PhD Research Proposal

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Persistence and co-existence of vegetation and ungulate species along the fringe zone of Lake Naivasha, Kenya.

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Table of contents

List of figures

List of Tables.

Abstract

The fringe zone along Lake Naivasha, Kenya, provides key ecosystem services that maintain the structure and functioning of the whole lake ecosystem. These include buffering the lake against nutrient and silt inflows, carbon sequestration and provision of habitat for numerous floral and faunal species. However over the last three decades, the fringe zone vegetation has been reduced. This has been attributed to a combination of decline in ground and lake levels, overgrazing by herbivores and agricultural expansion. These factors affect the plant species diversity, primary productivity and consequently the forage availability for large ungulate species. Eventually, the resilience of the fringe ecosystem as measured by the persistence and co-existence of vegetation and herbivore species and their related functions is also affected. Reduction of plant diversity in semi-natural communities may reduce productivity due to resultant decrease in functional groups and therefore the amount of niche space occupied in the resulting community. Thus the proposed study will first explore whether plant diversity can explain vegetation productivity. It will then identify and quantify the impact of resource availability gradients and disturbance regimes (grazing intensity) on vegetation productivity. Moreover, it will evaluate the impact of herbivore culling and predator introductions on vegetation productivity while also evaluating the optimal carrying capacity of herbivores on the fringe zone based on forage availability. This will be achieved through experiments, remote sensing, geostatistics, regression and deductive process modelling. The results will contribute to an understanding of factors affecting the productivity of semi-natural vegetation (trees, shrubs, grass and papyrus) and consequently forage availability for herbivores. In turn, this will facilitate the design of appropriate management plans to sustain riparian vegetation and ungulate species and their related ecosystem services.

1. Background

Although about 70% of the earth surface is covered by water, only about 2.5% is fresh water (Oki and Kanae, 2006). Freshwater bodies not only provide water for drinking, agriculture, industry and sanitation but they are essential habitats for numerous floral and faunal organisms (Ricciardi and Rasmussen, 1999). These include not only the aquatic organisms but also semi-aquatic and terrestrial organisms that depend on them. Thus freshwater bodies play a critical role in conservation of global biodiversity. However they are under intense threats from increased pollution, land use conversion and climate change (Sala et al., 2000). This poses serious threats to the biodiversity they support and consequently the ecosystem services they provide.

Freshwater resources are scarce in Kenya, a tropical and mostly semi-arid country. The available sources are under intense pressure due to a growing population and a changing climate. Among the existing freshwater lakes, Lake Naivasha is the second largest. The lake comprises four chemically distinct basins i.e. the main lake, Crescent island basin and two highly alkaline basins, Oloidien and Sonachi. The lake receives inflows from Rivers Malewa (80%), Gilgil (20%) and Karati, which is seasonal (Becht et al., 2006). The basin has no surface outflow but water flows through ground seepage (Becht and Harper, 2002). The lake itself is poor in biodiversity, comprising of seven exotic fish species and the Louisiana crayfish (Hickley et al., 2002, Hickley et al., 2004). The only endemic fish species *Aplocheilichthys antinorii* was last recorded in 1962 (Hickley et al., 2002). This is in addition to a variety of aquatic plants that are either submerged (*Potamogeton spp., Najas horrida, Ceratophyllum demersum*) or floating (*Nymphaea nouchalii* and *Cyperus papyrus*). Since the early 1980's the lake has been invaded by exotic floating water fern (*Salvinia molesta*) and in the 1990's by the water hyacinth (*Eichhornia crassipes*) (Mavuti and Harper, 2006).

However the ecological integrity of the Lake is threatened by declining water levels, eutrophication, overfishing, land use conversions and invasive species (Harper and Mavuti, 2004, Mavuti and Harper, 2006). The Lake fringe zone has experienced a drastic expansion in floriculture farming since early 1980's and currently occupy over 4,000 ha (Becht et al., 2006). The floriculture farms abstraction water for irrigation from the lake and groundwater hence altering the water balance (Becht et al., 2006). Moreover, it experience frequent changes in water levels that can extend to several vertical metres within a few months resulting to horizontal change of several kilometres (Mavuti and Harper, 2006). These fluctuations are associated with climatic variability (Hubble and Harper, 2001), land use conversions in upper catchment and water abstraction for agriculture and urban use (Becht and Harper, 2002, Mavuti and Harper, 2006).

Although the lake itself is relatively poor in biodiversity, the land-water ecotone along the lake is highly endowed with biodiversity. This contributed to the Lake and its underlying buffer-zone to be declared a Ramsar[1] site in 1995 (Ramsar, 1996) although it was subsequently listed under Montreux Record[2] in year 2008 in regard to declining ecological character (Schoemburg, 2008). The fringe zone is habitat to over 50 large wild mammal species that includes the endangered grevy's zebra (*Equus grevyi*), near threatened white rhino (*Ceratotherium simum*), beisa oryx (*Oryx beisa*) and gerenuk

[1] List of Wetlands of International Importance

[2] List of Ramsar sites that are under threat from "changes in ecological character as a result of technological developments, pollution, or other human interference"

(*Litocranius walleri*) (Mavuti and Harper, 2006, Becht et al., 2006, NWC, Unpublished). Other vulnerable species include Common hippopotamus (*Hippopotamus amphibious*) (Grey and Harper, 2002), cheetah (*Acinonyx jubatus*) and lion (*Panthera leo*) (Meredith, 2004). It is also an important grazing area for domestic ungulates reared in adjacent private ranches. Moreover nomadic pastoralists graze their livestock in the fringe zone mostly in the dry season (Harper and Mavuti, 2004, Mavuti and Harper, 2006). The ecotone is also an Important Bird Area (IBA) inhabited by ~400 bird species that include two globally endangered species; Basra reed warbler and Egyptian vulture; (Kuria, 2009, Henderson and Harper, 1992, Owino et al., 2002).

Until early 1980's, an extensive floating mat of papyrus occurred at the mouth of the two main rivers flowing into the Lake, (the North swamp) (Gaudet, 1977a). It then covered an area about 12 Km^2 (Gaudet, 1979). The rivers flowing into the lake diverged into a dendritic pattern and disappeared under the floating mat of papyrus. In this swamp over 108 plant species were observed (Gaudet, 1977a). Papyrus is one of the most productive tropical grasses mainly due to its C4 photosynthesis pathway (Van Dam et al., 2007). This enhances their role in nutrients cycling, sediment trapping and carbon sequestration (Jones and Humphries, 1999). Evidently, Gaudet (1977b) demonstrated that the North swamp "trapped the sediments, incorporated much of the nutrients into plant and microbial biomass, losing nitrogen by denitrification in the swamp mat, then releasing (over a much longer time-period) soluble and organic-bound nutrients into the submerged and floating-leaved aquatic plant zones and eventually to the lake". He also estimated that 780 t of sediments were trapped in the North swamp in 1976-77. Evidently also, Brix (1994) showed that papyrus can reach a peak uptake capacity of 1100 kg N ha^{-1} yr^{-1} and 50 kg P ha^{-1} yr^{-1}. Moreover, Muthuri & Jones (1997) estimated that harvesting all papyrus in then 2000 ha swamp would have removed 836 t of nitrogen and 115 t of phosphorous. This was corroborated by Boar et al., (1999) as they reported total papyrus biomass (roots, rhizomes and aboveground) of 11,540 g/m^2 that comprised of 4500g total $carbon/m^2$ and 100g total $nitrogen/m^2$.

By buffering the lake against the nutrients and silt inflows, papyrus reduced eutrophication of the lake. Eutrophication lowers turbidity of the lake that subsequently reduces fish density (Hickley et al., 2004). Low fish density leads to reduced catches in the commercial fishery and also affect the population of piscivorous birds that forage on fish (Harper et al., 2002).

In addition, papyrus has high water efficiency a fact that has been attributed to the lower evapotranspiration on the papyrus swamp than in the open lake (Jones and Humphries, 1999). Hence, it enhances water conservation when growing in the wetland. The papyrus swamp also provides foraging, nesting and breeding ground for many resident and migrant bird species including the globally endangered Basra Reed Warbler and the near-threatened grey-crested helmet-shrike (Henderson and Harper, 1992, Kuria, 2009). It is also habitat and foraging sites for mammals like hippo, buffalo and waterbucks (Harper and Mavuti, 2004).

Despite the papyrus, the fringe zone also has the yellow fever trees (*acacia xanthophloea*) woodland which is a key habitat for birds. The acacia woodland and associated undergrowth forms not only important grazing and shading sites for large mammals but also buffer the Lake against silts and nutrient (Becht et al., 2006).

