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Observing Changes in Riparian Buffer Strip Soil Properties Related to Land Use Activities in the River Njoro Watershed, Kenya

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Abstract Riparian buffer strip guidelines are under scrutiny in the River Njoro Watershed in Kenya. This study investigated soil properties (bulk density, carbon, nitrogen, and phosphorus) in different land use types (small scale agriculture in recent settlements, mixed agriculture in established peri-urban settlements, large-scale commercial agriculture, and the gazetted forest reference condition) and their adjacent buffer strips. Bulk density, carbon, nitrogen, and phosphorus within 30-m riparian buffer strips adjacent to recent settlement land use areas were similar to those of the gazetted forest reference condition, but only bulk density of the buffer strips adjacent to peri-urban and commercial agriculture land use areas were similar to the gazetted forest reference condition. Phosphorus is a sensitive indicator of the impacts of human activity, as increased concentrations were observed with increasing scale of land use activity. For riparian buffers adjacent to recent settlements, soil phosphorus was significantly higher in buffers narrower than 30 m (5.01 mg P kg^{-1}) than gazetted forest (3.40 mg P kg^{-1}) but not significantly different for riparian buffers wider than 30 m (3.81 mg P kg^{-1}) compared to gazetted forest. Based on the research, it is recommended that policies governing riparian buffer strips become (1) stricter, with the current “maximum” of 30 m considered a minimum; and (2) adaptive, with 30 m used in small-scale agricultural areas, and wider riparian buffer strips used in medium- and large-scale agricultural areas.

Keywords Riparian area · Buffer strip · Soil properties · River Njoro · Kenya

1 Introduction

Water sustainability depends on ecosystem structure and function; and in Kenya, water policy tends to ignore water as an ecosystem service (Baldyga 2005). In recent years, rural communities are increasingly encroaching on forest reserves, riparian areas, and commercial agricultural areas for their own pasture and crop production. This trend has persisted in the face of persistent dry conditions and decreasing water flows in rivers serving Kenyan rangelands, despite the recognition that these actions will impact the communities that depend on the rivers’ ecosystem services (Chemilil 1995).

Riparian buffer strips have become an integral part of watershed management in American and European

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landscapes (Decker 2003; Sweeney and Blaine 2007). Riparian buffer strips are vegetated areas adjacent to streams, rivers, lakes, and other waterways that protect aquatic environments from excessive sedimentation, surface runoff pollutants, and contaminants from the adjacent landscape. However, in many parts of Africa, riparian buffer strips are not used and scientific support for using riparian buffer strips to mitigate changes in water resources is needed within African landscapes. In traditional African culture, there is no demarcation or separation of people from nature since nature and people are viewed to be the same (Lelo et al. 2005). People in communal Africa have sustained their livelihoods for many years, practicing cultivation within riparian areas without posing a significant threat to the ecosystem (Derman 1998). Consequently, people visit and use riparian areas and streams on a daily basis (Mathooko 2001). However, with an increasing human population and increased intensity of adjacent land use due to increased commercial agricultural activities, there is need to pay more attention to these areas to ensure that they are not overburdened.

In the River Njoro Watershed, the riparian area provides resources to local communities and supports critical downstream watershed services. River Njoro has a narrow strip of indigenous riparian vegetation averaging about 15–20 m, and some sections have been completely cleared to provide access to the stream (Magana and Bretschko 2003; Mathooko 2001). The riparian areas are threatened by an incompatibility between (1) tribal norms, (2) communal regulatory mechanisms, and (3) government statutory enforcement mechanisms. The “free access” mentality has led to a decline in riparian services such as water quantity and water quality. The increased prevalence of downstream flooding during rainfall events due to increased runoff during the rainy season and decreased runoff during the dry season has been attributed to land use change (Baldyga et al. 2007; Lelo et al. 2005; Shivoga et al. 2007). Better quality stream water has been observed adjacent to intact riparian buffer strips compared to stream water adjacent to little or no vegetated riparian buffer strips (Shivoga et al. 2007). Additionally, a change from forested to agricultural and grazing land uses has affected the physical–chemical environment of River Njoro, reducing the diversity and evenness of benthic macroinvertebrates, an indicator of declining water quality (Kibichii et al. 2007).

Riparian buffer strips remove nutrients (carbon (C), nitrogen (N), and phosphorus (P)) from water flowing from adjacent lands to the river through biological (e.g., nutrient uptake by riparian vegetation, microbial assimilation, and microbial denitrification for N-based nutrients and microbial respiration for C) and physical–chemical (e.g., nutrient adsorption for phosphorus which binds to clay particles and sediments) processes. Not all riparian buffer strips are effective in mitigating changes to soil properties related to land use types. Hydrology will influence the degree of nutrient removal if (1) flows are dominated by surface/near surface pathways, effectively bypassing the riparian function and delivering nutrients straight to the river, or (2) flows are dominated by subsurface pathways where biological uptake, transformation, fixation, and adsorption processes can occur (Buttle 2002; Hill 2000).

Size impacts a buffer’s effectiveness because buffers that are too narrow may not adequately protect aquatic resources from adjacent land use activities, while buffers that are too wide may deny landowners productive use of their land (Castelle et al. 1994). The optimal size of the riparian buffer strip continues to generate debate, and no fixed width is universally accepted, although Castelle et al. (1994) suggest that a minimum of 15–30 m width is necessary to protect streams and wetlands. Generally, recommendations for riparian buffer strip widths vary from 10 to 100 m on each side of the stream and are usually based on a sound intuitive grasp of the processes that should be protected (Allan et al. 1997). Appropriate riparian buffer strip widths vary with stream size, stream order, and ecosystem type as well as aquatic resource functional value, intensity of adjacent land use, buffer characteristics, and specific buffer functions required (Castelle et al. 1994; Osborne and Kovacic 1993). These recommendations are sensible, but the scientific information for or against a specified riparian buffer strip width is limited (Osborne and Kovacic 1993). Generally, a specific riparian buffer width should sustainably remove as much nutrient capacity within the area as enters the area through upslope nutrient influx (Castelle et al. 1994; Cooper et al. 1995). Unfortunately, buffer policies worldwide are significantly influenced by political acceptability rather than scientific data (Castelle et al., 1994), and the River Njoro Watershed in Kenya is no exception. Within Kenya, the 2002 Water Act describes riparian zones as land lying within a distance equal to the width of the watercourse, with a minimum of 2 m and a maximum of 30 m (Republic of Kenya 2002). This policy is being debated, as some Kenyan stakeholders feel it is too wide, while others express a need for a wider buffer strip. There is no scientific basis to support a 30 m or any other width of riparian buffer strip. Advocacy for a properly functioning riparian buffer strip is strong because River Njoro is stressed by nutrients from land use activities within its catchment (Mokaya et al. 2004; Shivoga et al. 2007).

