Research paper

Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya

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Abstract

Land use change, especially conversion of native forests can have large impacts on water resources. Large scale conversion of native forests to agricultural land has occurred in the last few decades in the Mau Forest region. To quantify and understand landscape hydrologic responses, this study aimed at evaluating the effects of land use on soil infiltration, saturated hydraulic conductivity, bulk density, sorptivity, and soil moisture retention. A total of 136 plots representing five different land uses (native forest: n = 39, forest plantations: n = 14, tea plantations: n = 24, croplands: n = 23 and pasture: n = 36) were sampled in three catchments with similar parental material in the Mau Forest region, Western Kenya. Native forest topsoils (0–5 cm) had a bulk density of 1.0 ± 0.2 g cm^{-3} which was similar to values found for topsoils of forest plantations (1.1 ± 0.2 g cm^{-3}), but significantly lower than topsoils from croplands (1.4 ± 0.2 g cm^{-3}), tea plantation (1.3 ± 0.3 g cm^{-3}) and pastures (1.4 ± 0.2 g cm^{-3}). Similarly, soil infiltration rates were higher in native forest (76.1 ± 50 cm h^{-1}) and in forest plantation (60.2 ± 47.9 cm h^{-1}) than in croplands (40.5 ± 21.5 cm h^{-1}), tea plantations (43.3 ± 29.2 cm h^{-1}) and pastures (13.8 ± 14.6 cm h^{-1}). Native forest had the highest topsoil organic carbon contents (8.11 ± 2.42%) and field capacity (0.62 ±0.12 cm^3 cm^{-3}), while the highest permanent wilting point was recorded for pasture soils (mean of 0.41 ± 0.06 cm cm^{-3}). The highest plant available water capacity was recorded for soils in native forest (mean of 0.27 ± 0.14 cm cm^{-3}). Our study indicates that land use changes result in a significant degradation of soil hydraulic properties, which has likely resulted in changes of the regional water balance. Given the magnitude in which managed land use types have changed infiltration rates in our study area, we conclude that changes in land use types occurring in our study region in the last decades have already affected the hydrological regime of the landscapes and the compositions of flow components. The reduction in infiltration and hydraulic conductivity could result in increased surface run-off, erosion and frequency of flooding events.

Keywords: Infiltration rates; Water retention characteristics; Double ring infiltrometer; South West Mau; Land use change

1 Introduction

Changes in land use and land management have a strong impact on soil properties, such as hydraulic conductivity and bulk density (Batey, 2009; Celik, 2005; Price et al., 2010; Solomon et al., 2000). These key soil properties affect soil water infiltration, surface run-off and soil water retention. Thus, these soil properties affect the ratio between surface runoff and baseflow of stream networks (Price et al., 2010; Tetzlaff et al., 2007), as well as groundwater recharge. Changes in soil hydraulic properties have higher influence on soil water movement than parental material or topography (Schwartz et al., 2003; Zhou et al., 2008). Since land use and land use practices −e.g tillage or grazing- are known to alter soil pore structure and volume (Harden, 2006; Pietola et al., 2005; Price et al., 2010), understanding the relationship between land use and hydraulic soil properties is key for catchment water management (Minasny and George, 1999).

Several studies worldwide have shown strong decreases in the infiltration capacity and hydraulic conductivity as well as increases in soil bulk density following conversion of forest to agricultural land (e.g. Arnhold et al., 2015; Price et al., 2010). Moreover, reductions in infiltration and hydraulic conductivity result in increased surface run-off, erosion and frequency of flooding events (Batey, 2009; Delgado et al., 2007; Ehlers et al., 2000; Owuor et al., 2016).

