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IMPACT OF ENCLOSURE MANAGEMENT AND AGE ON TOPSOIL ORGANIC CARBON STOCKS IN CHEPARERIA, WEST POKOT COUNTY, KENYA

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Master dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Physical Land Resources by Albert Gikonyo Ituika (Kenya)

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Gent, August 2016

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BD</td>
<td>Bulk density</td>
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<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CEC</td>
<td>Cation exchange capacity</td>
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<tr>
<td>FAO</td>
<td>Food and Agricultural organization</td>
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<tr>
<td>Gt</td>
<td>Gigaton</td>
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<tr>
<td>HCL</td>
<td>Hydrochloric acid</td>
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<tr>
<td>K&lt;sub&gt;exch&lt;/sub&gt;</td>
<td>Exchangeable Potassium</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-Governmental organization</td>
</tr>
<tr>
<td>P&lt;sub&gt;avail&lt;/sub&gt;</td>
<td>Available Phosphorous</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil organic carbon</td>
</tr>
<tr>
<td>SOM</td>
<td>Soil organic matter</td>
</tr>
<tr>
<td>TN</td>
<td>Total Nitrogen</td>
</tr>
<tr>
<td>UNEP</td>
<td>United Nations Environmental Program</td>
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<td>UNCCD</td>
<td>United Nations Convention to Combat Desertification</td>
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Abstract
Use of enclosures has globally gained popularity as a dryland management tool and due to its potential to sequester carbon. Enclosures denote areas with restricted grazing for a period of time, usually several years.

In Chepareria, West Pokot County, Kenya, the use of enclosures has been widely adopted for the rehabilitation of formerly degraded land. This research studied the effect of different management systems on soil organic carbon (SOC) accumulation in Chepareria. Specific objectives included: (1) to determine the impact of current management strategies on soil properties, with specific attention to their impact on SOC accumulation in the location; (2) to assess the impact of enclosure age on soil physico-chemical properties and its influence on SOC accumulation; and (3) to assess the vertical topsoil organic carbon profile under these different management strategies.

The study was carried out in three locations in Chepareria, namely Ywalateke, Chepkopegh and Morpus. In each location, 20 fields were selected: 4 open grazing lands, 4 fenced crop lands and 12 enclosures with different age categories, namely 2 – 8 years (4 fields), 12 – 18 years (4 fields) and over 20 years (4 fields). Soil sampling was done up to 30 cm depth at intervals of 10 cm (0 – 10, 10 – 20, 20 – 30 cm). SOC, as well as pH,N,P,K,CEC,BD and soil texture were determined.

Though differences were not significant, SOC content (%) was highest in Ywalateke (0.58±0.13) and lowest in Chepkopegh (0.48±0.14). On the other hand, Chepkopegh (34.26±21.04) recorded higher concentrations of available phosphorus (P), while Ywalateke (15.65±7.0) had lowest. Only pH showed significant difference among the locations (p < 0.05), Chepkopegh (6.71±0.56a), Morpus (6.27±0.25a) and Ywalateke (5.62±0.34b).

SOC stocks (0-20 cm) ranges included, enclosures aged 2 – 8 yrs (14.42±1.9 to 19.8±3.8 ton/ha), 12 – 18 yrs (17.4±1.3 to 18.1±6.4 ton/ha) and above 20 yrs (12.5±2.6 to 18.3±1.9 ton/ha). Cultivated enclosures recorded SOC stocks of 14.2±1.1 and 21.0±5.5 ton/ha. Open grazing had a range of 10.3±2.3 to 17.5±2.0 ton/ha. Highest SOC contents and stocks were recorded in the younger enclosures (2-8 and 12-18 years).

Soil properties did not differ among the three management systems in the three locations. SOC content as well as C stocks did not significantly differ across the three management systems in the three locations. However, higher SOC contents and SOC stocks were recorded in the enclosures and crop lands compared to open grazing. Duration of enclosing did not have significant effect on the SOC carbon stocks in the enclosures.

Keywords: Chepareria, rangelands, enclosures, ecosystem services, semi – arid lands, drylands, livelihood, SOC accumulation.
1 Introduction

1.1 Problem statement

Due to increased anthropogenic pressure, ecosystems have been tremendously altered to the extent of threatening the services they provide to society (Balmford and Bond, 2005; MA, 2005; Swallow et al., 2009). A severe exploitation of ecosystem goods can reduce the ecosystem’s ability to produce services and, over a certain limit, can compromise ecosystem structures and functions (Häyhä and Franzese, 2014). Among the ecosystem services provided by soils, climate change mitigation through carbon sequestration is of growing interest (Franco et al., 2015). Soils are an important carbon (C) sink in the form of soil organic carbon (SOC) and are estimated to hold about two thirds of the planet’s terrestrial carbon pool (Stockmann et al. 2013). Due to their interaction with biosphere and atmosphere carbon pools (Kutsch et al., 2010), soils are a critical component in the global carbon cycle. Because of the size of SOC pool, even small changes of SOC stocks globally would result in a significant effect on the atmospheric CO₂ concentration (Lal, 2004).

Grasslands cover about 20–40% of the global ice free land mass, corresponding to 10–30% of global terrestrial SOC stocks (Anderson, 1991; Eswaran et al., 1993; Cernusca et al., 2008). If well managed (Scholes et al., 1996), they have a high potential to store a high fraction of atmospheric CO₂ in form of stable C in the soil (Reid et al., 2004). Rangelands also provide a range of provisioning services like forage supply for livestock production (Havstad et al., 2007; Yahdjian et al., 2015).

Nonetheless, about 10–20% of world’s drylands suffer from recent degradation as well as losses of soil carbon due to intensive grazing and agricultural practices (Trumper et al., 2008). Ultimate causes are typically associated with policies, socio-economic changes, or interactions of socio-economic and governance factors with climatic stressors such as drought (Bedunah and Angerer, 2012). The proximate causes of rangeland degradation include overgrazing, unsustainable fuel wood use, mining, and plowing of rangelands, with subsequent loss of soil productivity. Severe land degradation upsets the dynamics of the fragile arid and semi-arid rangeland ecosystems, and sometimes desertification has occurred where rangelands have been mismanaged (Jeddi and Chaieb, 2010; Pei et al., 2008; Qi et al., 2011). This in turn affects the hydrological cycles, biochemical cycles, energy flows and results in increased aridity (Dregne, 1992). Due to the fact that semiarid rangelands occupy a vast area, which is about 44% globally, their wellbeing, good soil quality and good vegetation is of great concern (FAO, 2004). This is because of their value for ecosystem services including food, water, and livelihoods for many of the worlds’ poor (Bedunah and Angerer, 2012) where about 33% of the population are food insecure (Perez et al. 2007).

Understanding how different land use and management systems can both maintain and enhance ecosystem services offered by rangelands, as well as identifying where the trade-offs between these goals are situated, pose key research challenges (Powlson et al., 2011). Increasing C
storage in the soil through carbon sequestration in the soil organic matter (SOM) pool could be one of the ways to counteract the ongoing global warming due to increasing atmospheric CO$_2$ concentrations (Breulmann et al. 2015). In addition, soil organic matter is an important source of plant nutrients and can enhance soil aggregation, reduce soil erosion, increase cation exchange, water holding capacities. SOC is therefore a key regulator of grassland ecosystem processes. Consequently, changes that reverse declining productivity can potentially also lead to increased soil carbon (Conant and Paustian, 2002).

Different management systems have been practiced which promote soil organic carbon sequestration. According to De Gryze et al. (2004), SOC sequestration could be achieved through afforestation as form of land conversion, but also through the establishment of enclosures (Bunning, 2009). Enclosures are “enclosed” parts of the rangeland that are excluded from routine activities such as grazing of animals for a given period of time, usually not less than three years, to restore degraded rangeland ecosystems (Behnke, 1986; Verdoordt et al., 2010). This allows the land to recover through regrowth of vegetation, which positively effects biodiversity (Asefa et al., 2002; Abebe et al., 2006) and soil fertility (Mekuria et al., 2007). Establishment of enclosures as a form of rangeland management has taken peak in most of the Sub-Saharan African rangelands. In Kenya and Ethiopia for example, it has gained acceptance in as an effective rangeland management tool among the local people (Mureithi et al., 2014; Wairore et al., 2015; Abebe et al., 2006).

As enclosures are established to improve the livelihood of the communities in the drylands through provision for their immediate needs, the vulnerability of these communities to vagaries of climate change cannot be underemphasized, especially in developing countries like Kenya. Monitoring the capacity of the current management practices to sequester carbon is of great importance to create a win-win situation. It is paramount also in understanding where the trade-offs are involved between peoples` needs and carbon sinking (Powlson et al., 2011).

This study focuses on enclosure management of the previously degraded semiarid rangelands of Chepareria West Pokot, Kenya. In this area, agroforestry and enclosures have been used for years to manage the rangelands. Since 1987, the Vi-Agroforestry organization has been running a rehabilitation program through enclosure management (Makokha et al., 1999). Several studies (Wairore et al., 2015; Svanlund, 2014; Makokha et al., 1999) have been conducted on how this enclosure management has impacted on the livelihood and vegetation in the region. However, no studies have been conducted to determine the stocks of SOC and the influence of the current management on soil properties on a larger scale in this region. This study focusses on the impact of enclosure management systems and enclosure age, cultivation and open grazing management regimes on soil properties and soil organic carbon accumulation. Moreover, it is aimed at setting a stage for which future studies on monitoring carbon sequestration in the region can be carried out.
1.2 Objectives and research questions

The main objective of this research is to study the effect of different management systems on SOC accumulation in Chepareria, West Pokot County, Kenya. SOC contents will be quantified and compared for fenced cropland, open grazing land and enclosures, and linked to their specific management and position in the landscape. Besides SOC, also other relevant physico-chemical soil quality indicators were determined. Lastly, the study aims to assess the effectiveness of enclosure management as a dryland management tool to sequester C and improve soil quality and atmospheric C regulation in Chepareria, West Pokot County, Kenya.

Specific objectives are:

1. To determine the impact of current management strategies on soil properties, with specific attention to their impact on SOC accumulation in the location
2. To assess the impact of enclosure age on soil physico-chemical properties and its influence on SOC accumulation
3. To assess the vertical topsoil organic carbon profile under these different management strategies

These objectives will answer the following research questions:

1. Is there a significant difference in soil physico-chemical properties between the fenced croplands, enclosures and open grazing lands?
2. What is the effect of enclosure age on soil physico-chemical properties in general and its specific influence on SOC accumulation?
3. Does sampling of up to 30 cm depth capture the effect of current management strategies on physical and chemical soil properties?
2 Literature review

2.1 Importance of drylands for SOC accumulation

Plants take up carbon dioxide from the atmosphere and integrate it into plant biomass through photosynthesis. Some of this carbon is emitted back to the atmosphere but the remainder, namely the living and dead plant parts, above and below ground make up an organic carbon reservoir (Trumper et al., 2008). Some of the dead plant matter is incorporated into the soil as humus, thereby enhancing the SOC pool (Trumper et al., 2008).

Carbon sequestration in drylands is severely constrained by limited water and erratic rain (FAO, 2004). This water scarcity limits plant productivity. Consequently, soils of drylands contain small amounts of C (between 1 and less than 0.5%) (Lal, 2002). Despite drylands exhibiting low plant biomass (6 kg m\(^{-2}\)) compared to other terrestrial ecosystems (8-10 kg m\(^{-2}\)), dryland carbon sequestration is of global significance because of the large surface area of drylands which covers about 40% of the earth ice free surface (Trumper et al., 2008). Dryland carbon reserves are estimated at about 27% of the total global SOC reserves (MA, 2005). In Africa, about 59% of the total C stock is held in drylands (Campbell et al., 2008; UNEP 2008).

Overgrazing and unsustainable agricultural practices lead to the depletion of the SOC pool (Lal, 2001a; Powlson, Smith and Coleman, 1998). This pool can be increased by addition of biomass to the soil (Powlson, Smith and Coleman, 1998).

There are some aspects of dryland soils that work in favour of carbon sequestration (CS) in arid locations. Dry soils are less likely to lose C than wet soils, as lack of water limits soil mineralization and therefore the flux of C to the atmosphere (Glenn et al., 1992). Consequently, the residence time of C in dryland soils is long, sometimes even longer than in forest soils (Olsson et al., 2001; FAO, 2004). The issue of permanence of C sequestered is an important one in the formulation of CS projects (FAO, 2004). Although the rate at which C can be sequestered in these locations is low, it may be cost-effective, particularly taking into account all the side-benefits resulting for soil improvement and restoration (Schlesinger, 1999). Soil-quality improvement as a consequence of increased soil C will have an important social and economic impact on the livelihood of people living in these areas (FAO, 2004).

Investigation by means of soil sampling and modeling showed that the potential to increase the soil carbon content in semiarid agro-ecosystems in the Sudan by increasing fallow periods, would result in increased soil organic matter (SOM) content (Olsson et al., 2001). It was concluded that economic gain from future carbon sequestration programs has the potential of making a significant contribution to the household economy (Olsson et al., 2001).

2.2 Characterizing and measuring of SOC accumulation in drylands

Measuring and characterization of SOC has faced many challenges which come primarily from the methods used to estimate the amount of C stored in the soil (Rossel et al., 2006; Jones et al.
Most conventional methods used usually disregard the complex and multi-component interactions that occur in the soil while trying to establish the relationship between soil chemical and physical properties (Awiti et al. 2008; Rossel et al., 2006).