Despite the critical ecosystem services provided by the fringe zone vegetation, it is experiencing pressure due to declining water levels, overgrazing, agricultural expansion and population explosion (Harper and Mavuti, 2004). Evidently the papyrus swamp that existed in the north has almost completely dried up (Harper and Mavuti, 2004). Thus, river Malewa currently flows directly into the lake hence depositing all its constituent nutrient and silt loads. This is despite the fact that nutrient loads in the river have increased tremendously compared to late 1970's as a result of high expansion of subsistence farming in upper catchment (Kitaka et al., 2002). The rapid expansion of floriculture along the fringe of the lake and consequent urban sprawl due to immigration of workers, has also increased nutrient inflows into the lake (Harper and Mavuti, 2004). All these factors have contributed to the current eutrophic status of the lake.

The decline of fringe vegetation is attributed to a combination of lowering water levels, grazing by ungulates and direct human clearance (Harper and Mavuti, 2004, Mavuti and Harper, 2006, Morrison and Harper, 2009). For example, the degradation of papyrus vegetation has been reported to be triggered by decline in lake levels as a result of increased abstractions both in the lake and upper catchment. The decline was also followed by steep undercutting of the Malewa River channel as a result of severe floods events due to deforestation in upper catchment. The deeper channel in the former swamp prevented it to spread in the dendritic pattern that ensured supply and distribution of water, nutrient and sediment loads into the swamp. The soils that dried as a consequence, allowed access of large mammals especially the buffalo (over 1500 individuals) (Morrison and Harper, 2009). Although previously the herd was confined into the delta area, with the decline of the lake levels they can freely move and forage on almost the entire northern shore of the Lake.

The ungulates degrade the papyrus through a natural facilitative process. In order to obtain fresh papyrus stems and umbels (flowering heads), buffaloes open up paths from landward side through the dense papyrus stands (Harper and Mavuti, 2004). Similarly hippos' also cut paths from lake ward side to access shorter and high quality grass on the fringe (Gaudet, 1977a). Consequently these paths facilitate incursions of other ungulates such as waterbucks (*Kobus ellipsiprymnus*), common zebra (*Equus burchelli*), giraffe (*Giraffa camelopardalis*) and cattle (*Bos Taurus*) (Harper and Mavuti, 2004). They feed on fresh papyrus shoots hence undermining their re-growth and survival (Harper and Mavuti, 2004, Morrison and Harper, 2009). Moreover the increasing light penetration as a result of opened paths enhances growth of climbing plants and creeping grasses e.g. Kikuyu grass (*Pennisetum clandestinum*). These grasses eventually overgrow the papyrus clumps and transform them into open hummocky (hilly) grassland (Harper and Mavuti, 2004, Morrison and Harper, 2009). The resulting grasslands form grazing lawns for several grazers.

The impact of ungulates on papyrus was demonstrated by Morrison and Harper (2009) who derived a papyrus "impact index" by comparing the condition of papyrus stands at four sites along the Lake with differing accessibility to buffalo and other ungulates. The "impact index" showed the magnitude of ungulates impact on various characteristics of papyrus stands at the four sites (Table 1). It revealed that papyrus stands were more degraded in sites that are more accessible to ungulates.

In addition, the grazing intensity on the grazing lawns is influenced by pasture conditions in the surrounding landscape matrix. This is because during the dry seasons the pasture conditions in adjacent rangelands decline while Lake level decline exposing large area of hydric soils. This is followed by germination of fresh shoots of littoral plants (Gaudet, 1977a). Consequently, wild ungulates immigrate while the nomadic pastoralists graze their cattle along the lake fringe (Harper and Mavuti, 2004). The herders also cut papyrus flowering heads (umbels) to feed their cattle (Harper and Mavuti, 2004, Morrison and Harper, 2009). Harper et al. (2009) observed 30,000 heads of nomadic cattle in southern section of the shore alone during the dry season. Such immigrations increase grazing intensity and are sources of conflict between riparian land owners and the nomadic pastoralists.

Although the ungulate impacts described above are natural processes that also occurred in the past during low lake levels (Harper and Mavuti, 2004), they would be expected to be reversed after subsequent water rise. Such reversals were witnessed between 1983 and 1987 when the lake level dropped three vertical metres causing a drying of papyrus and germination of aquatic/semi-aquatic plants dominated by annual grasses (Cynodon spp. and Polygonum spp.) (Harper et al., 1995). By 1987 only 7 km^2 (Table 3) of papyrus remained but after heavy rainfall in 1988, the resulting 1 m rise in lake level led to new germination of papyrus seedlings in the re-flooded soils (Harper et al., 1995).

However a number of factors are currently hindering such reversals. First, the numbers of ungulates especially wild buffalo (currently about 1500 heads) on north swamp has increased more than thrice compared to early 1990's (NWC, Unpublished, Morrison and Harper, 2009). This is attributed to human encroachment of Eburru forest to the west of the Lake that caused them to migrate (Harper and Mavuti, 2004). Secondly, the papyrus on the lake fringe is currently subjected to human damage even in private ranches with limited human access (Harper and Mavuti, 2004). Particularly illegal fishermen light fires overnight to scare away buffaloes. Fires spread well within dry papyrus.

Moreover the low lake levels allows domestic livestock and nomadic herdsmen to access the fringe zone freely (Harper and Mavuti, 2004). In areas with high access of livestock the papyrus has died (Table 2). Thirdly, the increased water abstractions together with climate change have altered the lakes hydrological regime thus affecting drying and flooding mechanisms. This has an implication to papyrus re-establishment because germination of papyrus is most favourable when periods of rapid water level decline (hence soil and seed drying) are followed by rapid water rise (Gaudet, 1977a). In such situations, the re-flooded bare soil will not have enough time to be colonized by terrestrial plants. However prolonged drying facilitate establishment of semi-aquatic and terrestrial plants that reduce recruitment success of germinated papyrus seedling through competition (Harper et al., 1995).

Evidently therefore, these threats affect vegetation productivity and consequently forage availability for herbivores. This affects the viability and co-existence of vegetation and ungulate species together with their related ecosystem functions. This can potentially lower the integrity of the whole Lake ecosystem due to feedback mechanisms within its various components. Hence there is need to quantify the factors affecting vegetation productivity and consequent effects on herbivore density to facilitate designing of appropriate management plans for the Lake ecosystem.

1.1. Research problem.

The fringe zone of Lake Naivasha has been reported to rich in plant diversity with observed 108 species (Gaudet, 1977a). Rich plant diversity has been linked to high primary productivity in (semi-)natural communities (Tilman et al., 2001, 2002, Hector et al., 1999, Tilman, 1999). To collaborate earlier observations by Hector et al. (1999), Tilman (1999) concluded that each halving of diversity leads to a 10 to 20% reduction in productivity. Although this conclusion remains contentious as some studies has reported highest diversity at regions of intermediate productivity (Kassen et al., 2000) while others do not show consistent effect of diversity on productivity (Huston et al., 2000). Nevertheless, if correct, it imply that the prevalent high rate of plant extinctions threatens the future productivity of earth’s natural and managed ecosystems and may hamper their ability to produce resources essential for human survival and to regulate atmospheric CO_2 concentration (Hector et al., 1999). Moreover, the fringe zone of Lake Naivasha experience frequent changes in water levels that create diverse environmental conditions over the year (Harper and Mavuti, 2004). Ecosystems experiencing high temporal fluctuations in resource availability often implies higher overall primary productivity as different species can reach peak biomass at varying periods over yearly cycle (Silva et al., 2009). In contrast, the intermediate productivity theory (Grime, 1973) posits that species diversity is high at regions of intermediate productivity. This has been associated with the “sampling effect” (Huston et al., 2000, Tilman, 1999) whereby there is higher probability of existence of highly productive and dominant species in more diverse communities that competitively exclude less productive species. Thus the diversity-productivity relationship in natural systems remains unresolved. Likewise, it remains unknown whether the rich plant diversity on the fringe zone of Lake Naivasha enhances plant primary productivity.

Primary productivity is an important indicator of overall ecosystem health (Tappan et al., 2004) and its ability to provide ecosystem services such as carbon sequestration and nutrient cycling. Thus understanding the factors limiting ecosystem primary productivity is crucial in designing appropriate management plans. This is more critical in ecosystem experiencing high temporal variability in resource availability as evident in the fringe zone of Lake Naivasha. Resource availability is one of the factors limiting vegetation primary productivity (Whiley et al., 2011, Fridley, 2002). However productivity in different ecosystems is limited by different resource gradients e.g. vegetation productivity in Tsavo ecosystem, Kenya, is limited by rainfall up to a threshold of 400 mm rainfall beyond which nutrient availability becomes the limiting factor (Wijngaarden, 1985). Although various authors have investigated the factors limiting productivity of papyrus (Jones and Muthuri, 1997, Kariuki et al., 2001, Muthuri et al., 1989, Boar et al., 1999), the limitation for other vegetation formations is not yet understood.

