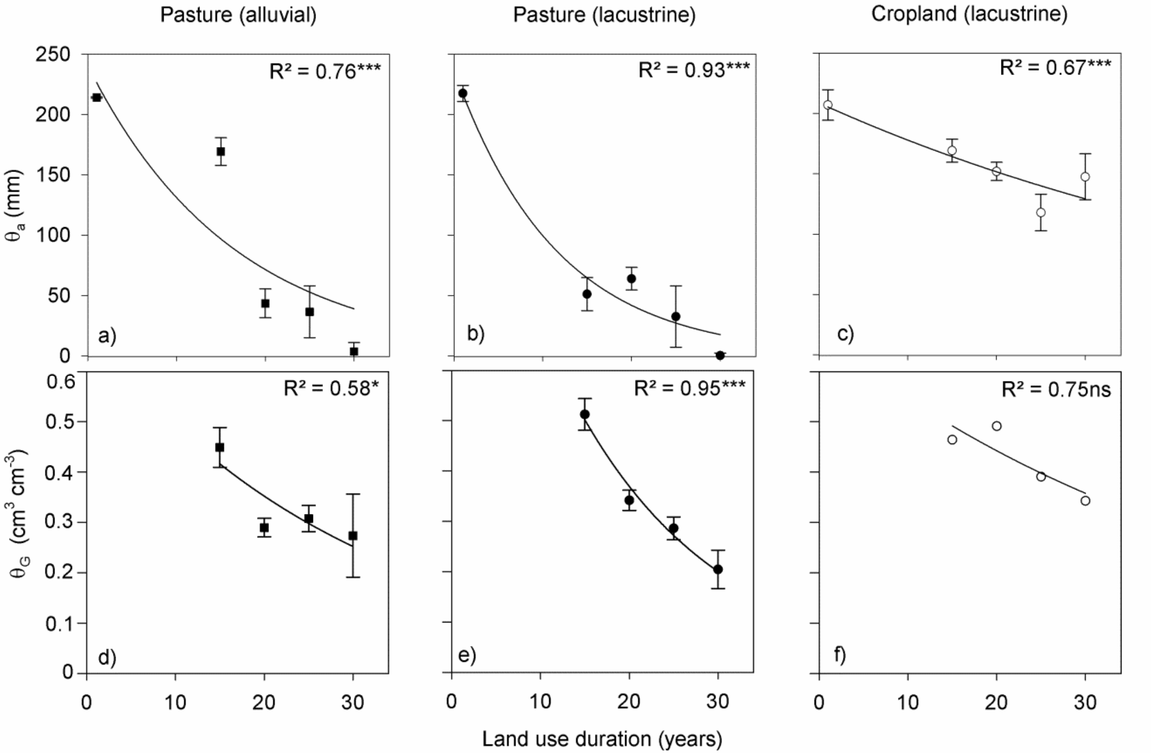


Figure 15. Plant available water (θ_a) (mm day^{-1}) in 0 – 60 cm soil depth and as affected by land use durations of 1 to 30 years on alluvial pasture (n = 119/121) (a), lacustrine pasture (n = 121) (b) and lacustrine cropland (n = 55/121) (c) as well as initial volumetric water content (θ_G) from 0 – 100 cm soil depth (n = 2/1) (d,e,f). Regression analysis uses a first order exponential model ($p < 0.05$). Bars present standard deviations.

4.4.2. Plant available water

The amount of plant available water was severely affected with increasing duration of land use, indicating that rain-fed plant and forage production became less predictable for farmers. Temporarily (November 2010 – August 2011), there was little if any plant available water in the upper 60 cm soil layer on the older pasture positions (i.e. from 20 years). An irrigation scheme of minimum water application could minimize but not fully compensate declines in plant available water on cropland. An increased dependency on irrigation water in periods of lake recession can therefore be expected, especially when the rainfall pattern is irregular distributed (Gaudet and Melack 1981) and evapotranspiration exceeds rainfall with r/Eo of 25% - 40% (Sombroek *et al.,* 1981). However, water use efficiency (31%) from small-scale farmers is low (Njiraini and Guthiga, 2013), and even the technically advanced horticultural flower production at Lake Naivasha requires 7 – 13 liters of water per rose (Mekonnen *et al.*, 2012). Irrigation water is either taken from groundwater seepage to the lake (Ramírez-Hernández*,* 2000), upstream from Malewa River and the catchment (Becht and Harper, 2002) or directly from the lake (own observation). Thus, all irrigation methods decrease the lake water input and increase the pressure on agricultural plant production. Excessive groundwater abstraction in the past caused groundwater drop below lake level (Ramírez-Hernández*,* 2000, van Oel *et al.*, 2013), and the same was observed on the pasture area in this study. On the other hand, the increase of lake level will inundate valuable agricultural land, making plant production a risky enterprise for small-scale farmers. Only a sound water management and irrigation scheme makes plant production sustainable in the littoral wetland. The decrease of soil water content negatively affected the amount of plant available water, endangering plant production and increasing the dependency on irrigation.

4.5. Conclusion

The study of soil moisture dynamics along a 30-year chronosequence of land use at Lake Naivasha highlighted that soil moisture content and the amount of plant available water decreased with distance from the lake shore. The decreasing lake water level resulted in a concomitant decline in groundwater depth and an associated decoupling of the topsoil from capillary water supply from the groundwater. Observed changes with time were more dramatic under pasture than under crop uses. With insufficient rainfall particularly older pastures dried up, while some supplementary irrigation was provided to crops. The production of both forages and crops in the littoral zone of Lake Naivasha is highly limited by soil moisture supply. Productive land use will hence be restricted to moist areas close to the lake or to environments where supplementary water for irrigation can be provided. Additional effect on the biogeochemistry of the littoral wetland can be expected.

5. Soil carbon pool changes along chronosequences of agricultural land use

5.1. Introduction

Wetlands in sub-Saharan Africa are gaining increasing importance as agricultural production areas, particularly for poor rural populations (Rebelo *et al.,* 2010). In East Africa, wetlands have been put under agricultural use, following tillage operations, crop and vegetation removal or topsoil dry off, all of which can affect soil physical and chemical attributes (Kamiri *et al.,* 2013). The wetland soils are not resilient to such pressure (Kamiri *et al.,* 2013), and agricultural activity has been identified as main driver of wetland degradation (Russi *et al.,* 2012). The ability of soil to maintain soil functioning during a period of anthropological or natural event disturbance, i.e., soil resistance (Seybold *et al.,* 1999), has been developed for land management systems with soil organic carbon (SOC) as indicator variable (Herrick and Wander, 1998). Hence, monitoring SOC and of its fractions turnover time like particle-size separates or $KMnO_4$-oxidizable C (Blair *et al.,* 1995) remain one of the most useful approaches also to evaluate soil degradation by different types of land management in drained wetlands. While effects of intensified or extended land use on SOC and SOC fractions are well-described for tropical upland soils (Hartemink, 2006), little information exists on such trends in wetlands other than paddy rice fields (Wissing *et al.,* 2011), swamps and floodplains (Kamiri *et al.,* 2013).

Wetlands in East Africa have been recognized for their agricultural potential since the last decades (Dixon and Wood, 2003), however an improved knowledge of soil resistance in different wetland types and under different management systems is required to assess wetlands' vulnerability (Kamiri *et al.,* 2013). The littoral wetland area of Lake Naivasha is used for small-scale crop production and pastoralism. Due to decreased rainfall and enhanced water abstraction, the lake has been shrinking between 1980 and 2011 (Mekonnen *et al.,* 2012), and the newly exposed land was converted into agricultural areas. This created chronosequences of 0 - 30 years of continuous land use with distance from the lake shore (space-for-time substitution), allowing to study soil carbon trends in a tropical littoral wetland. The Naivasha case provides the additional advantage that both different soil types (formed on either alluvial or lacustrine parent materials) and different land use systems (crop farming and pastures for livestock grazing) can be encountered, thus providing a model case to assess soil resistance under a range of disturbance scenarios. Here we assessed to which degree and how fast the stocks and properties of SOC changed in land being uncovered by the receding lake water level and under different land management and use durations, therewith allowing to elucidate possible factors influencing soil resistance in tropical littoral wetlands.

5.2. Material and Methods

5.2.1. Site Description

The study area lies at 1890 m altitude in the semi-arid Kenyan Rift Valley with 620 mm annual precipitation, comprising pasture (0°43' S, 36°22' E) and cropland (0°44' S, 36°25' E). The pasture land was located at the former North Swamp papyrus stand, near the inflow of Malewa River on the premises of the Kenya Agriculture Research Institute (KARI), while the cropland was situated at the former "North Lagoon" in the small-scale farmers' area at Kihoto on the Northeastern lake shore. The pasture sites are dominated by two grass species; kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and African star grass (*Cynodon plectostachyus*), which settled after the papyrus died back. All grassland areas have been continuously grazed by wildlife and cattle. The cropland sites were continuously used for crop production (mainly maize and diverse vegetables) with little amount of fertilizer application and irrigation. The parent material consists of lacustrine sediments, while at the fringes of Malewa River the parent material is dominated by reddish ferruginous alluvial silt deposits (Clarke *et al.,* 1990). These sites will thereafter be referred to "lacustrine pastures", "alluvial pastures" and "lacustrine cropland", based on differences in parent material and land use. Soils were mollic Fluvisols and haplic Cambisols on lacustrine cropland, gleyic Fluvisols, haplic and gleyic Vertisols on lacustrine pasture and gleyic Vertisols, haplic Gleysols and gleyic Fluvisols on alluvial pasture (IUSS, 2006) (chapter 3).

5.2.2. Experimental setup

Small-scale farmers and pastoralists have continuously converted newly exposed land area after lake level decrease from 1980 to 2011. The ideal position of the lake shore was identified using detailed lake level records and a geodetic GPS (Leica 500 coupled with a Nikon AP-7 Automatic Level). Thereafter, five transects were established, one at lacustrine cropland and two each on lacustrine and alluvial pasture, respectively. Chronosequence positions (durations of land use) of 0, 1, 20, 25 and 30 years (uncovered by the receding lake between the year 2011, 2010, 1990, 1985 and 1980) were identified on each of the three land use situations. The sampling area of each position comprised 400 m^2 on pasture and 150 m^2 on cropland, respectively.

Initial topsoil samples (0 – 15 cm) were taken as composites (n = 5) in three replications at all observation points, following the guidelines of Okalebo *et al.* (2002). The samples comprised the A-horizon on cropland soils and A- and humus-enriched B-horizons on pastureland. First sampling started in November 2010 at chronosequence positions 15 to 30 years. After further lake level decline, the 1 and 0 year position on lacustrine cropland was sampled in

April and June 2011, respectively. All samples were air-dried, sieved to < 2 mm, and stored dry until analysis. Additional five undisturbed bulk samples per observation point were taken with 100 cm^3 metal cans from a depth of 5 – 10 cm for determination of bulk density (BD) after oven-drying at 105°C for 24 h. Soil texture was determined with laser diffraction technique (Retsch LA-950 V2 Horiba).

Additional soil pits of 100 cm depth were opened per position of 1 to 30 years in January and April 2011 for the estimation of initial volumetric soil water content (θ_G) and SOC stocks in 0 – 100 cm. In total, 25 soil pits were opened on lacustrine pasture (10), alluvial pasture (10) and lacustrine cropland (5), respectively. Three bulk core samples from each horizon were taken after an initial identification of soil horizons (FAO, 2006), and bulk density (BD) estimated (oven-dried at 105°C for 24 h).

5.2.3. Soil water content

Initial soil water content (θ_G) in January 2011 was estimated from position 15 to 30 years (1 year sites were not included, as samples were taken in April 2011, where θ_G regimes have already changed at the other positions). The samples were weighed fresh and dry and θ_G from each soil pit was estimated with equation (2) (see chapter 4).

5.2.4. Soil organic carbon

From all soil pits one bulk core sample per horizon was sieved (< 2 mm) and stored for laboratory analysis. Soil (A, B and C) horizon samples of two lacustrine pasture positions (15 and 20 years) got lost during transport, i.e., no chemical analysis is available. Soil subsamples of soil horizons and topsoil (0 – 15 cm) were fine ground with a swing mill (Retsch GmbH, Germany), and analyzed for total carbon content using a CNS Elemental Analyzer (EuroEA 3000; Euro Vector SpA, Milan, Italy). The inorganic carbon content was measured by Scheibler method with air-dried and sieved (< 2 mm) samples, and soil organic carbon (SOC) was the difference between total carbon and inorganic carbon. Topsoil stocks (0 – 15 cm) of organic C (Mg ha^{-1}) were calculated as:

$$SOC = \%SOC * BD * h \qquad (6)$$

whereby: SOC = soil organic carbon stock (Mg ha^{-1}), %SOC = % soil organic carbon, BD = bulk density, h = soil depth (15 cm).

For the estimation of SOC stocks in 0 - 100 cm soil depth a first order exponential regression fit [$f(x) = a * \exp(-b * x)$] was used to describe changes of SOC stocks with profile depth. Input data comprised SOC stocks (g cm^{-3}) per horizon as dependent variable and the corresponding mean soil depth (cm) as independent variable. Thereafter, SOC (Mg ha^{-1}) in 0

– 100 cm soil depth was estimated as the area below the regression line according to the trapezoidal rule (see equation (1) in chapter 3).

5.2.5. Particulate organic matter carbon

Thirty g of topsoil (air-dried, sieved < 2 mm) from representative chronosequence position were physically fractionized according to Amelung and Zech (1999). The soil was dispersed in fractions of > 250 µm (POM1), 250 µm – 53 µm (POM2), 53 µm – 20 µm (POM3), and < 20 µm (non POM, i.e., mineral bound SOM). The soil water suspension (150 ml distilled H_2O) was treated with ultrasound ($E = 60$ J ml^{-1}) (Branson Sonifier, W-250 D, Emerson, Ferguson, Missouri, USA) and afterwards POM1 was retrieved by wet sieving. A second ultrasound treatment ($E = 440$ J ml^{-1}; 300 ml distilled H_2O) of the remaining suspension with subsequent wet-sieving recovered POM2 and POM3. In a final step, non POM was reclaimed from the collected suspension after a pre-treatment with magnesium chloride. All fractions were dried at 40°C – 60°C, weight after drying, and fine ground for analysis. Then, %SOC in each fraction was analyzed using a CNS Elemental Analyzer (EuroEA 3000) after a pre-treatment with hydrochloric acid to eliminate inorganic carbon content. Subsequently, carbon in each fraction (POM C) was estimated by multiplying %SOC with the dry weight proportion.

5.2.6. Permanganate oxidized and non-oxidized carbon

Air-dried and sieved (< 2 mm) topsoil samples with 15 mg of organic carbon content were weighed (0.17 – 1.37 g topsoil) in duplicates. Samples were treated with 25 ml of 33 mM $KMnO_4$ solution and shaken in darkness with an over-head shaker (12 rpm) for 24 h. Thereafter, samples were centrifuged (for 5 minutes; at 2185 rpm), and analyzed colormetrically at 565 nm wavelength with the spectrophotometer (Specord, Analytik Jena AG, Germany) (Blair *et al.,* 1995; Tirol-Padre and Ladha, 2004). Then, permanganate oxidized carbon (POC) was calculated according to Blair *et al.* (1995), and POC (Mg ha^{-1}) was estimated with equation (6). Non-labile carbon (NOC) was calculated as the difference between SOC and POC (Blair *et al.,* 1995).

POC originally referred to the labile carbon (Blair *et al.,* 1995), but the approach has been criticized for the permanganate to react with lignin and aromatic compounds (Tirol-Padre and Ladha, 2004, Skjemstad *et al.,* 2006). To counteract the method limitation, tumbling time was increased to 24 h in this study, which reportedly increases the oxidization of the labile carbon fraction (certain amino acids, sugars and organic acids) (Tirol-Padre and Ladha, 2004).

5.2.7. Statistical Analysis

The space for time approach underlies the premise that time is the most influential factor, while soil variability (as another influential factor) is low (Hartemink, 2006). Lake Naivasha soils have been formed under highly dynamic conditions (Taras-Wahlberg *et al.,* 2002), and soil variability could be expected within the chronosequence transects. Thus, the 1-year chronosequence positions and reference sites on pastureland were subsequently discarded from further analysis because of soil textural changes (Sand: 26% (8%)) compared to the other positions (Sand: 8% (5%)), which may influence SOC content. Further, the 15 year position on cropland was not included in analysis because farmers abandoned the site several times owing to the high soil ph (9.8) (see also chapter 3).

Significance levels of soil organic carbon, carbon fractions (POC, NOC) and bulk density (BD) between chronosequence positions were determined by one-way ANOVA ($p < 0.05$) and means were separated by Tukey Test after testing the normality of data distribution (Kolmogorov-Smirnov Test). Soil resistance was evaluated for SOC using the resistance index (RI) (Herrick and Wander, 1998), where high RI represents strong ability to resist disturbances and vice versa (Seybold *et al.,* 1999):

$$RI = SOC_t / SOC_i \qquad (7)$$

whereby: RI = resistance index, SOC_t = soil organic carbon (Mg ha^{-1}) at time t, SOC_i = initial soil organic carbon (Mg ha^{-1}) (i.e. pastureland: 15-year position; cropland: reference site (0 years)).

SOC dynamics were analyzed using a two parameter exponential decay model: [$SOC_t = SOC_0 * \exp(-k * t)$] (Dalal *et al.,* 2013, Hartemink, 2006). The equation was transformed into a linear function ($y = a + b * x$):

$$\ln(SOC_t) = \ln(SOC_0) - k * t \qquad (8)$$

whereby: k = rate constant (a^{-1}), SOC_0 = initial soil organic carbon (Mg ha^{-1}), SOC_t = soil organic carbon (Mg ha^{-1}) at time t, t = years of land use duration.

Both, the rate constant k and initial SOC_0 can be calculated by plotting $\ln(SOC_t)$ against land use duration t, where k is the slope and SOC_0 is the exponent of the linear function intercept. The rate constant k is a measure of carbon turnover (Dalal *et al.,* 2013). The rate constant k and SOC_0 were calculated for lacustrine pasture, alluvial pasture and lacustrine cropland, respectively. Mean annual decay rate was calculated as $dSOC/dt$. Rate constant k, initial amount (POC_0, NOC_0 and POM C_0) and decay rate was also assessed for POC (Mg ha^{-1}), NOC (Mg ha^{-1}) and POM C (g kg^{-1}). Relations between the POM C/bulk soil SOC proportions and duration of land use and relation between POM C and POC/NOC were analyzed with linear regression analyses ($p < 0.05$). The relation between soil water content and duration of land use was analyzed with Pearson correlation ($p < 0.05$). ANOVA analysis was performed with SPSS 21, while linear regression analysis, correlations and plotting were done using SigmaPlot 11.0 software package.