The other challenge is related to the expensive resources that have to be put in place during the whole process of measuring SOC (Jones et al., 2007; Brown et al., 2006). There arises a trade-off challenge between cost and accuracy of SOC measurement (Jones et al. 2007). The high spatial variability of soil means that a large number of samples need to be collected, increasing the cost, while reducing the number of samples compromises the accuracy (Jones et al. 2007). As result of this, only few locations are fully characterized. Hence the need to develop accurate and inexpensive methods that reduce this trade-off (Brown et al., 2006).

As a result of all these arising concerns, the scientific community has made a considerable effort in developing SOC measuring methods that include both ex situ and in situ techniques (Chatterjee et al., 2009). Ex situ methods conducted in the laboratories such as dry combustion are regarded ‘standard’(Stockmann et al., 2013). However, precise and cost effective methods that go along with efficient sampling methods at the farm or landscape unit scale that allow for acceptable ‘minimum’ replication which in turn lower the cost of sample processing and measurement in laboratory need be developed to validate and possibly monitor SOC (Stockmann et al., 2013). In situ methods such as visible near-infrared spectroscopy (VNIR) and mid-infrared spectroscopy (MIR) have been developed (Rossel et al. 2006; Awiti et al. 2008; Brown et al. 2006). A combination of this sampling and analytical techniques offer cost-effectiveness compared to traditional methods (Janik et al., 2007).

2.3 Dryland management challenges for carbon sequestration

Carbon sequestration in the drylands is limited by factors including low net primary productivity; limited ability to stabilize organic matter in soils low in soil carbon (Kimetu et al., 2009); and the nutrient costs of storing carbon in soils due to the simultaneous sequestration of nitrogen, phosphorus and potassium as the soil organic pool increases (Lal, 2004).

Yet, it is also well known that different management strategies affect various soil properties differently. Understanding the relationship between grassland management and the status of the soil properties such as the soil C and N is not only important academically, but also crucial for sustainable use of grassland available resources and support of grassland ecosystem services (Qiu et al., 2013). Earlier studies have shown that introduction of grazing, conversion to shrub land and introduction of agricultural activities in the grasslands reduced their soil and ecosystem C and N (Han et al., 2008; Qui et al., 2012).

Drylands are unsuitable for intensive agriculture or forestry because of climatic, edaphic or topographic limitations (Holechek et al., 2004). People usually depend on them mainly for livestock production and other ecosystem services such as water and food provision and cultural heritage (Teague et al., 2013; MA, 2005; Steinfeld et al., 2006). Additionally, these drylands store vast amount of carbon (Herrero et al., 2009). To realize optimum ecological services from
these drylands, they need to be kept healthy in order for them to be more stable, resilient and more productive (Heitschmidt and Taylor, 1991; Wessels et al., 2007). To achieve this, it requires adopting long-term plans, conserving of primary resources, choosing appropriate management goals and strategies, and continually adapting to the changing ecological, social, and economic conditions (Teague et al., 2013). However, changes in environmental conditions of these dryland ecosystems often happen so gradually that most people managing them are unaware of them until some threshold condition has been exceeded (Senge, 1994).

2.3.1 Impact of tillage on dryland SOC

Intensive and continuous tillage may cause serious losses of SOC, and induce soil degradation through soil structure destruction (Melero et al., 2009). Tillage strongly influences the distribution and storage of SOC by physically mixing soil and distributing crop residues in the soil (Yang & Wander, 1999) and enhanced contact of litter and inter-aggregate soil organic matter with decomposing organisms (Elliot, 1986; Doran and Werner, 1990).

A review on agricultural management impact on SOC storage showed that, integrated over a 30 cm depth, SOC declined to $0.69 \pm 0.13$ of that found in native lands in the dry tropical climate when land was under conventional tillage (Ogle et al., 2005). Ogle et al. (2005) also noted that when conservation tillage management was replaced by minimum tillage (mulch or chisel plowing) and no-tillage, SOC increased by a factor of $1.10 \pm 0.05$ and $1.17 \pm 0.05$ respectively in tropical dry climate. The one exception noted to this general pattern in climatic constraints on management impacts was the use of low input rotations, which showed mainly the same loss of SOC over 20 years to $0.91 \pm 0.04$ and $0.92 \pm 0.02$, or 91–92% of the amount of SOC found in medium input practices in moist and dry climates while on the other hand, after 20 years, high input and amendments increased SOC by factors of $1.34 \pm 0.08$ and $1.38 \pm 0.06$ in dry and moist climates, respectively for the upper 30 cm depth (Ogle et al., 2005). These results suggest that reducing input through residue removal, fallowing or planting low residue crops, has a consequential effect on C inputs and SOC amount and storage regardless of the climate and its influence on the biochemical mechanisms of these systems.

While climate plays a major role in affecting the changes in SOC under cultivation, it’s evident that management of the land also plays an important role, with decisions made by the land owner determining the increase or decrease of C (carbon) stocks in the soil. Farmers in Chepareria usually allow the animals in their cropped fields after harvest to feed mainly on the maize stable. In addition, they store most of the maize stock for the dry season. Therefore, little or no residues are left on the field. Maize stock is considered as low N and C input residues, but leaving them in the field brings along benefits, such as moisture conservation and reduced erosion.

Among other major C and N input sources in agro-ecosystems, crop roots and aboveground residues generally show different chemical composition (Torbert et al., 2000) and resistance to decomposition (Hooker et al., 2005). Crop residues are suggested to favor higher C:N ratio than the roots of crops (Torbert et al., 2000). The C:N ratio is an important soil quality indicator, as it
reflects the interaction or coupling between the SOC and the total nitrogen (TN) (Lou et al., 2012). This ratio is generally influenced by many factors such as climate (Miller et al., 2004), soil conditions (Diekow et al., 2005) and agricultural management (Dalal et al., 2011). The decrease in active soil organic matter over the decades results in lowered N mineralization rates (Parton et al., 1988). Such losses represented a significant loss of C into the atmosphere (Burke et al., 1991) as well as a significant loss of the productivity of a location (Bauer and Black, 1994).

In cropped systems, tillage continually mixes the upper 20-30 cm of the soil, thereby eliminating the spatial variation of the SOC created by individual plants (Ingrid et al., 2016). This is contrasted in the native perennial grasslands where a plant may remain in the same place for many years thereby creating a local scale variation and distribution of C and N (Vinton and Burke, 1995).

It was found that SOC storage increased when land was set aside from crop production (0.93 ± 0.05, or 82–93% of native stock levels in dry tropical climates), reducing tillage intensities, and increasing C input through cropping practices while SOC declined through plowing out native lands, greater tillage intensity, and decreasing C input through cropping practices for a period of 20 years (Ogle et al., 2005).

Chepareria being a semi – arid location usually experiences prolonged drought seasons like many other drylands. This implies that the high temperatures experienced increase the rate of organic matter decomposition (heterotrophic respiration) and mineralization processes leading to losses of CO₂ to the atmosphere (FAO, 2004).

As demand for agricultural related products increase in the location of Chepareria, expansion of land for agriculture will also increase to feed the ever increasing market for this agricultural products in the area. This means that agricultural operations will be intensified through the use of farm machinery, which will in turn contribute to release of CO₂ into the atmosphere. Tillage in the lands will reduce the organic matter due to rapid decomposition of organic matter through mixing of the soil and hence loss of SOC.

2.3.2 Effect of grazing on dryland SOC

Grasslands cover about 25% of the earth’s surface and account for about 10% of global carbon stocks hence present an important component for carbon cycling and sequestration (Yang et al., 2010; Reeder and Schuman, 2001). The main land use of grasslands is grazing. Therefore, understanding the effects of grazing on SOC accumulation and composition is key for the establishment of proper management strategies of rangelands that would enhance storage of carbon in the soil (Kaiser, 2000).

Increased global demand for livestock products has partly lead to continuous increase of livestock grazing intensity which may further impair biodiversity, strengthen climate change i.e. through additional carbon emissions or lowered sequestration capacity, accelerate soil erosion
and decrease water quality on rangelands (Dorrough et al., 2007; Steinfeld et al., 2006; White et al., 2000).

Petz et al. (2014) observed that annual carbon emission is highest (above 200 t C km\(^{-2}\)) in Sahel, North West Australia, North Africa, Western USA and in Brazil south of the Amazon Basin while annual carbon sequestration is highest (above 350 t C km\(^{-2}\)) in parts of Southern Africa, the southern edge of Australia and Southern Europe. In his results it was estimated that most of the rangelands are net carbon emitters which results from low biomass production and high livestock density.

Many studies conducted in rangeland ecosystems throughout the world have investigated the effect of grazing on soil quality indicators (Ghorbani et al. 2012; Holt, 1997; Qi et al., 2011; Raiesi and Asadi, 2006; Smith et al., 2012; Wen et al., 2013). According to these studies, grazing affects many soil quality indicators such as microbiological, physical and chemical properties. Conducting a study on the effect of grazing (sheep) on the soil in semi-arid Iran, (Raiesi & Riahi, 2014) found 22% increase in bulk density of the soil in heavily grazed sites compared to un-grazed lands which was attributed to compaction due to sheep and goat movement causing soil disturbance especially during rainy seasons. In the same study, pH was significantly higher in the heavily grazed compared to ungrazed sites (Raiesi & Riahi, 2014; Pei et al., 2008). This pH rise resulted from the hydrolysis of urea coming from the sheep’s urine (Haynes and Williams, 1999). It was also noted that, the non – woody sites did not have significant C stock changes with heavy grazing which was attributed to animals returning or balancing the stocks through organic matter addition from their animal waste (Raiesi and Riahi, 2014). The same case was reported by Reeder and Schuman (2002), where C was higher in the grazed compared to un-grazed pastures. He explained that when animals were excluded from grazing, C became immobilized and was localized to above ground litter and annuals that lacked deep roots.

While there exist contradicting results on the effects of grazing on the dryland C stocks (Milchunas and Lauenroth, 1993), many studies have found that continuous use of these lands by grazing resulted in severe degradation and erosion (Jeddi and Chaieb, 2010; Nosetto et al., 2006; Pei et al., 2008; Shrestha and Stahl, 2008). Arid and semi-arid ecosystems are very fragile and desertification has occurred where they have been mismanaged. With improved management strategies such as enclosures however, many have been restored (Jeddi and Chaieb, 2010; Li et al., 2012; Pei et al., 2008; Qi et al., 2011).

Literature from different researches have presented inconsistent results on the effect of grazing on carbon sequestration, with some studies reporting increased carbon storage, studies in Wyoming and Colorado showed that SOC content was significantly higher by 10Mg ha\(^{-1}\) for 30 cm depth in the lightly and heavily grazed mixed grass pastures compared to the non-grazed enclosures (40 years restricted grazing) (Reeder and Schuman, 2002), while others reported a decrease. Another study in Inner Mongolia, northwest China reported that 6 years of grazing exclusion resulted to an increase in SOC while decrease of SOC was recorded in the grazed
pastures (Pei et al., 2008; Qi et al., 2011). No significant difference was observed in carbon storage between enclosures and grazed pastures \((p = 0.42)\) in North West Patagonia (Nosetto et al., 2006). Medina-Roldán et al. (2012) also reported no significant difference in grazed pastures and grazing enclosures \((5889 \text{ g m}^{-2} \text{ and } 6238 \text{ g m}^{-2})\) respectively. Other studies that reported no differences include Johnston et al. (1971), Milchunas and Laurenroth, (1993), and Gill (2007).

Although the outcome of studies on the effect of grazing on SOC are fairly inconsistent (Reeder and Schuman, 2001), generally grazing has shown to affect directly or indirectly biochemical processes, microbial activities and SOC through different interrelated mechanisms (Raiesi and Riahi, 2014). Application of different grazing management techniques to increase forage production has shown to increase soil organic matter (SOM) leading to increased carbon sequestration (Conant et al. 2001).

2.4 Enclosures, an emerging rangeland grazing management system, and its influence on SOC

In sub-Saharan Africa, improvement in natural resource management is broadly observed to be the key to overcoming both developmental and environmental problems (Woodhouse, 2003). Many questions arise regarding the appropriateness of the technical choices in managing land and water (Reij, Scoones & Toulmin, 1996). However, there was a consensus in the United Nations Convention to Combat Desertification (UNCCD) in 1995 (Tomlin, 1995) on the need for reform of governance of these resources to allow a more decentralized management and more security of tenure to existing resource users (Woodhouse, 2003).

Different forms of rangeland management strategies have been used in the past. Pastoralists can practice fallowing by leaving some areas of the land unutilized during the rainy season, utilizing them as drought pastures during the dry season. However, due to the changes taking place in the drylands such as population increase, urbanization, cultivation, policies that encourage permanent settlement and the need to practice market based livestock production (Verdoodt et al., 2010; Angassa and Oba, 2010), new ways to manage these dry-lands had to be developed.

Use of enclosures has been found to be a promising and sustainable management tool for the rangelands (Mureithi et al., 2010). Enclosures are areas that have been closed off to exempt them from grazing for a given period of time, usually not less than 3 years (Verdoodt et al., 2010; Mureithi et al., 2014). The restriction of grazing allows vegetation regeneration, which has a positive effect on biodiversity (Abebe et al., 2006), soil fertility restoration (Mekuria et al., 2007; Su et al., 2005) and increasing of water availability (Hongo et al., 1995). Regeneration of vegetation allows enclosures to be used for rotational grazing (controlled grazing), contractual grazing (allowing other locals to graze their animals at a fee) and also for standing and cut hay.