Although, the fringe zone is an important foraging ground for large ungulates (domestic and wild) that attract tourists amongst other socio-economic benefits (Becht et al., 2006). However increased herbivore density may raise the grazing intensity beyond the ecosystem carrying capacity resulting to overgrazing (Weisberg et al., 2006). Overgrazing may lead to soil erosion that hamper vegetation regeneration (Van de Koppel et al., 1997). Evidently, depending on their density, herbivores may be both an asset and a threat to the integrity of ecosystem. Despite this, the impacts of ungulates grazing intensity in the fringe zone of Lake Naivasha are not clearly understood. Moreover the optimal carrying capacity of ungulates in the fringe zone has never been evaluated.

Herbivore management options such as culling and predator introductions may control their density thus easing the grazing intensity (Boone et al., 2002). The density of apex predators in Naivasha ecosystem is very low (NWC, Unpublished). Apex predators are known to induce trophic cascades that can control herbivore density. However, the effectiveness of culling and introduction of predators on controlling the herbivore density has never been evaluated.

The Fig. 1 below shows interactions between factors affecting vegetation productivity. The resource availability factors (soil moisture, groundwater, lake level, soil nutrients, lake nutrients) are shown on the right hand side) those affecting herbivore density (culling, predator density, migrations and patch permeability or accessibility) are shown on the left hand side. The herbivore density eventually affects vegetation productivity. B and R represent balancing and reinforcing (positive feedback) loops respectively.

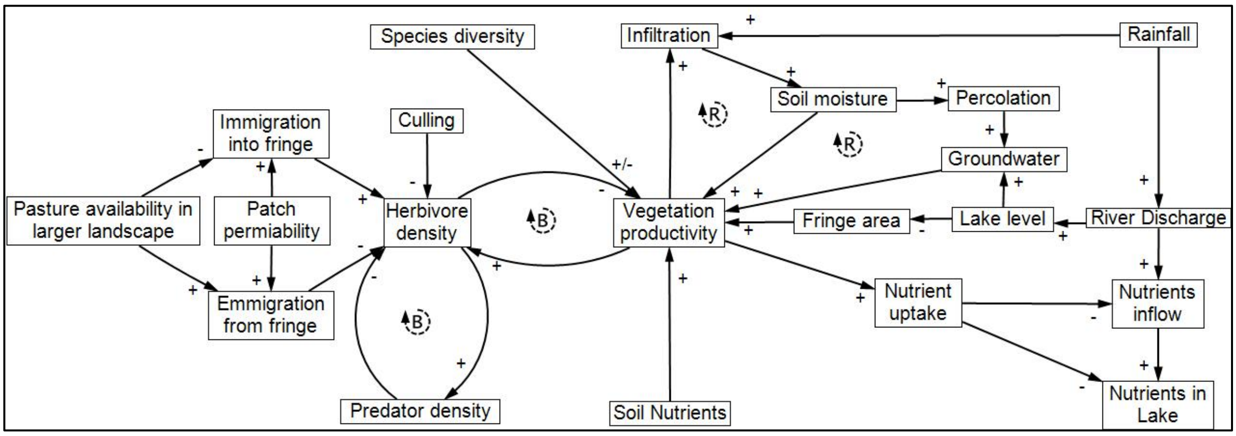

Fig. 1. Schematic representation of the research problem.

1.1. Justification.

Land-water ecotones are characterized by high biodiversity compared to their adjacent systems (Lachavanne and Juge, 1992) due to constant disturbances that facilitate existence of heterogeneous habitats. Hence they play a critical role in conservation of global diversity and support vital ecosystem services such carbon sequestration, nutrient and water cycling. Evidently, over 108 plant species belonging to 43 families has been recorded on the fringe zone of Lake Naivasha (Gaudet, 1977a). These species includes the *cyperus papyrus*, a highly productive tropical grass, that buffer the lake against nutrient and sediment inflows. Gaudet (1977b) estimated that 780 t of sediments were trapped in the swamp in 1976-77. Also, Brix (1994) showed that papyrus in Lake Naivasha attained a peak uptake capacity of 1100 kg ha^{-1} yr^{-1} nitrogen and 50 kg ha^{-1} yr^{-1} for phosphorus. By trapping nutrients and sediments the papyrus stands and other vegetation species may significantly control eutrophication of the lake.

Furthermore, the vegetation productivity contributes to carbon sequestration and storage thus reducing atmospheric concentration of greenhouse gases (Jones and Humphries, 2002). Particularly *cyperus papyrus* is highly productive, a fact that is associated with its C4 photosynthesis pathway (Jones and Humphries, 1999, Jones and Humphries, 2002, Jones and Muthuri, 1997). Evidently, Muthuri et al. (1989) reported papyrus net primary productivity (NPP) of 2.5 Kg C m^{-2} yr^{-1} in Lake Naivasha. Furthermore, Jones and Humphries (2002) using eddy covariance measurements showed that papyrus swamp in the north-west shore of Lake Naivasha has potential to sequester about 1.6 Kg C m^{-2} y^{-1}. The carbon storage potential was demonstrated by Boar et al., (1999) as they reported papyrus biomass of 11.5 Kg/m^2 that comprised of 4.5 Kg total carbon/m^2 in Lake Naivasha. Moreover the productivity of the tropical savannah and woodlands has been reported to range between 0.68 -1.9 Kg (DM) m^{-2} yr^{-1}, with an average of 1.4 Kg (DM) m^{-2} yr^{-1} thus the productivity of the savannah woodlands along the fringe zone also enhances its productivity.

The fringe zone is also a critical habitat for many faunal species. It provides foraging, nesting and breeding ground for over 400 resident and migrant bird species that include the globally endangered Basra reed warbler and the near-threatened grey-crested helmet-shrike (Henderson and Harper, 1992, Kuria, 2009). The swamp is also a key habitat and foraging site for over 50 large mammals including the habitat specialist hippo and waterbucks (Harper and Mavuti, 2004). The wildlife in the swamp attracts tourist's hence promoting ecotourism. Moreover, the fringe zone act as a key resource area (Butt, 2010) where large herbivores (both domestic and wild) aggregate in dry season in search of pasture (Harper and Mavuti, 2004, Morrison and Harper, 2009). Furthermore, the papyrus stands fringing the Lake is vital spawning site for fish (Hickley et al., 2004). Therefore, healthy and abundant fringe vegetation indirectly contributes to income generation and improved livelihoods as a result of earnings from sale of livestock, fish, ecotourism and provision of food (milk and meat) to nomadic herders.

Despite the diverse ecosystem services provided by the fringe vegetation, it is highly threatened by declining water levels, overgrazing, agricultural expansion and population explosion. (Harper and Mavuti, 2004, Morrison and Harper, 2009). Overgrazing emanates from high herbivore grazing intensity emanating from their high density beyond what ecosystem can support. Thus they compromise natural regeneration of vegetation. Thus the herbivores are both an asset as well as a threat to the integrity of ecosystem functions and biodiversity.

Thus for earlier detection of effects of disturbance regimes and to facilitate applying appropriate interventions long-term monitoring ecosystem monitoring is required. Vegetation productivity is an important proxy for assessing ecosystem vigour (Tappan et al., 2004). Thus assessment of spatial-temporal variations in vegetation productivity is a critical step towards understanding the factors driving local to global environmental change such as carbon and nitrogen cycling (Adjorlolo, 2008). Hence monitoring productivity may be an important component for determining whether current management practices are improving, degrading, or sustaining ecological integrity (Adjorlolo, 2008). Long-term monitoring of productivity may also help to detect potential sites undergoing degradation.

In addition, the spatial dynamics of vegetation productivity affects the density, diversity and distribution of wildlife species (Mutanga and Rugege, 2006). Therefore monitoring long-term vegetation productivity could provide an objective means of assessing forage utilization levels thereby facilitating decisions regarding optimal stocking and removal rates.

Evidently therefore, proper management of an ecosystem needs clear understanding of the drivers that shape its dynamics and their relative importance (Holdo et al., 2009). Thus, identifying and quantifying the interactions between resource availability gradients, vegetation primary productivity and forage availability in the fringe zone of Lake Naivasha can provide a clear understanding of the factors determining variability of vegetation and herbivore species. These facilitate designing of appropriate management plans that promotes not only the persistence and coexistence of plant and herbivore species but also the ecological integrity of the whole lake ecosystem.

1.2. Aim, objectives and hypothesis

The aim of the proposed study is to evaluate the resilience of the fringe ecosystem along Lake Naivasha as determined by persistence and co-existence of semi-natural vegetation and large ungulate species and their related ecosystem services. This will be achieved through analysis of factors influencing productivity of semi-natural vegetation and consequently the forage availability for large ungulates. The aim of this study will be accomplished by considering the following objectives:

1. Investigate the relationship between biodiversity and productivity of semi-natural vegetation forms (trees, shrubs, grass and papyrus) along the fringe of Lake Naivasha.