Previous studies in the River Njoro Watershed have focused on indicators of river water quality (Shivoga 2001; Shivoga et al. 2007); however, it is difficult to disentangle local effects from the cumulative effects of upstream activities. Comparing the properties of soils within riparian buffer strips adjacent to different land use types and to reference condition soils in a natural landscape provides a more robust picture of how buffer strips mitigate nutrient influx. Surface soils interact directly with surface runoff, and consequently, adjacent land use is expected to have the greatest impact on surface soil properties (Cooper et al. 1995) and the soil chemical properties in the riparian buffer are a reliable indicator of the quality of surface runoff discharged from the adjacent lands to the stream. For example, P mostly enters the stream adsorbed onto soil particles and organic materials in surface runoff after storm events (Pionke et al. 1996), influencing adjacent and downstream water quality. It may also adsorb to fine-grained sediment and be deposited onto the riparian buffer zone (Dillaha and Inamdar 1997), influencing the level of P in the riparian buffer strip soils as a result of sedimentation (Hoffman et al. 2009). Furthermore, a study by Cooper et al. (1995) comparing riparian soils under different land use areas in New Zealand revealed large differences in several key physical, chemical, and microbial properties that can influence the zone's role as a buffer of material transfer across the land–water interface.

The purpose of this research was to determine if Kenya's policy of 30-m riparian buffer strip width mitigates changes in soil properties related to land use activities adjacent to riparian buffers in the River Njoro Watershed. The soil properties of different land use areas, including recent settlements, peri-urban settlements, and commercial agriculture, were compared to a gazetted forest riparian buffer strip used as a reference condition. We evaluated the effectiveness of riparian buffer strips adjacent to different land use types by comparing bulk density and concentrations of C, N, and P in the soils to those in a gazetted natural forest. The objectives of this study were to (1) determine soil properties in different land use types; (2) determine soil properties within riparian buffer strips adjacent to different land use types; and (3) determine if the government regulated maximum riparian buffer strip (30 m) results in minimal changes to soil physical and chemical properties associated with land use activities in the surrounding landscape.

2 Study Area

The River Njoro Watershed covers approximately 280 km^2 (Fig. 1). The river originates at an elevation of about 3,000 m above sea level in the Eastern Mau Escarpment, and descends in a northeast direction before terminating at Lake Nakuru on the floor of the Rift Valley at about 1,800 m above sea level. The river provides 65% of the total freshwater in-flow to Lake Nakuru (Gichuki et al. 1997) and is on average 10 m wide (ranging from about 1 m to 15 m). The watershed has a population of over 300,000 people (Ministry of Finance and Planning 2002) and includes the urban center Njoro Town (30,000 people) and much of the Nakuru municipality (240,000 people; Lelo et al. 2005).

The climate is characterized by a trimodal precipitation pattern: long, intense rains from April to May; short, intense rains in August; and shorter, less intense rains from November to December. Total annual precipitation is 956 mm, and the mean annual temperature is 16.5°C, ranging from a minimum of 9°C (July) to a maximum of 24°C (January; Baldyga 2005). Geology is characterized by porous pumiceous formations (McCall 1967). Soils include Humic Acrisols (Ultisols), Phaeozems (Mollisols), Andosols, Planosols (Aqualfs), Plinthosols, and Fluvisols (Fluvents; Mainuri 2006). Soil textures range from clay loams in the lower watershed to sandy clay in the plantations and indigenous forest areas at higher altitude, the focus of this study. Vegetation cover ranges from 90% in upland indigenous forests that are difficult to reach due to extreme topographic relief on the eastern rift escarpment to 0% in areas affected by anthropogenic practices (Baldyga 2005).