Mekuria (2011) found that use of exclosures/enclosures had an effect on above ground soil C and also below ground soil C \((0.2 \text{ m})\). The author attributed this to increased biomass production, reduced soil erosion and improved water infiltration as a result of enclosure establishment. In Baringo, Kenya, Mureithi et al. (2014) found that use of enclosures increases soil carbon.
Improvements in rangeland management, for example, through enclosures, have the potential to sequester 1.3 to 2 gigatonne carbon dioxide equivalents (Gt CO$_2$eq) worldwide by 2030 (Smith et al., 2007). However, to be able to include livestock-based agro-pastoral drylands into the international C sequestration discourse and the associated potential payment schemes, a detailed understanding of C dynamics in different forms of enclosure management regimes is needed (Nyberg et al., 2015).

2.4.1 Opportunities for enclosures to sequester carbon

Several factors influence the capacity to sequester carbon, among them the climatic zone, past history and status of the land resources, soil and vegetation, and also the opportunities that are available to change the management practices such as management techniques, economic trade-offs, political will, social organization, land tenure and incentives (Bunning, 2009).

While some factors such as climate of a location cannot be changed, the opportunity to improve on sustainable use of available resources can be achieved through human intervention by use of different management techniques in the drylands such as use of enclosures. Enclosures offer a sustainable management strategy for controlled grazing in the rangelands. For example, studies in different locations of Ethiopia show increased soil carbon after establishment of enclosures. In Tigray, Ethiopia, Mekuria (2013) found an estimated increase in C of 3.1 Mg C ha$^{-1}$ yr$^{-1}$ under 20 years of enclosure, also Mekuria, (2011) reported 41 to 60% increase in C stocks as a result of enclosure establishment. In the semi-arid rangelands in Kenya, Baringo lake basin, Mureithi et al. (2014) reported a 43% increase in carbon content from 3.91 in open grazing to 5.60 mgC g$^{-1}$ soil in private enclosures and 150% C content increase from 3.69 in open grazing to 9.20 mgC g$^{-1}$ soil in the community enclosures.

Most of the increase in soil carbon is attributed to increase in biomass production that lead to increased litter size on the ground (Mekuria, 2013). Many studies (Alam et al., 2013; Verdoodt et al., 2009; Mekuria, 2011; Medina-Roldán et al., 2012; Pei et al., 2008; Wang et al., 2016; Mureithi et al., 2014; Angassa & Oba, 2010; Wairore et al., 2015; Mekuria, 2013; Wu et al., 2014) show that enclosures have led to increased biomass production. Descheemaeker et al. (2006) reported an increase of biomass from 20 g m$^{-2}$ in open grazing to 600g m$^{-2}$ in enclosures. In Kenya, West Pokot county, Chepareria, (MODIS NDVI) analysis of the vegetation pointed out that total vegetation had increased by 86% between 2001 and 2014 and only 10% of the area of Chepareria recorded a decrease in vegetation within this period (Nyberg et al., 2015). In enclosures total vegetation had increased by 40% compared to adjacent open grazing lands (Nyberg et al., 2015).

Thus enclosures offer opportunity of being integrated in carbon sequestration projects as highlighted by Olsson et al. (2001). Projects funded by developed-world organizations or governments to sequester carbon in smallholder systems in the developing-world could allow large areas of otherwise cultivated land to revert to semi-natural vegetation, at least in temporary, sometimes long-term fallow. Such schemes would also enable developing countries to become
active participants in the fight against climate change: something that is as close to a win-win situation (Olsson et al., 2001).

### 2.4.2 Effect of enclosure management and age on SOC

Verdooodt et al. (2010) observed that inside the private enclosures in Baringo, Kenya, rehabilitation of the standing crop with time is predominantly realized during the first 6 years of private enclosure management, where grazing and grass cutting activities are reduced immediately after enclosure establishment. In contrast, the standing crop of the communal enclosures tends to increase with enclosure age. Verdooodt et al. (2010) concluded that within the given time frame, both private and communal enclosure management strategies were equally successful in rehabilitating the herbaceous cover, but the standing crop cover was significantly lower in the private enclosures. Angassa and Oba (2009) indicated that the age of the enclosure did not have a significant effect on herbaceous biomass, grass basal cover and richness. Similar patterns were shown in published work in the highlands of Bolivia (e.g. Buttolph and Coppock, 2004), signifying that variation in age of enclosures had no significant effect on the aboveground biomass. However, findings by Angassa and Oba (2009) confirmed that herbaceous species richness declined with an increase in age of the enclosures. These findings are in correspondence with earlier studies conducted in East Africa (Asefa et al., 2003; Oba et al., 2001), Sahel rangelands (Hiernaux, 1998) and in the Inner Mongolia Autonomous location, northern China (Zhang et al., 2005), suggesting that short-term exclusion promoted herbaceous species richness, while long-term resting was not beneficial. Zhang et al. (2005), for example, reported that the number of species increased from 7 to 17 in the 6-year and 10-year enclosure, respectively, while it declined to 14 in the 18-year enclosure. Similarly, Hiernaux (1998) reported greater plant species richness in the 3-year-old than in the 14-year-old enclosure.

Studies of enclosures in Ethiopia high and low lands indicated increase of SOC with duration of enclosures (Mekuria, 2011). Mekuria (2013) found that increase in carbon stocks was only significant between the 5- year and 20 – year old enclosures thus change of the carbon stock was not linear with time. Girmay et al. (2009) recorded increase in soil organic C of 22.6 Mg C ha$^{-1}$ in the upper 15 cm of the top soil depth after 8 years of enclosure establishment while Tsetargachew (2008) found in the same depth an increase of soil organic C of 31.3 Mg C ha$^{-1}$ after 20 years. In Kenya, Verdooodt et al. (2009) recorded an increase of SOC of 6.6, 9.6, and 10.6 Mg C ha$^{-1}$ in the above 15 cm depth after 15, 18, and 23 years of enclosure establishment, respectively.

### 2.5 Feedback loops between climate and SOC accumulation in the sub-Saharan drylands

A much speculated effect of climate change is that the rise of temperatures will lead to increased microbial respiration resulting to increased soil organic matter decomposition rates (Fang et al., 2005; Davidson and Janssens, 2006). The likelihood for such a positive feedback, whereby increased temperatures will lead to loss of soil carbon thereby increasing atmospheric carbon
dioxide, thus further increasing temperature, is considered a serious threat to the stability of the Earth’s climate (Kirschbaum, 2006; Heimann and Reichstein, 2008).

Carbon sequestration is constrained by the high temperatures that prevail in many parts of Sub-Saharan Africa. Heat reduces the conversion of plant residue to humus and accelerates soil organic matter decomposition, which translate into lower levels of soil organic matter (0.5–1.0%), poor moisture retention capacity in soils, and loss of resilience related to increasing aridity and erratic rainfall (Lal, 2002a; FAO, 2004a).

There are studies that reported elevated temperature can have opposite effects on SOC change, concomitantly enhancing SOC input by promoting primary production and accelerating SOC decomposition rate as well (Davidson et al., 2002; Gao et al., 2013). Results from Poeplau et al. (2011) showed that soils are able to sequester carbon at a faster rate to reduce greenhouse gases under current global warming trend. Precipitation has been known to promote primary production and increase the roots, root exudates and plant residues into soils as SOC input (Kirschbaum, 1995; Gao et al., 2013). However, Xiong et al. (2014) observed a negative relationship between SOC sequestration rate in the top soils and mean annual precipitation. This was attributed to sandy texture of Florida soils with high permeability that allows more organic material to migrate vertically to lower layers under higher precipitation (Jobbágy and Jackson, 2000). This could however relate to many parts of the arid and semi-arid lands of the Sub-Saharan Africa.

### 2.6 SOC accumulation and improved livelihood in sub-Saharan drylands

The combined effect of climate change and globalization has profound implications for livelihood vulnerability in Africa (O’Brien and Leichenko, 2000). Soil carbon accumulation efforts may generate opportunities but also challenges to improving livelihoods in drylands.

#### 2.6.1 Opportunities for improved livelihood through SOC accumulation

Soil carbon fundamentally plays a critical role in the drylands, primarily as a driver of ecosystem services such as plant production, and contributes to increasing resilience to climate variability and change (Cowie et al., 2011). People living in dry areas especially in the sub-Saharan Africa are faced by many challenges, such as climate variability, soil erosion and drought.

The time Kyoto protocol opened the possibility for less developed countries to receive payments for carbon offsets based on land use, the view appeared that African communities may be able to benefit rather than only suffer from these global changes (Bartel, 2004; Tieszen et al., 2004). In a review, Grace et al. (2006) found that an estimate of 0.14 to 0.39 ton/ha/year C could be sequestered in the tropical savannahs if they were protected from fires and grazing which would even increase their capacity to sink more C. Research has shown that rangelands in semi-arid Africa have a greater potential to sequester carbon than the croplands in the same location and controlled grazing has been identified as one of the strategies to achieve such potential (Lal, 2002; Ringius, 2002).
Despite the challenges of carbon sequestration in the drylands, Perez et al. (2007) indicated that, for African pastoralists, even modest improvements in natural resource management may yield gains of 0.5 t C ha\(^{-1}\) yr\(^{-1}\), which translates into $50 yr\(^{-1}\) (estimating C at $10 per ton). This gain would bring about a 14% increase in income for the pastoralists, at least where half earn less than a dollar per day (Reid et al., 2004).

### 2.6.2 Trade-offs between SOC accumulation and improved livelihood

Climate change mitigation efforts that are linked to land use and land management generally seek to increase the amount of carbon stored in soils and biomass (Stringer et al., 2012). However, a trade-off exists in that, to realize many livelihood and ecosystem service benefits from SOC, it requires depletion of this same SOC, for example through crop production and thus a net release of CO\(_2\) (Janzen, 2006).

It is clear that resource users will invest in practices that enhance C pool if it promises benefits higher than those of the alternative use of land, labor and capital (Perez et al., 2007). If opportunity costs of land, labor and capital are low, as they are in most of Sub-Saharan Africa, there will be little motivation for producers to invest in more intensive C enhancing management practices (Diagana et al., 2007). In sub-Saharan Africa, concern arises on the issue of infrastructural and institutional weaknesses, poor systems of governance and political representation, and low levels of literacy and leverage among the rural poor that may give rise to obstacles, abuses, conflicts (Nelson and de Jong, 2003; Gundimeda, 2004). Also the formality and complexity of carbon accounting and trade agreements may favor those with clearly defined rights to resources and with the power and capacity to enforce them (Nelson and de Jong, 2003; Smith and Scherr, 2003; Gundimeda, 2004) leaving out the minority who do not have access to such resources (Asquith et al., 2002; Tipper, 2002).

In Chepareria, West Pokot, there’s already the issue of privatizing the land (private enclosures) to some extent has led to land conflict whereby some people have no access to enclosures and this has resulted to boundary disputes, livestock trespassing enclosed land and internal family disputes related to land use and land ownership (Nyberg et al., 2015). Similar observation was made by Mureithi et al. (2014) whereby privatization of land created a situation of the have and the have-nots creating a challenge for use of enclosures as a sustainable management technique of the rangelands in the semi–arid and arid parts of Kenya. The other issue is the need to use fertilizer in the cultivated parts of Chepareria, for improved productivities but socioeconomic constraints largely prevent such improvements, resulting in a very limited scope for changes in soil carbon management (Tiessen et al., 1998).

In addition to social differentiation, spatial variation in resource availability means that practices that seem feasible and eligible for C payments in one location are not necessarily so in another location (Tschakert, 2004.). It is important to understand these social, spatial, and sectoral variations in potential profitability in order to design a C credit scheme that contributes to poverty reduction (Perez et al., 2007).
3 Materials and Methods

3.1 Study area

3.1.1 Geographical location
Chepareria is located in West Pokot county, north west part of Kenya bordering Uganda at 1º19’N, 35º12’0E (Nyberg & Högb erg, 1995; Nyberg et al., 2015) (Figure 3.1). It is an administrative division consisting of six locations and fifteen subdivisions, with an area of approximately 500 km² (KNBS, 2009).

Figure 3.1: Location of Chepareria ward in West Pokot County, Kenya. Adapted from the National Drought Management Authority (NDMA) (NDMA, 2014)

3.1.2 Physiography and climate
Generally, the altitude of Chepareria ranges between 1200 and 1600 above sea level. It is characterised by a gently undulating plain that is surrounded by hills and mountains with peaks up to 3000 meters above sea level (Touber, 1991). Annual rainfall is highly variable depending on the altitude and ranges between 400-1500 mm·year⁻¹, while temperatures range between 20°C to 30°C (Jungerius et al., 2002). It has a bimodal rain pattern with the main rainy season starting in March and ending in June, whereas the short season runs from October to November (Huho et al., 2011).

3.1.3 Geology, soil, vegetation and water resources
The bedrock in Chepareria is primarily metamorphic with high levels of ferromagnesian minerals. The soil types vary from shallow and friable in the lowlands to deep, well-drained, reddish brown sandy loams in the upper locations of Chepareria while soil fertility varies from
low to moderate (Sposito 2013). Most of the rivers are generally dry during the two dry seasons of the year. Establishment of rain water harvesting techniques such as water pans and bore holes has served to reduce the severity of the scarcity of water (World Vision Kenya, 2014). Vegetation is steppe-like dominated by grasslands with scattered native and few exotic tree species (Wairore et al., 2015; Svunland, 2014). Signs of erosion act as indicators of modern day human activities in the location (Svunland, 2014).