   H1: The biodiversity of the semi-natural vegetation along Lake Naivasha is significantly higher in areas of intermediate productivity (1 - 1.5 Kg (DM) m^{-2} yr^{-1}) compared to areas of low (< 1 Kg (DM) m^{-2} yr^{-1}) and high productivity (> 1.5 Kg (DM) m^{-2} yr^{-1}).

2. Determine the impact of resource availability gradients (soil moisture and nutrient content (nitrogen and phosphorous), ground water level, solar radiation) on productivity of semi-natural vegetation (trees, shrubs, grass and papyrus) along the fringe of Lake Naivasha. For the papyrus, the nitrogen and phosphorous concentrations in the lake and lake level will also be included in the analysis.

   H1: The order of explained variance (from high to low) from the resource availability variables when modeling the productivity of semi-natural vegetation forms (trees, shrubs and grass) along the fringe of Lake Naivasha is as follows: soil moisture>groundwater level>soil nitrogen>soil phosphorus>solar radiation.

   H1: The order of explained variance (from high to low) from the resource availability variables when modeling the productivity of papyrus along the fringe of Lake Naivasha is as follows: lake level>ground water table>lake nitrogen>lake phosphorous>soil (sediments) nitrogen concentration, soil (sediments) phosphorous concentration, solar radiation.

3. Quantify the impact of grazing intensity on productivity of the semi-natural vegetation forms (trees, shrubs, grass and papyrus) along Lake Naivasha.

   H1: The productivity of the semi-natural vegetation along the fringe of Lake Naivasha is significantly higher in areas of intermediate grazing intensity (total ungulates biomass density ranging 1 - 3 t Km^{-2}) compared to areas of low (< 1 t Km^{-2}) and high grazing intensities (> 3 t Km^{-2}).

   H1: The grazing intensity measured as forage demand by ungulates species along the fringe of Lake Naivasha is significantly higher than the systems carrying capacity as determined by forage availability measured as the total edible above ground biomass of semi-natural vegetation (trees, shrubs, grass and papyrus).

H1: The herbivore culling and introduction of predators along the fringe zone of Lake Naivasha significantly increases the productivity of semi-natural vegetation forms (trees, shrubs, grass and papyrus).

1.3. Theoretical framework.

The proposed research will be based on the following theoretical framework.

1.3.1. Intermediate productivity theory.

The relationship between plant diversity and productivity has remained a highly contentious issue in community ecology. One of the hypotheses proposed to explain this relationship is the intermediate productivity hypothesis. It posits that species diversity first increases with productivity until it reaches a maximum at intermediate productivity values, then it declines to lower levels in highly productive systems (Kassen et al., 2000). Two explanations has been put forward for this pattern; first is the influence of sampling effect (Tilman, 1999), whereby in more diverse communities there is greater probability of existence of highly productive and dominant (abundant) species that competitively exclude the less productive rare species (Grime, 1973, Grime, 1997). Secondly, in many natural communities many-rare-species tend to co-occur with few-abundant species (Jiang et al., 2009). Thus in low diverse communities productivity is also low as it is dominated by rare and less productive species as the highly productive species are few.

However diversity has also been reported to increase monotonically with productivity (Tilman et al., 2001, 2002, Hector et al., 1999, Tilman, 1999). This has been linked to niche complementarity (Jiang et al., 2009) whereby highly diverse communities record higher overall primary productivity as different species depict temporal partitioning of resources that enable them to reach peak biomass at varying periods over the year cycle (Silva et al., 2009).

Evidently the diversity-productivity relationship remains unresolved. Moreover most conclusions on this relationship emanate from microcosms experiments (Jiang et al., 2009). Thus the little is known on many mature natural systems.

1.3.2. Ecosystem resilience.

Resilience refers to the capacity of a system experiencing disturbances to endure without changing into a different system (Holling, 1973). It is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same functions, structure, identity, and feedbacks (Walker et al., 2004). Resilience reflects the degree to which a complex adaptive system is capable of self-organization (versus lack of organization or organization forced by external factors) and the degree to which the system can build and increase the capacity for learning and adaptation (Carpenter et al., 2001). Ecosystem resilience is expressed in two forms: resistance and recovery (Ludwig et al., 2001). Resistance refers to the ability of an ecosystem to remain in its current state (resist change) while recovery is the ability of a system to return to its original state after disturbance (Ludwig et al., 2001).

Ecosystems experience disturbances (natural and anthropogenic) with differing magnitude and frequency. These disturbances include fires, flooding, diseases, overgrazing, climate change, deforestation, poaching, pollution etc. Such disturbances may gradually erode the resilience of ecosystems eventually driving them into different states. When resilience is eroded, the ecosystem becomes more vulnerable to change and gradual external perturbations can make it to shift to other states (Folke et al., 2004).

However, biodiversity within an ecosystem may reinforce its resilience by supporting functioning of various ecosystem services. Particularly the functional diversity within a system is of critical importance to its overall functioning and stability (Chapin Iii et al., 2000). Functional diversity represent group of organisms that undertake various ecosystem services such as pollination, predation, grazing, nitrogen fixation, seed dispersal and decomposition. Thus persistence of diverse functional groups in an ecosystem enhances its performance and provision of their related services (Folke et al., 2004).

However, introduction of a functional group in a system may dramatically change the structure and functioning of ecosystems (Chapin Iii et al., 2000). For example introduction of predators into a system may exert severe predation pressure on existing herbivorous preys. The resultant demographic decline or local extinction of such preys may lead to increased re-growth of palatable plant species. This may eventually impair the system ability for self-reorganization resulting to bush encroachment in hitherto open grassland. Evidently, overhunting and use of fire by humans some 30,000 to 40,000 years ago in Australia led to removal of large marsupial herbivores. Without large herbivores to prevent fire and fragment vegetation, an ecosystem of fire and fire-dominated plants expanded and irreversibly switched the ecosystem from a more productive state, dependent on rapid nutrient cycling, to a less productive state, with slower nutrient cycling (Flannery, 1994).

Importantly also, the variability of responses (response diversity) of species within functional groups to environmental change is critical to ecosystem resilience (Folke et al., 2004). This allows existence of species within each functional group that can survive under different environmental gradients (Elmqvist et al., 2003). This ensures continuous performance of a related ecosystem services under all environmental conditions e.g. the resilience of savannah rangelands is maintained by existence of high number of plant species with differing capacities to withstand drought and grazing pressure (Walker et al., 1999). Thus these species replaces each other periodically in respect to their tolerance to different magnitude of disturbance. Eventually this ensures provision of forage under different rainfall and grazing pressure.

Thus the proposed study aims at evaluating the resilience of the Lake Naivasha ecosystem. Particularly it will it focus on the role of resource availability gradients and natural disturbance regimes on vegetation productivity and ungulates density. It will examine whether under different resource availability and disturbance regimes, the ecosystem can be able to self-reorganise and ensure persistence and co-existence of vegetation and herbivore species and their related ecosystem services. Thus it will seek to answer the following questions:

1. Will the ecosystem productivity be capable to self re-organise after changes in resource availability?
2. Will the ecosystem productivity withstand differing magnitude of grazing intensity?
3. How will the ungulate species density respond to the changes in forage availability as a consequent of changing vegetation productivity?

2. Research methods and materials.

2.1. Study area.

The study will concentrate on the fringe zone of Lake Naivasha as defined by Ramsar site boundary (Fig. 2). The area covers about approximately 100 Km^2 in a narrow strip comprising the riparian properties. However the proposed study will concentrate on semi-natural vegetation communities by excluding many agricultural properties e.g. flower farms that surrounds the Lake.

Lake Naivasha (0^{0}45 'S and 36^{o}20' E) is the second largest freshwater lake in Kenya covering approximately 150 Km^2. It is located at the floor of Great Rift Valley at an altitude of 1890 m a.s.l. (Hubble and Harper, 2001). The lake comprise of four chemically distinct basins i.e. the main lake, Crescent island basin and two highly alkaline basins, Oloidien and Sonachi (Mavuti and Harper, 2006). Although it receives inflows from two main rivers (Malewa and Gilgil) and one seasonal river (Karati), it has no surface outlet but ground seepage is believed to exist (Becht and Nyaoro, 2005). Annual rainfall ranges about 680 mm and occurs in two rainy seasons while temperature ranges from (Fig 6.). Soils are silt loam to clay with humic topsoil in many places and it is relatively well drained (Hickley et al., 2004).

The land use in the area surrounding the lake has gradual evolved from pure nomadic pastoralism to sedentary farming and ranching to currently highly vibrant floriculture industry producing flowers mainly for export (Abiya, 1996). The floriculture industry has attracted many immigrant workers triggering the human population in the adjacent Naivasha town to burgeon to over 250,000 in 2004 (Morrison and Harper, 2009). Other economic activities include tourism, commercial fishing, geothermal electricity generation, ranching and wildlife conservation (Abiya, 1996).