Very few studies have investigated the effect of land use on soil hydrological properties in Sub-Saharan Africa (Omuto, 2008; Nyberg et al., 2012; Yimer et al., 2008) Understanding the impacts of land use on soil properties is crucial in a region that has experienced a relatively large scale deforestation and land use change during the last decades (Eva et al., 2006). A growing human population increases directly the demand for land for settlement and agriculture, a fact that has led to significant land use change in Mau region of Kenya (Olang and Kundu, 2011). The few studies available, for Kenya, analysing the impacts of land use change (Arnhold et al., 2015; Okelo et al., 2015; Omuto, 2008; Mureithi et al., 2014; Nyberg et al., 2012) are limited in their applicability as either only few parameters were investigated or the studies were mainly based on modelling rather than *in-situ* measurements. Okelo et al. (2015) reported a decrease in soil infiltration rates in a Kenyan watershed as a result of conversion of forest to agricultural land and pasture, but did not examine the soil moisture retention characteristics. Nyberg et al. (2012) found that land use change from natural forest to agricultural land in Nandi county, Western Kenya, led to substantial changes in bulk densities and infiltration capacities, but also did not quantify changes in soil water retention characteristics. Arnhold et al. (2015) noted that agricultural cultivation as well as intensive livestock grazing led to increases in bulk density and reduced hydraulic conductivity as well as plant available water storage in soils in the upper Lambwe Valley in western Kenya. However, information on plant available water availablility was derived from modelling and therefore based on information on soil texture and bulk density only. To our knowledge there is currently no information for Kenya, on how soil hydraulic properties and soil moisture retention characteristics change when native forest is replaced by tree plantations or tea plantations. Generally, studies on soil hydraulic properties and moisture retention characteristics on African montane forests is conspicously missing.

Our study aimed at quantifying the effects of land use change on soil water infiltration, soil moisture retention and soil saturated hydraulic conductivity in five land uses (native forest, forest plantation, tea plantation, croplands and pastures) in the South West Mau region of Kenya. These variables have been selected because they are sensitive to topsoil disturbances (Alegre and Cassel, 1996; Schoenholtz et al., 2000) and are therefore suitable indicators to assess how land use affects hydrologic properties and processes in tropical, montane regions. We hypothezised that soils under agricultural land use (i.e. tea plantations, croplands, pastures) have reduced soil water infiltration capacity, volumetric moisture content and increased bulk density compared to forests (i.e. native forest and forest plantations).

2 Materials and methods

2.1 Site description and experimental design

The study area is located in the Sondu basin (3470 km^2) in western Kenya (0°17′–0°22′ S, 34°04′–34°49′ E). The Sondu river drains into Lake Victoria near the city of Kisumu. Mean annual precipitation recorded at Applied Research Department of James Finlay (Kenya) Ltd. between 1905 and 2014 was 1988 ± 328 mm, with highest rainfall in April and May during the long rains (>250 mm per month) and lowest in January and February during the dry season (<75 mm per month). Mean monthly temperatures range from 16 °C to 22 °C with the coldest month being July (Ekirapa and Shitakha, 1996; Kinyanjui, 2009). Potential evapotranspiration ranges from 1400 to 1800 mm y^{-1} (Kinyanjui, 2009).

Topographically, the area has a rugged terrain with elevations ranging from 1100 to 2900 m a.s.l. Geologically, the area is covered by lava and volcanic deposits of Tertiary age. The main rocks constituting these lavas and volcanic deposits are Kericho phonolites, phonolitic nephelinites and tuffs which comprises tuffs of South West Mau and Pale grey eutaxitic crystal tuffs (Binge, 1962; Jennings, 1971). The Kericho phonolites that dominate the study area are porphyritic. The Kericho phonolites constitute the basal member of the sequence forming the Molo Plateau, and their upper surface slopes in a generally south-westerly direction. The study area is further characterized by well-drained, deep (> 1.8 m), reddish brown fine-textured soils with a humic topsoil (Sombroek et al., 1982). According to FAO (2015), the soils are classified as nitisols. These soils are in general highly suitable for agricultural production (Sombroek et al., 1982).

Within this basin, three catchments, C1 (27.6 km^2), C2 (36.6 km^2) and C3 (33.3 km^2) were selected (Fig. 1) representing the different land use types. The geology of the catchments is the same. In 2015 the rainfall for the three catchments was: 1627 mm for C1, 2045 mm for C2 and 1980 mm for C3 (Jacobs et al., 2017). Each of the three selected catchments differs in its dominant land use type with catchment C1 being dominated by smallholder agriculture (since 1940′s). Smallholder agriculture is characterized by growing a variety of crops including maize, tea, potatoes as well as livestock keeping. The catchment has remnants of native forests consisting of evergreen plants and pockets of bamboo. Plantations of exotic tree species such as eucalyptus (*Eucalyptus grandis*), cypress (*Cupressus lusitanica*) and pine (*Pinus sp*.), which have been planted by the Government of Kenya as restoration measure since 1940′s, also exist in the catchment. Groundwater is the major source of water supply for the residents.