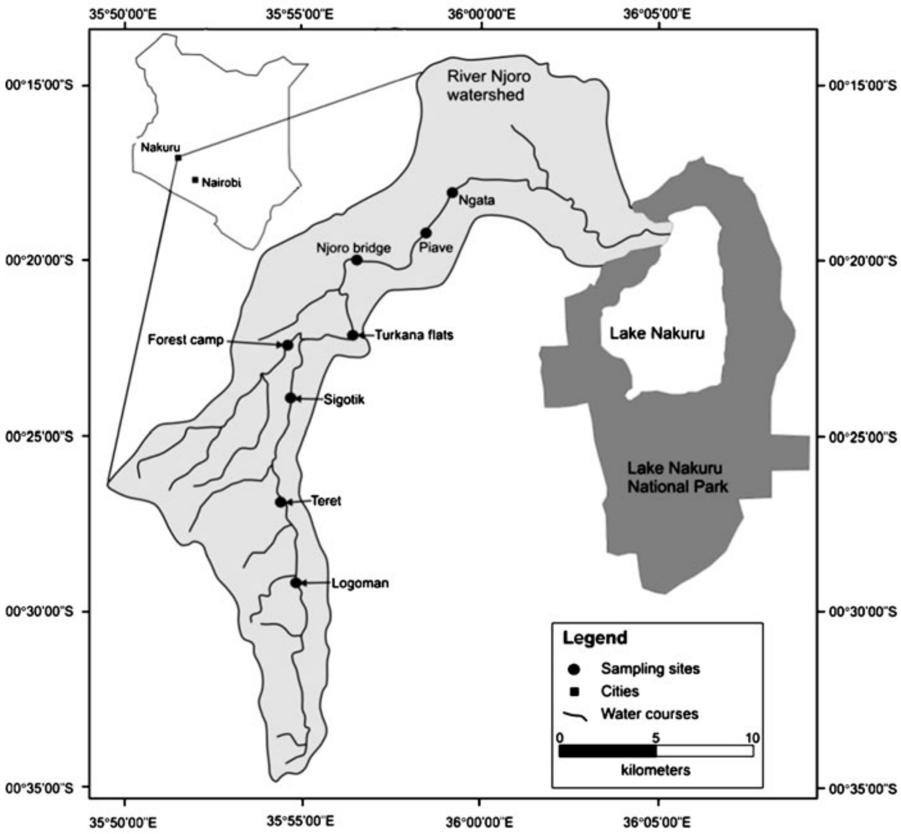

Fig. 1 Map of the River Njoro Watershed, Kenya

The study area was 30 m on each side of a 25-km length of river with similar riparian forest and soil compositions but different surrounding land use types (Fig. 1). These land use types include (1) predominantly protected government forests (i.e., gazetted forests; Fig. 2a); (2) small-scale agriculture associated with new settlements on recently felled plantation forests characterized by temporary structures (i.e., recent settlements; Fig. 2b); (3) medium-scale agriculture associated with older settlements surrounding urban areas (i.e., peri-urban settlements; Fig. 2c); and (4) large-scale agriculture with permanent structures (i.e., commercial agriculture; Fig. 2d; Lelo et al. 2005).

3 Methods

The study was conducted in a stratified randomized design. Four riparian areas with different neighboring land use types (Fig. 2) were selected. For each land use type, two sampling sites (eight in total) were selected at random, and for each, a sampling cluster of five transects positioned 50 m apart was established. Each transect centered on a watering point (points where human beings and livestock access the river for water) running 30 m to the left and right side of the river (Fig. 3), but the transects centered on the watering sites were not included in the analysis to minimize the effect of human disturbance within the riparian area. The riparian buffer strip covered the entire observed area for the gazetted government forest (i.e., 30 m on each side of the river) and ranged from no coverage to 30 m in width for the other land use types.

One soil sample was collected at three points (10, 20, and 30 m from the streambank) along each of the four transects on each side of the stream, giving a maximum of 24 samples per sampling site. Soil samples could not be obtained where there was extensive underlying bedrock. For bulk density, soils were sampled at surface (0–20 cm) depths using cylindrical core rings (50 mm height and 50 mm diameter), placed on aluminum trays where coarse organic matter was removed manually, oven dried at 105°C, cooled in a desiccator, and then weighed. Bulk

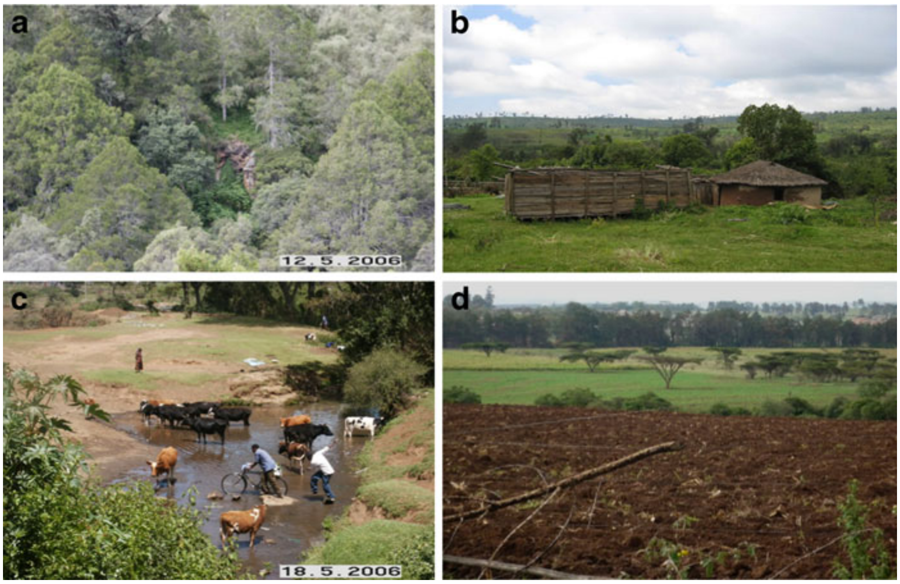

Fig. 2 Different land use types in the River Njoro Watershed **a** gazetted forest, **b** recent settlement, **c** peri-urban settlement, and **d** commercial agriculture

density (g/cm^3) was calculated using the mass of soil within the volume of the cylindrical core ring. Previous studies observed little change in bulk density 10 cm below the soil surface (e.g., Augeard et al. 2007), so soil samples were not collected to determine the bulk density of subsurface soils (20–50 cm).

For nutrient analyses, soils were sampled at surface (0–20 cm) and subsurface (20–50 cm) depths using a soil auger and placed on aluminum trays. Litter and roots were removed, and the soil was air dried, ground, passed through a 2-mm diameter sieve, then analyzed for C, N, and P using near-infrared technology. A Bruker MPA spectrometer was used to obtain soil spectral reflectance signatures on air-dried soil samples at the World Agroforestry Centre, formerly the International Centre for Research in AgroForestry laboratories, in Nairobi, Kenya. Air-dried and sieved soil samples were placed on a Petri dish and positioned on an optical window. Near-infrared light was then broadcast onto the sample and the reflected light was