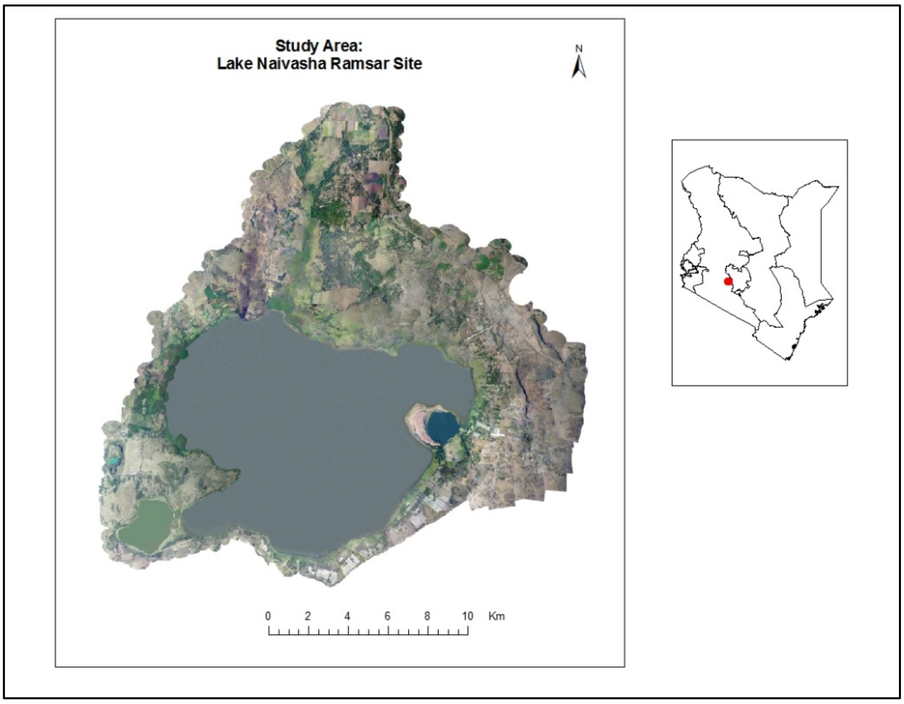

Fig. 2. Map of study area.
Map of study area.

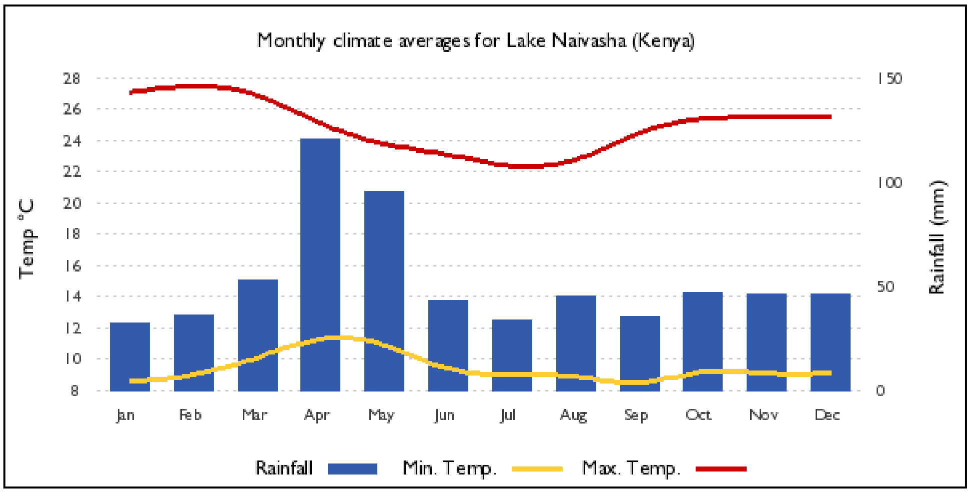

Fig. 3. Temperature and rainfall patterns in Lake Naivasha (JRC, 2010).

2.2. Methods.

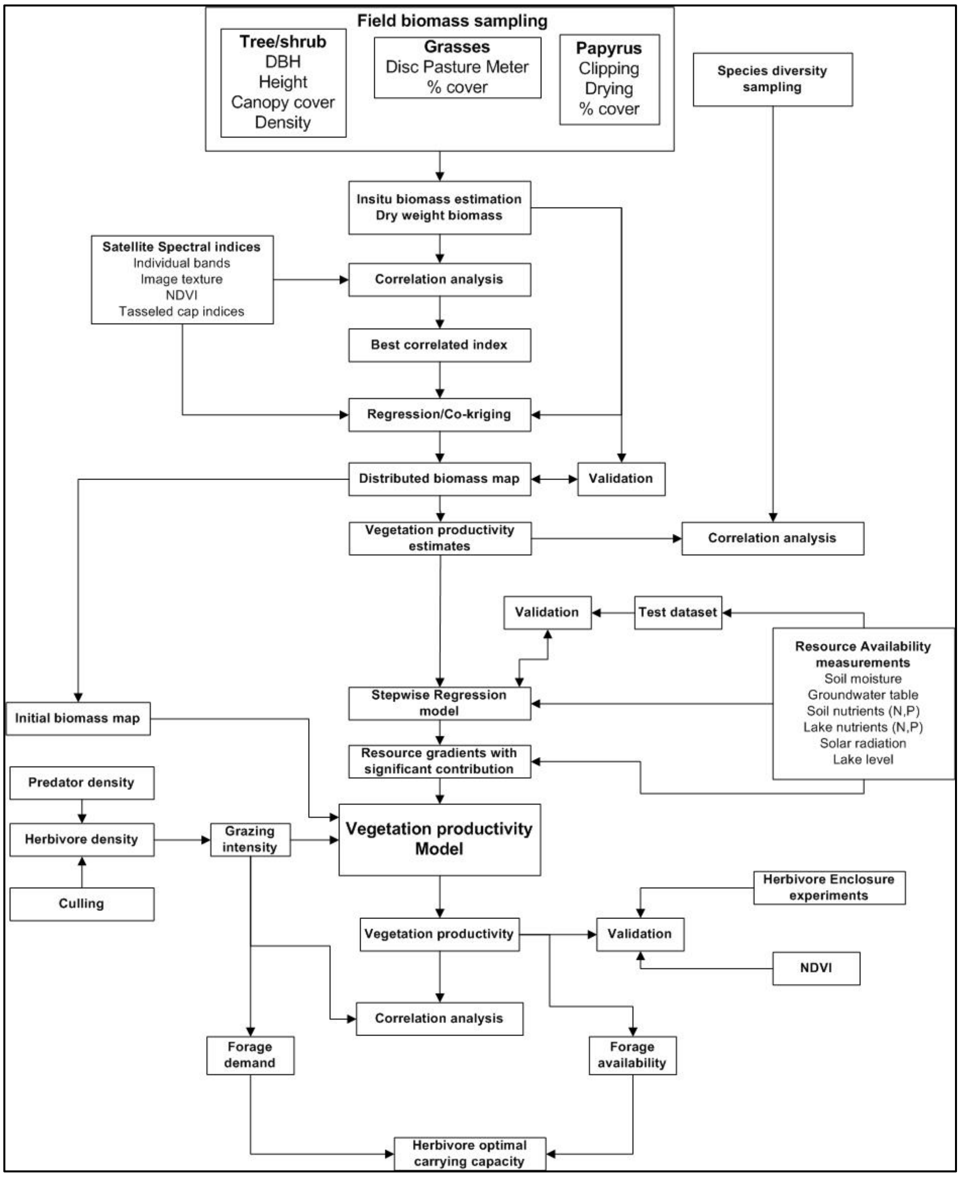

Fig. 4. General methodological approach for the study.

The methods to be utilised in the proposed study are discussed below:

2.2.1. Investigate the relationship between biodiversity and productivity of semi-natural vegetation along the fringe of Lake Naivasha.

Six sampling sites located on the four sides of the Lake (north, south, east and west) will be identified and used for sampling. In each site, 500 m long line transects will be established running perpendicular to the lake. Five plots measuring 30 x 30 m will be established along each transect line after every 100 m. Plant species diversity and productivity will be measured within each plot once every 3 months for a whole year and will be timed to coincide with the end of dry and wet seasons to correspond with low and peak productivity respectively. All plant species for the four plants structural formations (trees, shrubs, grasses and papyrus) will be identified and recorded together with their percentage coverage within the plot. The vegetation species will be identified with the help of field guides and an experienced botanist from the Kenya Agricultural Research Institute (KARI), Naivasha. The sampling unit for trees and shrubs species will be the whole the 30 x 30 m plot while grasses and papyrus species will be sampled within 10 random 1x1 m spacing sub-plots nested within the larger 30 x 30 m plot. The sum of grass and papyrus species in the 10 replicate sub-plots will represent the total number of species for each larger 30 x 30 m plot. The species data will be used to derive Shannon and Simpson's diversity indices for each sampling plot (30 x 30) m.