5.3. Results

5.3.1. Soil organic carbon, bulk density and soil water content

We investigated changes in soil organic carbon (SOC), soil water content (θ_G) and bulk density at all three land use situations. Bulk density on alluvial pasture averaged 0.76 g cm^{-3} and was not affected by land use. In contrast, on lacustrine pastures, bulk density increased from 0.82 g cm^{-3} (15 years) to 1.07 g cm^{-3} (30 year old pasture site). On lacustrine cropland bulk density varied from 0.86 (0 years) to 1.19 g cm^{-3} (30 years), and the 30 year site was most compacted relative to all other sites (Table 6).

With increasing distance to the lake, it was likely that the older sites stored less soil water. And indeed, the soil water content (θ_G) for all three land use situations was significantly and negatively correlated with land use duration (-0.77***; n = 19; Table 6) (see also chapter 4). Along that line, also mean topsoil SOC stocks changed (Figure 16). They declined from 64.4 to 53.5 and from 65.2 to 45.7 Mg ha^{-1} within 15 to 30 years of pasture management on alluvial and lacustrine parent material, respectively, whereas sites of similar duration under arable cropping almost lost the double amount of SOC (Table 6). Fitting an exponential model to the topsoil SOC decline revealed a rate constant k of -0.021 a^{-1} (Table 7) and mean SOC loss of -1.01 Mg ha^{-1} a^{-1} for both pastures combined, and an SOC loss with k = -0.016 a^{-1} at a magnitude of -0.95 Mg ha^{-1} a^{-1} for lacustrine cropland. The Resistance Index (RI) was thus 0.48 for lacustrine cropland (comprising 30 years of land use) and 0.70 and 0.83 for lacustrine and alluvial pasture (comprising 15 years of land use), respectively, overall suggesting that the type of parent material had only minor impact on SOC decline rates. Assuming that both land-use systems degraded with an exponential SOC decline, we even could not detect clear land-use effects on soil degradation in the littoral of these tropical wetlands.

Table 6. Mean soil organic carbon content (SOC) and gravimetrically measured volumetric water content (θ_G) (0 – 100 cm) and topsoil soil organic carbon content (SOC), permanganate oxidized (POC) and non-oxidized (NOC) carbon as well as bulk density (BD) from chronosequence position 0 to 30 years on alluvial pasture, lacustrine pasture, and lacustrine cropland. Standard deviations are presented in brackets. Data points with the same letter do not differ significantly by one-way ANOVA and Tukey Test ($p < 0.05$). * Chronosequence position not included in analysis.

Site	Land use Duration	θ_G (0 – 100 cm) ($cm^3\ cm^{-3}$)	SOC (0 – 100 cm) ($Mg\ ha^{-1}$)	SOC (0 – 15 cm) ($Mg\ ha^{-1}$)	POC (0 – 15 cm) ($Mg\ ha^{-1}$)	NOC (0 – 15 cm) ($Mg\ ha^{-1}$)	BD (5 – 10 cm) ($g\ cm^{-3}$)
Pasture (alluvial)	0*	nd	nd	51.8	13.5	38.4	1.11 (0.09)
	1*	nd	141.4 (58.4)	68.2 (16.7)	18.4 (4.8)	49.8 (11.9)	1.05 (0.19)
	15	0.45 (0.04)	180.3 (50.8)	64.4 (17.6)ab	15.9 (4.8)a	48.5 (13.7)ab	0.72 (0.06)ns
	20	0.29 (0.02)	222.4 (113.8)	78.4 (12.0)b	21.1 (3.8)b	57.3 (8.4)b	0.70 (0.07)ns
	25	0.31 (0.03)	185.0 (47.3)	55.9 (10.4)a	14.4 (4.6)a	41.5 (6.0)a	0.81 (0.10)ns
	30	0.27 (0.08)	145.8 (51.4)	53.5 (6.7)a	12.7 (1.5)a	40.8 (5.4)a	0.81 (0.15)ns
Pasture (lacustrine)	0*	nd	nd	26.5	6.4	20.1	1.24 (0.04)
	1*	nd	39.9 (5.4)	32.8 (6.6)	7.2 (1.6)	25.6 (5.2)	1.09 (0.12)
	15	0.51 (0.03)	110.8	65.2 (10.0)ab	18.6 (3.9)a	46.6 (6.3)a	0.82 (0.11)a
	20	0.34 (0.02)	120.1	71.1 (13.8)b	19.7 (3.6)ab	51.4 (10.5)a	0.98 (0.09)b
	25	0.29 (0.02)	97.1 (30.8)	56.2 (3.6)ac	13.9 (1.5)bc	42.4 (3.2)b	1.02 (0.10)b
	30	0.20 (0.04)	87.7 (14.0)	45.7 (1.4)c	11.4 (1.2)c	34.4 (1.0)b	1.07 (0.07)b
Cropland (lacustrine)	0	nd	nd	55.6	16.9	38.7	0.86 (0.05)a
	1	nd	54.0	40.7 (2.7)a	9.0 (0.3)a	31.7 (2.4)a	0.97 (0.04)b
	15*	0.46	78.7	23.7 (4.8)	4.1 (0.7)	19.5 (4.4)	1.13 (0.13)
	20	0.49	106.5	33.4 (1.9)ab	8.0 (0.5)b	25.4 (1.4)ab	1.02 (0.02)bc
	25	0.39	55.8	31.7 (3.1)b	7.3 (0.7)b	24.4 (2.5)b	1.07 (0.04)c
	30	0.34	76.6	26.9 (3.4)b	6.0 (0.3)c	21.0 (3.3)c	1.19 (0.03)d

SOC = soil organic carbon, POC = permanganate oxidized carbon, NOC = non-oxidized carbon, BD = bulk density, θ_G = gravimetrically measured volumetric soil water content, nd = no data.

Table 7. Linear regression analysis between the logarithmical values of topsoil soil organic carbon (SOC), permanganate oxidized (POC) and non-oxidized (NOC) carbon (dependent variable) and duration of land use (independent variable) for alluvial pasture, lacustrine pasture, a combined model of both pasture types and lacustrine cropland, respectively. Presented are the rate constant k, estimated initial soil carbon pools (SOC$_0$, POC$_0$, and NOC$_0$), the coefficient of determination R^2 and sample size n.

Site	*dt* (a)	SOC (Mg ha^{-1})				POC (Mg ha^{-1})			
		k (a^{-1})	SOC$_0$ (Mg ha^{-1})	R^2	n	k (a^{-1})	POC$_0$ (Mg ha^{-1})	R^2	n
Pasture (lacustrine)	15-30	-0.025	102.6	0.49***	24	-0.036	34.1	0.57***	24
Pasture (alluvial)	15-30	-0.016	88.8	0.16ns	24	-0.019	23.8	0.14ns	24
Pasture (both)	15-30	-0.021	95.5	0.28***	48	-0.028	28.5	0.31***	48
Cropland (lacustrine)	0-30	-0.016	45.0	0.76***	13	-0.018	10.9	0.63**	13
		NOC (Mg ha^{-1})							
	dt (a)	k (a^{-1})	NOC$_0$ (Mg ha^{-1})	R^2	n				
Pasture (lacustrine)	15-30	-0.021	69.5	0.41**	24				
Pasture (alluvial)	15-30	-0.015	64.7	0.15ns	24				
Pasture (both)	15-30	-0.018	67.0	0.25***	48				
Cropland (lacustrine)	0-30	-0.015	33.9	0.77***	13				

SOC = soil organic carbon, POC = permanganate oxidized carbon, NOC = non oxidized carbon, k = rate constant, *dt* = time span of land use,* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant.

The SOC stocks in 0 – 100 cm were higher on alluvial sediments with maximum of 303 Mg ha^{-1} than in lacustrine pasture or cropland soils with maximum of 120 and 106 Mg ha^{-1} (Table 6, see also Figure 6 and Figure 7 in chapter 3). Overall, 56% (± 15%) of total SOC was stored in the subsoil, with exceptions at the recent 1-yr sites, of which the pastures were already identified as outliers (see Methods section), storing less than 32% (± 17%) of total SOC in the subsoil. Fitting an exponential model to total SOC stocks (0 – 100 cm) or subsoil SOC stocks (15 – 100 cm) and duration of land use was not significant at all three land use situations (not presented), reflecting that land-use and drainage effects did not develop into the deeper, heterogeneous subsoil.

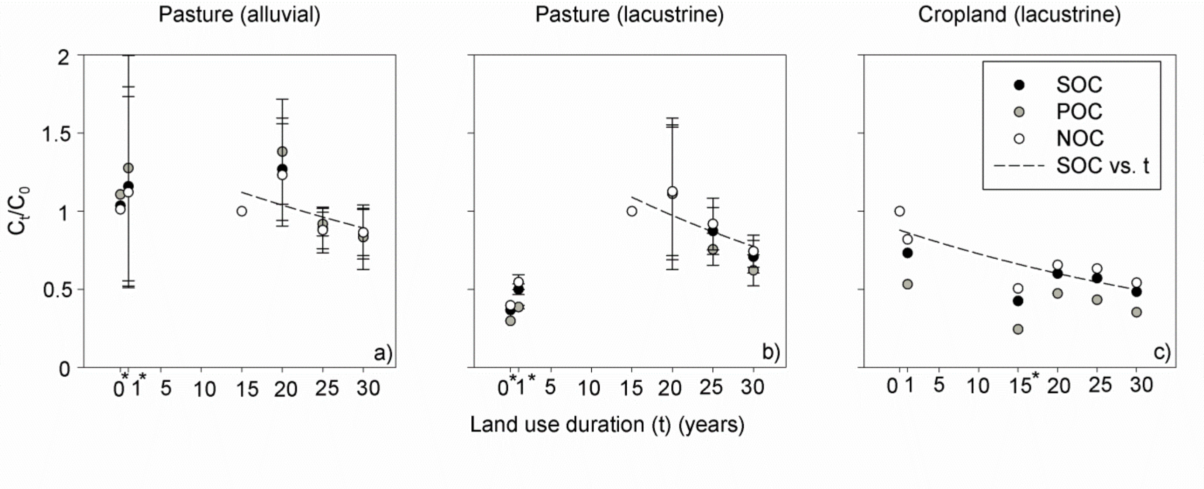


Figure 16. Relative decline (C_t/C_0) of topsoil soil organic carbon (SOC), permanganate oxidized (POC) and non-oxidized (NOC) carbon, and regression line of soil organic carbon against duration of land use (t) (here: using the mean values of n = 8 for pastures and n = 5 for cropland) on all three land use situations along the chronosequence positions 0 – 30 years. Note that initial carbon value (C_0) is the 15-year position on pastureland, and the reference site (0 years) on cropland. Bars represent standard deviations. * Chronosequence position not included in analysis, because of atypical soil properties or land management practice (see Material and Methods section).

5.3.2. Carbon in particulate organic matter

To better understand the mechanisms of SOC losses, we fractionated SOM according to particle size and chemical oxidizability. The SOC shares in particulate organic matter (POM) decreased in the order non POM C > POM1 C > POM3 C > POM2 C, making up 72%, 11%, 10% and 7% of total bulk SOC, respectively, with little if any variations among land-use systems and parent materials (Figure 17). However, the proportion of C stored in non POM was positively (0.76***, n = 14), those of POM2-C (-0.60*, n = 14) and POM3-C/bulk SOC (-0.75***, n = 14) were negatively related to increasing land use duration (Figure 17), i.e., SOC losses occurred indeed primarily from the more labile C pools. A first order exponential model was significant for the POM1 C (lacustrine pasture and cropland) and the non POM C fraction (lacustrine and alluvial pasture). Thereby, the POM1 C rate constant was -0.058 and

-0.040 a^{-1} on lacustrine pasture and cropland, while the POM4 rate constant was -0.038 and -0.039 a^{-1} on lacustrine and alluvial pasture, respectively (Table 8).

5.3.3. Permanganate oxidized and non-oxidized carbon

Both the mean stocks of POC and NOC declined with increasing duration of land use (Figure 16, Table 6). Mean POC stocks ranged from 11.4 to 21.1 Mg ha^{-1}, while mean NOC stocks were larger and ranged from 34.4 to 57.3 Mg ha^{-1} on the alluvial and lacustrine pasture land (15 to 30 years), respectively (Table 6). Hence, and similar to bulk SOC and the POM fractions, the rate constants of POC and NOC did not differ between lacustrine and alluvial pastures. A combined first order exponential model was highly significant (Table 7), and revealed a mean loss rate (dSOC/dt) of -0.35 and -0.67 Mg ha^{-1} a^{-1} for POC and NOC, respectively. The arable sites had again lower POC and NOC stocks (Table 6), in line with their lower SOC values (see above), and the rate constants k and decline rates were in similar magnitude as for the pastures (POC: -0.36 Mg ha^{-1} a^{-1}; NOC: -0.59 Mg ha^{-1} a^{-1}). Overall, the portion of total SOC that was lost by chemical oxidation averaged 25% ± 3% for the pasture systems and 22% ± 3% for the cropland systems, supporting the results above that there were only little if any differences between land-use systems on overall SOC loss rates. However, there was a highly significant relation between POM C > 250 µm fractions (POM1 + POM2 + POM3) to POC as well as between the contents of non POM C (< 20 µm) to NOC (Figure 18), thus giving support to the idea that both the C pools isolated by physical fractionation and those characterized by chemical oxidation were causally related.

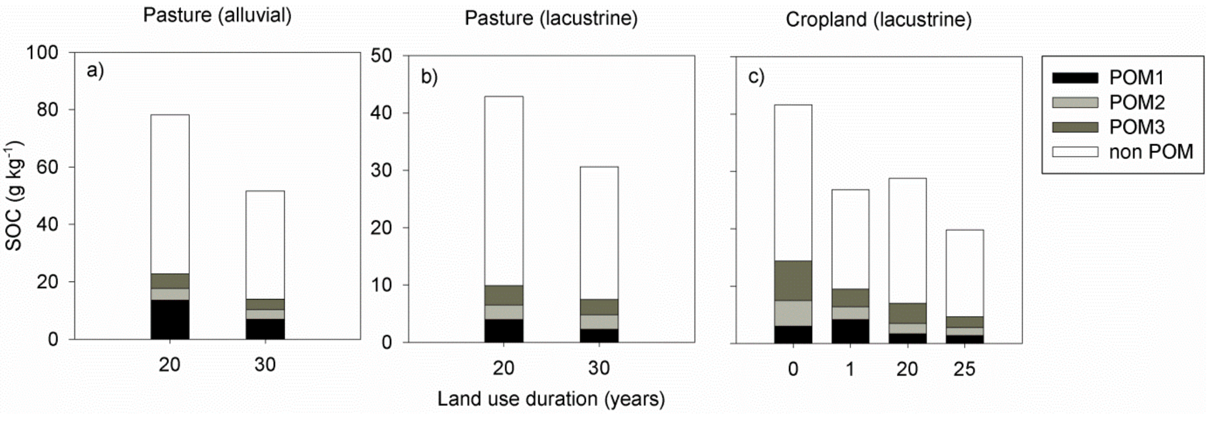


Figure 17. Soil organic carbon content (SOC) (g kg^{-1}) subdivided in four particle size fractions (POM): POM1 (>250 µm), POM2 (250– 53 µm), POM3 (53– 20 µm) and non POM (< 20 µm) of chronosequence position 20 and 30 years on alluvial pasture (a) and lacustrine pasture (b), and position 0 – 25 years on lacustrine cropland (c), respectively.

5.4. Discussion

5.4.1. Bulk density

Bulk density changes are common when switching from natural vegetation to arable land use. Here, on the lacustrine cropland, bulk density increased shortly after land conversion and the 30-year site was most affected, due to tillage and subsequent loss of soil structure and SOM (Dalal and Mayer, 1986). In contrast, the bulk densities of the pasture land were hardly affected, thus questioning soil compaction as major driver of soil degradation as commonly observed in other ecosystems due to overgrazing (Kotzé *et al.,* 2013).

5.4.2. Soil organic carbon with respect to soil water content

This study focused mostly on topsoil attributes as the A-horizon was affected most by the water level recession and anthropogenic disturbances. While the stocks of SOC decreased exponentially in 0 – 15 cm soil depth, no such trend could be observed for the whole 0 – 100 cm profile. The SOC stocks in deeper soil layers are more likely connected to pedogenetic processes, which again were reflected in changing reference soil groups (RGB) along the chronosequence.

A reduction in SOC stocks occurs when decomposition exceeds the accumulation of organic carbon (Neue *et al.,* 1997). In principle, tropical wetlands are carbon sinks due to high net primary productivity of wetland vegetation and low decomposition rates of plant debris (Sahrawat, 2003). Here, probably both mechanisms have been affected during continuous land use at Lake Naivasha. The SOC stocks decreased with continuous cultivation time at all three land use situations (Table 6). Thereby, as in other ecosystems, soils could not resist anthropogenic disturbance. Intriguingly the rate constants of SOC losses were similar between sites of different parent material or land use systems, yet, covering different time intervals on pasture and cropland (Table 7). Such finding reveals that other factors than land use was major drivers of SOC losses. The rate constants are similar in magnitude to those observed on Australian upland arable soils in a similar agro ecosystem after 23 years of cultivation, but turnover rates on respective pasture was lower (Dalal *et al.,* 2013) than in the Naivasha case. Clearly, the abundance of water is one of the most influential factors on the biogeochemistry of wetland soils (Sahrawat, 2003). The drainage of soils and reduction of soil water contents with increasing duration of land use in the littoral wetland area resulted in water unsaturated soils, especially at the older chronosequence positions. There, aerobic conditions now probably accelerated organic matter decomposition. Overall, the soil moisture regime along the chronosequence changed from aquic until aridic according to observed volumetric water content (θ_V) trends from November 2010 until August 2011 (see chapter 4).