3.1.4 Land use
Located in the semi-arid location of Kenya, sedentary pastoralism forms the basis of livelihood. In the earlier time, 3 to 4 decades ago, Pokot people used to be nomads moving with their livestock in search of water and pasture. Since the intervention of Vi-Agroforestry (Swedish funded non- governmental organization) in 1987, there has been a change in the direction of management systems from open range grazing to use of enclosures for controlled grazing (Svunland, 2014). Establishment of enclosures has seen the Pokot people lead a settled life raising their animals in their own land without having to move. Mixed farming is practiced in the higher altitude areas with more rainfall, while the lower altitude area of Chepareria is mainly dominated by sedentary agro-pastoralism (Wairore et al., 2015). The main income generating economic activity is livestock production. Cultivation of crops such as maize, millet, beans and sorghum is also carried out (Öborn et al., 2015). Although the NGO intervention was faced out in 2001 (Kitalyi et al., 2002), enclosures adoption by the Pokot people has continued ever since after the locals saw the benefits. There are two main land management regimes in these three locations, mainly livestock dominated enclosures and crop dominated enclosures. The main objective of livestock dominated management regimes is to support livestock production. However, this is also integrated with some farming which is mainly for subsistence crop production. On the other hand, crop dominated management regime’s main objective is to support crop production. Again under this management some integration with livestock is practiced (Wairore et al., 2015). Table 3.1 adopted from Wairore et al. (2015) summarizes the land use in the three locations.
Table 3.1: Enclosure management regimes and practices in three locations of Chepareria

<table>
<thead>
<tr>
<th>Location/Site</th>
<th>Livestock-based agro-pastoralism</th>
<th>Crop-based agro-pastoralism</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grazing and farming</td>
<td>Grazing, farming and contractual grazing</td>
<td>Farming, grazing and fodder production</td>
</tr>
<tr>
<td>Ywalateke</td>
<td>30.0</td>
<td>13.4</td>
<td>13.3</td>
</tr>
<tr>
<td>Chepkopegh</td>
<td>66.7</td>
<td>15.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Morpus</td>
<td>76.7</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Average Chepareria ward</td>
<td>60.0</td>
<td>13.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>

3.1.5 Field selection

Three administrative locations were selected in Chepareria, namely: Ywalateke, Chepkopegh and Morpus. Ywalateke is located on a higher altitude, at about 1680 m above sea level, Chepkopegh and Morpus are situated at about 1570 m above sea level. Ywalateke experiences a more stable and higher rainfall compared to Chepkopegh and Morpus (Wairore et al., 2015) with approximately 700 mm per annum in Ywalateke and about 400 mm in Chepkopegh and Morpus. Vi Agroforestry was active in these three locations before facing out and most of the enclosures established in these locations were as a result of the intervention of Vi-Agroforestry (Wairore et al., 2015).

A systematic random sampling strategy was adopted to select fields. Selection criteria included land management (open rangeland, enclosure, and cropland) and age of enclosure (three age classes). Table 3.1 provides an overview of the selection criteria and number of fields. In each of the three locations, an equal number of plots per land management type were sampled (i.e. 12 enclosures, 4 cropland areas, and 4 open grazing areas per location). Random sampling was done based on lists of households provided by the local administrations.
Table 3.2: Characterisation of the selected fields

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Classes</th>
<th>N° of fields selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Ywalateke</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Morpus</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Chepkopegh</td>
<td>20</td>
</tr>
<tr>
<td>Land management</td>
<td>Enclosures</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Cultivated</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Open grazing</td>
<td>4</td>
</tr>
<tr>
<td>Enclosure age</td>
<td>2 – 8 yrs</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>12 – 18 yrs</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Over 20 yrs</td>
<td>4</td>
</tr>
</tbody>
</table>

Record of elevation and coordinates of each sampled field was taken (figure 3.2). In addition, distribution of vegetation and the physical condition of the sampled fields was also briefly described.

Figure 3.2: Geographic location of the sampling sites (white points) within Ywalateke, Chepkopegh and Morpus shown on a Google Earth map
3.2 Soil sampling design

Sampling was done using a zigzag sampling strategy at equal distance intervals between the sampling points as shown in figure 3.3. The distance between one sampling point and another depended on the size of the area being sampled, with a 15m minimum distance between points and a maximum of 20m for relatively small fields and large fields respectively. To avoid edge effect, a distance of 5m from the edges was maintained. Nine sampling locations were selected on the outlined zigzag for each field.

Using an auger, disturbed soil samples were taken at three soil depth intervals of 10 cm up to a maximum of 30 cm depth. The nine collected samples for each depth interval were thoroughly mixed to generate three composite samples of about 500g from each field, representing the soil at 0-10 cm, 10-20 cm and 20-30 cm depth. These disturbed soil samples were then put in well labeled clean plastic bags.

![Figure 3.3](image)

**Figure 3.3:** A representation of the sampling strategy that was employed during soil sample collection in the field. Big black dots indicating the sampling points in the field.

Undisturbed soil samples for bulk density determination were collected using Kopecky rings (100 cm³). Three locations within each field were sampled at 0-10 cm and 10-20 cm depth. These rings were then carefully labeled, covered and placed in a box for transport to the lab for analysis.

3.3 Soil lab analysis

Soil parameters analyzed were SOC (%), total nitrogen (Ntot, %), exchangeable potassium (K, cmol (+)/kg), available phosphorus (Pav, ppm), cation exchange capacity (CEC, cmol (+)/kg),...
soil pH-H₂O was measured in water using a 1:2.5 soil solution ratio, bulk density (BD, g/cm³), and soil texture (sand, silt and clay content, w %).

SOC was analyzed using Walkley and Black method (Walkley and Black, 1934). Total Nitrogen was analyzed using the Kjedhal method (catalyst and acid digestion). Mehlich method was used for available phosphorus analysis where 1.1N HCL and 0.025N H₂SO₄ were used for P extraction with the weight ratio of soil to volume of solution being 5.0g to 50.0ml (10) and time used to shake being 30 minutes. Exchangeable Ca, Mg Na and K were extracted from the soil by leaching with 1M ammonium acetate then reading with flame photometer for K. For CEC, after leaching by washing with alcohol, ammonium was replaced with potassium chloride, and distilled. Bulk density was determined using the core method (Blake and Hartge, 1986). Texture was measured using the hydrometer method (Gee and Bauder, 1982). All lab analysis were done at the University of Nairobi College of Agriculture and Veterinary Sciences.

Soil organic carbon stock (SOC stock, ton ha⁻¹) was determined using the formula:

\[ \text{SOC} = \left(\frac{\text{SOC}}{100} \times \text{BD} \times \text{depth (m)} \times 10000 \text{ m}^2 \text{ ha}^{-1}\right) / 1000 \]

Where, SOC is soil organic carbon content in (%) and BD is bulk density in (kg/m³). Calculation of SOC stock was done for each depth separately at 0-0.1m and 0.1- 0.2 m. The values of the C stock were added together to give the stock in the 20 cm topsoil.

3.4 Data analysis

To evaluate the effects of various treatments (location, land management, enclosure age) on soil properties and changes of soil properties with depth, test for normality and equality of variance was carried out and then analysis of variance (ANOVA) and robust tests were conducted to compare the means. Tukey and Tamhanes post-hoc tests were used to identify significant differences between treatments. Pearson correlation was used to assess the interaction of soil properties. All the statistical analyses were carried out using Statistical Package for Social Sciences (SPSS) version 16.

In the data, some values of some soil properties (SOC, N_{tot} and K_{exch}) showed extreme variation from the rest, on the lower side was one value of SOC, and on the higher side few values of N_{tot} and K_{exch}. These values strongly affected the outcome of the analyses and separating them from the rest of the data was important to facilitate the analyses in order to detect the differences more easily.
4 Results

4.1 General characterization of the topsoil (0-30 cm) dataset

Table 4.1 provides an overview of the statistical descriptives characterizing the collected soil dataset, using topsoil 30 cm (or 20 cm for bulk density) averaged values.

The soils in these three locations are characterized by high sand, and low silt and clay content (Table 4.1). The soil showed high variability within and among the three locations. This soil in these three location falls under four textural classes which include, sand, loamy sand, sandy loam and sandy clay loam.

Soil pH generally is near neutral for the three locations with several differences within the locations. SOC content is quite low, just slightly above 0.5%, however, this may be expected for a semi-arid region. Available P for the combined locations is generally on the medium level, however, variations among the locations can be expected as will be seen later in the analyses.

The clay content of the soil is quite low hence affects the CEC. From Table 4.1, combined CEC is quite low.

Generally, the difference in terms of geographical location among these three locations which may influence the climatic orientation of each location may result to some differences in soil properties. Several analyses are therefore carried out to determine this differences.

Table 4.1: Statistical descriptives of the topsoil 30 cm average physico-chemical properties collected in the selected fields.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>n°</th>
<th>Mean</th>
<th>StDev</th>
<th>Min</th>
<th>Max</th>
<th>CV</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>%</td>
<td>60</td>
<td>0.53</td>
<td>0.14</td>
<td>0.23</td>
<td>0.89</td>
<td>0.27</td>
<td>0.18</td>
<td>-0.18</td>
</tr>
<tr>
<td>N&lt;sub&gt;tot&lt;/sub&gt;</td>
<td>%</td>
<td>60</td>
<td>0.06</td>
<td>0.02</td>
<td>0.02</td>
<td>0.11</td>
<td>0.32</td>
<td>0.22</td>
<td>-0.35</td>
</tr>
<tr>
<td>C/N</td>
<td></td>
<td>60</td>
<td>9.47</td>
<td>2.21</td>
<td>6.40</td>
<td>16.60</td>
<td>0.23</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>P&lt;sub&gt;av&lt;/sub&gt;</td>
<td>ppm</td>
<td>60</td>
<td>23.24</td>
<td>17.24</td>
<td>4.27</td>
<td>85.00</td>
<td>0.74</td>
<td>1.79</td>
<td>3.54</td>
</tr>
<tr>
<td>K&lt;sub&gt;exch&lt;/sub&gt;</td>
<td>cmol&lt;sup&gt;+&lt;/sup&gt;/kg</td>
<td>60</td>
<td>0.33</td>
<td>0.27</td>
<td>0.08</td>
<td>2.07</td>
<td>0.83</td>
<td>4.54</td>
<td>27.85</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>60</td>
<td>6.20</td>
<td>0.60</td>
<td>4.90</td>
<td>7.80</td>
<td>0.10</td>
<td>0.46</td>
<td>0.48</td>
</tr>
<tr>
<td>Sand</td>
<td>%</td>
<td>60</td>
<td>74.07</td>
<td>6.36</td>
<td>58.00</td>
<td>85.00</td>
<td>0.09</td>
<td>-0.30</td>
<td>-0.49</td>
</tr>
<tr>
<td>Silt</td>
<td>%</td>
<td>60</td>
<td>8.71</td>
<td>2.70</td>
<td>4.00</td>
<td>19.00</td>
<td>0.31</td>
<td>1.03</td>
<td>3.04</td>
</tr>
<tr>
<td>Clay</td>
<td>%</td>
<td>60</td>
<td>17.24</td>
<td>5.84</td>
<td>7.00</td>
<td>32.00</td>
<td>0.34</td>
<td>0.20</td>
<td>-0.57</td>
</tr>
<tr>
<td>CEC</td>
<td>cmol&lt;sup&gt;+&lt;/sup&gt;/kg</td>
<td>60</td>
<td>9.04</td>
<td>1.22</td>
<td>6.57</td>
<td>13.15</td>
<td>0.13</td>
<td>0.42</td>
<td>1.06</td>
</tr>
<tr>
<td>CEC&lt;sub&gt;clay&lt;/sub&gt;</td>
<td>cmol&lt;sup&gt;+&lt;/sup&gt;/kg</td>
<td>60</td>
<td>48.45</td>
<td>18.32</td>
<td>24.37</td>
<td>105.57</td>
<td>0.38</td>
<td>1.20</td>
<td>1.10</td>
</tr>
<tr>
<td>BD</td>
<td>g/cm³</td>
<td>58</td>
<td>1.49</td>
<td>0.10</td>
<td>1.25</td>
<td>1.71</td>
<td>0.07</td>
<td>-0.41</td>
<td>0.27</td>
</tr>
</tbody>
</table>

As expected, the correlation analysis results (Table 4.2) show a strong and very significant (p < 0.001) correlation between the granulometric fractions, and between CEC and clay fraction. Absence of a significant correlation between CEC and SOC content might suggest the relatively low contribution of generally low SOC contents to the CEC. SOC and N<sub>tot</sub> were very
significantly strongly positively correlated. $P_{\text{avail}}$ is significantly positively correlated to pH and CEC.

**Table 4.2:** Pearson correlation among the topsoil 30 cm average physico-chemical properties collected in the selected fields (n=58 for bulk density; n=60 for all others).

<table>
<thead>
<tr>
<th></th>
<th>SOC(%)</th>
<th>$N_{\text{tot}}$ (%)</th>
<th>$P_{\text{avail}}$ (cmol/kg)</th>
<th>$K_{\text{exch}}$ (cmol/kg)</th>
<th>pH</th>
<th>SAND (%)</th>
<th>SILT (%)</th>
<th>CLAY (cmol(+)/kg)</th>
<th>CEC (cmol/kg)</th>
<th>BD (g m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC(%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{tot}}$ (%)</td>
<td>.788**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{\text{avail}}$ (cmol/kg)</td>
<td>0.071</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{\text{exch}}$ (cmol/kg)</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-0.056</td>
<td></td>
<td>0.293*</td>
<td>0.247</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-0.069</td>
<td></td>
<td>-0.144</td>
<td>0.105</td>
<td>0.312*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.041</td>
<td></td>
<td>0.214</td>
<td>0.075</td>
<td>.494**</td>
<td>-.403**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.057</td>
<td></td>
<td>0.056</td>
<td>-0.147</td>
<td>0.113</td>
<td>-.905**</td>
<td>-0.023</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>0.062</td>
<td></td>
<td>.289*</td>
<td>0.208</td>
<td>0.25</td>
<td>-.449**</td>
<td>.083</td>
<td>.452**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>BD (g m$^{-3}$)</td>
<td>-0.205</td>
<td></td>
<td>-0.216</td>
<td>-0.013</td>
<td>0.226</td>
<td>0.266</td>
<td>-.282*</td>
<td>-.115</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

*Significant at P < 0.05,  **Significant at P < 0.001

4.2 Topsoil (0-30 cm) physico-chemical properties at the three locations

Several topsoil (0 – 30 cm) parameters varied with regard to location. Table 4.3 lists the physico-chemical topsoil properties recorded in the three locations.