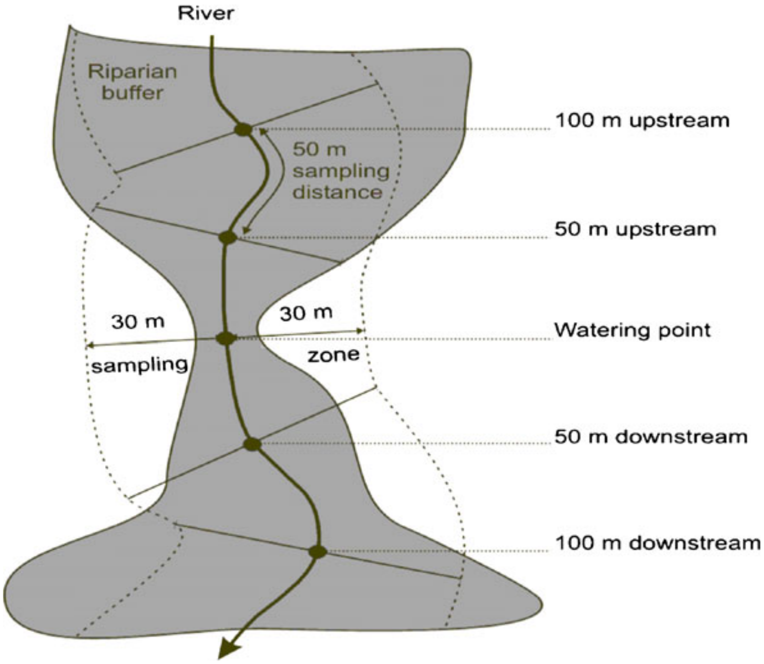

Fig. 3 Experimental design at each sampling station. *Dotted lines* are a schematic representation of the 30 m strip of riparian buffer, while the *gray shaded area* is a representation of how the actual strip of riparian buffer varied. Transects are perpendicular to the stream

collected as a reflection spectrum. The reflection spectrum was converted to standard units with calibration models developed using standard methods on subsamples from 30 samples. The required soil physical and chemical properties [C (%), N (%), and extractable inorganic P (mg/kg)] were predicted with high reproducibility (99%; Shepherd 2005).

One-way analysis of variance (ANOVA) was used to test for significant differences among the bulk density, C, N, and P levels in the soil of different land use types and within the buffers adjacent to the different land use types (McBride and Booth 2005). Tukey's pair-wise tests were performed where ANOVAs yielded significant differences. To assess the adequacy of the buffers, the soil properties within buffers ("Inside") were compared to both the soil properties of the land use areas ("Outside" buffers) and the reference condition, first using one-way ANOVAs and then Tukey's pair-wise comparisons. To determine if the government regulated maximum of 30 m was effective in mitigating changes to soil properties, the soil properties of (1) the reference condition, (2) the riparian buffer strips less than 30 m, and (3) buffer strips at least 30 m in width were compared using one-way ANOVAs and then Tukey's pair-wise comparisons. Data analysis was performed using Sigma Plot 11.0. Significance was assessed at the $p<0.05$ level.

Due to the study design, there were large differences in sample sizes for the different land use types. The gazetted forest had the largest sample size, because it had the most intact riparian forest buffer, while the other land use types were much more likely to have riparian buffers of less than the full 30 m transect. To account for these differences in sample sizes, comparable sample sizes were randomly selected and analyzed. There were minimal differences between these data sets and the full data set, so the full data set is reported here.

4 Results

4.1 Slope in Different Land Use Types

The slope in commercial agriculture land use type was significantly larger than that in the reference condition represented by gazetted forest land use type (Table 1). However, there were no significant differences in slope between commercial agriculture land use type and peri-urban and recent settlement land use types or among gazetted forest land use type and recent settlement and peri-urban land use types.

Table 1 Slopes of the riparian buffer strips. Means are reported with standard deviation in parentheses

Land use	*N*	Slope (degrees)
Gazetted forest	20	7.51 a (3.943)
Recent settlements	20	12.46 ab (4.209)
Peri-urban settlements	20	9.29 ab (8.839)
Commercial agriculture	20	13.39 b (6.942)

Means with the same letter are not significantly different from each other (based on Tukey's pair-wise comparisons, $p<0.05$)

4.2 Soil Properties among Land Uses

Land use activities had a significant effect on all four soil properties (Table 2). There was a general increase in the bulk density of the surface soils (0–20 cm) with increasing intensity of land use activity. Gazetted forest land use type had significantly lower bulk density than peri-urban land use type but not significantly lower than recent settlement and commercial agriculture land use types. There was a general decrease in C and N with increasing intensity of land use activity. In surface soils, there was significantly more C in the gazetted forest than in peri-urban and commercial agriculture land use types. There was also significantly more C in the recent settlements than in the peri-urban land use type. Similarly, there was significantly more N in the gazetted forest and recent settlements relative to the peri-urban and commercial agriculture land use types. The same general trends were seen in the subsurface soils, but the differences were smaller. Concentration of P was significantly lower in the surface soil in the gazetted forest relative to recent settlement and peri-urban land use types. The general trend of increasing P with increased intensity of land use was similar in both surface and subsurface soils.

4.3 Soil Properties within Riparian Buffer Strips Adjacent to Different Land Use Types

Within the riparian buffer strips, all four soil properties varied significantly (Table 3). There was significantly less bulk density in the surface soils of the buffer strips adjacent to commercial agriculture

Table 2 Surface (0–20 cm) and subsurface (20–50 cm) soil properties outside riparian buffer strips (within different land use areas) and inside the gazetted forest reference condition in the River Njoro Watershed

Land use	*N*	Bulk Density (g/cm^3)	Carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)
Surface (0–20 cm)					
F		4.238	27.95	25.15	4.235
p		0.008	<0.001	<0.001	0.008
Gazetted forest	48	0.85 a (0.25)	5.14 c (1.25)	0.46 b (0.11)	3.40 b (0.68)
Recent settlements	18	0.88 ab (0.21)	4.19 b (1.03)	0.42 b (0.11)	4.49 a (0.91)
Peri-urban settlements	17	1.05 b (0.16)	2.69 a (0.91)	0.23 a (0.09)	4.24 a (1.66)
Commercial agriculture	9	1.01 ab (0.22)	3.00 ab (1.01)	0.30 a (0.09)	3.99 ab (1.46)
Subsurface (20–50 cm)					
F			6.579	3.929	2.650
P			<0.001	0.011	0.054
Gazetted forest	48	NA	3.58 b (1.26)	0.31 b (0.12)	2.90 (0.48)
Recent settlements	18	NA	2.69 ab (0.81)	0.28 ab (0.79)	3.41 (1.39)
Peri-urban settlements	17	NA	2.57 a (0.52)	0.22 a (0.06)	3.59 (1.05)
Commercial agriculture	9	NA	2.56 a (1.00)	0.26 ab (0.09)	3.40 (1.62)