The productivity of the four vegetation structural components (trees, shrubs, papyrus and grasses) in each sampling plot will be measured concurrently with the resource gradient sampling. Vegetation productivity will be computed as change in standing above ground biomass plus the litter lost between two sampling periods (*t*) (Costa, 2004):

$$\boldsymbol{NPP_{nVeg}} = \sum[(\boldsymbol{B_{t+1}} - \boldsymbol{B_t}) + (\boldsymbol{L_{t+1}} \times (\boldsymbol{B_{t+1}}) \qquad \textbf{Equation 1}$$

Where NPP_{nVeg} is net primary productivity of vegetation formation *n* (trees, shrubs, papyrus and grasses), B_t *and* B_{t+1} are total above ground biomass at the beginning and end of measured interval respectively and L_{t+1} is the percentage litter or vegetation loss during the interval. The percentage of litter lost will be estimated as a constant rate based on literature.

Therefore the above ground biomass of the four vegetation forms will have to be estimated to necessitate calculation of productivity at each time interval. Following Samimi & Kraus (2004), the disc pasture meter (DPM) will be used to estimate the above ground biomass of grass (including forbs). Before estimating the biomass the disc pasture meter will be first calibrated. To calibrate the disc meter, each 30x 30 m plot will be subdivided into 1x1 m spacing grids. The nested 1 m spacing grids will be coded before using a random number generator to select 30 random grids for sampling. The nearest grass patch to the selected grids will be used to measure biomass using the disk pasture meter. The settling height (cm) of disc pasture meter for each measurement will be recorded. A total of 30 readings will be done in the larger 30x30 m plot. After every reading, the grass layer under the plate of the disc pasture meter will be cut at ground level, oven dried at 70^0C to constant weight and weighed to obtain dry weight (g/m^2).

Following Dorgeloh (2002) linear regression will be conducted between the recorded disc settling heights (cm) and measured above ground biomass (g/m^2) (in an area covering the dimension of the disc plate). The linear regression will be performed on untransformed disc heights (independent variable) and above ground biomass (dependent variable) per square. In addition, regression analyses will be conducted with different transformed disc heights (independent variables) i.e. (1) square (x^2), (2) square root (√x), (3) reciprocal (1/x), (4) natural log (ln x), and (5) log x. The regression analysis having the best fit as determined by the coefficient of determination (r^2) will be used for estimating the biomass from the disc readings.

After calibrating the disc pasture meter, 30 random disc pasture meter readings per plot (30 x 30 m) will be recorded and their mean disc height used to estimate the grass biomass (g/m^2) using the calibrated regression equation. The estimated grass biomass (g/m^2) will be multiplied by the percentage cover grass cover in each plot (30 x 30m) to derive the total grass biomass in the plots.

For papyrus, ten 1 m spacing random sub-plots nested within the larger 30x30 m plots will be selected and all above ground materials within it clipped, oven dried at 70^0C to constant weight and weighed to obtain dry weight (g/m^2). The average dry weights (g/m^2) of the ten replicates will be will be used as the papyrus biomass per 1 m spacing sub-plot. This will be multiplied by the percentage coverage of papyrus in the larger (30x30m) plot to derive the total papyrus biomass within the plot.

For trees and shrubs, the sampling will be conducted within the 30 x 30 m plot. Shrubs will be defined as woody vegetation taller than 0.5 m with multiple stems and bushy appearance (FDC, 1997). A tree will be defined as any woody perennial with a single main stem, or in the case of coppice with several stems, having more or less definite crown and a height greater than breast height (5 m) (FDC, 1997). Thus woody vegetation with height less than 5 m will be regarded as shrubs. Parameters to be measured for both trees and shrubs per plot includes: height, diameter at breast height (DBH) for trees and 10 cm above ground for shrubs and tree samplings (Roy and Ravan, 1996), density (number of tree/shrub stems per plot), crown diameter and percentage canopy cover.

The tree height will be measured using a clinometer, crown width with tape measure and DBH with calliper and diameter tape. Percentage tree/shrub canopy cover per plot will be estimated visually using the Bonham (1989) method and the results averaged for each 30 x 30 m plot. Trees crown diameter will be determined by measuring individual tree canopy in the north-south and east-west directions. Crown diameter of individual trees will be pooled by calculating the average canopy diameter per plot.

Trees in each sample plot will be categorized into girth classes of 10 cm intervals. The mean DBH and height for each species for a given girth class will be used to estimate above ground biomass of average tree using allometric regression equations developed by Kiruki et al. (2010) (for Naivasha), Brown et al. (1989) and (FAO, 1997). For shrubs species that have no developed allometric equations, new equations will be developed following Kiruki et al. (2010). The estimated biomass of average tree/shrub will then be multiplied by trees/shrubs density in that girth class to obtain the biomass of particular girth class in the plot. Biomass values of all girth classes within a plot will be summed to derive the total woody and shrub biomass for each sample plot at each sampling period.

Following Samimi & Kraus (2004) and Roy & Ravan (1996) Landsat satellite derived individual spectral bands (Landsat bands 1-5 and 7), image texture and vegetation indices (Normalised Difference Vegetation Index (NDVI), the greenness, brightness and wetness indices of the tasseled cap transformation) will be correlated with the measured above ground biomass for the each of the four vegetation structural formations in the sample plots. The spectral bands, image texture or vegetation indices that are highly correlated with measured above ground biomass will be selected and used to derive a distributed above ground biomass for the whole study area.

Two methods of estimating the distributed above ground biomass will be evaluated: (1) regression analysis (Lu, 2005) , and (2) co-kriging (Mutanga and Rugege, 2006) using the selected spectral information and measured biomass for each vegetation structural form. Following Lu (2005), the predictive ability of the regression and co-kriging models will be evaluated using the Root Mean Square Error (RMSE) resulting from comparison of the measured and predicted above ground biomass. The available aerial photos will be also used to validate the spatial distribution of the predicted above ground biomass. The derived equation for the method with the highest predictive power will be used to estimate aboveground biomass in consequent intervals (every 3 months) using the corresponding spectral indices.

The productivity of each vegetation structural form at each interval will be derived using equation 1 above. The productivity values at each interval corresponding to pixels used as sampling plots will be abstracted. Finally, a correlation analysis between the derived diversity and productivity values for each plot at all sampling intervals (seasons) will be conducted to infer the relationship between diversity and productivity. The strength of the relationship will be evaluated using the correlation coefficient (r).

2.2.2. Determine the impact of resource availability on productivity of semi-natural vegetation along the fringe of Lake Naivasha.

To determine the impact of resource availability on the productivity of semi-natural vegetation forms, backward stepwise regression models between the estimated vegetation productivity (dependent variable) and measured resources availability (independent variables) will be run. The explanatory variables for trees, shrubs and grasses productivity models will be: Soil moisture content, soil nitrogen (N) concentration, soil phosphorous (P) concentration, ground water table and solar radiation. While explanatory variables for papyrus productivity model will be Lake level, ground water table, nitrogen concentration in the Lake, phosphorous concentration in the lake, soil (sediments) nitrogen concentration, soil (sediments) phosphorous concentration, solar radiation.

Measurements for all explanatory variables will be conducted in the same sampling plots as in objective 1 above. Within each sampling point soil moisture will be measured using soil moisture probes. Soil (or sediments in case of papyrus) samples will also be collected for measuring concentration of plant extractable mineral nitrogen (nitrate + ammonium) and extractable mineral phosphorous in the laboratory. For terrestrial environment soil samples (100 g) will be collected from the top 10 cm soil in each plot, however in papyrus swamp sediments (500g) samples will be collected among the roots of papyrus. Soil samples will be collected for six months (3 months in dry and wet seasons respectively) in one year. Analysis of extractable mineral nitrogen (nitrate + ammonium) and phosphorous will be conducted following (Muthuri and Jones, 1997) in Water Resources Management Authority (WRMA) laboratory, Nakuru, Kenya. Nutrient concentrations for each season (3 months) will be averaged to give a seasonal mean.

Moreover, water samples will be collected within the fringing papyrus swamp for nitrogen and phosphorous concentration analysis in the same laboratory. The lake levels (water depth) will also be measured at the same points of nutrient sampling. However, the groundwater levels data will be obtained by measuring the levels of shallow wells along fringe zone on weekly basis in corroboration with Water Resources Management Authority (WRMA), Naivasha. The weekly measurements will be averaged to yield the mean for each season (3 months). Since shallow wells are not necessarily located within the selected sampling plots, the seasonal averaged groundwater levels will be interpolated for the whole study area. The interpolated groundwater levels corresponding with the sampling plots will be abstracted in GIS. Furthermore, Leaf Area Index (LAI) will be used as a proxy for solar radiation interception and will be measured using Licor LAI 2000 equipment.