As a result, the final SOC loss rates were comparable to reports on rapid SOC losses induced by upland cropping in other study areas (e.g. Dalal and Mayer, 1986; Lobe *et al.,* 2001). We thus conclude that soil aeration was one of the main drivers for wetland degradation.

The results show some similarites to other East African lowlands and mid-hill wetlands, which exhibited similar SOC stocks in drained pasture and cropland, though lower than under flooded natural vegetation (Kamiri *et al.,* 2013). Furthermore, under flooded conditions soil organic C accumulate as, e.g. previously reported for paddy rice systems (Wissing *et al.,* 2011). The latter aspect has also been observed in the former Lake Naivasha North Swamp, which had accumulated plant debris to such a degree that a peat layer had formed below the floating papyrus mats (Gaudet, 1979). However, with decreasing lake level, the detritus decomposed under the aerobic conditions, changing this Lake Naivasha papyrus swamp from a carbon sink to a carbon source (Jones and Humphries, 2002). Similar trends have also been observed for Lake Victoria after land conversion (Saunders *et al.,* 2012). Land conversion to pasture and cropland has probably lowered also net primary production of the littoral wetland area, but that aspect relies only on previous studies: The annual production of the former Lake Naivasha papyrus swamp was estimated to 5110 g C m^{-2} a^{-1} (Muthuri *et al.,* 1989). In comparison, savanna vegetation has a net primary production < 400 g C m^{-2} a^{-1} (Neue *et al.,* 1997). The overall SOC stocks were higher on pasture and on alluvial sediments, probably the consequence of former organic matter accumulation from papyrus vegetation in the North Swamp area (Gaudet, 1979) and sediment inflow from Malewa River (Taras-Wahlberg *et al.,* 2002) (chapter 3). Nevertheless, this elevated SOC content in the littoral wetland area could not be maintained with prolonged land use and soil drainage, implying that soils were not resistant to anthropogenic influence, irrespective of parent material and of land use system.

5.4.3. Carbon in particulate organic matter

The turnover of SOC depends, among others, on the physico-chemical protection of carbon within the soil mineral matrix and the chemical recalcitrance of the carbon compounds (von Lützow *et al.,* 2007). Accordingly, SOC can be categorized as ‘labile’ and ‘stable’. The labile fraction is rapidly degraded with higher turnover rates, while the stable fraction can last for decades to centuries in soils (Parton *et al.,* 1987). Here, POM C > 250 µm is considered to be hardly protected from decomposition (POM1 C), 250 – 53 µm (POM2 C), may already partly be occluded in aggregates to a higher degree and inlcudes POM at higher degree of decomposition, POM C < 53 µm (POM3 C), may still contain fine POM materials, whereas non POM usually consists of silt- and clay- asociated, microbial residues and stabilized carbon (Amelung *et al.,* 1998). There are certainly transitions, as labile carbon products have also been found in smaller carbon fractions (Kader *et al.,* 2010). Nevertheless, SOC turnover usually increases in the order clay- and silt-associated C < POM2-C < POM1-C (Lobe *et al.,* 2001). In the Naivasha wetland, most carbon was found as non POM (Figure 17), indicating the importance of organo-mineral interactions that usually respond slowly to land use change. However, here the contents of all POM C fractions decreased with increasing land use duration, and again irrespective of parent material and land use (Figure 17). The SOC in POM1 was lost faster than that in non POM, indeed, reflecting that SOC in non POM was more stable than that of other POM pools. As a result, also the portion of SOC associated with non POM (in percent of total SOC) increased with increasing overall SOM decline.

Table 8. Linear regression analysis between duration of land use (independent variable) and the logarithmical values of topsoil carbon content in the particulate organic matter (POM) fractions: POM1 (> 250 µm), POM2 (250– 53 µm), POM3 (53– 20 µm) and non POM (< 20 µm) (dependent variables). Analysis includes sites on lacustrine cropland, alluvial pasture and lacustrine pasture. Presented are the rate constant k, estimated initial soil carbon pools (POM_0), coefficient of determination R^2 and sample size n.

Site		POM1 C (g kg^{-1})				POM2 C (g kg^{-1})			
	dt (a)	k (a^{-1})	POM1 C_0 (g kg^{-1})	R^2	n	k (a^{-1})	POM2 C_0 (g kg^{-1})	R^2	n
Pasture (lacustrine)	20-30	-0.058	12.9	0.96*	4	-0.022	4.1	0.14ns	4
Pasture (alluvial)	20-30	-0.071	58.1	0.88ns	4	-0.025	6.9	0.79ns	4
Cropland (lacustrine)	0-25	-0.040	3.9	0.81*	6	-0.028	3.0	0.64ns	6
		POM3 C (g kg^{-1})				non POM C (g kg^{-1})			
	dt (a)	k (a^{-1})	POM3 C_0 (g kg^{-1})	R^2	n	k (a^{-1})	non POM C_0 (g kg^{-1})	R^2	n
Pasture (lacustrine)	20-30	-0.032	6.7	0.56ns	4	-0.038	71.2	0.92*	4
Pasture (alluvial)	20-30	-0.039	11.7	0.41ns	4	-0.039	120.2	0.98*	4
Cropland (lacustrine)	0-25	-0.028	4.3	0.50ns	6	-0.009	20.7	0.23ns	6

POM = particulate organic matter, k = rate constant, *dt* = time span of land use,* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant.

5.4.4. Permanganate oxidized and non-oxidized carbon

Chemical oxidation, i.e. POC, has been successfully used to analyze C pool dynamics after land conversion (Blair *et al.,* 1995, Lobe *et al.,* 2011), and differences in soil carbon due to land management or environmental factors (Culman *et al.,* 2012). Especially the reduction of NOC is difficult to rehabilitate – and, thus, it is an indicator for soil resistance. Here, the contents of both POC and NOC declined with increasing time after wetland conversion (Table 6), though NOC proved to be more stable than POC. The strong reduction of POC after land conversion on cropland is probably connected to the decline of easily mineralized carbon and lignin in the soil. On arable land, SOC inputs from crop residues are typically low in lignin, and POC is likely to react sensitive to such land use changes (Skjemstad *et al.,* 2006). On South African arable uplands, NOC and POC decreased below 60% and 40% after ~ 30 years of land use, suggesting that easy mineralized lignin compounds are more likely to degrade by continuous cropping (Lobe *et al.,* 2011). The NOC decay is probably related to the stable carbon fraction and is an indicator that littoral wetland soils were not resistant to land use changes, while the reduction of POC probably indicates the decay of easy mineralized carbon and lignin compounds. There is a common understanding that the permanganate oxidation method is less sensitive for assessing labile carbon pools than physical fractionation, however, there are some relationships between both methods (Skjemstad *et al.,* 2006). In the Naivasha case, the POC content was related to POM C fractions with sizes of > 20 µm (POM1-3) while NOC was related to POM fractions < 20 µm (non POM), and this with an intercept near zero and a gradient near one (Figure 18). The finding indicates that chemically and physically separated carbon fractions can be causally linked. Previous studies found similar relations between POC and POM C with a particle size of > 53 µm (Skjemstad *et al.,* 2006) and 250 µm – 53 µm (Culman *et al.,* 2012). The significant correlation of chemically oxidized and physically fractionized carbon probably derives from the distribution of lignin among particle-size separates. Several findings suggest that lignin does not necessarily contribute to the stable carbon pool (Amelung *et al.,* 1996, Thevenot, 2010), and sand-bound lignin fractions had reportedly faster turnover rates than clay-bound lignin (Lobe *et al.,* 2002). Apparently, the permanganate method succeeded here in subdividing POC as a fraction of labile carbon, and NOC, definitely referring to the stable carbon pool. Additional contributions to the lignin behavior on land use change can be expected.

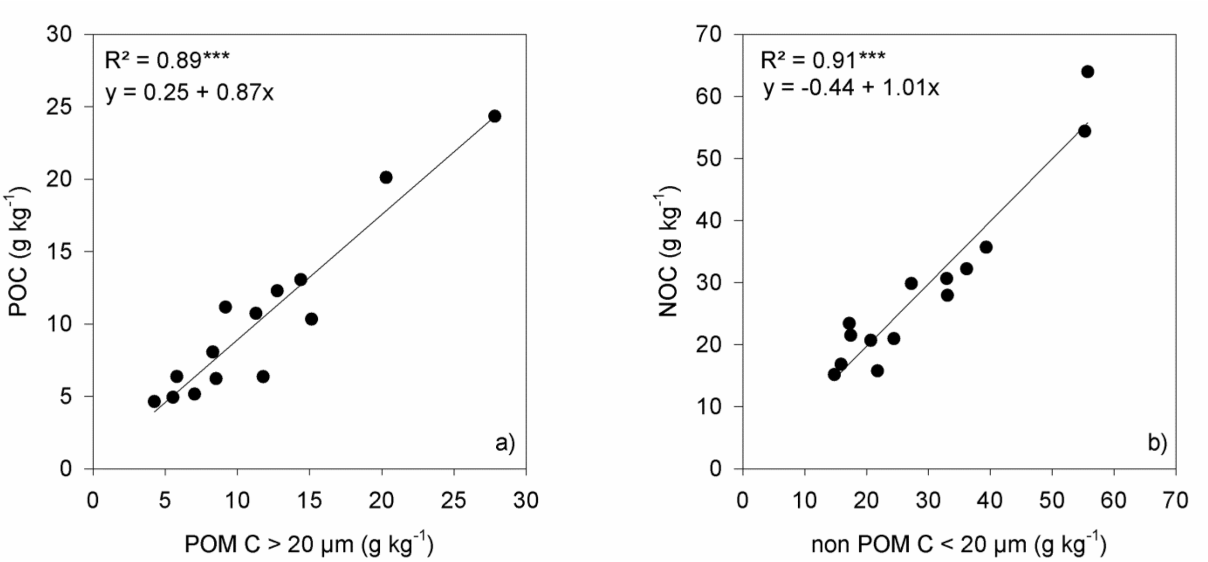


Figure 18. Linear regression analysis ($p < 0.05$) of a) POM C > 20 µm (POM1 + POM2 + POM3; g kg^{-1}) to POC (g kg^{-1}) and b) non POM C (< 20 µm; g kg^{-1}) to NOC (g kg^{-1}) combining soils from alluvial pasture, lacustrine pasture and lacustrine cropland, respectively (n = 14).

5.5. Conclusion

The decay of soil organic matter with increasing land use duration was evident in both the stable and labile carbon pools, and irrespective of parent material and land use system, reflecting the effect of increased soil aeration with increased duration of land use. In periods of lake recession, Lake Naivasha littoral wetland soils are thus not resistant to agricultural land use changes, and topsoil degradation may severely threaten the sustainability of wetland use in the long-term.

6. Soil nutrient and plant biomass changes along chronosequences of land use

6.1. Introduction

In Sub-Saharan Africa, wetlands are important agricultural areas for both farmers and pastoralists. However, the abstraction of irrigation water and the over-use of soil resources threaten the continuance of wetlands as production sites (Mitchell, 2013). Especially the seasonally flooded wetland fringes are continuously claimed for crop production, following the clearing of the (semi-)natural vegetation and the construction of drainage canals (Dam *et al.,* 2013). Lake Naivasha is a freshwater lake located in a semi-arid zone of the Kenyan Rift Valley. The presence of freshwater in a semi-arid environment combined with easy physical access and proximity to the market made the littoral wetlands of Lake Naivasha a hotspot of diverse agricultural activities, including horti- and floricultural agro-industry, small-scale food crop production and cattle grazing during the dry season. While the lake level has been strongly fluctuating during the past centuries (Verschuren *et al.,* 2000), an accelerated and continuous decline has been observed between 1980 and 2011, which was ascribed to water abstraction for agricultural irrigation and domestic purposes (Becht and Harper, 2002; Mekonnen *et al.,* 2012). During this period, the land that has been newly exposed by the recession of the lake water was continuously put under agricultural uses, creating chronosequences or transects of increasing land use duration with distance from the lake shore. The littoral swamp at the northern lake shore, which had formerly been dominated by *Cyperus papyrus*, has been converted into grazing land for cattle and wildlife, while the land along the eastern shore has been claimed by small-scale farmers for continuous cultivation of (irrigated) maize and vegetables. While the eastern and north-eastern shore area is dominated of lacustrine sediments, the grasslands along the northern shore comprise soils derived from alluvial deposits (Clarke *et al.,* 1990). The consequences of extended use duration as pasture land or for small-scale agriculture are largely unknown. Previous studies on the impact of the receding lake levels largely disregarded soil attribute changes and rather focused on performance attributes of the papyrus stands (Harper, 1992; Boar *et al.,* 1999). While drainage and intensified cropping of floodplains and inland valley swamps in East Africa is reportedly associated with severe declines in soil N and C and negative crop responses (Kamiri *et al.,* 2013), there is no available information on littoral wetlands and on non-crop uses. The chronosequences at Lake Naivasha offer the possibility to study such trends in a tropical littoral wetland with both crop and pasture uses and with soils formed from different substrates, and may thus serve as a model to analyze nutrient dynamics and agricultural performance responses to increasing wetland use intensity. We assessed the effects of land use type (cropped fields and pasture land), land use duration (0 - 30 years of continuous use), and soil (formed from alluvial and lacustrine sediments) on changes in selected soil attributes and crop performance parameters to answer the following questions: (1) how do soil parameters in littoral wetlands change under continuous land use? And (2) how are food crop and pasture plants affected by soil attribute changes?

6.2. Material and Methods

6.2.1. Site Description

The study area is located at 0°43' S and 36°22' E in the Kenyan Rift valley at about 1890 masl altitude with a mean annual precipitation of 620 mm. The two dominant soil-based agricultural land uses comprise pastures for cattle grazing and small-scale food crop production. The land under pasture use is predominantly found along the northern lake fringe, near the inflow of Malewa River into Lake Naivasha. The area was previously dominated by dense stands of *Cyperus papyrus* and is now mostly located within the premises of the Kenya Agriculture Research Institute (KARI). The area is being grazed by game and cattle and the vegetation on the drier parts of the littoral area is dominated by kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and African star grass (*Cynodon plectostachyus*). Around the mouth of Malewa River, the base parent material of lacustrine sediments is overlain by alluvial deposits of grayish brown silt and reddish brown ferruginous coarse sand or gravel (Clarke *et al.,* 1990). The influence of these alluvial deposits diminishes towards the easter shore and the cropland area. The cropland is largely concentrated along the eastern lake shore around the Kihoto settlement. The croplands are regularly tilled for vegetable and maize production, and crops receive small amounts of mineral or organic fertilizer applications as well as occasional irrigation. Based on the differences in the parent material the sites will thereafter be referred to either “alluvial” or “lacustrine” and the land uses are differentiated as “pasture” or “cropland”. Soils were identified as mollic Fluvisols and haplic Cambisols on lacustrine cropland, as gleyic Fluvisols, and haplic Vertisols on lacustrine pasture and as gleyic Vertisols and haplic Gleysols on alluvial pasture (IUSS, 2006) (chapter 3).

6.2.2. Experimental setup

With continued lake level declines between 1980 and 2011, the newly exposed land areas have been gradually put under agricultural uses by both pastoralists and small-scale farmers. Based on detailed lake level records since 1980, we identified the position of the lake shore in 1980, 1985, 1990, 1995 and 2010 using a geodetic GPS (Leica 500 coupled with a Nikon AP-7 Automatic Level). In each of the three land use situations (lacustrine cropland, lacustrine and alluvial pasture) these positions represent transects of chronosequence positions (durations of land use) of 1, 15, 20, 25 and 30 years. Five such transects were established (two on lacustrine pasture, two on alluvial pasture and one on lacustrine cropland). After further lake level recession in 2011, we included a reference site at each of the three land use situations (0 years). The identified chronosequences were used for an analysis of the effects of land use duration on nutrient dynamics and agricultural production. Initial soil samples were taken from all chronosequence positions and on both pasture and cropland between November 2010 and June 2011, for both physic-chemical analyses and for the greenhouse experiment using potted soil.

6.2.3. Soil sampling and analysis

This study focuses only on topsoil attributes as the A-horizon is most affected by the water level recession and anthropogenic disturbances such as tillage operations. Initial topsoil samples (0 – 15 cm) were taken at the onset of the study as composites ($n = 5$) in three replications at twenty-five observation points (five transect lines with five chronosequence positions, each), and one additional composite sample in 2011 on the reference sites (0 years). The samples were air-dried, sieved to < 2 mm, and stored until analysis. Five undisturbed bulk samples per observation point were taken with 100 cm^3 metal cans from a depth of 5 – 10 cm for determination of bulk density after oven-drying at 105°C for 24 h. Soil texture was determined with laser diffraction technique (Retsch LA-950 V2 Horiba).

6.2.4. Soil nitrogen and N supplying capacity

Soil subsamples were analyzed for total N using a CNS Elemental Analyzer (EuroEA 3000; Euro Vector SpA, Milan, Italy). The subsamples were fine ground with a swing mill (Retsch GmbH, Germany). Soil stocks of total N (Mg ha^{-1}) was calculated as:

$$N = \%N * BD * h \qquad (9)$$

whereby: N = total N content (Mg ha^{-1}); BD = bulk density (g cm^{-3}); h = soil depth (15 cm).

Ammonium mineralization potential (N supplying capacity) was quantified according to the anaerobic incubation method of Keeney and Nelson (1982). Five g of air-dried and sieved soil were incubated in 50 ml plastic vessels with 12.5 ml of distilled water in a dry oven at 30° C (± 1°C) for one and eight days. After incubation, 12.5 ml of 0.1 M K_2SO_4 was added and samples were shaken for 1 h on a horizontal shaker. The filtered solution was analyzed for NH_4-N with continuous flow analyzer (Multitest MT 7, Bran + Luebbe, Norderstedt, Germany), and the mineralizable NH_4-N was calculated as:

$$\text{Net } NH_4\text{-}N = (NH_4\text{-}N_{8d} - NH_4\text{-}N_{1d}) * v / m \qquad (10)$$

whereby: Net NH_4-N = NH_4-N Net-Mineralization (mg $kg^{-1}week^{-1}$); NH_4-N_{8d}= the mineralized ammonium after 8 days (mg L^{-1}); NH_4-N_{1d} = the mineralized ammonium after 1 day (mg L^{-1}); v = extract volume (25 ml); m = soil sample mass (0.005 kg).