NA not available

Means are reported with standard deviation in parentheses. Means with the same letter are not significantly different from each other (based on Tukey's pair-wise comparisons, $p<0.05$)

land use types than the recent settlement buffers. There was a general decrease in C and N with increasing intensity of adjacent land use activity for both surface and sub-surface soils. In surface soils, the gazetted forest reference condition had significantly more C than the buffer strips adjacent to the peri-urban and commercial agriculture land use types. Recent settlement buffers also had significantly more C than

Table 3 Surface (0–20 cm) and subsurface (20–50 cm) soil properties inside riparian buffer strips adjacent to different land use areas and inside the gazetted forest reference condition in the River Njoro Watershed

Land use	*N*	Bulk Density (g/cm^3)	Carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)
Surface (0–20 cm)					
F		3.993	8.629	7.95	13.745
p		0.01	<0.001	<0.001	<0.001
Gazetted forest	48	0.85 ab (0.25)	5.14 a (1.25)	0.46 a (0.11)	3.40 a (0.68)
Recent settlements	27	0.81 b (0.18)	4.80 ab (1.77)	0.47 a (0.16)	3.81 a (1.27)
Peri-urban settlements	15	0.99 ab (0.17)	3.53 bc (1.52)	0.31 b (0.15)	4.21 a (1.49)
Commercial agriculture	15	1.02 a (0.28)	3.36 c (1.43)	0.33 b (0.14)	5.64 b (1.86)
Subsurface (20–50 cm)					
F			4.001	3.648	6.070
p			0.01	0.015	<0.001
Gazetted forest	48	NA	3.58 a (1.26)	0.31 ab (0.12)	2.90 b (0.48)
Recent settlements	27	NA	3.19 ab (1.56)	0.32 a (0.14)	4.09 a (1.74)
Peri-urban settlements	15	NA	2.54 b (0.93)	0.22 b (0.09)	3.87 ab (0.93)
Commercial agriculture	14	NA	2.51 b (1.18)	0.24 ab (0.11)	4.19 a (2.69)

NA not available

Means are reported with standard deviations in parentheses. Means with the same letter are not significantly different from each other (based on Tukey's pair-wise comparisons, $p<0.05$)

commercial agriculture buffers. Similarly, the concentration of total N in surface soils from gazetted forest and recent settlements were both significantly more than the N concentration in peri-urban settlement and commercial agriculture buffer strips. For subsurface soils, there was significantly more C in the reference condition soils than in peri-urban and commercial agriculture buffer soils, and there were significant differences among N amount in the subsurface soils with recent settlement buffer soils having significantly more N than peri-urban buffer soils.

The P of surface and subsurface soils within riparian buffers generally increased with more intensive land use in adjacent areas. The commercial agriculture buffer soils had significantly more P in their surface soils than the buffer soils in the reference condition, peri-urban, and recent settlement land use types. The subsurface soils within the reference condition had significantly less P than the buffers adjacent to commercial agriculture land use types but were not significantly different than those of the peri-urban areas and recent settlements, although the value was still lower. All buffer soils (surface and subsurface) adjacent to the three land use types had more P relative to the reference condition gazetted forest.

4.4 Comparison of Soil Properties Outside vs. Inside the Riparian Buffer Strips

There was only one case where the buffer had significantly different soil properties than the adjacent land: The commercial agriculture had higher P within the buffer strip than in the adjacent land (Table 4). The soil properties of the reference condition gazetted forests were significantly different than the buffers adjacent to the different land use types in most cases (Table 4; Fig. 4). The P concentration in the reference condition was significantly lower than the P within recently settled land use type but not significantly different than soils in the riparian buffer strips adjacent to recently settled areas. Bulk density within the peri-urban land use type was significantly higher than that in gazetted forest, and differences between riparian buffers adjacent to peri-urban bulk density and gazetted forest were not significant. However, for C and N, the reference condition had significantly

Table 4 Comparison of surface soil properties in the gazetted forest reference condition, riparian buffer strips that meet the government regulation (≥30 m), and those that are narrower than the government regulation (<30 m) in different land use areas

Riparian Buffer Width	*N*	Bulk Density (g/cm^3)	Carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)
Recent settlement					
F		1.345	2.481	1.160	10.089
p		0.266	0.09	0.319	<0.001
Gazetted forest	48	0.85 (0.25)	5.14 (1.25)	0.46 (0.11)	3.40 b (0.68)
At least 30 m	27	0.81 (0.18)	4.80 (1.77)	0.47 (0.16)	3.81 b (1.27)
Less than 30 m	9	0.95 (0.23)	3.96 (1.74)	0.39 (0.14)	5.01 a (1.42)
Peri-urban settlement					
F		2.234	8.87	8.42	5.167
P		0.114	<0.001	<0.001	0.008
Gazetted forest	48	0.85 (0.25)	5.14 a (1.25)	0.46 a (0.11)	3.40 b (0.68)
At least 30 m	15	0.99 (0.17)	3.53 b (1.52)	0.31 b (0.15)	4.21 a (1.49)
Less than 30 m	14	0.94 (0.22)	3.87 b (2.07)	0.35 b (0.20)	3.47 ab (0.39)
Commercial agriculture					
F		4.42	23.55	14.598	22.653
P		<0.015	<0.001	<0.001	<0.001
Gazetted forest	48	0.85 b (0.25)	5.14 a (1.25)	0.46 a (0.11)	3.40 b (0.68)
At least 30 m	15	1.02 ab (0.27)	3.36 b (1.43)	0.33 b (0.14)	5.64 a (1.84)
Less than 30 m	14	1.04 a (0.21)	2.97 b (0.85)	0.29 b (0.10)	5.00 a (1.84)

Means are reported with standard deviations in parentheses. Means with the same letter are not significantly different from each other (based on Tukey's pair-wise comparisons $p<0.05$)