The productivity of the four vegetation structural formations estimated in objective 1 will be used together with resource availability gradients data to develop backward stepwise regression models for each vegetation formation. This will ensure only the resource gradients with significant contribution to the productivity models are included in the final model for each vegetation formation. The models will be trained with random 75% of the productivity measurements while the remaining 25% will be reserved for model validation. The productivity of each vegetation structural components (trees, shrubs, papyrus and grass) will be the dependent variable while the resource gradients variables will be the independent variables.

The models will be validated using the 25% random productivity measurements for each vegetation formation initially set aside as testing dataset. The model performance will be evaluated by the coefficient of determination (r^2) that measures the percentage of variation explained by the regression model (Lu, 2005). The variance explained by each resource gradient in the productivity model for each vegetation formation will be used to assess it's the relative contribution to productivity of that particular vegetation formation. The statistical significance of the contribution of each resource gradient in productivity models for each vegetation formation will also be tested ($p=0.05$). The relative importance of each resource gradients in productivity models of each vegetation formations will be ranked from the highest to lowest in based on the variance explained.

2.2.3. Quantify the impact of grazing intensity on productivity of the semi-natural vegetation along the fringe of Lake Naivasha.

The impact of large herbivorous mammals grazing intensity on semi-natural vegetation productivity will be quantified by developing a spatially explicit vegetation productivity model. The vegetation productivity model will be driven by resource gradients with the significant impact on the productivity of each vegetation formations as determined in objective 2 above while also adding large ungulates herbivory as disturbance force. The model will be simulated at 30 m spacing grid cells in a monthly time steps for a period of 18 years starting from 1995 to year 2013. The timing is due to availability of large mammals' census data.

The productivity models for each vegetation formation will be initialized by above ground biomass map of initial year (1995) derived using Landsat imagery vegetation (spectral) indices as described in objective 1 above. The model will simulate biomass accumulation and for each time step the productivity will be derived using equation 1 above. The processes driving the above ground biomass accumulation for each vegetation formation includes: competition for resources (soil moisture, light and nutrients), leaf senescence, mortality and herbivory.

The herbivore species to be simulated are shown in Appendix 7.1. The selection of the species is based on biannual (dry and wet season) large mammal's census data collected by Nakuru Wildlife Conservancy (NWC) and Kenya Wildlife Service (KWS) on the riparian properties surrounding Lake Naivasha. Following Toxopeus (1994) the herbivorous mammals (grazers and browsers) will be simulated to forage on the vegetation depending on their diet preferences and forage availability. Following Coughenour (1993) herbivores diet composition will be derived using preference weighting that depend on relative availability of different forage types in each grid cell and known diet preferences or avoidances of the simulated herbivores. The preference weighting PrfW will be derived as:

$$\mathbf{PrfW = Prft_{nVeg} * Tavb_{nVeg}} \qquad \textbf{Equation 2}$$

Where $\mathrm{Prft_{nVeg}}$ is the preference for a certain n vegetation formation i.e. (trees, shrubs, papyrus and grasses) while $\mathrm{Tavb_{nVeg}}$ is the total available biomass for all simulated vegetation formation in each grid cell.

Herbivores do not exploit all the available forage biomass. Thus to the available grass, papyrus and shrub forage in each grid cell will be calculated by accounting for grazing efficiency, forage loss and a "proper use factor" (45% of standing biomass) (Toxopeus et al., 1994). While only browseable tree biomass that is within the height reachable by herbivores will be considered as available for browse (De Knegt et al., 2008). In addition, the movement of herbivores and thus accessibility to forage will be restricted by fences. Thus fence map will be input in the model as force maps that restrict forage accessibility in certain properties.

Moreover, herbivores will be simulated to forage optimally thus maximising the energy gained from each foraging bout. They will select the cell to forage based on its attractiveness that is itself determined by forage abundance and quality (Owen-Smith, 2002). The instantaneous intake rate for both grazers and browsers will be will be derived using a Holling type II functional response (Owen-Smith, 2002):

$$\mathbf{I = \frac{i_{max} * F}{g_{1/2} + F}} \qquad \textbf{Equation 3.}$$

Where $\mathrm{i_{max}}$the maximum food intake rate at high food abundance, F is is the food availability and $\mathrm{g_{1/2}}$ is the food availability at which I reach half of its saturation. The forage digestibility will be simulated to decline as standing biomass increases (Prins and Olff, 1998), thus decreasing the instantaneous energy gained from foraging in a cell. Thus the instantaneous rate of energy gain after foraging in a cell (E) will be derived by adding a reduction term for digestibility of forage (Owen-Smith, 2002):

$$\mathbf{E = \frac{i_{max} * F}{g_{\frac{1}{2}} + F}(1 - q)^F} \qquad \textbf{Equation 4.}$$

Where q is the coefficient of the decrease in forage quality with increasing standing biomass. Therefore, grazers will increase the attractiveness of grazed cells by decreasing the standing crop and thereby increasing the nutritive quality of forage. Hence grazed cells will be revisited more often as long as the re-growth of grazable forage is faster than the time within which grazers return (De Knegt et al., 2008). Similarly, browsers will be able to facilitate themselves by increasing the amount of reachable forage by keeping the trees short and stimulating the re-growth of trees and shrub vegetation after defoliation (De Knegt et al., 2008).

The monthly forage intake for each herbivore species will be derived a as a proportion of their body mass (Owen-Smith, 2002):

$$\mathbf{req_F = f_d p_{size}} \qquad \textbf{Equation 5.}$$

Where $f_d$is the monthly dry matter intake as proportion of herbivore body mass and p_{size} is the population size of each herbivore species expressed as total biomass. Summation of forage intake for all herbivore species will yield the forage demand in each time step. Following Groen (2007), increase in herbivore density will depend on forage intake and conversion efficiency of consumed forage biomass into herbivore biomass. Thus the change in herbivores biomass will be represented as:

$$\mathbf{\frac{dG}{dt} = e_H GH - d_G G} \qquad \textbf{and} \qquad \mathbf{\frac{dB}{dt} = e_W GW - d_B B} \qquad \textbf{Equation 6.}$$

Where G and B are grazer and browser biomass respectively, e_H and e_W is coefficient for consumption and conversion efficiency of forage biomass to grazers and browsers biomass respectively, H and W are the total grazable (grass) and browsable (trees, shrubs and papyrus) biomass respectively, d_G and d_B are the specific mortality rate of grazers and browsers respectively.

In addition, herbivore management options such as culling and introduction of predators may control the grazing intensity to exceed the ecosystem carrying capacity as determined by forage availability. Therefore culling and predator introduction will be added to evaluate their impact on productivity of the riparian vegetation. Following Boone et al. (2002) two culling regimes will be explored; (1) culling a specified number of animals each year using an annual culling rate (proportion of herd culled) (2) every year on particular month x (culling month) the populations are reduced to a specified density per each herbivore species. To assess the effect of management alternatives, three more models will be simulated: (1) model with only culling (2) model with only predator introduction (3) model with both culling and predator introduction.

Model calibration, validation and analysis.

Following Boone et al (2002) the model for the first year (1995) will be calibrated by adjusting the control parameters until the simulated values coincides or closely matches the observed herbivore population and vegetation. The calibrated model will then be run for the entire simulation period.

The results will be validated by correlating the modelled above ground biomass with Normalised Difference Vegetation Index (NDVI) derived from satellite imagery and the simulated herbivore biomass with the census data. It will also be compared with measured above ground biomass and estimated productivity for each vegetation formation as determined in objective 1.

The results will be further validated using herbivore enclosure experiments (Augustine et al., 1998). Enclosures will be set-up in sites with high herbivore densities to create "low herbivore density" within the enclosure as compared to control site outside the enclosure. Enclosures measuring 10 m^2 will be built and paired with two adjacent unenclosed control plots of equal size. For each enclosure and the respective control plots, vegetation biomass will be measured during dry and wet season using the method described in objective 1 above. Paired statistical tests will be used to compare the vegetation biomass within the enclosures and the control plots.

To analyse the impacts of grazing intensity on the vegetation productivity, the simulated productivity of various forage classes will be correlated with the simulated herbivore density. This will discern the feedback mechanisms between the vegetation and herbivores i.e. how variations in herbivore (grazing intensity) impact on vegetation productivity and consequently the forage availability and vice versa. The ungulates carrying capacity will be evaluated by comparing the seasonal forage demand (forage required by simulated herbivore population to satisfy their daily dry matter intake) with forage availability (simulated edible forage biomass of different vegetation forms). The effectiveness of different culling regimes on vegetation productivity and herbivore density will be evaluated by comparing the results of the three models simulating different management alternatives with the "control" model without management options.