6.2.5. Soil organic carbon

Soil subsamples were analyzed for total C with CNS Elemental Analyzer (EuroEA 3000). Inorganic carbon content was analyzed with Scheibler method and soil organic carbon (g kg^{-1}) (SOC) was calculated as total C – inorganic carbon. Soil subsamples from selected chronosequence positions were fractionized according to Amelung and Zech (1999) in particulate organic matter (POM) fractions of > 250 µm (POM1), 250 – 53 µm (POM2), 53 – 20 µm (POM3), and < 20 µm (non POM, i.e. mineral bound carbon). All fractions were dried at 40°C – 60°C, weight after drying, and fine ground for analysis. Then, SOC in each fraction was analyzed using a CNS Elemental Analyzer (EuroEA 3000) after a pre-treatment with hydrochloric acid to eliminate inorganic carbon content. Subsequently, POM C was estimated by multiplying SOC with the dry weight proportion of each fraction (see chapter 5).

6.2.6. Phosphorus and soil pH

Available P was analyzed according to Olsen and Sommers (1982) by extracting 1.5 g of air-dried soil (< 2 mm) with 30 ml of 0.5 M $NaHCO_3$ (pH 8.5 ± 0.2) and the photometric determination of the P-blue color complex at 880 nm (Genesys 10 UV ThermoFisher Scientific Inc., U.S.A). Soil pH was determined in a soil water suspension at a ratio of 1:2.5.

6.2.7. Plant biomass and N uptake

Besides the physico-chemical analyses, attributes of soils from different types and durations of land use were further characterized by crop response parameters. The greenhouse experiment with potted soil from each land use type and chronosequence positions (1 to 30 years) was conducted at the Institute of Crop Science and Resource Conservation of the University of Bonn, Germany, from August to September 2011. The greenhouse was adjusted to mean day/night temperature of 31°C/23°C, with a 12 h light phase and a light intensity of 800 µmol m^{-2} s^{-1} (sodium vapor lamps). Fifty g of topsoil from each observation point (twenty-five positions) were filled into 200 ml PVC pots and three pots each were planted with two seedlings of seven-day-old kikuyu grass. Additional 200 g of topsoil were filled in 512 ml PVC pots and three pots each were planted with one seedling of ten-day-old maize (Kenyan variety PAN 4M-19 - Pannar Ltd.). The pots were maintained at about 70% field capacity by daily weighing and watering with distilled water. The aboveground biomass was collected, and oven-dried at 70°C after 28 (kikuyu grass) and 22 days (maize). Fine-ground dry biomass samples were analyzed for total N content using a CNS Elemental Analyzer (EuroEA 3000).

6.2.8. Statistical analysis and data preparation

The time for space approach holds only true, where soil variability does not bias the effect of land use duration, which eventually can lead to misinterpretations (Hartemink, 2006, Walker *et al.,* 2010). Thus, the chronosequence position 15 years on cropland was subsequently discarded from further analysis owing to the high soil pH (9.8), which inhibited crop production. Further, the one-year position and the reference sites on pastureland were excluded from analysis owing to changes in soil texture and localized accumulation of sodium carbonate crystals on the soil surface (Table 9, chapter 3).

Significance levels of plant nutrients and biomass between chronosequence positions were determined by one-way ANOVA ($p < 0.05$) and means were separated by Tukey Test after testing the normality of data distribution (Kolmogorov-Smirnov Test).

N dynamics were analyzed using a two parameter exponential decay model: [$N_t = N_0 * \exp(-k * t)$] (Dalal *et al.,* 2013, Hartemink, 2006). The equation was transformed into a linear function ($y = a + b * x$):

$\ln(N_t) = \ln(N_0) - k * t$ (11)

whereby: k = rate constant (a^{-1}); N_0 = total N (Mg ha^{-1}) at initial time t_0; N_t = total N (Mg ha^{-1}) at time t; t = years of land use duration

Both, the rate constant k and initial nitrogen stock N_0 were calculated by plotting $\ln(N_t)$ against land use duration t, where k is the slope and N_0 is the exponent of the linear function intercept. The rate constant k was used as a measure of nitrogen turnover (Dalal *et al.,* 2013). Mean annual decay rates of soil N (Mg ha^{-1} a^{-1}) were calculated as dN/dt. Rate constant k, decay rate and initial amount were also analyzed for NH_4-N mineralization potential (mg kg^{-1}), and plant N uptake (g pot^{-1}). Relations between N uptake, soil nitrogen stocks or N supplying capacity were analyzed with Pearson linear correlation. Factors influencing N supplying capacity were analyzed with Pearson linear correlation and multiple linear regression analysis ($p < 0.05$). Factors influencing plant biomass were assessed by multiple linear regression analysis ($p < 0.05$). Multi-co-linearity between independent variables was verified with the variance inflation factor (VIF), and all independent variables included in the analysis had a $VIF < 1 / (1 - R^2)$ (O'brien, 2007).

ANOVA was performed with SPSS 21, while multiple regression analysis, linear regression analysis, correlations and plotting were done using SigmaPlot 11.0 software package.

6.3. Results

6.3.1. Soil attribute changes under continuous land use

Soil pH and available phosphorus

Soils of alluvial and lacustrine origin differed in pH with slightly acidic to neutral soils on alluvial sediments and slightly alkaline to strongly alkaline soils on lacustrine parent material (Table 9, chapter 3). Available P differed between land use types but showed no effects of land use duration on either pasture or cropland with maximum available P of 28.8, 16.9 and 40.5 mg kg^{-1} on alluvial pasture, lacustrine pasture and lacustrine cropland, respectively (Table 9).

Soil nitrogen, N supplying capacity and organic carbon stocks

Nitrogen stocks on pastureland sites of 25 or 30 years of land use were significantly different from the 15 or 20 year sites on both the lacustrine and the alluvial soils (Table 9). A significant first order regression model provided a rate constant k of -0.019 a^{-1} (Table 12). Mean annual rates were estimated at -85 kg N ha^{-1} a^{-1}. Nitrogen stocks significantly differed between the very recent and the 25 and 30 year sites on lacustrine cropland (Table 9), following a first order exponential model (k = -0.012 a^{-1}) with rates of -75 kg N ha^{-1} a^{-1} (Table 12). At the pasture sites on lacustrine deposits, mean N supplying capacity significantly declined from 15 to 20, 25 and 30 years of land use (Table 9); also following a first order exponential model (Table 12). At the pasture sites on alluvial soils, the N supplying capacity ranged from 57.7 (15 years) to 48.1 mg kg^{-1} week^{-1} (30 years), and was not significant (Table 9). However, a combined first order exponential model of both pasture sites was highly significant (Table 12) with a mean annual decay rate of -1.8 mg kg^{-1} week^{-1} a^{-1}. On cropland N mineralization potential did not differ between chronosequence positions (mean decay rate of -0.6 mg kg^{-1} week^{-1} a^{-1}). The N supplying capacity was significantly correlated to SOC (r = 0.74***; n = 60) and to the POM fractions 2 and 3 as well as the non POM fraction (Table 13). The soil organic C and POM C fractions are presented in Table 10 and their dynamics have been discussed in chapter 4.

Table 9. Mean nitrogen content, nitrogen supplying capacity, available phosphorus (P Olsen) and pH of alluvial and lacustrine pasture (n = 6) and lacustrine cropland (n = 3) soils under 0 - 30 years of continuous land use. Soil texture from all three land use situations (n = 2). Standard deviations are presented in brackets. Data points with the same letter do not differ significantly by Tukey Test ($p < 0.05$). * Chronosequence position not included in analysis.

Site	Land use duration	Total N (Mg ha^{-1})	N supplying capacity (mg kg^{-1} week^{-1})	Available P (mg kg^{-1})	Soil pH	%S	%Si	%C
Pasture	0*	4.0	42.7	20.1	6.7	22	70	8
(alluvial)	1*	6.2 (1.6)	13.9 (11.8)	26.3 (5.1)	8.1 (0.1)	31 (16)	62 (14)	7 (2)
	15	6.0 (1.5)ab	57.7 (18.2)ns	27.2 (17.2)ns	6.7 (0.5)	9 (7)	82 (7)	9 (0)
	20	6.4 (0.9)a	73.7 (18.0)ns	28.8 (9.9)ns	6.3 (0.1)	4 (1)	86 (1)	10 (0)
	25	5.0 (0.9)ab	49.3 (10.5)ns	24.0 (10.1)ns	6.3 (0.3)	3 (1)	85 (2)	11 (1)
	30	4.6 (0.5)b	48.1 (30.7)ns	21.0 (4.3)ns	6.2 (0.1)	6 (5)	81 (5)	13 (0)
Pasture	0*	2.3	0.3	3.0	7.9	24	72	4
(lacustrine)	1*	2.8 (0.6)	19.1 (5.7)	5.2 (1.8)	8.9 (0.3)	25 (3)	70 (2)	5 (1)
	15	5.4 (0.7)ab	74.9 (23.4)a	13.5 (6.9)ns	7.4 (0.4)	13 (0)	79 (3)	8 (3)
	20	6.2 (0.8)b	45.2 (13.1)b	16.1 (6.0)ns	7.5 (0.3)	8 (6)	81 (5)	11 (1)
	25	5.0 (0.4)bc	22.2 (21.6)b	11.7 (1.9)ns	7.6 (0.1)	8 (6)	77 (5)	15 (1)
	30	4.2 (0.2)c	31.7 (9.6)b	16.9 (3.1)ns	7.8 (0.2)	16 (1)	78 (1)	5 (0)
Cropland	0	5.0	19.6	12.0	7.6	12	80	8
(lacustrine)	1	4.0 (0.2)a	2.4 (4.2)ns	26.0 (3.7)ns	8.5 (0.1)	17	79	4
	15*	2.2 (0.3)	13.9 (6.6)	4.7 (1.8)	9.8 (0.1)	24	72	4
	20	3.5 (0.2)ab	3.3 (4.3)ns	21.1 (3.7)ns	8.1 (0)	25	72	3
	25	3.4 (0.2)b	0ns	26.5 (2.9)ns	8.5 (0.1)	25	71	3
	30	2.8 (0.2)c	0.7 (1.2)ns	40.5 (32.7)ns	9.0 (0.1)	25	71	4

%S = % sand content, %Si = % silt content, %C = % clay content, ns = not significant, nd = no data.

Table 10. Mean soil organic carbon (SOC) and different fractions of particulate organic matter (POM) for selected chronosequence positions on alluvial and lacustrine pasture (n = 6) and lacustrine cropland (n = 3) soils under 0 - 30 years of continuous land use, (POM1: > 250 µm, POM 2: 250 – 53 µm, POM3: 53 – 20 µm, and non POM: < 20 µm). Standard deviations are presented in brackets. * Chronosequence position not included in analysis.

Site	Land use duration	SOC ($g\ kg^{-1}$)	POM1 C ($g\ kg^{-1}$)	POM2 C ($g\ kg^{-1}$)	POM3 C ($g\ kg^{-1}$)	non POM C ($g\ kg^{-1}$)
Pasture	0*	31.0	nd	nd	nd	nd
(alluvial)	1*	43.0 (6.0)	nd	nd	nd	nd
	15	59.5 (15.1)	nd	nd	nd	nd
	20	74.5 (11.1)	14.2 (2.3)	4.2 (0.5)	5.7 (2.5)	55.5 (0.3)
	25	45.6 (6.4)	nd	nd	nd	nd
	30	44.4 (5.0)	7.0 (1.5)	3.3 (0.1)	3.6 (0.3)	37.8 (2.2)
Pasture	0*	14.2	nd	nd	nd	nd
(lacustrine)	1*	20.4 (5.6)	nd	nd	nd	nd
	15	54.1 (12.9)	nd	nd	nd	nd
	20	48.3 (8.8)	4.0 (0.2)	2.7 (0.5)	3.6 (0.9)	33.0 (0.1)
	25	36.7 (2.3)	nd	nd	nd	nd
	30	28.4 (0.9)	2.2 (0.3)	2.2 (1.1)	2.6 (0.4)	22.5 (2.6)
Cropland	0	42.9	3.0	4.4	6.9	27.2
(lacustrine)	1	27.9 (1.8)	4.2 (1.2)	2.5 (0.4)	3.5 (0.8)	17.3 (0.2)
	15*	13.9 (2.8)	nd	nd	nd	nd
	20	21.9 (1.2)	1.7	1.8	3.5	21.8
	25	19.8 (1.9)	1.5 (0.6)	1.5 (0.3)	1.9 (0.1)	15.3 (0.8)
	30	15.1 (1.9)	nd	nd	nd	nd

SOC = soil organic carbon, POM = particulate organic matter, nd = no data.

6.3.2. Effect of land use on plant growth and nitrogen uptake

Kikuyu grass accumulated up to 196 mg pot^{-1} on alluvial pasture soil, 108 mg pot^{-1} on lacustrine pasture and 73 mg pot^{-1} on cropland soil, while maize accumulated 1.2, 0.9, and 0.3 g pot^{-1}, respectively (Table 11). Dry weight of both crops on sites of 25 or 30 years of pastureland use were significantly lower than those on 15 or 20 year sites, irrespective of the soil type. In contrast to maize, the biomass accumulation by kikuyu grass was lower on 25-year and 30-year than on the 1-year cropland soil (Table 11). Biomass accumulation was in all cases significantly related to soil nitrogen and ammonium mineralization potential and tended to correlate with plant available P and soil pH. While higher soil pH reduced plant dry biomass, higher plant available P, soil N and ammonium mineralization potential improved plant performance (Table 14). Maize N uptake reached 1.83 g pot^{-1} on alluvial pasture, 1.16 g pot^{-1} on lacustrine pasture and 0.41 g pot^{-1} on lacustrine cropland soils, while N uptake by kikuyu grass was 346, 173 and 87 mg pot^{-1}, respectively (Table 11). Similar to the biomass accumulation, the N uptake by maize and kikuyu grass declined with the duration of land use. The N uptake was significantly correlated to soil N concentration for all three land use situations (Figure 19).

Table 11. Mean biomass accumulation and nitrogen uptake by maize and kikuyu grass of alluvial pasture (n = 6), lacustrine pasture (n = 6) and lacustrine cropland (n = 2 – 3) soils under 0 – 30 years of continuous land use (0 – 15 cm soil depth). Standard deviations are presented in brackets. Data points with the same letter do not differ significantly by Tukey Test ($p < 0.05$). * Chronosequence position not included in analysis.

Site	Land use duration	Maize (g pot^{-1})		Kikuyu grass (mg pot^{-1})	
		Biomass	N uptake	Biomass	N uptake
Pasture (alluvial)	0*	nd	nd	nd	nd
	1*	0.5 (0.2)	0.9 (0.3)	50 (21)	87 (44)
	15	0.9 (0.2)a	1.11 (0.31)a	114 (41)a	172 (73)a
	20	1.2 (0.2)b	1.83 (0.41)b	196 (69)b	346 (145)b
	25	1.0 (0.2)ab	1.10 (0.21)a	136 (41)ab	218 (74)ab
	30	0.7 (0.2)a	0.83 (0.31)a	100 (43)a	136 (65)a
Pasture (lacustrine)	0*	nd	nd	nd	nd
	1*	0.3 (0.1)	0.4 (0.2)	29 (21)	53 (31)
	15	0.9 (0.2)a	1.16 (0.23)a	108 (29)a	173 (40)a
	20	0.8 (0.2)a	0.83 (0.16)b	86 (30)a	136 (56)a
	25	0.5 (0.2)b	0.50 (0.23)c	43 (19)b	67 (39)b
	30	0.5 (0.1)b	0.50 (0.07)c	42 (13)b	61 (22)b
Cropland (lacustrine)	0	nd	nd	nd	nd
	1	0.3 (0.1)ns	0.41 (0.10)a	73 (12)a	87 (17)
	15*	0.1 (0)	0.1 (0)	14 (6)	16
	20	0.3 (0.1)ns	0.32 (0.06)ab	49 (14)ab	57 (20)
	25	0.3 (0.2)ns	0.27 (0.11)ab	29 (11)bc	42 (19)
	30	0.2 (0)ns	0.19 (0.03)b	10 (2)c	nd

ns = not significant, nd = no data.

6.4. Discussion

6.4.1. Soil parameter changes in littoral wetlands

Soil pH and phosphorus

Soil pH affects soil chemistry and the plant availability of phosphorus, and there was a clear difference in soil pH between lacustrine and alluvial parent material, with favorable soil pH for plant growth on alluvial sediments. Thus, P availability was not generally limiting crop production in the littoral wetland area, but was rather connected to parent material and soil management practices. The pasture soils with slightly acidic to neutral alluvial sediments contained more available P (28.8 mg kg^{-1}) than the slightly alkaline lacustrine sediment (16.9 mg kg^{-1}), while fertilizer application has probably increased the available P in cropland soils (40.5 mg kg^{-1}). Alluvial soils have reportedly been enriched with detritus inflow of N- and P-rich material via the Malewa River, which may also have contributed to a lower soil pH (Gaudet, 1979). The alkaline soil conditions on lacustrine sediments probably derive from Na-rich rocks of volcanic origin (Saggerson, 1970), and soils tend to have sodic properties

(Siderius and Muchena, 1977). Additionally, soil parameters other than pH, N and C typically show relatively low short-term decay/accumulation rates (Hartemink, 2006). Soils of the littoral wetland zone were clearly influenced by alluvial sediment inflow which changed soil attributes. The continued agricultural use of the littoral area has not affected plant available P, or such effects were buffered by external inputs.