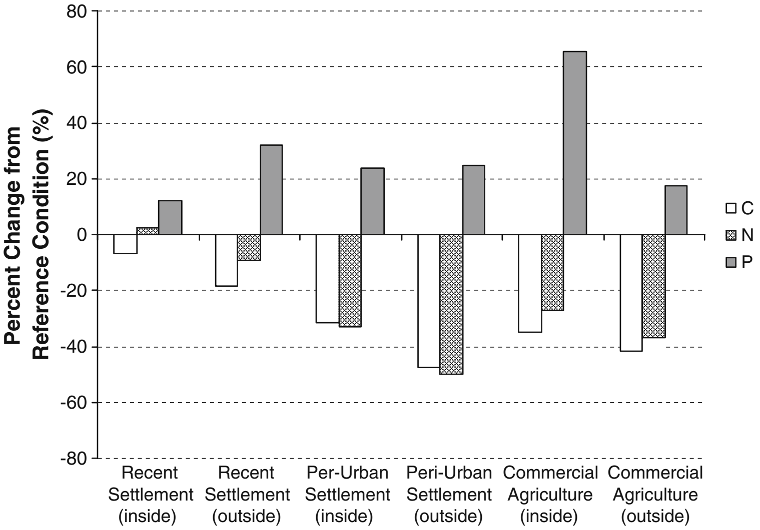

Fig. 4 Percent change relative to reference condition in concentration of carbon (C, %), nitrogen (N, %), and phosphorus (P, mg/kg) in soils inside and outside riparian buffer strips in different land use areas (recent settlement, peri-urban settlement, commercial agriculture)

higher values than soils in riparian buffers adjacent to peri-urban land use types, while the concentration of P was significantly higher in riparian buffers adjacent to peri-urban land use type than the reference condition. Commercial agriculture land use type had significantly lower C and N compared to the reference condition, while P concentration was significantly higher in commercial agriculture land use type than in the reference condition. Concentration of P was significantly lower in soil in commercial agriculture land use type than the adjacent riparian buffer.

Comparison between inner (within riparian buffer) and outer (outside riparian buffer, within the land use type itself) using *t* tests revealed similar trends to those observed with multiple pair-wise comparisons after running the ANOVA (Table 5). There was significantly more P inside (5.638 mg/kg) than outside (3.990 mg/kg) riparian buffers adjacent to commercial agriculture land use type (t=2.836, p=0.009). Differences in P in recent settlement and peri-urban land use types were not significantly different, although higher values were observed outside than inside the buffer strip. However, for bulk density, carbon, and nitrogen there were no significant differences in soil properties between inside and outside riparian buffers in all land use types.

4.5 Evaluation of the Government Regulated 30 m Maximum

There were no significant differences in soil properties between riparian buffers of at least 30 m wide and buffers narrower than 30 m wide in all land use types, except for P within recent settlements (Table 5; Fig. 5). The concentration of soil P was significantly higher in riparian buffer strips narrower than 30 m wide compared to riparian buffer strips that were at least 30 m wide. However, the concentration of P within the soils of the reference condition and riparian buffer strips that were at least 30 m wide adjacent to recent settlement land use were not significantly different. Therefore, within the recent settlement land use type, riparian buffer strips that were at least 30 m wide did not differ significantly in their soil properties compared to gazetted forest land but other land use types (commercial agriculture and peri-urban) had significantly less C and N than gazetted forest and significantly more P than the gazetted forest land use type.

5 Discussion

Riparian areas are interfaces between terrestrial and aquatic ecosystems. They represent an important filter of sediments, nutrients, and contaminants in water flowing from contributing hill slopes to streams (Bilby 1988). Riparian buffer strip widths are based on a sound intuitive grasp of the processes that should be protected (Allan et al. 1997), although scientific information for or against a specified riparian buffer strip width is limited (Osborne and Kovacic 1993). Government regulations, in Kenya, describe riparian zones as land lying within a distance equal to the

Table 5 Comparison of surface soil properties inside and outside riparian buffer strips in different land use areas and reference condition gazetted forest

Outside vs. Inside Riparian Buffer Strip	*N*	Bulk Density (g/cm^3)	Carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)
Recent settlements					
Inside buffer	27	0.807 (0.18)	4.797 (1.77)	0.469 (0.16)	3.809 (1.27)
Outside buffer	9	0.875 (0.21)	4.190 (1.03)	0.417 (0.11)	4.492 (0.91)
t		−0.933	0.970	0.910	−1.481
p		0.357	0.339	0.369	0.148
Peri-urban settlement					
Inside buffer	15	0.989 (0.17)	3.531 (1.52)	0.307 (0.15)	4.213 (1.49)
Outside buffer	17	1.047 (0.16)	2.689 (0.91)	0.229 (0.09)	4.238 (1.66)
t		−1.021	1.932	1.802	−0.044
p		0.315	0.063	0.82	0.965
Commercial agriculture					
Inside buffer	15	1.016 (0.28)	3.356 (1.43)	0.334 (0.14)	5.638 (1.86)
Outside buffer	18	1.013 (0.22)	3.003 (1.01)	0.290 (0.09)	3.990 (1.46)
t		0.026	0.830	1.060	2.854
p		0.981	0.413	0.270	0.008

Means are reported with standard deviations

width of a watercourse with a minimum of 2 m and a maximum of 30 m (Republic of Kenya 2002). However, there is no scientific basis to support a riparian buffer strip width of between 2 m and 30 m or any other width. Herein, we assess the suitability of this regulation.