**Table 4.3:** Mean and standard deviation (SD) of the physico-chemical topsoil properties recorded in the three selected locations of Chepareria (n = 20; ±SD). All topsoil values have been averaged over the 30 cm topsoil depth. Bulk density represents topsoil 20 cm. Different letters by column indicate statistically significant differences (p < 0.05). CE = cultivated enclosures, A1 = enclosures aged 2 – 8 years, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazing.

<table>
<thead>
<tr>
<th>Location</th>
<th>SOC (%)</th>
<th>$N_{\text{tot}}$ (%)</th>
<th>C/N</th>
<th>$P_{\text{avail}}$ (ppm)</th>
<th>$K_{\text{exch}}$ (cmol(+)/kg)</th>
<th>CEC (cmol(+)/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ywalateke</td>
<td>0.58±0.13a</td>
<td>0.09±0.12a</td>
<td>8.91±1.86a</td>
<td>15.65±7.00a</td>
<td>0.24±0.13a</td>
<td>8.53±1.08a</td>
</tr>
<tr>
<td>Morpus</td>
<td>0.54±0.14a</td>
<td>0.07±0.04a</td>
<td>9.08±2.18a</td>
<td>17.57±12.76a</td>
<td>0.40±0.15a</td>
<td>8.99±0.89ab</td>
</tr>
<tr>
<td>Chepkopegh</td>
<td>0.48±0.14a</td>
<td>0.07±0.05a</td>
<td>8.65±1.60a</td>
<td>34.26±21.04b</td>
<td>0.37±0.42a</td>
<td>9.50±1.38b</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>pH- H$_2$O</th>
<th>sand (%)</th>
<th>silt (%)</th>
<th>clay (%)</th>
<th>BD (g/cm$^3$)</th>
<th>CECclay (cmol(+)/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ywalateke</td>
<td>5.62±0.34a</td>
<td>76.3±6.04a</td>
<td>67.1±3.19a</td>
<td>17.1±5.82a</td>
<td>1.49±0.10a</td>
<td>54.58±15.99a</td>
</tr>
<tr>
<td>Morpus</td>
<td>6.27±0.25b</td>
<td>73.4±5.26a</td>
<td>9.7±1.25b</td>
<td>16.9±5.52a</td>
<td>1.53±0.07a</td>
<td>59.29±22.40a</td>
</tr>
<tr>
<td>Chepkopegh</td>
<td>6.71±0.56b</td>
<td>72.5±7.27a</td>
<td>9.9±3.12b</td>
<td>17.6±6.40a</td>
<td>1.48±0.08a</td>
<td>60.57±22.59a</td>
</tr>
</tbody>
</table>
4.2.1 Soil texture and bulk density
Results from the three locations showed a generally high sand content, exceeding 70% (Table 4.3). Sand and clay content didn’t differ significantly among the locations. However, silt content (p < 0.05) was significantly higher in Morpus and Chepkopegh compared to Ywalateke despite the three locations having similar textural classes (Table 4.3).

There was no significant difference in bulk density (p > 0.05) at 0-0.2 m depth among the three locations. The bulk densities (1.4 – 1.7g/cm³; Table 4.3) were well within range for the type of soil textures in these locations which have high sand content.

4.2.2 Soil pH, CEC and CEC\textsubscript{clay}
Soil pH (p < 0.001) showed a high statistical difference among the locations, with pH in Chepkopegh and Morpus being significantly higher than that in Ywalateke.

There was a significant difference in the CEC (p < 0.05) among the three locations. Chepkopegh recorded significantly higher CEC (p < 0.05) compared to Ywalateke while Morpus was not different from both locations (Table 4.3). However, this difference is very minimal and may not account for a big difference in this property. This is seen in the CEC\textsubscript{clay} which is not significantly different among the three locations.

4.2.3 SOC and N\textsubscript{tot} content
SOC and N\textsubscript{tot} contents did not show any significant differences between the locations. The values of these two parameters were quite low. Among the three locations, Ywalateke recorded highest for SOC content while Chepkopegh recorded lowest. N content was almost similar in amount for the three locations (Table 4.3).

4.2.4 Available phosphorus (P\textsubscript{avail}) and exchangeable potassium (K\textsubscript{exch})
Despite the high variability in available phosphorus (P\textsubscript{avail}) observed within the three locations (Table 4.3), a significantly higher P\textsubscript{avail} (p < 0.05) was reported in Chepkopegh compared to Ywalateke and Morpus. Exchangeable potassium (K\textsubscript{exch}) content did not differ significantly by location.

4.3 Management system effects on topsoil (0-30 cm) physico-chemical soil properties
Some physico-chemical topsoil properties differed as a result of land management and/or age of enclosure, while others did not show any significant differences in the three locations.

4.3.1 Soil texture and bulk density
Bulk density in all the three locations did not significantly differ across the management types (Table 4.4). Soil texture that is, sand, silt and clay, was not affected significantly by management in Ywalateke and Chepkopegh.

In Morpus however, silt content (p < 0.05) was significantly higher in enclosures aged 2 – 8, 12 – 18 years and cultivated enclosures than that in the open grazing, the differences are very minimal in reality and this difference may not mean much. Clay as well was significantly higher
in enclosures of over 20 years than that in enclosures aged 12 – 18 years and open grazing. Sand also did show significant variability with management in the same location whereby open grazing recorded significantly higher sand content than over 20 years enclosures. Across the different age classes of enclosures, no significant differences were detected with regard to BD for the three locations (Table 4.4).

**Table 4.4**: Means and standard deviation of soil physical properties (0 - 20cm for BD and 0 - 30 cm for texture) under open grazing, rangeland enclosures of various age classes and cropland within three locations in Chepareria. Letters, a, b and c indicate the statistical differences (p < 0.05) per location with (n = 4; ± SD). CE = cultivated enclosures, A1 = enclosures aged 2 – 8 years, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazing.

<table>
<thead>
<tr>
<th>Location</th>
<th>Management</th>
<th>BD (gm-3)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ywalateke</td>
<td>OG</td>
<td>1.50±0.10a</td>
<td>79±7.2a</td>
<td>14±5.7a</td>
<td>7±1.0a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.43±0.06a</td>
<td>73±10.7a</td>
<td>18±6.1a</td>
<td>9±5.7a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.40±0.10a</td>
<td>72±8.1a</td>
<td>22±7.9a</td>
<td>6±1.0a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.43±0.20a</td>
<td>81±7.8a</td>
<td>14±8.7a</td>
<td>5±1.5a</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>1.47±0.06a</td>
<td>75±5.0a</td>
<td>19±8.2a</td>
<td>7±2.9a</td>
</tr>
<tr>
<td>Morpus</td>
<td>OG</td>
<td>1.57±0.06a</td>
<td>79±2.9a</td>
<td>13±3.5b</td>
<td>8±0.6b</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.53±0.06a</td>
<td>71±2.3bc</td>
<td>20±2.9ab</td>
<td>10±0.6a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.57±0.11a</td>
<td>77±2.1ab</td>
<td>13±2.6b</td>
<td>10±0.6a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.46±0.15a</td>
<td>68±0.6cb</td>
<td>23±1.0a</td>
<td>10±0.6a</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>1.50±0.10a</td>
<td>75±5.3abc</td>
<td>17±5.8ab</td>
<td>9±0.8ab</td>
</tr>
<tr>
<td>Chepkopegh</td>
<td>OG</td>
<td>1.57±0.15a</td>
<td>75±1.0a</td>
<td>17±1.2a</td>
<td>8±0.6a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.50±0.10a</td>
<td>70±8.4a</td>
<td>20±9.0a</td>
<td>10±4.6a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.43±0.06a</td>
<td>72±14.1a</td>
<td>17±10.6a</td>
<td>10±4.0a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.50±0.01a</td>
<td>79±4.9a</td>
<td>12±6.2a</td>
<td>9±1.5a</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>1.43±0.06a</td>
<td>77±3.6a</td>
<td>16±5.0a</td>
<td>8±2.0a</td>
</tr>
</tbody>
</table>

**4.3.2 Soil organic carbon (SOC), nitrogen (N\textsubscript{tot}), CEC**

Topsoil (0-30 cm) SOC and N\textsubscript{tot} (p > 0.05) did not have any significant difference across the management types among the three locations. In Chepkopegh, CEC (p < 0.05) was significantly higher in the cultivated enclosures than in the open grazing as well as the oldest enclosures (Table 4.5 Chepkopegh).

With regard to age, soil chemical properties in Ywalateke did not show any significant changes across the different age categories of enclosures, although from the results, 2 – 18 and over 20 years old enclosures had the highest OC content (Table 4.5).

In Chepkopegh high variability in soil properties with age were evident. SOC (p = 0.037) was significantly higher in the younger enclosures (2 – 8 years) than in the open grazing lands. CEC
(p < 0.05) was significantly higher in the 2 – 8 years compared to open grazing and over 20 years old enclosures. 12 – 18 years’ enclosures as well had a significantly higher CEC (p < 0.05) than the open grazing (Table 4.5). SOC content as shown in Table 4.5 in this location show a declining trend with increase in duration of enclosing, that is, the oldest enclosures recorded the lowest SOC content.

No significant differences were induced by age of enclosures in Morpus for any of the soil chemical properties analyzed (Table 4.5). However, SOC increased with enclosure age up to the 12 – 18 years category and a decline started occurring in older enclosures, > 20 years enclosures.

The C:N ratio in the different management systems was low, below 10 for the three locations except for open grazing in Ywalateke which recorded slightly higher than 10 (Figure 4.1). C:N ratio increased from enclosures, cultivated to open grazing in Ywalateke. In Morpus, enclosures and open grazing recorded similar C:N values while the lowest value was in cultivated enclosures. In Chepkopegh however, all the managements recorded almost similar values for C:N (Figure 4.1).

4.3.3 Soil pH, available phosphorus (P_{av}) and exchangeable potassium (K_{exch})

Soil pH and P_{av} did not differ significantly across the management regimes for all the three locations (Table 4.5). In Chepkopegh, K_{exch} (p < 0.05) was significantly higher in the cultivated enclosures compared to grazing enclosures and open grazing (Table 4.5 Chepkopegh). Similarly, in Morpus K (p <0.05) was significantly higher in cultivated enclosures than open grazing (Table 4.5 Morpus). Open grazing in Ywalateke had the highest available P in this location compared to the other management types.

![Figure 4.1: C: N ratio among the different management systems within the three locations at 30 cm depth. (n = 12 for enclosures, n = 4 for cultivated and open grazing), error bars represent the SD.](image)
Table 4.5: Means and standard deviation of soil chemical properties (0 – 30 cm) under open grazing, rangeland enclosures of various age classes, and cropland within three locations in Chepareria. Letters, a, b and c indicate the statistical differences (p < 0.05) per location with (n = 4; ± SD). CE = cultivated enclosures, A1 = enclosures aged 2 – 8 years, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazing

Ywalateke

<table>
<thead>
<tr>
<th>Age years</th>
<th>pH-H₂O (-)</th>
<th>OC (%)</th>
<th>N₁₀₀ (%)</th>
<th>CEC (cmol/kg)</th>
<th>K_exch (cmol/kg)</th>
<th>P_avail (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OG</td>
<td>5.5 ± 0.5a</td>
<td>0.52 ± 0.09a</td>
<td>0.05 ± 0.01a</td>
<td>8.29 ± 1.25a</td>
<td>0.24 ± 0.1a</td>
<td>22.19 ± 5.97a</td>
</tr>
<tr>
<td>A1</td>
<td>5.6 ± 0.3a</td>
<td>0.51 ± 0.14a</td>
<td>0.07 ± 0.03a</td>
<td>8.21 ± 1.4a</td>
<td>0.18 ± 0.03a</td>
<td>18.32 ± 7.72a</td>
</tr>
<tr>
<td>A2</td>
<td>5.6 ± 0.2a</td>
<td>0.60 ± 0.07a</td>
<td>0.08 ± 0.01a</td>
<td>9.03 ± 1.08a</td>
<td>0.31 ± 0.15a</td>
<td>10.67 ± 6.68a</td>
</tr>
<tr>
<td>A3</td>
<td>5.7 ± 0.4a</td>
<td>0.64 ± 0.07a</td>
<td>0.06 ± 0.03a</td>
<td>8.36 ± 1.10a</td>
<td>0.14 ± 0.06a</td>
<td>14.64 ± 6.76a</td>
</tr>
<tr>
<td>CE</td>
<td>5.7 ± 0.5a</td>
<td>0.62 ± 0.24a</td>
<td>0.07 ± 0.02a</td>
<td>8.78 ± 0.87a</td>
<td>0.34 ± 0.16a</td>
<td>12.44 ± 4.76a</td>
</tr>
</tbody>
</table>