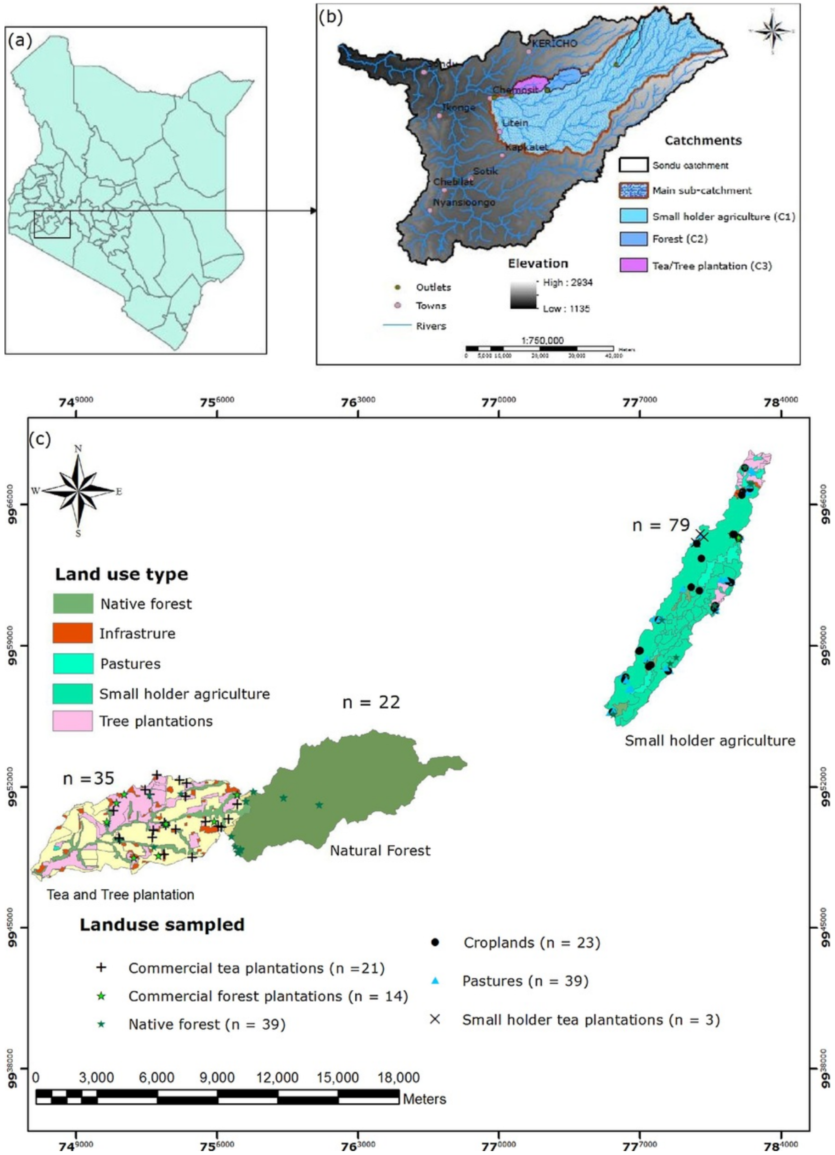

Fig. 1 Location of the study area and sampling plots. (a) Map of Kenya showing location of South West Mau. (b) Extent of Sondu basin. (c) Location of the sampling plots.

alt-text: Fig. 1

Catchment C2 is almost entirely covered by natural forest, consisting of evergreen native trees (mainly *Prunus africana* and Prunus/Muiri) and thick bamboo forests (Kerfoot, 1964). It is a tropical montane forest, which is partly degraded through livestock grazing, illegal logging and charcoal burning.

Large-scale commercial tea/tree plantations, established approximately 90 years ago, characterize catchment C3. Native forests are found in the riparian areas in this catchment. Eucalyptus and cypress plantations are also found in the catchment and are used to provide firewood for the tea factories.

The 136 randomly selected sampling plots were distributed as follows among the major land use types samples: native forest: n = 39, forest plantation: n = 14, tea plantation: n = 24, croplands: n = 23 and pastures: n = 36 (Fig. 1). Due to the different dominating land uses within each catchment, land use types of the plots were not evenly distributed among the catchments. The size of the plot with the land use type under consideration measured at least 20 m × 20 m. One time infiltration measurement as well as soil samples were taken from areas inside the plot, which were considered representative for the land use type. Infiltration tests and soil sampling were taken between May and July 2015.