Decay of soil nitrogen and N supplying capacity

The maintenance of native soil nitrogen over a period of cultivation is particularly relevant for resource-poor small-scale farmers, who cannot afford to compensate N removal or losses by external inputs. In the Naivasha case, there was a significant decline of soil N which resulted in a reduction of 22% of the total soil N stocks within 15 years of continuous pasture use. Under crop uses, this decline reached 44% after 30 years. Thereby, the N turnover rates were similar at all land use situations, implying that decay dynamics were not influenced by parent material or management practices. However, observed declines in soil N stocks on cropland were most severe immediately after the conversion to cropland, which is probably connected to soil disturbance/aeration by tillage activities (Brady and Weil, 2008) and land clearing (Kamiri *et al.,* 2013). The higher N contents on pasture were possibly associated with the deposition of debris of the former papyrus vegetation (Gaudet, 1979). In a comparable agro-climatic zone in South Africa, Lobe *et al.* (2001) could show very similar soil N declines in upland soils (0 – 20 cm) by 45% after 30 years of cropping. In yet another study on upland soils in Australia, the total N losses were estimated at 20% on pasture with an annual decay rate of 33.2 kg ha^{-1} a^{-1} and at 38% on cropland with an annual decay rate of 61.5 kg ha^{-1} a^{-1}, after 23 years of land use (Dalal *et al.,* 2013). Also in East African valley swamps and floodplains that had been converted to cropland and pastures significantly declines in soil N stocks and contents compared to unused reference wetlands have been reported (Kamiri *et al.,* 2013), implying that both land use systems entail the same N dynamics after soil aeration. Increased soil N mineralization was also reported from Kenyan seasonal papyrus wetlands after agricultural soil disturbance, eventually leading to land degradation (Dam *et al.,* 2013). N supplying capacity followed total soil N trends, although data showed large variations with coefficients of variation of 4% - 25% for total soil N and 23% - 173% for the N supplying capacity, and reportedly responded less to the duration of land use than total N (Dalal and Mayer 1987). The decline in NH_4-N was higher than that of total soil N, with 35% after 15 years of land use. Similar decay rates imply no difference in NH_4-N dynamics between lacustrine and alluvial pasture. However, the reference site on lacustrine cropland (0 - 1 years of land use) showed high NH_4-N mineralization rates while only little ammonium was mineralized from soils that were longer in use, implying a massive soil N supply immediately after land conversion. The high rate constant of NH_4-N indicate a rapid decline of available nitrogen at all three land use systems. Cropped upland soils in semi-arid areas have reportedly very similar rates of decline in nitrogen mineralization and similar rate constants with duration of land use (Dalal and Mayer 1987), indicating comparable processes. We suspect that with soil aeration following lake level decline similar transformation processes occur in wetland as in upland soils. The littoral wetland soils could thereby not maintain their N content and N stocks under continuous land use, irrespective of parent material and land use system.

Nitrogen in relation to soil organic matter

Soil N stocks tend to be related to the recalcitrance of soil organic matter (Kirk, 2004), but the mechanisms behind soil N mineralization are not fully understood. Different factors are likely to influence the capability to mineralize soil native nitrogen (Kader *et al.,* 2013). The N supplying capacity in the littoral wetland depended on the soil organic carbon stocks, especially on the carbon fraction < 250 µm. About 80% of the data variation could be explained by the non POM C fraction (< 20 µm), and a simple linear regression model can largely explain N mineralization dynamics, excluding possible multi-colinearity (Ros *et al.,* 2011). The relation to soil organic carbon has been previously reported for West African submerged rice fields (Narteh and Sahrawat, 2000), and the coarse (> 250 µm) and medium (250 - 53 µm) POM fraction was related to N mineralization in temperate arable soils (Kader *et al.,* 2010). The severe impact of non POM C would imply a considerable input from the stable fraction to easy mineralized nitrogen, which reportedly has been released from the physically protected organic matter after soil disturbance (Hassink, 1992). That could explain the relation to non POM on arable soils in this study. Furthermore, soil re-wetting influences N mineralization (Hassink, 1992), and soil moisture measurements could successfully predict N mineralization (Paul *et al.,* 2003), which may account as a secondary factor (Kader *et al.,* 2010). Water is the main driving factor of soil organic carbon in wetlands (Sahrawat, 2003), and most probably has also influenced the grassland and cropland soils in the Naivasha wetland area (chapter 4, chapter 5). Additionally, the low molecular-weight POM fractions include labile N fractions, or N mineralization may depend on organic matter quality (Kader *et al.,* 2010). However, the use of different analytical approaches makes a comparison between published studies difficult (Benbi and Richter, 2002). Despite open questions on the mechanisms behind N mineralization, soil N content and N supply depended mainly on soil organic carbon stocks in the littoral wetland area and both are likely to limit plant production with extended durations of land use.

Table 12. Linear regression analysis between total soil nitrogen, nitrogen supplying capacity, nitrogen uptake of maize and kikuyu grass (dependent variable) and the duration of land use (independent variable) for alluvial pasture, lacustrine pasture, a combined model of both pasture and for lacustrine cropland soils, respectively. Presented are the rate constant k, estimated amounts of initial soil and plant nitrogen (N_0, NH_4-N_0), the coefficient of determination R² and the sample size (n).

Site		Total N (Mg ha^{-1})				N supplying capacity (mg kg^{-1} week^{-1})			
	dt (a)	k (a^{-1})	N_0 (Mg ha^{-1})	R²	n	k (a^{-1})	NH_4-N_0 (mg kg^{-1} week^{-1})	R²	n
Pasture (lacustrine)	15-30	-0.019	7.8	0.39**	24	-0.068	173	0.29**	23
Pasture (alluvial)	15-30	-0.020	8.3	0.27*	24	-0.029	101	0.12ns	24
Pasture (both)	15-30	-0.019	8.1	0.31***	48	-0.049	132	0.19**	47
Cropland (lacustrine)	0-30	-0.012	4.4	0.73***	13	-0.060	13	0.62ns	5
		N Maize (g pot^{-1})				N Kikuyu grass (mg pot^{-1})			
	dt (a)	k (a^{-1})	N_0 (g pot^{-1})	R²	n	k (a^{-1})	N_0 (mg pot^{-1})	R²	n
Pasture (lacustrine)	15-30	-0.062	2.7	0.49***	24	-0.080	0.6	0.56***	24
Pasture (alluvial)	15-30	-0.029	2.2	0.17*	24	-0.026	0.3	0.06ns	24
Pasture (both)	15-30	-0.046	2.4	0.24***	48	-0.053	0.4	0.19**	48
Cropland (lacustrine)	0-30	-0.024	0.4	0.49*	12	-0.029	0.1	0.53*	8

k = rate constant, *dt* = time span of land use, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ns = not significant.

Table 13. Multiple (linear forward stepwise) regression ($p < 0.05$) of nitrogen supplying capacity (dependent variable) and carbon in particulate organic matter (POM1: > 250 µm, POM2: 250 – 53 µm, POM3: 53 – 20 µm, and non POM C: < 20 µm) ($n = 14$).

	N supplying capacity (mg kg^{-1} $week^{-1}$)		
	$R^2 = 0.92$		
Variables	Coefficient	cum. R^2	p
Constant	-0.0207	---	---
non POM C (g kg^{-1})	0.00192	0.80	<0.001
POM3 C (g kg^{-1})	-0.0125	0.88	0.004
POM2 C (g kg^{-1})	0.0152	0.92	0.044
POM1 C (g kg^{-1})	---	---	ns

POM = particulate organic matter

Table 14. Multiple (linear forward) regression ($p < 0.05$) of dry biomass accumulation (dependent variable) by kikuyu grass and maize with total soil nitrogen stock, nitrogen supplying capacity, plant available P (P Olsen), and soil pH (independent variables) from soils of the same origin (four-week greenhouse study with constant water supply in potted soil; $n = 54$).

Dry Weight	Kikuyu grass (mg pot^{-1})			Maize (g pot^{-1})		
	$R^2 = 0.63$			$R^2 = 0.80$		
Variables	Coefficient	cum. R^2	p	Coefficient	cum. R^2	p
Constant	0.107	---	---	0.806	---	---
Net NH_4-N (mg kg^{-1} $week^{-1}$)	0.000718	0.67	0.006	0.00503	0.62	<0.001
Total soil N (Mg ha^{-1})	0.0132	0.74	0.02	0.0752	0.72	0.001
Soil pH	-0.0184	0.77	0.03	-0.107	0.77	0.002
available P (mg kg^{-1})	0.00107	0.80	0.018	0.00436	0.79	0.017

6.4.2. *Plant growth and N uptake affected by soil attribute changes*

We tested the performance of a typical grassland species (kikuyu grass) and a Kenyan maize variety under controlled soil moisture conditions on grassland and cropland soils of alluvial and lacustrine parent material. Dry biomass of kikuyu grass and maize was generally higher in the order alluvial pasture > lacustrine pasture > lacustrine cropland. Thus, plants tended to perform better on the slightly acidic to neutral alluvial sediments with higher P availability than on the alkaline lacustrine sediments. The influence of soil pH and plant available P on biomass originates probably from differences in soil type rather than the duration of land use. However, the significant reduction of soil N and/or net NH_4-N mineralization over time affected biomass accumulation and N uptake of both kikuyu grass and maize at all sites. Thereby, 74% of data variability was connected to soil nitrogen. This trend was confirmed by a decline in plant biomass and N uptake with land use duration that was significantly related to changes in soil nitrogen. Similar effects have been demonstrated for East African wetland soils, where rice biomass accumulation and nitrogen uptake was negatively affected by cultivation as a result of reduced nutrient availability (Kamiri *et al.,* 2013). Also in littoral wetland areas plant production declined of both grassland and crop species due to the decay of soil fertility, and irrespective of land use and parent material.

6.5. Conclusion

Most of the exposed wetland fringes of receding Lake Naivasha are threatened in their longer-term agricultural potential. At current land use activities, the native soil nitrogen tend to decline with land use duration, negatively affecting plant production, irrespective of the land use system and the parent material. The applicability of the chronosequence model for studying process changes associated with land use duration was confirmed for littoral wetland areas.

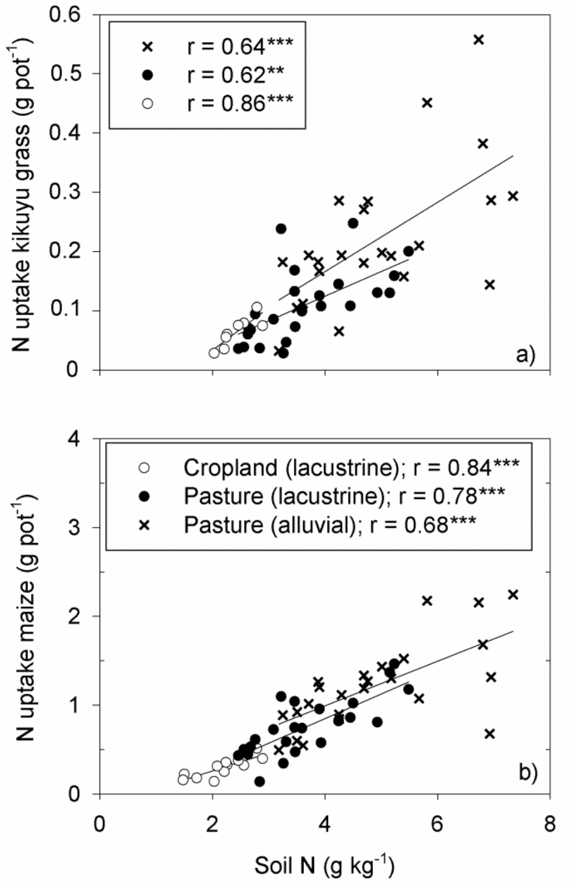


Figure 19. Pearson linear correlation ($p < 0.05$) between soil nitrogen concentration (g kg^{-1}) and plant nitrogen uptake by (a) kikuyu grass and (b) maize (g pot^{-1}).

7. Changes in resin adsorbed phosphorus along chronosequences of land use

7.1. Introduction

Ion exchange resins have been widely applied in soil science and plant nutrition to analyze available plant nutrients, nutrient leaching or soil contaminants (Quian and Schoenau, 2002). The capsules contain highly acidic and basic ion exchange resins. Once in contact with the soil, the resin reacts with the ions in the soil solution, simulating the adsorption processes of plant roots (Dobermann *et al.*, 1994). The resins act as a sink, and nutrients diffuse to, adsorb and accumulate on the resin surface. The ion accumulation depends on the capability of the soil to release ions to the soil solution, and on environmental attributes favoring ion diffusion (Dobermann *et al.*, 1994). Resins can remain in the soil for months (Quian and Schoenau, 2002), but rarely exceed four weeks (Dobermann *et al.*, 1997, 2002, Pampolino and Hatano, 2000). A high coherence between resin adsorbed nutrients and soil nutrient availability have been reported under water saturated soil conditions (Pampolino and Hatano, 2000), while relatively poor relation has been reported for resin adsorbed phosphorus under unsaturated conditions (Pampolino and Hatano, 2000, Jones *et al.*, 2013b). While ion exchange resins have been used *in-situ* in a wide range of soils, there is no information on resin adsorbed phosphorus from littoral wetlands, where both, water saturated and unsaturated soil conditions can prevail. The littoral wetland area of Lake Naivasha, Kenya, offers the possibility to study P sorption trends under different land use systems and parent materials. The lake water receded between 1980 and 2010, and small-scale farmers and pastoralists continuously used the newly exposed land area for agriculture, creating chronosequences of land use, providing the opportunity to study trends in ion adsorbed phosphorus affected by land use duration. We assessed resin adsorbed phosphorus under field conditions in the littoral wetland area of Lake Naivasha along a chronosequence of 1 to 30 years of continuous pasture or cropland uses and on two different parent materials.

7.2. Material and methods

7.2.1. Site Description

The study area lies at 1890 masl altitude in the semi-arid Kenyan Rift Valley with 620 mm annual precipitation, comprising pasture (0°43' S, 36°22' E) and cropland (0°44' S, 36°25' E) uses. The pasture sites are dominated by kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and African star grass (*Cynodon plectostachyus*), that are continuously grazed by wildlife and cattle. The cropland sites were continuously used for production of maize and vegetable with small amounts of supplementary fertilizer and irrigation provided.

The parent material consists of amorphous slightly alkaline lacustrine sediments (Siderius and Muchena, 1977). At the fringes of Malewa River, the parent material is dominated by reddish ferruginous alluvial silt deposits (Clarke *et al.*, 1990). The sites will thereafter be referred to “lacustrine pastures”, “alluvial pastures” and “lacustrine cropland”, based on differences in parent material and land use. Soils were identified as mollic Fluvisols and haplic Cambisols on lacustrine cropland, haplic and gleyic Vertisols on lacustrine pasture and gleyic Vertisols, haplic Gleysols and gleyic Fluvisols on alluvial pasture (IUSS, 2006) (chapter 3).

7.2.2. Experimental setup

The position of the lake shore was identified using lake level records and a geodetic GPS (Leica 500 coupled with a Nikon AP-7 Automatic Level). Five transects were established, one at lacustrine cropland and two each on lacustrine and alluvial pasture, respectively. Chronosequence positions (durations of land use) of 0, 1, 20, 25 and 30 years (uncovered by the receding lake between the year 2011, 2010, 1990, 1985 and 1980) were identified on each of the three land use situations. The sampling area of each position comprised 400 m^2 on pasture and 150 m^2 on cropland, respectively.

This study focuses only on topsoil attributes as the A-horizon is most affected by the water level recession and anthropogenic disturbances such as tillage operations (chapter 2 and 4). Initial topsoil samples (0 – 15 cm) were taken as composites (n = 5) in three replications at all observation points. First sampling started in November 2010 at chronosequence positions 15 to 30 years. After further lake level decline, the 1 year position on lacustrine cropland was sampled in April 2011, respectively. All samples were air-dried, sieved to < 2 mm, and stored dry until analysis. Additional five undisturbed bulk samples per observation point were taken with 100 cm^3 metal cans from a depth of 5 – 10 cm for determination of bulk density (BD) after oven-drying at 105°C for 24 h. Soil texture was determined with laser diffraction (Retsch LA-950 V2 Horiba, Haan, Germany), and soils had a soil texture of sandy to loamy silt.

7.2.3. Precipitation, irrigation and soil water content

Rainfall was measured in three rain gauges, one each on lacustrine pasture and lacustrine cropland from November 2010 and July 2011 and alluvial pasture from March to July 2011, respectively. Additionally, amount of irrigation on lacustrine cropland was recorded.

Soil pits of 100 cm depth were opened per position of 15 to 30 years for the estimation of initial volumetric soil water content (θ_G) in January 2011. Three bulk core samples from each horizon were taken after an initial identification of soil horizons (FAO, 2006). The samples were weighed fresh and dry (oven-dried at 105°C for 24 h) and θ_G from each soil pit was estimated with equation (2) (see chapter 4).

7.2.4. Soil chemical analyses

Soil subsamples of topsoil (0 – 15 cm) were fine ground with a swing mill (Retsch GmbH, Germany), and analyzed for total carbon content using a CNS Elemental Analyzer (EuroEA 3000; Euro Vector SpA, Milan, Italy). The inorganic carbon content was measured by Scheibler method with air-dried and sieved (< 2 mm) samples, and soil organic carbon (SOC) was the difference between total carbon and inorganic carbon. Topsoil stocks (0 – 15 cm) of organic C (Mg ha^{-1}) were calculated with equation (6) (see chapter 5). Soil pH was determined in a soil water suspension of 1:2.5 ratio. Available P was analyzed according to Olsen and Sommers (1982) by extracting 1.5 g of air-dried soil (< 2 mm) with 30 ml of 0.5 M $NaHCO_3$ (pH 8.5 ± 0.2) and the photometric determination of the P-blue color complex at 880 nm (Genesys 10 UV Thermo Fisher Scientific Inc., U.S.A) (chapter 6).