5.1 Defining a Reference Condition

One of the challenges of determining the effectiveness of riparian buffer strips in mitigating changes in soil properties related to adjacent land use activities is identifying a reliable reference condition (White and Walker 1997). The upper and mid sections of the River Njoro Watershed have historically had similar land use types before being converted to their current land use types. Therefore, differences in the soil's physical and chemical properties are likely mainly due to current land use activities. Natural factors like underlying bedrock composition may be important in less disturbed or more uniformly disturbed areas (Allan 2004), but in the River Njoro Watershed the

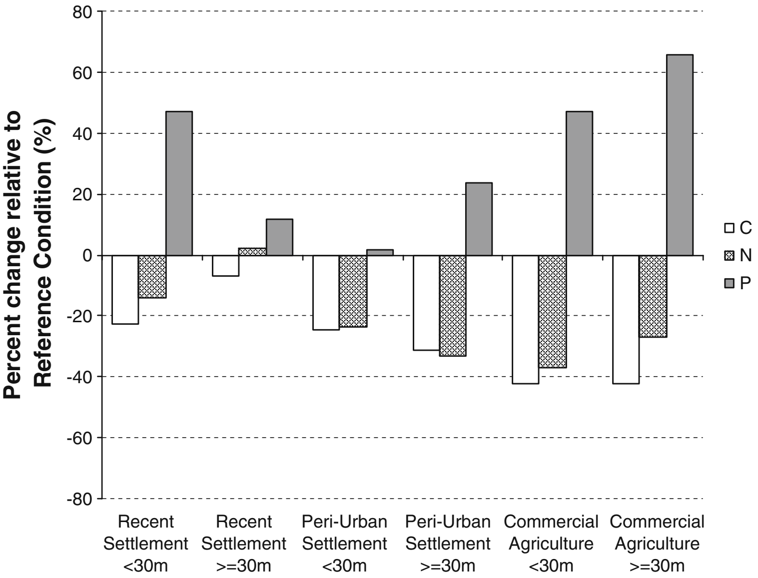

Fig. 5 Percent change relative to the reference condition in concentration of carbon (C, %), nitrogen (N, %), and phosphorus (P, mg/kg) in soils within riparian buffer strips <30 m and ≥30 m adjacent to different land use areas (recent settlement, peri-urban settlement, and commercial agriculture)

different degrees of human activity (e.g., recent settlements, peri-urban settlements, and commercial agricultural land use) likely have had a much larger impact than natural variation. There is a comparatively intact and undisturbed section of riparian buffer strip within the natural gazetted forest. It was used by Kibichii et al. 2007 as an "unpolluted reference" in a study examining macroinvertebrate assemblages along a land use gradient, reinforcing the notion that it provides a suitable reference condition for soil properties in the River Njoro Watershed. Slope among the different land use types was comparable (Table 1). The only significant difference observed was between the commercial agriculture land use and gazetted forest. The rest of the pairs of the land use types were similar which implies that slope may not have had a pronounced effect on the other soil properties in the comparable land use types.

5.2 Riparian Buffer Strip Widths

Riparian buffer strips of 30 m were only able to minimize changes in soil properties related to adjacent land use activity in some cases. Bulk density generally increased with the scale of land use activity. Bulk density provides an indication of erosion caused by land use activities. Sediment eroding from contributing areas can become trapped within the riparian buffer strip thereby increasing bulk density (Cooper and Gilliam 1987). In the River Njoro Watershed, humans and livestock use the area surrounding the river daily, as is common in other tropical countries (Mathooko 2001). In addition, humans and livestock spend a large portion of the day seeking shelter from equatorial sunlight and heat in the shade of riparian trees (Wyant and Ellis 1990). Intensive human activities in riparian areas interrupt natural drainage as riparian soils become compacted, sedimentation rates increase, solar radiation increases, and stream channels are altered (Klapproth and Johnson 2000). This leads to increased bulk density, as witnessed here in the peri-urban and commercial agricultural areas of the River Njoro Watershed with a general increase in soil bulk density with increased human activity.

Soil C and N concentrations decreased with scale of land use activity. Soil C and N are closely related because over 90% of the N in soils is associated with organic matter (Oldham 2003a). The decrease in soil C and N may be linked to reduced organic matter. There are many natural sources of organic matter in the gazetted forest. Recently settled lands (small-scale agriculture) had the second highest C concentrations, possibly because these areas have been only recently converted from gazetted forest, and the soils may still contain residues of organic matter left over from the previous land use. In addition, recent settlement land use activities restrict the harvest of organic material to the crop itself, leaving the plant residues to be incorporated into the soils, thereby maintaining the soil C and N concentrations. In contrast, soil C and N concentrations in peri-urban settlements and commercial agriculture were much lower. Increased urbanization creates more impermeable surfaces in the watershed and changes the flow regime by increasing runoff to streams and decreasing infiltration into the ground water. This causes organic matter and associated nutrients to wash down-slope and into the stream, bypassing the riparian buffer resulting in lower C as observed in peri-urban land use types compared to commercial agriculture land use type. Dissolved organic C and nitrate-N are mobile and therefore may be flushed out of the riparian buffer strip to the stream (Creed and Band 1998; Hornberger et al. 1994), or in the case of nitrate-nitrogen, become denitrified (Vidon et al. 2010). Shivoga et al. (2007) observed no net contribution of nitrate into surface waters from sites near recent settlements, but they observed a significant contribution of nitrate–N into surface waters near land use areas with a higher intensity of human activity. This suggests that N in the peri-urban settlements and commercial agriculture riparian buffer strips is being flushed to the adjacent River Njoro; hence, the low concentration of soil C and N in riparian buffer strips adjacent to this land use types.

Soil P concentrations increased with scale of land use activity. The movement of P within landscapes is closely associated with the mobilization of soils with sedimentation of particulate P during overland flow as a major retention system in riparian buffers (Hoffman et al. 2009; Oldham 2003b). Phosphorus adsorbs to soil particles and is less likely to wash away like C and N, thus P presence strongly indicates the effects of human activities. Laundry detergent from individuals washing clothes, along with waste from humans and domesticated animals using the river, are the most likely sources of inorganic P in peri-urban land use areas and adjacent riparian buffer strip soils. In commercial agriculture areas, di-ammonium phosphate, the main fertilizer used in the commercial agricultural farms (Mokaya et al. 2004), is the most likely source of phosphorus. These factors may explain the large levels of extractable inorganic P in soils in riparian buffer strips adjacent to peri-urban settlements and commercial agriculture land use types. Hoffman et al. (2009) notes that sedimentation which is the main physical process in riparian buffers may account for high retention P rates of up to 128 kg P ha^{-1} year^{-1} with plant uptake temporarily immobilizing approximately 15 kg P ha^{-1} year^{-1}. In addition, riparian buffer strips, because of their flatter slopes and high surface roughness, effectively reduce the lateral movement of suspended soil particulates which reduces phosphate concentrations in streams (Amador et al. 1997; Lowrance et al. 1984), causing increased loads in soils in riparian buffer strip soils.