Morpus

<table>
<thead>
<tr>
<th>Age years</th>
<th>pH-H₂O (-)</th>
<th>OC (%)</th>
<th>N₁₀₀ (%)</th>
<th>CEC (cmol/kg)</th>
<th>K_exch (cmol/kg)</th>
<th>P_avail (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OG</td>
<td>6.3 ± 0.1a</td>
<td>0.45 ± 0.09a</td>
<td>0.05 ± 0.02a</td>
<td>8.99 ± 0.69a</td>
<td>0.33 ± 0.13a</td>
<td>11.84 ± 3.26a</td>
</tr>
<tr>
<td>A1</td>
<td>6.3 ± 0.3a</td>
<td>0.54 ± 0.25a</td>
<td>0.07 ± 0.03a</td>
<td>9.36 ± 0.69a</td>
<td>0.40 ± 0.18a</td>
<td>22.48 ± 16.17a</td>
</tr>
<tr>
<td>A2</td>
<td>6.1 ± 0.1a</td>
<td>0.60 ± 0.12a</td>
<td>0.08 ± 0.02a</td>
<td>8.44 ± 1.60a</td>
<td>0.40 ± 0.16a</td>
<td>14.49 ± 11.92a</td>
</tr>
<tr>
<td>A3</td>
<td>6.2 ± 0.4a</td>
<td>0.58 ± 0.1a</td>
<td>0.06 ± 0.01a</td>
<td>8.92 ± 0.92a</td>
<td>0.32 ± 0.05a</td>
<td>22.34 ± 19.94a</td>
</tr>
<tr>
<td>CE</td>
<td>6.4 ± 0.3a</td>
<td>0.52 ± 0.07a</td>
<td>0.11 ± 0.08a</td>
<td>9.22 ± 0.17a</td>
<td>0.58 ± 0.12a</td>
<td>16.7 ± 10.0a</td>
</tr>
</tbody>
</table>

Chepkopegh

<table>
<thead>
<tr>
<th>Age Years</th>
<th>pH-H₂O (-)</th>
<th>OC (%)</th>
<th>N₁₀₀ (%)</th>
<th>CEC (cmol/kg)</th>
<th>K_exch (cmol/kg)</th>
<th>P_avail (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OG</td>
<td>6.8 ± 0.5a</td>
<td>0.35 ± 0.08b</td>
<td>0.04 ± 0.01a</td>
<td>8.15 ± 0.37c</td>
<td>0.16 ± 0.04a</td>
<td>28.15 ± 7.56a</td>
</tr>
<tr>
<td>A1</td>
<td>6.9 ± 0.7a</td>
<td>0.60 ± 0.1a</td>
<td>0.08 ± 0.02a</td>
<td>10.6 ± 0.5a</td>
<td>0.23 ± 0.09a</td>
<td>39.55 ± 25.65a</td>
</tr>
<tr>
<td>A2</td>
<td>6.9 ± 0.8a</td>
<td>0.58 ± 0.14a</td>
<td>0.08 ± 0.03a</td>
<td>9.70 ± 0.89ab</td>
<td>0.36 ± 0.08a</td>
<td>44.90 ± 26.80a</td>
</tr>
<tr>
<td>A3</td>
<td>6.6 ± 0.1a</td>
<td>0.38 ± 0.11ab</td>
<td>0.05 ± 0.02a</td>
<td>8.50 ± 0.69bc</td>
<td>0.31 ± 0.21a</td>
<td>33.83 ± 31.23a</td>
</tr>
<tr>
<td>CE</td>
<td>6.4 ± 0.5a</td>
<td>0.51 ± 0.08a</td>
<td>0.09 ± 0.04a</td>
<td>10.5 ± 1.9a</td>
<td>0.34 ± 0.19a</td>
<td>24.85 ± 6.28a</td>
</tr>
</tbody>
</table>

4.4 Change of soil physico-chemical properties with depth

4.4.1 Soil texture and bulk density

Soil physical properties did not show significant changes with depth of sampling across the different management types and different ages of enclosures (Table 4.6). In the three locations, all management types indicate a higher bulk density on the 10 – 20 cm except for few cases that recorded higher bulk density in the 0 – 10 cm interval.

High sand content was recorded in the upper 20 cm of the soil while clay content was higher between the 10 to 30 cm. Silt content was evenly distributed in the entire 30 cm depth (Table 4.6)
Table 4.6: Evolution of granulometry and bulk density with depth in the top soil (30 cm for granulometry; 20 cm for bulk density), n = 4; ± SD. Different letters indicate the statistical significant differences (p < 0.05) with change in depth per location. CE = cultivated enclosures, A1 = enclosures aged 2 – 8 years, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazi

<table>
<thead>
<tr>
<th>Management</th>
<th>BD (g m⁻³)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10 cm</td>
<td>10-20 cm</td>
<td>0-10 cm</td>
<td>10-20 cm</td>
</tr>
<tr>
<td>Ywallateke</td>
<td>CE</td>
<td>1.43±0.15a</td>
<td>1.53±0.05a</td>
<td>77±4.7a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.43±0.05a</td>
<td>1.43±0.07a</td>
<td>81±7.6a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.33±0.21a</td>
<td>1.47±0.06a</td>
<td>77±6.4a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.50±0.26a</td>
<td>1.47±0.15a</td>
<td>81±5.3a</td>
</tr>
<tr>
<td></td>
<td>OG</td>
<td>1.50±0.10a</td>
<td>1.57±0.05a</td>
<td>78±7.5a</td>
</tr>
<tr>
<td>Morpus</td>
<td>CE</td>
<td>1.47±0.06a</td>
<td>1.56±0.15a</td>
<td>74±4.6a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.60±0.10a</td>
<td>1.47±0.12a</td>
<td>73±4.2a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.57±0.06a</td>
<td>1.60±0.17a</td>
<td>78±4.2a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.47±0.15a</td>
<td>1.47±0.05a</td>
<td>68±1.4a</td>
</tr>
<tr>
<td></td>
<td>OG</td>
<td>1.53±0.06a</td>
<td>1.60±0.10a</td>
<td>82±4.2a</td>
</tr>
<tr>
<td>Chepkoppeg</td>
<td>CE</td>
<td>1.47±0.17a</td>
<td>1.50±0.07a</td>
<td>78±4.0a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>1.53±0.06a</td>
<td>1.50±0.04a</td>
<td>68±9.1a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1.37±0.08a</td>
<td>1.47±0.07a</td>
<td>71±12.8a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1.47±0.09a</td>
<td>1.50±0.01a</td>
<td>78±4.7a</td>
</tr>
<tr>
<td></td>
<td>OG</td>
<td>1.50±0.10a</td>
<td>1.60±0.15a</td>
<td>74±0.5a</td>
</tr>
</tbody>
</table>
### 4.4.2 Soil chemical properties

Generally, in the enclosures, depth of sampling (30 cm) did not result in significant differences in SOC content (Table 4.7). In Chepkopegh and Morpus, a gradual decrease of SOC content was observed as depth increased (Table 4.9), though changes were not significant. Though not significant (p > 0.05), in Ywalateke, according to Table 4.7, OC at 10 – 20 cm is lower than SOC at 20 – 30 cm and thus change in OC did not follow a gradual decrease with depth. This was observed in enclosures aged 12 – 18 years and those of over 20 years (Table 4.9).

Furthermore, $K_{\text{exch}}$ was significantly higher (p < 0.05) from 0 – 10 cm compared to 20 – 30 cm in Chepkopegh (Table 4.7), and $N_{\text{tot}}$ (p < 0.05) was significantly higher at 0 – 10 cm than 20 – 30 cm depth in Morpus (Table 4.7). The other chemical properties, CEC, pH and P did not significantly change with depth although from Table 4.7, CEC is higher at 10 – 20 cm depth than 0 – 10 and 20 – 30 cm in Chepkopegh. CEC is fairly constant in all the depth intervals in Ywalateke and Morpus. The pH followed an increasing trend with depth for all the three locations, though not by a big difference. P was highly variable in all three locations and declined with increase in depth in the location of Chepkopegh. In Morpus, P increased with depth while in Ywalateke P was higher in 20 – 30 and 0 – 10 cm than 10 – 20 cm (Table 4.7).

#### Table 4.7: Changes of soil chemical properties with depth (30 cm) in enclosures in three locations of Chepareria. (n = 12; +SD). Different letters indicate significant statistical difference at p < 0.05 by depth. CE = cultivated enclosures, A1 = enclosures aged 2 – 8 years, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazing

<table>
<thead>
<tr>
<th>Ywalateke</th>
<th>Depth cm</th>
<th>pH-H$_2$O (-)</th>
<th>OC (%)</th>
<th>$N_{\text{tot}}$ (%)</th>
<th>CEC (cmol/kg)</th>
<th>$K_{\text{exch}}$ (cmol/kg)</th>
<th>$P_{\text{avail}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
<td>5.5 ± 0.2a</td>
<td>0.60 ± 0.16ab</td>
<td>0.08 ± 0.02a</td>
<td>8.6 ± 1.33a</td>
<td>0.25 ± 0.2a</td>
<td>16.5 ± 11.27a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>5.6 ± 0.33a</td>
<td>0.65 ± 0.15a</td>
<td>0.08 ± 0.03a</td>
<td>8.38 ± 1.43a</td>
<td>0.19 ± 0.13a</td>
<td>12.13 ± 7.42a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>5.8 ± 0.45a</td>
<td>0.49 ± 0.14b</td>
<td>0.06 ± 0.02a</td>
<td>8.61 ± 1.34a</td>
<td>0.18 ± 0.15a</td>
<td>15.00 ± 12.77a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Morpus</th>
<th>Depth cm</th>
<th>pH-H$_2$O (-)</th>
<th>OC (%)</th>
<th>$N_{\text{tot}}$ (%)</th>
<th>CEC (cmol/kg)</th>
<th>$K_{\text{exch}}$ (cmol/kg)</th>
<th>$P_{\text{avail}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
<td>6.1 ± 0.3a</td>
<td>0.69 ± 0.19a</td>
<td>0.08 ± 0.02a</td>
<td>8.89 ± 0.98a</td>
<td>0.44 ± 0.19a</td>
<td>16.53 ± 13.43a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>6.3 ± 0.3a</td>
<td>0.51 ± 0.19a</td>
<td>0.06 ± 0.03ab</td>
<td>8.71 ± 1.35a</td>
<td>0.30 ± 0.15a</td>
<td>20.46 ± 17.82a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>6.3 ± 0.6a</td>
<td>0.52 ± 0.21a</td>
<td>0.05 ± 0.03b</td>
<td>9.12 ± 1.42a</td>
<td>0.37 ± 0.26a</td>
<td>22.33 ± 26.27a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chepkopegh</th>
<th>Depth cm</th>
<th>pH-H$_2$O (-)</th>
<th>OC (%)</th>
<th>$N_{\text{tot}}$ (%)</th>
<th>CEC (cmol/kg)</th>
<th>$K_{\text{exch}}$ (cmol/kg)</th>
<th>$P_{\text{avail}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 – 10</td>
<td>6.7 ± 0.6a</td>
<td>0.59 ± 0.19a</td>
<td>0.09 ± 0.04a</td>
<td>9.68 ± 1.85ab</td>
<td>0.47 ± 0.23a</td>
<td>42.12 ± 29.52a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>6.7 ± 0.7a</td>
<td>0.53 ± 0.18a</td>
<td>0.06 ± 0.03ab</td>
<td>10.07 ± 1.57a</td>
<td>0.24 ± 0.19ab</td>
<td>40.10 ± 28.96a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>7.1 ± 0.7a</td>
<td>0.45 ± 0.19a</td>
<td>0.05 ± 0.03b</td>
<td>9.04 ± 0.94b</td>
<td>0.18 ± 0.1b</td>
<td>36.06 ± 21.38a</td>
</tr>
</tbody>
</table>
In the open grazing lands, no significant changes in soil properties with change in depth were observed. Soil pH showed an increasing trend with increase in depth while the other soil properties showed no specific trend with changing depth (Figure 4.2).

**Figure 4.2:** Changes of soil chemical properties with depth over a 30 cm depth in fields under open grazing in the three locations (n = 4). Error bars indicate SD.
In the cultivated enclosures, changes with depth were insignificant for all soil parameters and in all locations, except for N\textsubscript{tot} in Chepkopegh. N (p < 0.05) was significantly higher on the top, 0 – 10 cm than that in 20 – 30 cm depth. The changes observed in the means of SOC demonstrated very minimal changes of OC content with depth for the three locations (Table 4.8).

**Table 4.8:** Evolution of chemical properties with depth in the top soil of **cultivated enclosures** (n = 4; ± SD) within three locations. Different letters indicate statistically significant differences (p < 0.05) of parameter by depth.