7.2.5. Resin adsorbed phosphorus

Available phosphorus in the liquid soil solution was determined with ion exchange resin capsules (PST-1, UNIBEST Inc., WA, USA) on three transects (one transect each on alluvial pasture, lacustrine pasture and lacustrine cropland) on chronosequence position 1 to 30 years on cropland on pasture, respectively (total: 15 sites). The resins were embedded in disturbed soil in an area of 1 m^2 and in 10 cm soil depth for a period of 4, 8 and 12 weeks (three resins per period) and during two seasons, from November 2010 to February 2011 and April 2011 to July 2011, respectively. The 1 year chronosequence position was only sampled for the second season. While on pasture the resins were installed below the grass vegetation, the resins were embedded between the maize rows on cropland. Thereafter, the resins were excavated, cleaned with deionized water, and stored cool until laboratory analysis. The ion exchange resins (and blanks) were shaken once in 20 ml 2N hydrochloric acid for 30 minutes, and the extract was filtered. Thereafter, extracted phosphorus was measured colormetrically (molybdenum blue) (Murphy and Riley, 1962) in 1 to 5 ml of the extracted aliquot with spectrophotometer (Eppendorf ECOM 6122, Hamburg, Germany) at 586 nm wavelength. P concentration was calculated as (Dobermann *et al.*, 1995):

$$c = m * abs * D \qquad (12)$$

whereas: c = phosphorus concentration (mg L^{-1}); m = regression coefficient; abs = absorbance reading; D = dilution factor (50 ml solution / 1 to 5 ml of resin aliquot)

Then, resin adsorption quantity of phosphorus (µmol cm^{-2}) (RAQ P) was estimated for each resin capsule:

$$RAQ\ P = ((c_{sample} - c_{blank}) * v) / (M * A) \qquad (13)$$

whereas: RAQ P = resin adsorption quantity of phosphorus (µmol cm^{-2}); c = P concentration of sample and blanks (mg L^{-1}); v = total volume of resin aliquot (here: 20 ml); M = molecular weight of P (30.97 g mol^{-1}); A = surface area of resin capsule (11.4 cm^2)

7.2.6. Statistical analyses

The chronosequence positions 15 years (cropland), 0 and 1 year (pastureland) were subsequently discarded from further analyses because of localized changes in soil texture, accumulation of carbonates on the soil surface (pastureland) and high soil pH (cropland) (see chapter 3) (Hartemink, 2006). Mean RAQ P was calculated from three resin capsules for each chronosequence position (1 to 30 years, 15 to 30 years), period (4, 8 and 12 weeks) and season. In three cases the mean was calculated from two resins: one capsule was destroyed in field, and in two cases RAQ P showed high variation compared to the other two samples. Thereafter, mean RAQ P and standard deviation was calculated from two seasons (n = 2), from November 2010 to February 2011 and April 2011 to July 2011, respectively. Furthermore, a first-order exponential regression model with RAQ P (µmol cm^{-2}) as dependent variable and time of soil embedment (weeks) as independent variable was used to analyze RAQ P kinetics in both seasons. Thereafter, the model derived a- and k-coefficient as well as RAQ P (4 weeks, 1st season – similar period than initial soil sampling) were correlated to initial soil parameters (bulk density, soil texture, soil water content, Olsen P, soil organic carbon (SOC) and soil pH) with Pearson linear correlation. Also, rainfall and irrigation events were cumulated according to the exact embedment period of resins (4, 8, 12 weeks, two seasons for lacustrine pasture and cropland, one season for alluvial pasture) and related to RAQ P with Pearson linear correlation. A first-order exponential regression model with 12 week RAQ P (µmol cm^{-2}) as dependent variable and land use duration (years) as independent variable was used to analyze RAQ P kinetics along the chronosequence of land use. Regression analysis, Pearson correlation and graphs were established with SigmaPlot 11.0 software package.

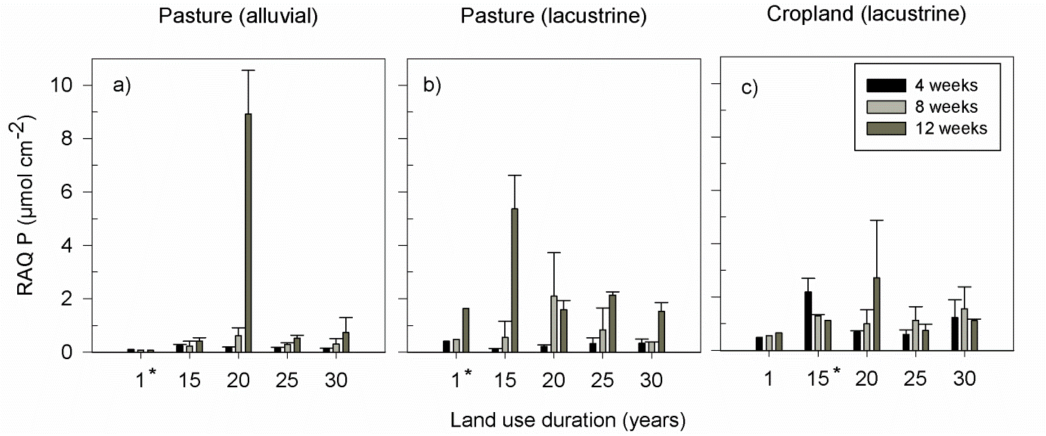


Figure 20. Resin adsorption quantity of phosphorus (RAQ P) (µmol cm^{-2}) on chronosequence position 1 to 30 years on alluvial pasture (a), lacustrine pasture (b) and lacustrine cropland (c) after 4, 8 and 12 weeks, respectively. Bars represent mean and error bars the standard deviation from two seasons, from November 2010 to February 2011 and April 2011 to July 2011, respectively. * indicates chronosequence positions excluded from analysis.

7.3. Results

The amount of plant available phosphorous in littoral wetland soils was analyzed using ion exchange resins for two seasons on cropland and pastureland (alluvial sediments and lacustrine parent material). Mean resin adsorption quantity of phosphorus (RAQ P) on lacustrine cropland was 0.8, 1.1 and 1.4 µmol cm^{-2} after 4, 8 and 12 weeks, respectively. On lacustrine pastureland it was 0.2, 1.0 and 2.6 µmol cm^{-2} during the same period. On alluvial soils under pasture use, RAQ P was 0.2, 0.4 and 2.6 µmol cm^{-2} (4, 8 and 12 weeks), respectively (Figure 20). The increase in RAQ P with time of soil embedment followed a first-order exponential model, which was significant on the 15-year position (lacustrine pasture), the 20 and 25-year position (alluvial pasture), and the 1 and 20-year position (cropland) (Table 15). The increment rate constant (k) was highest on 15-year (lacustrine pasture) and 20-year (alluvial pasture) position with 0.68 week^{-1}, respectively (Table 15). Resin adsorbed phosphorus on pastureland was also highest on the 20-year alluvial pasture site after 12 weeks of soil embedment with mean RAQ P of 8.9 µmol cm^{-2}. Thereby, RAQ P (12 weeks) decreased exponentially with duration of land use on lacustrine pasture, while it was not significant on cropland and on alluvial soils (Figure 20). RAQ P was rather related with other soil physical and chemical attributes or environmental factors. The resin adsorbed phosphorous correlated significantly with the amount of rainfall and irrigation on pasture (0.81**; n = 9) and cropland (0.93**; n = 6), but was not related to volumetric water content (Table 16). Additionally, RAQ P (4 weeks), the model derived a- and k-coefficient were correlated to soil texture, bulk density, Olsen P or soil pH (Table 16).

Table 15. First-order exponential fit of resin adsorbed phosphorus (RAQ P) (µmol cm^{-2}) for the periods from November 2010 to February 2011 and April to July 2011. The coefficient a represents RAQ P_0 (µmol cm^{-2}), while k represents the increment rate ($week^{-1}$). Presented are the mean values with standard deviation in brackets.

Site	Land use duration	a	k	p < 0.05
Pasture (alluvial)	15	0.24 (0.06)	0.07 (0.02)	ns
	20	0 (0)	0.68 (0.08)	***
	25	0.10 (0)	0.14 (0.02)	*
	30	0.06 (0.01)	0.20 (0.08)	ns
Pasture (lacustrine)	15	0.01 (0.02)	0.68 (0.31)	***
	20	0.59 (0.62)	0.13 (0.11)	ns
	25	0.14 (0.18)	0.30 (0.18)	ns
	30	0.05 (0.01)	0.29 (0)	ns
Cropland (lacustrine)	1	0.41	0.04	**
	20	0.31 (0.18)	0.17 (0.13)	**
	25	0.71 (0.25)	0.02 (0)	ns
	30	1.17 (0.7)	0.02 (0.03)	ns

The first-order exponential model was significant at $p < 0.05$: * = first season only; ** = second season only; *** = both seasons; ns = not significant in both seasons.

7.4. Discussion

The measurement of resin adsorbed plant available phosphorus has been successfully applied in a wide range of arable soils (Dobermann *et al.,* 1994), specifically in paddy rice *in-situ* and under controlled conditions (Dobermann *et al.,* 1997) as well as in upland soils (Dobermann *et al.,* 2002). A power function has been used to model resin adsorption quantity kinetics *in-situ* and under controlled conditions (Dobermann *et al.*, 1994, 1997). However, in this study we found better relation with a first-order exponential model (Table 15). It has been postulated, that the power function fit was low or non-significant under unsaturated soil water conditions (Pampolino and Hatano, 2000). Unsaturated conditions negatively influence nutrient diffusion to the resin, similar to the situation for plants in dry soils (Qian and Schoenau, 2002). The littoral wetland soils covered a wide range of soil moisture regimes, from permanently aerated (aridic) to water saturated (aquic) (chapter 4). Furthermore, the power function was validated with embedment periods $\leq$ 28 days (Pampolino and Hatano, 2000; Dobermann *et al.*, 1994), and RAQ P after 2 weeks was considered to express best the P supplying capacity of soils (Dobermann *et al.*, 2002). However, RAQ P in the littoral area substantially increased after embedment time > 4 weeks, with up to 13- and 55-fold amounts after 8 and 12 weeks, respectively. Hence, the first-order exponential model may describe RAQ P kinetics more accurate, where *in-situ* long-term P supplying capacity under unsaturated conditions is required. Thereby, the coefficients derived from the first-order exponential model may be interpreted as the coefficients from the power function. The a-coefficient reflects the initial RAQ P_0, the readily available phosphorous in the soil solution, while the k-coefficient is a measure of continuous P supply, driven by P solubility from solid inorganic or organic pools from greater distances to the resin and/or slow release processes (Dobermann *et al.*, 1994). Still, the exponential model was only significant on few chronosequence positions (Table 15), with a coefficient of variation (CV) of 1% to 130% (n = 3). That is probably connected to *in-situ* related soil moisture changes, which reportedly can increase resin variation (Qian and Schoenau, 2002). In paddy fields the CV reportedly varied from 30% to 67% (n = 64; 1 and 14 days embedment time), and three to five resins have been recommended for plots sizes ≤ 0.25 ha (Dobermann *et al.*, 1997). The littoral wetland area of Lake Naivasha were quite heterogeneous in both soil moisture (chapter 4) and soil physical and chemical attributes (chapter 5, chapter 6), and a sample size > 3 may be necessary to reduce *in-situ* RAQ P variation under such conditions.

Table 16. Pearson correlation between selected initial soil parameters(soil texture, bulk density (g cm^{-3}), soil pH, soil organic carbon (SOC, Mg ha^{-1}), Olsen P (mg kg^{-1}), and volumetric soil water content (θ_G, cm³ cm^{-3}) and resin adsorption quantity of phosphorus (RAQ P) (µmol cm^{-2}) after a 4-week period from November to December 2010 (n =11), mean RAQ P a and k coefficient from first order exponential model (n = 12), from chronosequence position 1 to 30 years on lacustrine cropland, lacustrine pasture and alluvial pasture, respectively.

	RAQ P (4 weeks) (µmol cm^{-2})	mean a-coefficient	mean k-coefficient
%S	0.88***	0.69*	-0.45ns
%Si	-0.76**	-0.70*	0.50ns
%C	-0.82**	-0.46ns	0.24ns
Bulk density (g cm^{-3})	0.80**	0.71**	-0.53ns
SOC (Mg ha^{-1})	-0.85***	-0.67*	0.84***
pH	0.84**	0.77**	-0.52ns
Olsen P (mg kg^{-1})	0.52ns	0.65*	-0.22ns
θ_G (cm³ cm^{-3})	0.12ns	0.12ns	-0.02ns

%S = % sand content, %Si = % silt content, %C = % clay content, ns = not significant

The amount of resin adsorbed phosphorous (4 weeks) was low compared to the phosphorous supply of other soils (Dobermann *et al.*, 2002), and that reportedly derives from low soil moisture content (Pampolino and Hatano, 2000). Only on lacustrine cropland RAQ P (4 weeks) was high, probably due to continuous irrigation, which positively influenced amount of resin adsorbed phosphorous. RAQ P (12 weeks) was only connected to land use duration on lacustrine pasture soils, implying that other influential factors such as the soil moisture regime prevailed. However, volumetric soil water content appeared to be less predictive to RAQ P (Table 16), while cumulative rainfall and irrigation was highly correlated. The relation between precipitation and resin adsorbed nutrients has previously been illustrated for resin adsorbed nitrogen (Reichmann *et al.*, 2013). Hence, soil moisture was one important factor influencing the amount of available phosphorous. Also influential factors on P diffusion (bulk density, soil texture) are indirectly associated with soil water changes (Pampolino and

Hatano, 2000). Thus, most soil chemical or physical attributes related to resin adsorbed phosphorous were connected to the unsaturated soil water conditions, revealing that mainly soil moisture influenced the amount of resin adsorbed phosphorous on all three land use situations.

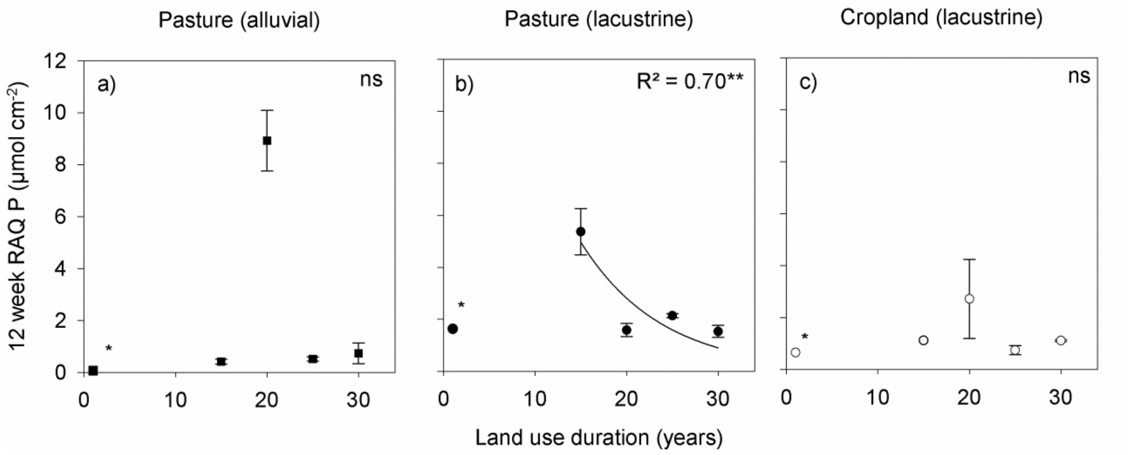


Figure 21. First-order exponential model of 12 week resin adsorption quantity of phosphorus (RAQ P) (µmol cm^{-2}) against land use duration on alluvial pasture (a), lacustrine pasture (b) and lacustrine cropland (c), respectively. Error bars present the standard deviation from two seasons, from November 2010 to February 2011 and April 2011 to July 2011, respectively. * indicates chronosequence positions excluded from analysis; ** significant at $p < 0.01$; ns = not significant at $p < 0.05$.

Olsen P was non-related to Resin P *in-situ* (Jones *et al.*, 2013b) and under controlled conditions (Jones *et al.*, 2013a), while it was reportedly related to the a-coefficient (Dobermann *et al.,* 1994), which both was also apparent in this study. Olsen P and RAQ P cover different soil phosphorous pools (Dobermann *et al.,* 1994), and may relate poorly under water unsaturated conditions (Jones *et al.*, 2013b). Surprisingly, RAQ P (after 4 weeks) and the readily available phosphorous (a-coefficient) were positively related to soil pH (6.0 to 9.0) (Table 16), although P-fixing soil conditions have been connected to low Resin P response (Dobermann *et al.,* 1994). At the same time soil pH was negatively (non-significant) correlated to the continuous P supply (k-coefficient), indicating that P-fixing soil conditions may negatively influence the longer-term phosphorous availability rather than the initial amount of available phosphorous. In addition, the k-coefficient was related to soil organic carbon (Table 16), which may indicate that the continuous P supply was mainly driven by P solubility from solid organic pools (Dobermann *et al.*, 1994). Thus, the amount of resin adsorbed phosphorous was not directly related to duration of land use. While the readily available phosphorous (a-coefficient, RAQ P) was connected to soil water conditions, the continuous phosphorous supply (k-coefficient) depended mainly on the soil organic carbon pool.

7.5. Conclusion

Available phosphorus in the soil solution in the littoral wetland was differently affected by selected soil chemical and physical attributes. Rainfall and irrigation increased resin adsorption of phosphorus (RAQ P) under unsaturated soil conditions. The continuous P supply was mainly influenced by the soil organic carbon content. A negative effect of continuous land use on plant-available P was only apparent on lacustrine soils under pasture use and not on alluvial soils or in croplands.

8. General discussion

In Sub-Saharan Africa, wetlands are important production sites for poor rural populations, and apart from other economic services, wetlands are valuable for crop production and pastureland (Dixon and Wood, 2003, Rebelo *et al.,* 2010). Communities may totally depend on wetlands (Schyut, 2005). Upland soil degradation and the unpredictability of rainfall patterns have accelerated the shift of cultivation towards the wetlands, where sufficient water supply and soil fertility are ensured. However, the excessive use of irrigation water and soil resources endangers the production potential of wetlands (Mitchell, 2013). The impact of extended land use on plant production, soil attributes and hydrology has been well-described for tropical uplands, but only few information exist on those dynamics in wetlands other than paddy rice fields (Roth *et al.,* 2011, Wissing *et al*., 2011), and small inland wetlands (Kamiri *et al.,* 2013, Böhme *et al.,* 2013). The dynamics of carbon, nutrients and soil water and the impact on plant production in tropical littoral wetlands is widely unknown. The space for time approach is an indirect method to investigate changes in soil conditions and vegetation (Walker *et al*., 2010). The chronosequence model established at Lake Naivasha offered the possibility to study such trends, and may thus serve to analyze the dynamics of water, carbon and nutrients in relation to changes in the wetland's production potential. The Naivasha case provided the additional advantage of including different land uses, such as crop farming and pastures. This study showed that selected soil and hydrological parameters as well as plant production in a tropical littoral wetland were severely affected by duration of land use, irrespective of land use system and parent material. The Naivasha model could account for the observed changes, but was only suitable for selected chronosequence positions, where the space-for-time approach held true, and thus, may only be applicable in certain littoral wetlands.