Based on the observed soil properties, we found that a riparian buffer strip of at least 30 m (where the policy would require 15 m) is needed to minimize the effects of adjacent recent settlement land use activities. Soil P in riparian buffer strips adjacent to recent settlement use that were wider than 30 m was similar to soil P in the gazetted forest, implying that the riparian buffer resets the soil P to what would be expected naturally (reference condition). Additionally, soil P in riparian buffers narrower than 30 m was elevated, implying an overload in the narrow but undisturbed riparian buffer strip. In peri-urban settlement settings, a 30-m riparian buffer strip is not adequate to prevent changes to soil properties, because the soil P in riparian buffers narrower and wider than 30 m was comparable. There was also no significant difference between soil P in riparian buffers narrower than 30 m and the gazetted forest land use, suggesting that the buffer is too narrow. Most of the sediment-bound P is washed off to the stream, leaving very low levels of P in the narrow buffer given that higher P levels were observed outside the riparian buffer in the peri-urban land use and more P in stream water as observed by Shivoga et al. (2007). In the commercial agriculture land use type, there was significantly more P in both the riparian buffers narrower and wider than 30 m compared to the gazetted forest, and there was no observable difference between soil P in riparian buffers narrower or wider than 30 m. This suggests that the P entering even the 30 m buffer is much more than the buffer can process. Therefore, a 30-m wide riparian buffer is not adequate to mitigate changes in soil properties related to commercial agriculture land use type. For the commercial agriculture land use type, soils within buffer strips of at least 30 m did not have significantly different bulk density than the reference condition, and the soils within buffer strips of both less than and more than 30 m in width that were adjacent to peri-urban and commercial agriculture land use types had higher C, N, and P values than the reference condition. In general, riparian buffers narrower than 30 m were less effective in mitigating changes to C, N, or P to reference condition levels than buffers that were at least 30 m (Fig. 5).

The maximum 30 m wide riparian buffer strip should become the standard for buffer strips adjacent to relatively low intensity land use activities such as the recent settlements. A larger buffer strip is needed to mitigate changes in soil properties within buffer strips adjacent to higher intensity land use activities such as peri-urban settlements and commercial agriculture land use types.

5.3 Potential Links between Terrestrial and Aquatic C/N/P Ratios

Changes to the soil properties of riparian buffers could have far reaching effects. If the C/N/P ratio of the soil properties reflect the C/N/P ratio of the water that is discharged from the riparian buffer strip, as is the case for nitrate concentrations (Ohrui and Mitchell 1998), these changes may have fundamental consequences for not only the riparian vegetation but also the downstream communities and Lake Nakuru, the terminus of River Njoro. Although C (which is the main component of organic matter) is not a pollutant, riparian organic matter export to aquatic ecosystems affects the rates of most biologically mediated reactions. This regulates the fate of contaminants such as N, P, Hg, and pesticides, thereby influencing ecosystem metabolism (Vidon et al. 2010). Given River Njoro's high functional value (Castelle et al. 1994), elevated nutrient concentrations in the riparian buffer strips would increase primary productivity; however, if the nutrient load exceeds the rate of vegetation uptake, nutrients will end up in the river. Increased nutrient loads would likely lead to an increase in primary productivity in the adjacent aquatic ecosystem and the potential for harmful algal blooms (Kronvang et al. 2001) as well as sediment filling up Lake Nakuru. This would pose a threat to flamingo populations and the tourism industry, upon which Kenya heavily relies for foreign exchange.

5.4 Policy Implications

Recent initiatives within the management of the River Njoro Watershed are affecting the government regulation of riparian buffer widths. For example, Water Resource Users Associations (WRUAs) have become important in the management of rivers in Kenya. The WRUAs are responsible for a given stretch of the river and make recommendations on the best way to manage the river. Initially, longitudinal tours were conducted along the river in order to familiarize upstream WRUAs with how their actions impact the downstream communities. Similarly, downstream WRUAs toured the upstream communities to understand the sacrifices the upstream WRUAs make in order to ensure that the downstream communities continue to enjoy the services provided by River Njoro. The WRUAs have been developing buffer strip width recommendations within some portions of the River Njoro Watershed, especially in the recent settlements, which suggests better conservation practices within the country. Unfortunately, regulatory mechanisms that enforce sustainable management of communal property resources have failed and each community is applying its own cultural values and experiences to the use of riparian resources (Lelo et al. 2005). This suggests that following traditional communal use of riparian resources cannot continue and more intensive, inclusive management strategies must be employed using scientifically based criteria for establishing buffer requirements and subsequent utilization by policy makers and resource agencies (Castelle et al. 1994).

6 Conclusions

This study assessed the suitability of the Kenyan policy regulating a riparian buffer strip equal to the width of the river, with a minimum of 2 m up to a maximum of 30 m, for management of the River Njoro Watershed. The research findings of this study suggest that:

1. The current policy may be appropriate in mitigating changes in soil properties related to small-scale human activities (i.e., recent settlements) where settlers coexist with indigenous peoples, and respect one another’s ways of life. However, the current policy is not appropriate for mitigating changes in soil properties related to larger-scale human activities (i.e., peri-urban and commercial agricultural land use areas).
2. Surface soils better indicate the effects of changes in soil properties related to land use activities in the River Njoro Watershed than subsurface soils.
3. Phosphorus is a more sensitive indicator of the impacts of human activity, as increased concentrations were found at all scales of land use activity. Carbon and nitrogen concentrations were reduced only in the larger-scale land use activities of peri-urban settlement and commercial agriculture.
4. The soil properties of riparian buffer strips could have far-reaching effects, because if the C/N/P ratio of the soil properties reflect the C/N/P ratio of the water discharged from the riparian buffer strip, then these changes may have consequences not only for the riparian vegetation but also for the aquatic ecosystems dependent on this riparian buffer strips.

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