<table>
<thead>
<tr>
<th>Ywalateke</th>
<th>Depth cm</th>
<th>pH-H\textsubscript{2}O</th>
<th>OC (%)</th>
<th>N\textsubscript{tot} (%)</th>
<th>CEC (cmol/kg)</th>
<th>K (cmol/kg)</th>
<th>P\textsubscript{avail} (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
<td>5.7 ± 0.45a</td>
<td>0.67 ± 0.25a</td>
<td>0.08 ± 0.03a</td>
<td>9.35 ± 1.24a</td>
<td>0.35 ± 0.21a</td>
<td>12.4 ± 8.69a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>5.7 ± 0.52a</td>
<td>0.57 ± 0.21a</td>
<td>0.06 ± 0.02a</td>
<td>8.30 ± 1.39a</td>
<td>0.41 ± 0.22a</td>
<td>14.2 ± 8.30a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>6.0 ± 0.45a</td>
<td>0.65 ± 0.33a</td>
<td>0.08 ± 0.04a</td>
<td>8.41 ± 0.17a</td>
<td>0.31 ± 0.14a</td>
<td>9.97 ± 10.68a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Morpus</th>
<th>Depth cm</th>
<th>pH-H\textsubscript{2}O</th>
<th>OC (%)</th>
<th>N\textsubscript{tot} (%)</th>
<th>CEC (cmol/kg)</th>
<th>K (cmol/kg)</th>
<th>P\textsubscript{avail} (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
<td>6.3 ± 0.4a</td>
<td>0.56 ± 0.28a</td>
<td>0.08 ± 0.03a</td>
<td>9.73 ± 0.18a</td>
<td>0.56 ± 0.13a</td>
<td>15.5 ± 11.47a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>6.4 ± 0.3a</td>
<td>0.53 ± 0.07a</td>
<td>0.07 ± 0.03a</td>
<td>9.68 ± 0.85a</td>
<td>0.53 ± 0.06a</td>
<td>16.48 ± 9.98a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>6.5 ± 0.3a</td>
<td>0.49 ± 0.15a</td>
<td>0.05 ± 0.03a</td>
<td>8.27 ± 1.13a</td>
<td>0.64 ± 0.27a</td>
<td>18.15 ± 14.13a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chepkopegh</th>
<th>Depth cm</th>
<th>pH-H\textsubscript{2}O</th>
<th>OC (%)</th>
<th>N\textsubscript{tot} (%)</th>
<th>CEC (cmol/kg)</th>
<th>K (cmol/kg)</th>
<th>P\textsubscript{avail} (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
<td>6.3 ± 0.7a</td>
<td>0.58 ± 0.08a</td>
<td>0.08 ± 0.01a</td>
<td>10.92 ± 1.77a</td>
<td>0.62 ± 0.35</td>
<td>29.96 ± 3.85a</td>
</tr>
<tr>
<td></td>
<td>10 - 20</td>
<td>6.6 ± 0.4a</td>
<td>0.51 ± 0.19a</td>
<td>0.07 ± 0.01a</td>
<td>10.80 ± 2.54a</td>
<td>0.53 ± 0.40</td>
<td>21.23 ± 6.54a</td>
</tr>
<tr>
<td></td>
<td>20 - 30</td>
<td>6.4 ± 0.6a</td>
<td>0.44 ± 0.06a</td>
<td>0.04 ± 0.01b</td>
<td>9.88 ± 1.59a</td>
<td>0.37 ± 0.37</td>
<td>23.36 ± 13.99a</td>
</tr>
</tbody>
</table>

## 4.5 Effect of age of enclosure on SOC at the top 10cm depth

It’s been noted in previous studies that current management systems mostly affect soil properties, both chemical and physical, in the upper 20 cm (Yimer et al., 2007; Don et al., 2007). However, SOC accumulation/degradation takes several decades for any significant changes to occur as a result of current management. Various studies therefore suggest testing of these changes at even smaller depth intervals of about 0 – 5 cm (Fultz et al., 2013).

In this case, the test interval was 0 – 10 cm. From the results, it was found that in Ywalatake, SOC content was consistent, almost equal, across all the ages of enclosures at this depth (Table 4.9). Hence no significant differences were observed between the different age classes.

In Chepkopegh, the age of enclosure did have an effect on SOC (p > 0.05). SOC (p < 0.05) was higher in enclosures aged 2 – 8 years compared to open grazing at the depth of 10 cm. SOC content declined in this depth, 0 – 10 cm, with increase in age of enclosures (Table 4.9).
In Morpus location, similar to Ywalateke, age did not significantly affect SOC on the upper 10 cm of the topsoil (Table 4.9). Changes in SOC content at this depth were minimal in this location, however, the youngest enclosures recorded the highest SOC content while the other two age categories had almost equal SOC contents.
Table 4.9: Comparison of means of SOC content (n = 4; ± SD) as influenced by depth, age of enclosures and the management type among the three locations. Cultivation and open grazing management were compared against the three age categories of the enclosures (age indicated on the table). Different letters by column indicate statistically significant differences (p < 0.05) within each location. CE = cultivated enclosures, A1 = enclosures aged 2 – 8 yrs, A2 = 12 – 18 yrs enclosures, A3 = more than 20 yrs enclosures and OG = open grazing

<table>
<thead>
<tr>
<th>Location</th>
<th>Management and age</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 - 10 cm</td>
</tr>
<tr>
<td>Ywalateke</td>
<td>OG</td>
<td>0.53 ± 0.09a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>0.58 ± 0.18a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>0.61 ± 0.24a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>0.62 ± 0.04a</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>0.67 ± 0.25a</td>
</tr>
<tr>
<td>Morpus</td>
<td>OG</td>
<td>0.40 ± 0.12a</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>0.75 ± 0.30a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>0.65 ± 0.13a</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>0.66 ± 0.15a</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>0.56 ± 0.28a</td>
</tr>
<tr>
<td>Chepkopegh</td>
<td>OG</td>
<td>0.34 ± 0.11b</td>
</tr>
<tr>
<td></td>
<td>A1</td>
<td>0.70 ± 0.13a</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>0.62 ± 0.23ab</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>0.45 ± 0.13ab</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>0.58 ± 0.08ab</td>
</tr>
</tbody>
</table>
4.6 Carbon stocks under different management systems within the locations

SOC stocks were analyzed for the top 20 cm depth. In the enclosures aged 2 – 8 years, SOC stock ranged between 14.42±1.9 ton/ha in Ywalateke to 19.8±3.8 ton/ha in Chepkopegh. In the 12 – 18 years category, SOC stocks were 17.4±1.3 ton/ha in Ywalateke to 18.1±6.4 ton/ha in Chepkopegh. SOC stocks in enclosures above 20 years ranged between 12.5±2.6 ton/ha in Chepkopegh to 18.3±1.9 ton/ha in Ywalateke. Cultivated enclosures recorded SOC stocks of 14.2±1.1 ton/ha in Chepkopegh to 21.0±5.5 ton/ha in Ywalateke. Open grazing had a range of 10.3±2.3 ton/ha in Chepkopegh to 17.5±2.0 ton/ha in Ywalateke.

Results from analysis of variance (ANOVA) for the three locations (Ywalateke, Chepkopegh and Morpus) show that carbon stocks (p > 0.05) did not significantly vary with the type of management. In Ywalateke, open grazing had higher organic carbon stock compared to enclosures aged 2 – 8 and 12 – 18 years (Table 4.10).

In Ywalateke, youngest enclosures have the lowest carbon SOC stock, followed by middle aged enclosures and open grazing. Enclosures above 20 years have the highest SOC stocks. In Morpus, an increase from youngest enclosures to middle aged enclosures is observed. SOC stocks are however lower in enclosures of over 20 years in age. SOC stocks in Chepkopegh followed a declining trend from the youngest enclosures to the oldest enclosures. However, in this location, SOC stocks nearly doubled with conversion of open grazing to enclosures as seen in youngest enclosures (Table 4.10).

Table 4.10: Average and standard deviation of carbon stocks (tons/ha) for the topsoil (0-20 cm) under different management systems in three locations of Chepareria (n = 4; ± SD). Enclosures (2 – 8, 12 – 18, > 20 years), CE = Cultivated enclosures, OG = Open grazing. Different letters within columns indicate statistically significant differences at p < 0.05.

<table>
<thead>
<tr>
<th>Management</th>
<th>Ywalateke</th>
<th>Morpus</th>
<th>Chepkopegh</th>
</tr>
</thead>
<tbody>
<tr>
<td>OG</td>
<td>17.5 ± 2.0a</td>
<td>14.6 ± 5.0a</td>
<td>10.3 ± 2.3a</td>
</tr>
<tr>
<td>A1</td>
<td>14.2 ± 1.9a</td>
<td>14.8 ± 3.5a</td>
<td>19.8 ± 3.8a</td>
</tr>
<tr>
<td>A2</td>
<td>17.4 ± 1.3a</td>
<td>17.9 ± 3.7a</td>
<td>18.1 ± 6.4a</td>
</tr>
<tr>
<td>A3</td>
<td>18.3 ± 1.9a</td>
<td>17.7 ± 2.1a</td>
<td>12.5 ± 2.6a</td>
</tr>
<tr>
<td>CE</td>
<td>21.0 ± 5.5a</td>
<td>14.3 ± 2.3a</td>
<td>14.2 ± 1.1a</td>
</tr>
</tbody>
</table>

Figure 4.3 highlights the differences in SOC stocks among the three locations for each management type. There was no significant differences in SOC stocks for any management type in the three locations. However, some variations in amount of C stocks can be observed such as, SOC stocks in OG were higher in Ywalateke compared to Morpus and Chepkopegh. Ywalateke also recorded highest SOC stocks in CE among the three locations. SOC stocks at A2 was comparable among the three locations. Chepkopegh location recorded highest SOC stocks in A1 enclosures as well as lowest SOC stocks in A3 enclosures among the three locations (Figure 4.3).
**Figure 4.3:** Comparison of SOC stocks reported within the various management system of three locations, (n = 4), error bars indicate SD. Letters indicate statistical significant differences at (p < 0.05) among the three locations per management.
5 Discussion

5.1 Locational influence on the soil characteristics

The geographical location of a given location can influence the characteristics of the soil and hence influence the landowner’s choice in the selection of management type of that land. This may have resulted from the differences in climate, geological characteristics among others. Although differences in altitude within the study location were not big (about 1680 m for Ywalateke and about 1570 m above sea level for Chepkopeg and Morpus), Ywalateke experiences a more stable climate and higher rainfall compared to the other two locations, Chepkopeg and Morpus (Wairore et al., 2015).

The location of Chepkopeg did seem to differ in pH, CEC and $P_{\text{avail}}$ from Ywalateke (Table 4.3). The high pH in Chepkopeg and Morpus indicate drier conditions in these locations compared to Ywalateke. High $P_{\text{avail}}$ in Chepkopeg is as a result of the high pH (near neutral) which has favored high availability of P in the soil (Adeoye and Agboola, 1985). A significant positive correlation of pH and $P_{\text{avail}}$ was observed an indication of the major contribution of pH to P availability.

Although the clay content is low for all the three locations, Chepkopeg recorded slightly higher CEC compared to Ywalateke and Morpus. This may have resulted from the slightly higher CECclay recorded for this location (Table 4.3).

5.2 Differences in soil properties among managements as result of enclosure management establishment

Establishment of enclosures has not yet led to significant changes in the soil properties in the location. This is in line with several studies conducted in other locations which reported similar cases. Also Kinyua et al. (2009) reported that the recovery of soil chemical properties of degraded rangelands takes a long time.

The major difference in the soil chemical properties was observed in Chepkopeg location. Enclosures had significantly higher N and K contents compared to the open grazing. Higher CEC occurred in the cultivated enclosures and in the youngest enclosures compared to the open grazing (Table 4.5). Addition of cow dung resulting to addition of organic matter in cultivated enclosures may have contributed to this increase in the CEC.

Enclosures and cultivated enclosures did not differ in the soil chemical properties. This may have resulted from the maintenance of the soil properties when an enclosure was converted to cultivation and on the other hand improvement of the soil when an open grazing was converted to cultivation through the use of farm inputs such as addition of manure, in this case, cow dung and crop residues. A similar observation was made by Svanlund, (2014) in a pilot study in Chepareria. After maize harvest, the main crop grown in this location, a given amount of the maize residue is fed to cattle while still in the field, while the rest is stored as dry period pasture. Although feeding the cattle in the field allows for direct N and other nutrient input to the soil, Castellanos-Navarrete et al. (2015) pointed out that maize residue is known to be low in N.
contents and has high levels of lignocellulose which lower the nutrient digestibility. Cow dung is also collected from animal sheds and carried to the field mostly during plant season. Although manure is used on the crop fields, observation from the results showed that this did not translate to major increases in N contents in the crop fields compared to enclosures and open grazing. A study by Castellanos-Navarrete et al. (2015) in western Kenya showed that the feeding of residue to cattle only resulted in small total N outputs (< 1.7 % N) through animal excreta and relatively low quality manure. It was pointed out in the same study that about 73% of N in the animal excreta was lost before reaching the crop fields (Castellanos-Navarrete et al., 2015).

The unaffected soil properties such as the SOC might be explained by the fact that changes in soil properties in semi-arid locations characterized by low rainfall and thus limiting plant growth and production, require long-term C addition to the soil from primary production (Ghorbani et al., 2012) in the enclosures. On the other hand, the balance of SOM storage by grazing animals in the open grazing lands compensates for low C input through addition of manure from their excretion (Raiesi and Riahi 2014). This may explain the reason why there is not much difference in soil properties especially SOC among the different management systems in these locations even with enclosures older than 20 years.

Continuous use of this lands, open grazing as well as enclosures could also contribute to the high soil bulk densities. A similar observation was made by Yusuf, Treydte, and Sauerborn (2015). This study reported a BD of up to 1.8 g cm$^{-3}$ in southern Ethiopia pastoral lands composed of open grazing as well as enclosures with some enclosures recording up to 1.6 gm$^{-3}$ depending on the intensity of use. In the open grazing areas, the continuous use may have led to compaction of the soil from the trampling hooves of the herbivores resulting to high bulk densities. The texture of the soil, high sand content, combined with the high temperature contribute to the low SOC content observed in the results for this location (Jobbágy and Jackson 2000). In the Jemp’s flats in the Lake Baringo basin, Mureithi et al. (2012) recorded bulk densities of 1.31 and 1.19 gm$^{-3}$ in the private and communal enclosures respectively and 1.57 and 1.48 gm$^{-3}$ in the private and communal open grazing respectively. Looking also at the texture of the soil in the same location of Baringo, sand content was very low, 9 % in both private and communal enclosures and 12 and 13 % in the private and communal open grazing.