8.1. Hydrology influencing soil parameters

The submergence of wetland soils is one the most influential factors on the wetland´s biogeochemistry (Sahrawat, 2003). The anaerobic soil conditions affect nutrient stocks and availability, and furthermore determine plant growth and production potential. Especially wetland fringes are claimed for agriculture, which is often connected with soil drainage during land reclamation. The subsequent soil desiccation negatively affects the hydrological soil status and enhances mineralization processes (Dam *et al.,* 2013). In this study we could observe similar processes in the littoral wetland area of Lake Naivasha, and soil moisture reduction was connected to the duration of land use, irrespective of land use system or parent material. From the selected soil nutrient parameters, plant available (resin bound) phosphorus was related to precipitation, showing a direct link between both, nutrient availability and soil water. Carbon and nitrogen were not directly related to soil moisture, as it has been reported in previous studies (Hassink, 1992, Paul *et al.,* 2003). However, soil moisture might have been indirectly linked to carbon and nitrogen as mineralization processes may have increased or net primary production has decreased with increasing land use (Neue *et al.,* 1997). Thus, the chronosequence model (land use effects connected with soil drainage) could account better for soil attribute dynamics in a littoral wetland than using soil moisture content.

8.2. Wetland vulnerability and resistance

Wetlands in East Africa have reportedly been vulnerable to agriculturally induced changes (Dixon and Wood, 2003), and analysis of soil resistance for different wetland types and management systems has been postulated to help understand wetland degradation (Kamiri *et al.,* 2013). Soil resistance with soil organic carbon as parameter has been applied on mineral upland soils to measure the ability of soils to resist against human-induced soil disturbance (Herrick and Wander, 1998, de Moraes Sá *et al.,* 2014). No information on soil resistance or the vulnerability of tropical littoral wetland soils has yet been available to our knowledge. According to our chronosequence model, the tropical littoral wetland of Lake Naivasha was vulnerable to land use changes and could not resist land conversion and continuous agricultural land use, irrespective of parent material and land use system. Thereby, the applied chronosequence model followed an exponential reduction of soil organic carbon (and fractions) and nitrogen with duration of land use, similar to previous studies with a space-for-time experimental set-up (Dalal *et al.,* 1986, Dalal *et al.,* 2013, Lobe *et al.,* 2011). We therefore believe that the Naivasha model was suitable for the analysis of soil resistance and wetland vulnerability to anthropological changes.

8.3. Plant production and agricultural land use

The consequences of extended use duration as pasture land or for small-scale agriculture in littoral wetlands are largely unknown. Previous studies in the littoral wetland on Lake Naivasha on the impact of the receding lake levels largely focused on performance attributes of the papyrus stands (Harper, 1992; Boar *et al.,* 1999), while pastureland and crop production was largely neglected. Under the premise of the Naivasha chronosequence model, plant production in the littoral wetland area has been severely affected, irrespective of land use system and parent material. Most of the exposed wetland fringes of receding Lake Naivasha are threatened in their agricultural potential by current land use activity. Rain-fed plant production will be negatively affected as indicated by decreasing plant available water with duration of land use. That will increase the need for supplementary irrigation, especially in the dry season. The decline in biomass accumulation under controlled water conditions was largely related to changes in soil nitrogen, indicating that the soil fertility in terms of soil native nitrogen was additionally affecting plant production. The chronosequence model was applicable for the analysis of plant production affected by soil attribute and hydrological changes in a tropical littoral wetland.

8.4. Recommendations

1. The space-for-time approach has been successfully applied to analyze soil carbon (and fractions), nitrogen, phosphorus, bulk density, soil moisture and plant production for a period of 30 years in a tropical littoral wetland. Other soil attributes have been excluded in this study, and a further analysis of other soil parameters such as nitrogen in particulate organic matter, organic carbon in soil aggregates and resin adsorbed nutrients under controlled conditions would be an important asset.
2. In this study, only the topsoil of selected chronosequence positions was suitable for the chronosequence model, because the studied area underlay highly dynamic soil and sedimentation processes. It has to be stressed that similar influencing factors has to prevail within a chronosequence. Otherwise, a misinterpretation of the results derived from the chronosequence model is likely to occur.
3. A further analysis of soil resistance and soil resilience in tropical littoral wetlands or other wetland types using the proposed chronosequence model is recommended, where similar conditions prevail.
4. Finally, a sustainable use of the Naivasha wetland area on both pasture and cropland is recommended to tackle the decline of soil fertility. Possible management practices on cropland include the increase in water use efficiency, the use of external inputs such as mineral fertilizer (e.g. Urea) and the incorporation of organic material, which will subsequently also stabilize the soil pH. Further, a better control of animal stock density may have positive effect on the pasture area.

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Appendix

1 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'49.60"S, 36°22'39.60"E, 1886.6 masl

Vegetation: evolving grassland after inundation; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), small *Cyperus sp.*

a) Gleyic Fluvisols (calcaric)

Ahk (0 – 18 cm): olive brown (2.5Y 4/4), crumbly, clay texture, coarse and abundant light gray hard concretions (10YR 8/1) (*secondary carbonates*), no coarse fragments, slightly moist, abrupt, smooth boundary

ACg (18 – 55 cm): olive brown (2.5Y 4/3), massive to subangular blocky, sandy loam (clay poor), many and coarse very dark reddish brown mottles (7.5R 2/2) (*gleyic color pattern*) and olive black (7.5Y 3/1) laminae (*fluvic material*), no coarse fragments, moist, abrupt, smooth boundary

1C (55 – 75 cm): olive brown (2.5Y 4/4), massive, clay loam, very few, fine light gray (2.5Y 8/1) concretions, no coarse fragments, wet, abrupt, smooth boundary

2Ck (75 – 110 cm): dark brown (10YR 3/3) soil, massive, clay loam, very few, fine light gray (10YR 8/1) hard concretions (*secondary carbonates*), no coarse fragments, wet to very wet

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ahk	8.0	0.3	1.2	1.3	2.8	0.1
ACg	8.2	0.2	1.2	0.2	0.6	0
1C	8.5	0.2	1.0	0.1	1.4	0
2Ck	8.4	0.2	1.1	0.3	2.5	0

1 year lacustrine pasture

Vegetation: evolving grassland after inundation; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), small *Cyperus sp.*

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'48.60"S, 36°22'27.45"E, 1886.8 masl

b) Gleyic Fluvisols (calcaric)

Ahk (0 – 14 cm): brownish black (10YR 2/2), crumbly, silt loam (clay rich), abundant, coarse light gray (10YR 8/1) concretions (*secondary carbonates*), no coarse fragments, slightly moist, smooth, abrupt boundary.

1C (14 – 53 cm): grayish olive (5Y 4/2), massive, loamy sand, no mottles or coarse fragments, wavy, clear boundary, no coarse fragments, wavy, abrupt boundary; moist.

2Cgk (53 – 114 cm +): dull yellowish brown (10YR 4/3), massive, clay loam, many, coarse mottles (10YR 4/1) brownish gray (*gleyic color pattern*) and 10YR (8/1) light gray (*secondary carbonates*) no coarse fragments, moist to very wet.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ahk	8.4	0.3	1.1	1.2	3.4	0.1
1C	8.0	0.2	1.2	0.2	1.1	0
2Cgk	8.3	0.2	1.1	0.1	4.3	0

15 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'40.05"S; 36°22'47.01"E; 1887.2 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone)

a) Haplic Vertisols

Ah (0 – 8 cm): brownish black topsoil (5YR 2/1), crumbly, silt loam (clay poor), no mottles and no coarse fragments.

Bik (8 – 77 cm): brownish black (2.5Y 3/1), prismatic to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), common and medium light gray (2.5Y 8/1), hard concretions, moderate HCl reaction (indicates 2 – 10% *secondary carbonates*), few, very fine orange (7.5YR 6/8) mottles, no coarse fragments, dry.

C (77 – 110 cm +): brown (10YR 4/4), massive, silty clay loam texture, with few and very fine light gray (2.5Y 8/1) hard concretions, no coarse fragments, moderate HCl reaction (indicates 2 – 10% *secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	nd	nd	1.0	nd	nd	nd
Bik	nd	nd	1.1	nd	nd	nd
C	8.9	0.2	1.1	nd	nd	nd

15 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'44.28"S; 36°22'40.93"E; 1887.3 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone)

b) Gleyic Vertisols

Ah (0 – 5 cm): olive black (7.5Y 3/2), crumbly, silt loam (clay poor), no mottles or coarse fragments, dry.

Bi (5 – 60 cm): black (5Y 2/1), prismatic to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), few and medium light gray (5Y 8/1) hard concretions, no coarse fragments, dry to slightly moist.

Cg (60 – 100 cm +) dark olive brown (2.5Y 3/3), massive, clay loam, many and coarse gray mottles (10Y 5/1) (*gleyic color pattern*), hard concretions, ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, moist to wet.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	6.8	0.1	0.8	6.2	0	0.5
Bi	7.7	0.4	1.1	1.0	0	0.1
Cg	9.2	0.1	1.2	0.1	0.5	0

20 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'36.19"S; 36°22'49.46"E; 1887.6 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

a) Haplic Vertisols

Ah (0 – 5 (10) cm): black (7.5YR 2/1), crumbly, silt loam (clay rich), no mottles, moderate HCl reaction (indicates 2% – 10% *secondary carbonates*), no coarse fragments, dry, clear and wavy boundary.

Bi (5 – 38 cm): dull yellowish brown (10YR 4/3), prismatic to angular wedge-shaped structure, silt loam (clay rich), slickensides and cracks (*vertic properties*), no mottles, moderate HCl reaction (indicates 2% – 10% *secondary carbonates*), no coarse fragments, dry, diffuse and wavy boundary.

Bik (38 – 80 cm): dull yellowish brown (10YR 4/3), prismatic to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), many, sharp light gray (10YR 8/1) hard concretions, moderate HCl reaction (indicates 2% – 10% *secondary carbonates*), dry, clear, smooth boundary.

C (80 – 100 cm +): dull yellowish brown (10YR 5/4), massive, silt loam (clay poor), no mottles, moderate HCl reaction (indicates 2% – 10% *secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	7.0	0.7	0.9	nd	nd	nd
Bi	nd	nd	1.3	nd	nd	nd
Bik	nd	nd	1.2	nd	nd	nd
C	8.8	0.5	1.1	nd	nd	nd

20 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'36.08"S; 36°22'40.24"E; 1887.6 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

b) Haplic Vertisols

Ah (0 – 2 cm): brownish black (5YR 2/1), crumbly, silt loam (clay rich), no mottles, no coarse fragments, dry, clear, smooth boundary.

Bi (2 – 80 cm): brownish black (10YR 3/2), subangular blocky to angular wedge-shaped structure, silty clay loam, slickensides and cracks (*vertic properties*), very few and medium black mottles (10YR 1.7/1), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, slightly moist, gradual and wavy boundary.

C (80 – 100 cm +): grayish yellow brown (10YR 4/2), massive, clay, no mottles, ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, moist.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.5	0.5	0.9	7.8	0	0.7
Bi	8.9	0.5	1.2	0.5	0.5	0
C	9.4	0.4	1.3	0.4	1.7	0

25 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'23.28"S; 36°22'53.09"E; 1888.0 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

a) Haplic Vertisols

Ah (0 – 5 cm): brownish black (10YR 2/3), crumbly, silt loam (clay poor), no mottles, no coarse fragments, dry, wavy, abrupt boundary

Bi (5 – 33 cm): brownish black (10YR 2/2), subangular blocky to angular wedge-shaped structure, clay loam, slickensides and cracks (*vertic properties*), few and fine light gray (10YR 8/1) concretions and orange (5YR 6/8) mottles, no coarse fragments, slightly moist, wavy and gradual boundary.

Bigk (33 – 68 cm): dark grayish yellow (2.5Y 4/2), prismatic to angular wedge-shaped structure, sandy clay texture, slickensides and cracks (*vertic properties*), common and medium light gray (2.5Y 8/1) hard concretions (*secondary carbonates*), and common and medium black (2.5Y 2/1) mottles (*gleyic color pattern*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, dry, wavy and abrupt boundary.

Ck (68 – 100 cm +): dark brown (10YR 3/4), massive, clay, medium and few light gray (10YR 8/1) hard concretions (*secondary carbonates*) and black mottles (10YR 1.7/1), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, dry.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.9	0.5	0.8	5.5	0	0.5
Bi	7.8	0.4	1.0	1.2	0	0.1
Bigk	9.6	0.6	1.4	0.2	4.6	0
Ck	9.6	0.3	1.1	0	2.0	0

25 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'23.28"S; 36°22'53.09"E; 1888.0 masl (a); 0°43'28.33"S; 36°22'41.13"E; 1888.1 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

b) Haplic Vertisols

Ah (0 – 12 cm): brownish black (10YR 2/3), crumbly, loam, no mottles and no coarse fragments, very dry, smooth, gradual boundary.

Bik1 (12 – 65 cm): dark brown (10YR 3/3), subangular blocky to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), no coarse fragments; common and fine light gray (10YR 8/1) concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, slightly moist; gradual and wavy boundary.

Bik2 (65 – 85 cm): dark olive brown (2.5Y 3/3), prismatic to angular wedge-shaped structure, sandy clay, slickensides and cracks (*vertic properties*), no coarse fragments, common and fine light gray (10YR 8/1) concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, slightly moist, gradual smooth boundary.

Cgk (85 – 100 cm +): dark grayish yellow (2.5Y 4/2), massive, sandy clay, no coarse fragments; common and fine light gray (2.5Y 8/1) concretions (*secondary carbonates*) and black (2.5Y 2/1) mottles (*gleyic color pattern*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, dry.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	6.6	0.4	1.1	4.5	0	0.4
Bik1	9.1	0.5	1.0	0.6	0.6	0
Bik2	9.9	0.8	1.3	0.3	2.1	0
Cgk	9.7	0.4	1.2	0.3	1.6	0

30 year lacustrine pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'17.34"S; 36°22'56.57"E; 1888.6 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

a) Gleyic Vertisols

Ah (0 – 15 cm): dark olive brown (2.5Y 3/3), crumbly to subangular blocky, silt loam (clay rich), no mottles and no coarse fragments, dry, smooth and abrupt boundary.

Bigk1 (15 – 42 cm): grayish olive (5Y 4/2) (*gleyic color pattern*), prismatic to angular wedge-shaped structure, clay loam, slickensides and cracks (*vertic properties*), many and medium light gray hard concretions (5Y 8/1) (*secondary carbonates*) and very few and medium black mottles (5Y 2/1), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, dry, gradual and irregular boundary.

Bigk2 (42 – 83 cm): brownish black (2.5Y 3/2), prismatic to angular wedge-shaped structure, sandy clay, slickensides and cracks (*vertic properties*), many and medium light gray hard concretions (5Y 8/1) (*secondary carbonates*) and common and medium black mottles (5Y 2/1) (*gleyic color pattern*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, very few fine to coarse fragments of obsidian, dry, gradual and irregular boundary.

Ck (83 – 100 cm +): brown (7.5YR 4/4), massive, clay loam, many and medium light gray hard concretions (7.5YR 8/1) (*secondary carbonates*) and few and medium black mottles (7.5YR 2/1), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, slightly moist.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	7.6	0.3	1.2	3.6	0.3	0.3
Bigk1	8.9	0.3	1.4	0.1	0.4	0
Bigk2	9.5	0.4	1.2	0.2	3.2	0
Ck	9.6	0.2	1.1	0.1	1.4	0

30 years of land use duration

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'23.33"S; 36°22'44.15"E; 1888.5 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

b) Haplic Vertisols

Ah (0 – 2 cm): brownish black (10YR 2/3), crumbly, sandy loam (clay rich), no mottles and no coarse fragments, dry, smooth, abrupt boundary.

Bi (2 – 36 cm): dark olive brown (2.5Y 3/3), prismatic to angular wedge-shaped structure, sandy clay loam, slickensides and cracks (*vertic properties*), very few and fine mottles of bright brown color (7.5YR 5/8), no coarse fragments; dry to moist; smooth and abrupt boundary.

Bik (36 – 69 cm): Yellowish gray (2.5Y 4/1), prismatic to angular wedge-shaped structure, sandy clay loam, slickensides and cracks (*vertic properties*), few and fine mottles of bright brown (7.5YR 5/8), black (10YR 1.7/1); and yellow (5Y 8/6) color, light gray (10YR 8/1) hard concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments; dry to slightly moist.

Ck (69 – 100 cm +): brown (7.5Y 4/3), massive, clay loam, few and fine light gray (10YR 8/2) concretions (*secondary carbonates*), and black (10YR 1.7/1) mottles, ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, dry to slightly moist.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.5	0.6	0.9	7.7	0	0.7
Bi	8.7	0.7	1.3	0.8	0.4	0
Bik	9.6	0.8	1.4	0.4	3.3	0
Ck	9.8	0.3	1.2	0.1	3.7	0

1 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'44.90"S; 36°22'9.20"E; 1886.75 masl

Vegetation: evolving grassland after inundation; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and small *Cyperus sp.;* papyrus mounds

a) Gleyic Fluvisols

Ah (0 – 12 cm): brownish black (7.5 YR 2/2), crumbly to subangular blocky, silt loam (clay poor); few distinct red mottles, light gray mottles (10R 4/6; 7.5R 8/1).

1Cg1 (12 – 20 cm): dark brown (10YR 3/3), massive, sand (*fluvic material*), abundant and coarse red and black mottles (10R 4/8; 10YR 1.7/1) (*gleyic color pattern*).

2Cg2 (20 – 68 cm): brownish black (10YR 3/1), massive, clay, coarse, common red and black mottles (10YR 1.7/1; 10R 3/4) (*gleyic color pattern*), relatively high carbon content (*fluvic material*), moist.

2Cg3 (68 – 83 cm): brownish black (10YR 3/1), massive, clay to clay loam, coarse and abundant dark red and black mottles (*gleyic color pattern*) (5YR 4/8; 10YR 1.7/1), relatively high carbon content (*fluvic material*), wet.

3Cg4 (83 – 100 cm+): brownish black (2.5Y 3/1), massive, clay, common, fine red and black mottles (10R 4/8; 2.5YR 1.7/1) (*gleyic color pattern*), relatively high carbon content (*fluvic material*), wet to very wet.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	7.3	1.7	1.0	3.0	0.2	0.3
1Cg1	7.3	0.7	1.0	0.9	0.1	0.1
2Cg2	7.4	0.4	0.9	0.6	0	0.1
2Cg3	7.6	0.2	1.1	0.9	0	0.1
3Cg4	7.3	0.2	1.0	0.9	0	0.1

1 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'44.70"S; 36°21'48.50"E; 1886,86 masl

Vegetation: evolving grassland after inundation; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and small *Cyperus sp.;* papyrus mounds

b) Gleyic Fluvisols

Ahg (0 – 15 cm): dark brown (7.5YR 3/3), crumbly to subangular blocky, sandy clay loam, many, coarse reddish brown (10R 4/4) mottles (*gleyic color pattern*), slightly salty (EC > 2 dS m^{-1}), no coarse fragments, slightly moist, gradual and smooth boundary.