2.3. Data requirement and availability.

Table 1. Data availability

Category	Available	Time span Available	Source	Resolution Temporal	Resolution Spatial	To be corrected
Animal population						
Wild mammals Density	Y	1995-Todate	NWC	Bi-annual	Farms	1977-1995
Livestock density in ranches	N		Ranches/Vet. Dept.	Monthly	Farms	1977- To date
Nomadic livestock	N		Vet. Dept.		Ecotone	1977- To date
Water levels						
Lake levels	Y	1930 - To date	Water Dept.	monthly		
Ground water levels	Y	1930-Todate	LNRA/Farms	Various		
Land cover						
Aerial Photos	Y	1967-2001	LNRA/SOK	Various	Ecotone	
Satellite imagery-Landsat	Y	1975-Todate	GLOVIS	Monthly	Ecotone	
Climate data						
Solar radiation		1995 To date	Kenya Met. Dept.	Monthly	Ecotone	
Soils						
Soil types & characteristics	Y	2004	Kenya Soils Survey		Ecotone	

3. Relevance to EOIA project.

The EOIA aims at integrating knowledge over a range of disciplines to provide new information on sustainable management of the Lake Naivasha ecosystem. This will be achieved through the use of Earth Observation (EO) and derivative geo-information in integrated assessment models. The aim of biodiversity subcomponent is to assess how the lake level induced fluctuations in fringe habitat area affect population viability of a number of species of concern. The study will focus on riparian vegetation and large herbivorous mammals' species. It will mainly focus on interrelationships between hydrology-vegetation- herbivore dynamics. This is because riparian vegetation provides essential ecosystem services like biological buffers against nutrients and sediments, habitat provision and food for herbivores. However it is threatened by decline in water levels, direct clearing and overgrazing by domestic and wild ungulates. Therefore the riparian vegetation and ungulates are species of concern not only because of the ecosystem services they provide but also due to the fact that they are interdependent on each other.

The biodiversity sub-project interrelates with the other sub-components (PhDs) as follows:

1. Hydrology: The amount of inflowing water (discharge) influences the lake levels. Decline in the lake levels reduces the area of the lake that is poor in biodiversity while increasing the area of the fringe zone which is rich in biodiversity. Declining water levels have direct implications to vegetation productivity and may also facilitate gradual change of riparian vegetation from water dependent species to less dependent species. The upstream land use/land cover changes influence water quantity and quality downstream. The inflowing rivers deposit their nutrient and sediment loads on the fringe zone hence influencing productivity of riparian vegetation. Land-use changes such as clearing vegetation for agricultural expansion often lead to changes in biodiversity and vegetation structure (Adler et al., 2001).
2. Limnology: The riparian vegetation (e.g. papyrus), buffer the lake against nutrient and sediment loads thus enhancing water quality and transparency in the lake. This affect fish productivity and population dynamics of fish eating birds. The lake also is daytime refuge for hippos that agents for nutrient transfer from terrestrial fringe to the lake. This is because they forage on the fringe nocturnally and defecate on the lake.
3. Socio-economics: The riparian area provides environmental services such as provision of habitat, biological buffer and carbon sequestration that are considered for Payment of environmental (PES) scheme. Moreover, the riparian biodiversity contributes to the economy through income generated from ecotourism and sale of livestock and fish. It also improves livelihoods by provision of food (milk and meat) especially for nomadic herders. The increased floriculture farming abstract water for irrigation, contributing significantly to decline in lake levels and consequent effects on riparian biodiversity. The socio-economic drivers of land use/ land cover change could be linked with the natural drivers of vegetation productivity to give wholesome (natural and anthropogenic) integrated study of drivers of primary productivity within the system.
4. Governance: The current institutional and legal context (water, land, wildlife legislations) influence the management of these resources hence their sustainability.

3.1. Indicators of assessment.

The ecosystem health will be assessed using the following indicators:

1. **Species diversity -** Shannon and Simpsons diversity indices will be for vegetation communities within the fringe zone.
2. **Species composition -** Vegetation species composition will be derived by identifying and enumerating species within the vegetation structural formations.
3. **Relative abundance:** This will be derived by estimating the percentage coverage of each vegetation species/structural formation in the sampling plots.
4. **Vegetation productivity**: This will indicate accumulation of biomass (g m^2/yr^{-1}) for various vegetation structural formations per interval in the growing calendar.
5. **Biomass density**: The above ground biomass (AGB) of vegetation class will be measured using a combination of ground-based methods and satellite derived spectral indices for the entire landscape. Moreover herbivore density will measure as average live weight multiplied by number of individuals of each species.
6. **Carrying capacity**: Herbivore carrying capacity will be expressed in terms of total available edible forage from all vegetation structural forms.

4. Budget

The estimated budget is outlined below. However only vote heads that will be expedited in the field are shown (some administration costs e.g. fees are not accounted).

Table 2. Budget

Votes	Amount (Euro)
Fuel and Transportation	8400
Materials and Equipment	3422*
Chemicals and detergents	2760*
Conferences & courses	1500
Bench fee	3500
Field Assistant	600
Communication	100
Contingency	1888
Total Expense	21670

*Estimates to be reviewed once all quotations are consolidated

5. Workplan.

Table 3. Timeline

Task	Description	Years																		
		2010			2011				2012				2013				2014			
Proposal development	Literature survey	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
	Proposal development	■	■	■	■															
Field Data collection	Sample and secondary data collection				■	■	■	■	■	■	■	■	■	■	■	■				
Data Analysis and research output	Analysis on diversity-productivity relationship						■	■			■	■								
	Writing & submission research paper 1 & 2								■			■								
	Analysis on resource gradients vs. productivity							■	■	■		■								
	Writing & submission research paper 3												■							
	Analysis on grazing intensity vs. productivity									■	■	■	■	■	■	■				
	Writing & submission research paper 3 & 4															■	■			
Thesis writing	Chapters compilation & synthesis															■	■			
	Submission and defense																■			

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7. Appendix

7.1. The herbivore species to be simulated.

Common name	***Species***
	Grazers
Hippo	*Hippopotamus amphibious*
Buffalo	*Syncerrus cafer*
Zebra	*Equus burchelli*
Wildebeest	*Connochaetes taurinus*
Waterbuck	*Kobus ellipsiprymnus*
Thompsons Gazelle	*Gazella thomsoni*
Impala	*Aepyceros melampus*
Grants Gazelle	*Gazella grantii*
Kongoni	*Alcelaphus bucelaphus*
Warthog	*Phacochoerus africanus*
Bushbuck	*Tragelaphus Scriptus*
Reedbuck	*Redunca redunca*
Oryx	*Oryx gazella*
Topi	*Damaliscus korrigum*
Duiker	*Sylvicapra grimmia*
Oribi	*Ourebia ourebi*
Kirk's DikDik	*Madoqua kirkii*
Cattle	*Bos Taurus*
Sheep	*Ovis aries*
	Browsers
Giraffe	*Giraffa camelopardalis*
Eland	*Taurotragus oryx*
Goats	*Capra aegagrus*

7.2. Vegetation sampling datasheet

Vegetation sampling Datasheet

Nr. …………………………. Date …………

. . Locality ……………………………………………

Coordinates ………………………………………... Altitude …………………………………

Aspect……………………………………………….. Slope……………………………………..

Size of the stand……………………………………. Plot size………………………………….

Plant community……………………………. …………………………………………

Soil type……………………………………………………………………………………….

Land use……………………………………………………………………………………….

Species	%cover	Height	DBH	Canopy diameter	Density

Observations:

7.3. List of available aerial photos for Lake Naivasha

S no.	Photo Particulars	Year	Scale
1	Aerial photographs (B/W) full coverage of Naivasha lake and surroundings	1967	1:50000
2	Aerial photographs (B/W) full basin-wide cover of Naivasha	1970	1:50000
3	Aerial photographs (B/W) full coverage of Naivasha lake and surroundings	1984	1:12500
4	Aerial photos (B/W) cover of the geothermal plant area (Olkaria & southern part of lake Naivasha	1990/91	1:10000
4	Aerial photographs (Colour) full coverage of Naivasha lake and surroundings	1998	1:5000
6	Aerial photographs (Colour) full coverage of Naivasha lake and surroundings	2001	1:5000
7	Aerial photographs (Colour) full coverage of Naivasha lake and surroundings	2009	1:5000

7.1. List of materials and equipments.

No	Material
1	Disc Pasture meter
2	Clinometer
3	Calliper
4	Meter tapes (30 m and 50 m lengths)
5	GPS receiver
6	Field guides (Plant and mammals identification field books)
7	Satellite imagery (Landsat, Aster)
8	Cooler boxes
9	Aerial photos and topographic maps
10	Hand shears, hand saw and machete
11	Fencing posts
12	Barbed wires
13	Binoculars
14	Chemicals and detergents
15	Wooden frame quadrants
16	Soil moisture probes
17	Licor LAI 2000 equipment