Organic C contents did show an increasing trend in SOC. However, there were inconsistencies when C stocks were calculated in tons/ha (Table 4.8, Table 4.10). A similar observation was made by Svanlund, (2014), though in her study sampling was up to 100cm. However, calculation of C stock at 20 cm depth was convenient as most of soil C (70%) is located in this depth (Yimer et al., 2007) thus appropriate to capture effect of current management on soil C (Mekuria 2013; Mureithi, Verdoordt, Gachene, et al. 2014; January and Mekuria 2011). Change of management in this location did not significantly lead to change in BD of the soil unlike observation made by Verdoordt et al. (2009) in Baringo, Kenya, whereby private and communal enclosures lead to decrease in BD from 1.54 Mg m$^{-3}$ in open grazing to 1.31 Mg m$^{-3}$ and 1.19 Mg m$^{-3}$ respectively.
5.3 Soil property changes in relation to enclosure duration

In the Jemps flats in Baringo, Mureithi et al. (2014) reported a positive high correlation of SOC contents with the herbaceous biomass production with coefficients of 0.91 and 0.89 respectively in the oldest enclosures (23 years). This observation was in agreement with the results of SOC content in Ywalateke in which enclosures over 20 years old had higher SOC contents compared to 0 – 8 years old and 12 – 18 years old enclosures. This could be attributed to higher rainfall in the location compared to the other two locations (Chepkopegh and Morpus), which results in higher plant growth and production (Wairore et al., 2015). Similar results of increased C in the soil due to increased biomass production resulting to increased litter input into the soil were obtained by Descheemaeker et al. (2006). She found that litter input increased from 20 g m⁻² in degraded open grazing to 600 g m⁻² in 20 years enclosures.

Contrary to Ywalateke, oldest (over 20 years) enclosures in Chepkopegh recorded the lowest SOC contents compared to younger enclosures, although there were no significant differences among the enclosures (Table 4.5). Organic carbon contents in Chepkopegh also followed a declining trend with age, though less severe compared to Chepkopegh. A similar observation was made by Svanlund (2014). The author suggested that this trend could be explained by the initially more severe degradation of these older enclosures compared to the younger ones as well as mismanagement and over use of these older enclosures by the owners. A similar observation of the low amount of SOC carbon in older enclosures was made by Mureithi et al. (2014), where SOC (1,029 g C/m²) was considered below average compared to SOC (1,471 g C/m²) in the younger enclosures.

For the three locations, SOC in the enclosures did not significantly differ from that of the open grazing (Table 4.5). With the increased privatization of land in this location, management of grazing is no longer communal. Discussing with the owners, it was evident that each owner determines how to utilize his pastures, when to use the land and the number of animals the owners wants in the enclosure. Cattle reduced by 26% with only a slight increase by 4% in sheep and goat in these locations (Nyberg et al., 2015). The reduced stocks of animals has led to reduced pressure on the open grazing lands. During seasons with high pasture production, the open grazing lands are not utilized, which means they get their fair share of rest too. This could contribute to the insignificant differences observed in SOC storage among the three management systems.

In a pilot study in Chepareria, Svanland (2014), found that there was no correlation of tree density with SOC content and suggested that the possibility of this could be the counter effect of the shrubs in the plots of experiment. The grass undergrowth would have more effect on SOC in areas of grazing exclusion more than other tree species (Nyberg & Högberg, 1995).

In Ywalateke and Morpus the duration of enclosing did not show significant effect on total N, available P, exchangeable K and CEC. In Chepkopegh however, duration of enclosing did
significantly lead to increase in CEC (p < 0.05) especially in the younger enclosures (Table 4.5). Other soil properties were not affected by the age of enclosures.

Carbon stocks increased with enclosure duration in Ywalateke and Morpus though not significant. In Chepköpegh however, C stocks declined with enclosure age (Table 4.10). Non-linear influence of enclosure age on ecosystem carbon stock was also recorded by January and Mekuria (2011).

5.4 Variation of soil properties with sampling depth
Although the sampling depth in this study was only 30 cm, several studies have highlighted that effects of current management are usually most experienced at this depth (Yimer et al., 2007; Don et al., 2007).

As expected for SOC, the content decreased with increase in depth in Chepköpegh and Morpus except in Ywalateke. Possibility of carbon transport to deeper soil profile by plant roots and termites/ants was highlighted by Don et al. (2007). Although not many termite mounds were encountered in the field, high plant growth and high sand content in the soil in this location of Ywalateke could be a factors contributing to C movement deeper in the soil profile.

At the depth of 10 cm, only Chepköpegh showed a significantly higher SOC in enclosures of age 2 – 8 years compared open grazing. No significant changes were observed at this depth for SOC in other enclosure age categories as well as in cultivated enclosures and open grazing (Table 4.7). The 10 cm depth interval may have been too large to detect any significant changes in SOC for recently established management regimes. Studies suggest sampling beginning at the depth of 0 – 5 cm on the upper layer to capture the very minimal changes of soil C within short time durations (Fultz et al., 2013).

The lack of redistribution of SOC in cultivated enclosures in Chepköpegh and Morpus (Table 4.8) may be an indication of shallow ploughing (less than 20 cm deep) during land preparation. Deep ploughing of about 30 cm in Ywalateke was evident as the land owners use hired tractors (disc plough) for tilling the land and those using hoes practice deep ploughing as well to about the depth of 20 cm. This results in the mixing of the soil in the 20 – 30 cm depth and mixing of soil with plant residues thus highly influencing the distribution and storage of SOC, hence no difference with depth in the cultivated fields (Yang & Wander, 1999; Ingrid, Burke, Lauenroth, & Coffin, 1995).

Other soil properties showed inconsistent changes with depth except for pH which had an increasing trend with increase in depth (Table 4.7, Table 4.8, and Figure 4.2).

5.5 Ecosystem carbon stock in enclosures and cultivated enclosures
Determination of carbon stocks was done for the top soil (20 cm depth) as this is the depth mostly affected by current management practices (Yimer et al., 2007), especially tillage (Dolan et al., 2006).
Continuous cultivation can lead to low SOC due to crop growth disruptions and mining of soil nutrients. The higher SOC stocks in the cultivated enclosures to those of the open grazing could be as a result of establishment of farming lands on the most suitable soils in the locations. On the other hand, use of crop residues on the field such as maize and bean residues and manure from cow dung in cultivated enclosures add to the organic matter and may have regulated major loss of C from the soil. Descheemaeker et al. (2006b), sampling at the depth of 30 cm, recorded increase in carbon stocks of about 75.0 Mg C ha\(^{-1}\) in 20-year-old enclosure while Mekuria, (2013) found increase in C stock of about 3.1Mg C ha\(^{-1}\) yr\(^{-1}\) under 20 year enclosure. In Kenya, Verdoordt et al. (2009) recorded 6.6, 9.6, and 10.6 Mg C ha\(^{-1}\) in the upper 15 cm depth after 15, 18, and 23 years of enclosure establishment, while Mureithi et al. (2014) recorded 1,633 g C/m\(^2\) C stock when communal enclosures were established which was double that of surrounding open grazing. In the three locations, increase of C stocks with establishment of enclosures was noticeable but not significantly higher than that of the open grazing (Table 4.10).

Manna et al. (2005) pointed out that soil type could be one of the most important parameters affecting C storage in the soil. He highlighted that a major portion of SOC is maintained through clay-organic matter interaction indicating the importance of the inorganic part of the soil as a substrate to bind the organic carbon. The fact that the soils in these three locations are characterized by high sand content and low clay content in the soil (Figure 4.1) could be a major factor affecting the C stocks in the location. The fields that had higher clay content (about 2 fold higher) recorded higher SOC compared to the other fields (Manna et al., 2005). A positive correlation of SOC content and clay content was observed though not significant. This weak correlation came from the fact that the three locations recorded low and almost similar amounts of clay contents which could also be one of the factor resulting to similarity in SOC amounts.

It is clear that in these three locations, Ywalateke, Chepkopegh and Morpus, establishment of enclosures has influenced the use of the available resources in a significantly beneficial way to the local people. Increase in biomass production and woody species as a result of grazing exclusion is well documented in many studies (Wairore et al., 2015; Mekuria and Veldkamp, 2011; Verdoordt et al., 2010; Moe et al., 2009), hence the increase in above ground carbon and plant carbon with grazing exclusion (January and Mekuria 2011). The considerable differences in regulating ecosystem service between enclosures and open grazing areas is largely due to effect of enclosures in enhancing carbon storage, control soil erosion and vegetation restoration (Mekuria 2013). However, in this study area, changes in soil chemical and physical properties among the different management systems were insignificant. SOC in particular showed insignificant changes with time. This may result from the lengthy time required for any significant changes in SOC to be detected in the soil with some studies indicating durations of over four decades (Xiong et al., 2014) due to many factors that influence the decomposition of this above ground biomass (Medina-Roldán, Paz-Ferreiro, and Bardgett 2012). The other factor that may have resulted to this lack of significant change of SOC with time is the highlighted
establishment of older enclosures in more severely degraded open grazing as well as mismanagement of these older enclosures.

Such practices of combining livestock production and cultivation are social economically driven whereby the land owners want to diversify sources of household income. This brings about the trade-offs between the need to satisfy immediate human needs in the location and at the same time sequester carbon to regulate/reduce CO$_2$ increases in the atmosphere locally.

5.6 Adapting SOC storage with current management
Due to limitation of farm inputs such as expensive fertilizers, alternative and innovative strategies to manage available inputs such as manure in order to efficiently deliver nutrients to the soil would be a great advantage in the drier locations of Chepkopegh and Morpus. This would not only benefit SOC storage but also food production in the location, thus creating a win–win situation. However, to achieve this, studies and research for the best practice that is locally adapted need to be conducted in the location. Also, controlled grazing which has already been well adopted in the location is a major milestone towards achieving major benefits from this semi-arid ecosystem. If achieved, moderate grazing eliminates the trade-off between the provisioning and the regulating ecosystem services, that is forage provision and CO$_2$ regulation, as both are maximized at moderate grazing (Oatibia, Aguiar, & Semmartin, 2015).

5.7 Significance for this baseline study of carbon stock determination in the location
This study forms a baseline for which future monitoring studies to predict the changes in soil characteristics related to soil carbon sequestration, a regulating service of utmost importance, as the rise of greenhouse gases in the atmosphere continues. As pointed out by Mekuria (2011), reliable baseline information is necessary for the implementation of future C sequestration projects. Locational documentation of the estimated amounts of C in the soil has increased as calls for carbon credit markets continue to rise, hence the need for accounting of the amount of C removed from the atmosphere. Through innovative management changes such as enclosure management in arid locations, the local people would not only benefit from the regulating and provisioning services that come with this management strategies, but could also earn income from carbon credits hence the need for rigorous documentation of C sequestered.

Though no conclusive evidence has been obtained to show significant increase in SOC due to change of management from open grazing to enclosures, evidence from the ground show improvement of livelihood of the locals as a result of enclosure establishment. As such, studies that show the changes in soil properties are required to determine the chances of establishing projects such as carbon sequestration projects in the future.
6 Conclusions and recommendations

6.1 Conclusions
There was no major differences in physico-chemical properties among the three management systems. However, enclosures and cultivated enclosures had higher values for SOC and N compared to the open grazing. Among the three management systems, enclosures had the highest SOC stocks while open grazing recorded the lowest SOC stocks.

Soil carbon stocks did show an increase with duration of enclosing in Ywalateke and Morpus though this linear increase with age was very weak and insignificant. In Chepkopegh, the duration of enclosing seemed to affect the C stocks negatively. High SOC contents and SOC stocks were recorded in the younger enclosures, 2 – 8 and 12 – 18 years.

SOC stocks were quite low in cultivated enclosures in the locations of Morpus and Chepkopegh compared to Ywalateke. This may have resulted from the drier conditions in the former locations than the later.

While sampling up to the depth of 30 cm is recommended to capture effect of current management on the soil properties of the top soil, capturing any changes especially that of SOC at this depth is difficult. As such, even sampling of the upper 10 cm was not able to capture any significant changes in SOC with regard to current management and duration of enclosing.

6.2 Recommendations
Since cultivation has become an embedded livelihood activity for the local people in Chepareria, experimental studies for the best practice, sustainable and locally adapted methods to improve C stocks in cultivated enclosures is paramount. This will ensure the continuous trend of C increase in the soil even with conversion of land from grazing enclosure to cultivated enclosure. It’s recommended as well that research on efficient methods of manure storage and delivery be conducted. This proper practices may allow for compensation of soil C and other soil nutrients lost due to mining and crop growth disruption in cultivated enclosures.

SOC seems to decline with increase in age of enclosures especially in Chepkopegh and Morpus. Though the decline cannot be solely attributed to the age of enclosures, monitoring of these older enclosures for factors that may affect SOC accumulation would be important to ensure increase of SOC as well as maintain this SOC. To detect any significant effect of current management on SOC, sampling at a much smaller interval (0 – 5 cm) is recommended.
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Appendices

Figure 7.1: Comparison of average soil organic carbon content (OC) at different depths, a = (0 – 10cm, b = 10 – 20cm and c = 20 – 30cm under different management systems for three locations. EA1 = enclosures aged 2 – 8 years, EA2 = enclosures aged 12 – 18 years, EA3 = enclosures of more than 20 years, CE = cultivated enclosures, OG = open grazing (n = 4; error bars represent ± SD).
Figure 7.2: Changes of soil chemical properties with depth over a 30 cm depth in fields under enclosure management systems in the three locations (n = 12). Error bars indicate SD.