ACg (15 – 85 cm): brownish black (10YR 3/2), massive to subangular blocky, clay, coarse, many very dark reddish brown (10R 2/2) and coarse, common red (10R 4/6) mottles (*gleyic color pattern*), relatively high carbon content (*fluvic material*), no coarse fragments, moist to wet, abrupt and smooth boundary.

2Cg (85 – 100 cm +): dark reddish brown (2.5YR 3/2), massive, fine sand (*fluvic material*), coarse, abundant dark reddish gray (10R 3/1) and reddish black (10R 2/1) mottles (*gleyic color pattern*), no coarse fragments, wet to very wet.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ahg	7.6	2.1	1.0	4.7	0.2	0.5
ACg	7.7	0.4	1.1	1.2	0.7	0.1
2Cg	6.7	0.1	1.2	0.2	0	0

15 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'31.11"S; 36°22'12.80"E, 1887.4 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), papyrus mounds

a) Haplic Gleysols

Ah (0 – 7 cm): brownish black (10YR 2/2), crumbly, clay loam, no mottles and coarse fragments, dry, abrupt and smooth boundary.

Bg (7 – 75 cm): olive black (5Y 3/1), prismatic to subangular blocky, clay, many, coarse mottles of red (10R 5/8) and black (5Y 2/1) color (*gleyic color pattern*), no coarse fragments, moist.

2Abg (75 – 100 cm): brownish black (2.5Y 3/2) (*buried A horizon*), prismatic to subangular blocky, heavy clay, abundant and coarse black (5Y 2/1) mottles (*gleyic color pattern*), no coarse fragments, wet.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	5.7	0.7	0.7	9.5	0	0.9
Bg	6.3	0.2	1.0	1.2	0	0.1
2Abg	6.1	0.3	1.0	1.9	0	0.2

15 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'37.70"S; 36°21'49.19"E, 1887.4 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), papyrus mounds

b) Gleyic Fluvisols

Ah (0 – 10 cm): brownish black (10YR 2/3), subangular blocky, silt loam (clay rich), very few, fine reddish orange mottles (10R 6/8), no coarse fragments, dry, clear, smooth boundary.

1Cg1 (10 – 47 cm): dark brown (10YR 3/4), massive, clay, many, medium black (10YR 1.7/1) and red (10R 4/8) mottles (*gleyic color pattern*), relatively high carbon content (*fluvic material*), no coarse fragments, dry to moist, gradual, smooth boundary.

2Cg2 (47 – 59 cm): dark brown color (7.5YR 3/4), massive, loam (*fluvic material*), many, medium black (5YR 1.7/1), bright reddish brown (5R 5/8) mottles (*gleyic color pattern*), wet, gradual, smooth boundary.

3Cg3 (59 – 100 cm +): brownish gray soil (10YR 4/1), massive, clay, many and medium reddish brown (5YR 4/8) and brownish black (5YR 2/1) mottles (*gleyic color pattern*), relatively high carbon content (*fluvic material*), no coarse fragments, wet.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	6.6	1.3	0.8	9.9	0	0.9
1Cg1	8.0	0.5	1.2	0.9	0.1	0.1
2Cg2	7.2	0.2	1.3	0.4	0	0.1
3Cg3	7.9	0.1	1.1	0.8	0	0.1

20 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'23.52"S; 36°22'20.74"E, 1887.6 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone); papyrus mounds

a) Gleyic Vertisols

Ah (0 – 2 cm): brownish black (10YR 2/3), subangular blocky, silt loam (clay poor), no mottles, no coarse fragments, dry; smooth and abrupt boundary.

Big (2 – 60 cm): brownish black (10YR 2/2), subangular blocky to angular wedge-shaped structure, silty clay loam, slickensides and cracks (*vertic properties*), many and coarse mottles of reddish brown (2.5YR 4/8) and orange (5YR 6/8) color (*gleyic color pattern*), very few, fine hard concretions of light gray (10YR 8/1) color, no coarse fragments, dry to slightly moist, gradual and irregular boundary.

Cg (60 – 100 cm +): dark olive brown (2.5Y 3/3), massive, clay loam, many, coarse orange (5YR 6/8) and fine, few black (10YR 1.7/1) mottles (*gleyic color pattern*), very few, fine light gray (10YR 8/1) hard concretions, no coarse fragments, slightly moist.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.0	0.6	0.7	8.7	0	0.7
Big	5.9	0.3	1.0	4.8	0	0.4
Cg	7.3	0.1	1.3	0.5	0	0.1

20 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 36°21'53.40"E, 1887.7 masl

Vegetation: grassland; dominantly Kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone); papyrus mounds

b) Haplic Gleysols

Ah (0 – 5 cm): brownish black (5YR 3/1), subangular blocky, loam, no mottles and coarse fragments, dry, smooth and clear boundary.

Bg (5 – 59 cm): brownish gray (5YR 4/1), prismatic to subangular blocky, clay, abundant and coarse orange (5YR 7/8), bright reddish brown (5YR 5/8) and black (5YR 1.7/1) mottles (*gleyic color pattern*), no coarse fragments, dry, smooth and clear boundary.

Cg (59 – 100 cm +): grayish brown (7.5YR 4/2), massive, clay, abundant and coarse dark red (10R 3/6), bright reddish brown (5YR 5/8) and black (5YR 1.7/1) mottles (*gleyic color pattern*), no coarse fragments, slightly moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	6.2	0.7	0.5	12.3	0	1.0
Bg	6.5	0.2	1.1	1.1	0	0.1
Cg	6.0	0.3	1.0	0.8	0	0.1

25 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'19.56"S; 36°22'24.06"E, 1888.1 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*), papyrus mounds

a) Gleyic Vertisols

Ah (0 – 3 (7) cm): brownish black (10YR 2/2), subangular blocky, silt loam (clay poor), no mottles, coarse fragments, dry, wavy, abrupt boundary.

Big (3 – 39 cm): brownish black (10YR 3/2), subangular blocky to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), prominent, coarse orange (5YR 6/8) mottles (*gleyic color pattern*), no coarse fragments, dry; smooth, abrupt boundary.

1Cg (39 – 70 cm): yellowish gray (2.5Y 4/1), massive, silty clay, common and medium orange (5YR 6/8) mottles (*gleyic color pattern*), no coarse fragments, dry.

2C (70 – 100 cm +): brown (10YR 4/6), massive, silt loam (clay rich) texture, very few, medium black (10YR .7/1) mottles and few, medium light gray (2.5Y 8/1) hard concretions, no coarse fragments, dry.

Horizon	pH$_{H2O}$	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.0	0.5	0.8	7.5	0	0.6
Big	6.2	0.2	1.1	2.1	0	0.2
1Cg	7.0	0.1	1.3	0.3	0	0
2C	7.6	0.2	1.2	0.1	0.9	0

25 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya, 0°43'17.02"S; 36°21'57.41"E, 1888.1 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*), papyrus mounds

b) Gleyic Vertisols

Ah (0 – 11 cm): brownish black (7.5YR 2/2), subangular blocky, silt loam (clay poor), no mottles and coarse fragments, dry, irregular and clear boundary.

Big (11 – 60 cm): grayish brown (7.5 YR 4/2), prismatic to angular wedge-shaped structure, heavy clay, slickensides and cracks (*vertic properties*), coarse and abundant dark reddish brown (2.5YR 3/6) and few and medium black (7.5YR 2/1) mottles (*gleyic color pattern*), no coarse fragments, dry, smooth, abrupt boundary.

2Abg (60 – 80 cm): black (10YR 2/1) (*buried A horizon*), prismatic, heavy clay, many, coarse bright reddish brown (5YR 5/8), light gray (10YR 8/1) and black (10YR 1.7/1) mottles (*gleyic color pattern*), no coarse fragments, moist, smooth and clear boundary.

2Big (80 – 100 cm +): brownish black (10YR 3/2), prismatic to angular wedge-shaped structure, heavy clay, slickensides and cracks (*vertic properties*), medium and common black (10YR 1.7/1), red (10R 5/8) and light gray (10YR 8/1) mottles (*gleyic color pattern*).

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Ah	6.1	0.5	0.7	7.6	0	0.7
Big	4.9	0.2	1.0	1.3	0	0.1
2Abg	5.3	0.3	1.0	2.0	0	0.2
2Big	5.5	0.2	1.1	1.0	0	0.1

30 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya; 0°43'12.61"S; 36°22'30.05"E, 1888.6 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

a) Gleyic Vertisols

Ah (0 – 6 cm): black (7.5YR 2/1), crumbly to subangular blocky, silty loam (clay poor), no mottles and coarse fragments, very dry, clear, smooth boundary.

Big (6 – 45 cm): dark brown (10YR 3/3), prismatic to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), common and medium reddish brown (2.5YR 4/8) and very dark reddish brown (2.5YR 2/2) mottles (*gleyic color pattern*), no coarse fragments, very dry, gradual, wavy boundary.

C (45 – 100 cm +): brown (10YR 4/4), massive, clay, fine and few red (10R 4/8), reddish black (2.5YR 2/1) mottles, no coarse fragments, very dry.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	5.6	0.4	0.6	10.9	0	0.9
Big	6.2	0.1	1.1	1.0	0	0.1
C	6.8	0.1	1.1	0.2	0	0

30 year alluvial pasture

Location: Kenya Agricultural Research Institute; Naivasha, Kenya, 0°43'3.91"S; 36°22'2.35"E, 1888.6 masl

Vegetation: grassland; dominantly star grass (*Cynodon plectostachyus*)

b) Gleyic Vertisols

Ah (0 – 10 cm): brownish black (7.5YR 2/2), crumbly to subangular blocky, silt loam (clay poor), no mottles, no coarse fragments, dry, smooth and clear boundary.

Big (10 – 23 cm): grayish yellow brown (10YR 4/2), prismatic to angular wedge-shaped structure, silty clay, slickensides and cracks (*vertic properties*), many, medium bright reddish brown (5YR 5/8) (*gleyic color pattern*), very few, fine light gray (5YR 8/1) mottles, no coarse fragments, dry, gradual, irregular boundary.

2Abg (23 – 64 cm): brownish black (5YR 3/2) (*buried A horizon*), prismatic to subangular blocky, clay, common and medium bright reddish brown (5YR 5/8) and black (5YR 1.7/1) mottles (*gleyic color pattern*), no coarse fragments, slightly moist, gradual, irregular boundary.

2Big (64 – 100 cm +): brownish gray (5YR 4/1), prismatic to angular wedge-shaped structure, clay, slickensides and cracks (*vertic properties*), abundant, coarse brownish black (7.5YR 3/1) and few, fine yellow orange (7.5YR 7/8) and black (7.5YR 1.7/1) mottles (*gleyic color pattern*), no coarse fragments, slightly moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Ah	5.8	0.5	0.7	8.1	0	0.7
Big	5.4	0.1	1.1	1.5	0	0.2
2Abg	5.5	0.2	0.9	2.8	0	0.2
2Big	6.3	0.1	1.3	0.7	0	0.1

1 year lacustrine cropland

Location: Lake Naivasha, small-scale farmer area Kihoto, Kenya; 0°44'3.90"S, 36°24'53.80"E, 1886.9 masl

Vegetation: cropland, mainly cultivation of maize and vegetables

Mollic Fluvisols

Apk (0 – 10 cm): olive black (5Y 3/2), crumbly, silty clay texture, medium common pale yellow (5Y 8/4) mottles (*gleyic color pattern*), and light gray (5Y 8/1) hard concretions (*secondary carbonates*), no coarse fragments, slightly moist, clear, wavy boundary.

Ak (10 – 38 cm): both A-Horizons together: *mollic horizon*, olive black (5Y 3/2), subangular blocky, sandy clay texture, many, medium pale yellow (5Y 8/3) mottles, and light gray (5Y 8/1) hard concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, about 15% gravel, slightly moist, clear, wavy boundary.

Cgk (38 – 95 cm +): olive black (5Y 3/2), massive, medium sand, 90% fine gravel, abundant, coarse light gray concretions (5Y 8/1) (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, with 2 massive crust layers of 0.8 and 1.5 cm thickness and pale yellow (5Y 8/4), light gray (5Y 8/1) and yellow orange (10Y 7/6) color (*fluvic material*) at 82 and 63 cm soil depth, respectively (probably 2% - 10% carbonate content), slightly moist.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	% Carbonate	%N
Apk	7.6	0.7	0.9	3.7	1.7	0.4
Ak	8.9	0.3	1.3	0.3	3.3	0.1
Cgk	8.9	0.2	0.8	0.2	1.1	0

15 year lacustrine cropland

Location: Lake Naivasha, small-scale farmer area Kihoto, Kenya; 0°44'2.54"S; 36°24'56.96"E, 1887.4 masl

Vegetation: abandoned cropland, mainly grass cultivation

Mollic Fluvisols

Apk (0 – 5 (9) cm): brownish black (2.5Y 3/2), crumbly, loam, no mottles and coarse fragments, ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, slightly moist, clear, wavy boundary.

Ak (5 – 35 cm): both A-Horizons together: *mollic horizon*, dark olive brown (2.5Y 3/3), subangular blocky, clay loam, many, common bright yellowish brown (2.5Y 6/6) mottles, light gray (2.5 8/1) concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, no coarse fragments, slightly moist, clear and wavy boundary.

Ck (35 – 60 cm +): brownish black (10YR 3/1), massive, sandy loam (clay rich) and about 50% fine gravel content, many, common dull yellow orange (10YR 6/4) and light gray (2.5Y 8/1) concretions (*secondary carbonates*), ultra-basic (pH > 8.7), most likely presence of $MgCO_3$ or Na_2CO_3, relatively high carbon content (*fluvic material*), moist to very wet.

Horizon	pH_{H2O}	EC (dS m^{-1})	BD (g cm^{-3})	% SOC	% Carbonate	% N
Apk	9.1	0.6	0.9	1.8	2.7	0.2
Ak	9.4	0.4	1.3	1.1	2.0	0.1
Ck	9.2	0.4	1.0	0.6	2.2	0.1

20 year lacustrine cropland

Location: Lake Naivasha, small-scale farmer area Kihoto, Kenya; 0°43'59.36"S; 36°25'8.42"E, 1887.6 masl

Vegetation: cropland, mainly maize and vegetable cultivation

Haplic Cambisols (calcaric)

Apk (0 – 15 cm): brown (10YR 4/4), crumbly, silt, many, fine light gray (10YR 8/1) concretions (*secondary carbonates*), no coarse fragments, slightly moist, clear, smooth boundary.

Bwk (15 – 64 cm): brownish black (7.5YR 3/2), subangular blocky, silt, many, fine orange (5YR 7/8) mottles, light gray (5YR 8/1) concretions (*secondary carbonates*), no coarse fragments, dry.

Cgk (64 – 100 cm +): dark brown (10YR 3/3), massive, silt loam (clay rich), many, fine yellow orange (10YR 8/6) mottles and light gray (10YR 8/1) concretions (*secondary carbonates*), no coarse fragments, slightly moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	%SOC	% Carbonate	%N
Apk	7.6	0.2	0.9	0.9	0	0.1
Bwk	7.0	0.3	1.1	2.0	0	0.3
Cgk	8.1	0.1	1.2	0.3	1.2	0

25 year lacustrine cropland

Location: Lake Naivasha, small-scale farmer area Kihoto, Kenya; 0°43’58.51”S; 36°25’10.09”E, 1888.3 masl

Vegetation: cropland, mainly maize and vegetable cultivation

Haplic Cambisols (calcaric)

Ap (0-10 cm): brownish black (2.5Y 3/2), crumbly, silt loam (clay rich), no mottles or coarse fragments, very dry, clear and smooth boundary.

Bwk (10 – 60 cm): brownish black (2.5Y 3/2), subangular blocky, silt loam (clay rich), few, medium yellow (2.5Y 7/8) mottles and common, medium light gray (7.5Y 7/1) concretions (*secondary carbonates*), no coarse fragments, very dry, gradual, wavy boundary.

Ck (60 – 100 cm +): dark olive brown (2.5Y 3/3), silt loam (clay poor), massive, few, medium brownish black (2.5Y 3/2), bright reddish brown (5YR 5/8) mottles and common, medium light gray (10Y 8/1) concretions (*secondary carbonates*), no coarse fragments, slightly moist.

Horizon	pH_{H2O}	EC ($dS\ m^{-1}$)	BD ($g\ cm^{-3}$)	% SOC	% Carbonate	% N
Ap	7.6	0.3	1.0	1.8	0.1	0.2
Bwk	8.5	0.1	1.3	0.4	0.2	0.1
Ck	8.0	0.1	1.2	0.2	4.4	0

30 year lacustrine cropland

Location: Lake Naivasha, small-scale farmer area Kihoto, Kenya; 0°43'57.27"S; 36°25'10.75"E, 1889.2 masl

Vegetation: cropland, mainly maize and vegetable cultivation

Haplic Cambisols (calcaric)

Apk (0 – 20 cm): dark brown (10YR 3/3), crumbly, loam, few, fine grayish white (10GY 7/1) concretions (*secondary carbonates*), 1% fine gravel, very dry, abrupt, smooth boundary.

Bwk (20 – 67 cm): brown (10YR 3/4), subangular blocky, clay loam, common, medium grayish white (10GY 7/1) concretions (*secondary carbonates*), few, medium bright brown (7.5YR 5/6), reddish brown (2.5YR 4/6) mottles, no coarse fragments, very dry.

C (67 – 100 cm +): dark brown (10YR 4/4), massive, sandy clay loam, few, fine grayish white (10GY 7/1) concretions, no coarse fragments, slightly moist.

Horizon	pH$_{H2O}$	EC (dS m^{-1})	BD (g cm^{-3})	%SOC	%Carbonate	%N
Apk	8.0	0.3	1.0	1.4	1.8	0.2
Bwk	8.4	0.3	1.4	0.5	6.0	0.1
C	8.4	0.2	1.3	0.3	1.8	0