2.2 Field measurements

In-situ infiltration rates were measured using the confined one-dimensional pressure double ring infiltrometer method (Bouwer, 1986), an approach considered easy and affordable (Teixeira et al., 2003). The method assumes vertical flow of water into the soil. The double ring model 09.04 (Eijkelkamp Agrisearch Equipment BV, Giesbeek, The Netherlands) of 32/57 cm diameter and 25 cm height were driven into the soil approximately 10 cm with caution to avoid disturbance of the soil surface. The smaller ring was placed inside the larger one. The outer ring served to ensure that the water flow was vertically one − dimensional by reducing lateral flow (Bouwer, 1986). Water was carefully poured into both rings, to a height of approximately 10 cm and infiltration rates determined using the constant head method as described by Bouwer (1986), where water was added regularly and infiltration rate calculated from the drop in water level over the time period between adding water. The inner ring was always filled to the same level. Measurements continued until a constant infiltration rate was attained, which usually took about 45–90 min.

At each location where infiltration measurements were made, soil samples were taken after infiltration studies were done within a radius of 1 m from the spot where the double rings were placed. Intact soil samples were collected in triplicates from the top 5 cm of soil profile using soil cores of 5 cm diameter and 5 cm height. Consequently, a smooth and undisturbed horizontal soil surface was prepared with a scraper, thereby removing e.g. leave litter or the aboveground grass vegetation. The sampler was driven carefully from the top into the soil to fill the inner cylinder, then carefully excavated and trimmed (Soil Survey Investigation Report, 2014). The intact soil cores were wrapped in Parafilm to avoid moisture loss and they were transported to the Mazingira Centre at the International Livestock Research Institute, Nairobi for soil water retention analysis and determination of soil bulk density and soil carbon and nitrogen analysis. In addition, soil samples at 5 depths (0–5 cm, 5–20 cm, 20–30 cm, 30–50 cm,0–100 cm) were collected from the same locations for texture analysis. Single disturbed samples were collected at a depth of 0–5 cm and 5–20 cm using cylindrical stainless steel rings (5 cm diameter of 5 cm and 5 cm height). The stainless steel ring was driven in the soil to the desired depth of interest while disturbed samples were collected for the other depths using a soil auger. All the samples were packed, labeled and transported to the laboratory for texture analysis. The soil from 5 to 20 cm depth were also used for determination of bulk density as well.

2.3 Laboratory measurements

The samples for texture analysis were air- dried and oven dried at 35 °C and then crushed and passed through a 2 mm sieve. A portion (50 g) of the sample was packed and transported to the Kenya Agricultural and Livestock Research Organization (KALRO) laboratory in Nairobi, where the samples were dispersed in sodium hexametaphostate and analyzed for particle size distribution by the hydrometer method (Gee and Bauder, 1986).

2.4 Estimation of soil hydraulic properties

Sorptivity (S) characterizes the ability of the soil to absorb water in the absence of gravity. Hydraulic conductivity (K) as defined by Kruseman and de Ridder (1990), is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic conductivity is a property of water-bearing geologic material that relates to its ability to transmit water at a standard temperature and density (Sterrett, 2007).

For every infiltration measurement, sorptivity and hydraulic conductivity were calculated by optimizing Philip’s equation (1957; Eq. (1)) in R version 3.22 (R Core Team, 2015, see Appendix A).

$$i\left(t\right)=\frac{1}{2}St^{1/2}+K \qquad \textbf{(1)}$$

where i is infiltration rate (cm h^{-1}), t is time for infiltration, S is the sorptivity (cm $h^{-1/2}$), and K is hydraulic conductivity (cm h^{-1}).

Intact soil cores were used for the determination of soil water retention characteristics. Filter papers were placed at the bottom part of the cores and held in place by a thin strip of Parafilm. The samples were placed in sandbox model 08.01(Eijkelkamp Agrisearch Equipment BV), which uses sand to convey the suction from the drainage system to the soil samples. The flexible sand surface enhanced the contact between samples and the sand after samples were removed for weighing. Water was slowly supplied to the sandbox until the water level was 1 cm below the top of the sample ring. The sandbox was covered with a lid to avoid evaporative water losses. The samples were saturated at water column of 0 cm (equal to pF = 0). pF refers to the negative logarithm of the absolute value of pressure head in centimeters. Water was allowed to rise through the soil sample by capillary rise until the time when the sample was fully saturated, i.e. at the time when the sample achieved a constant weight. Equilibrium was achieved when there was no change in the weight of the samples between two consecutive measurements separated by 24 h period. It took about 1–2 weeks in order to achieve equilibrium. After saturation, the suction regulator was adjusted so that a pressure head of −37 cm (pF = 1.8) was applied and the samples were then left to equilibrate. After completing the measurement at pF = 1.8, which included weighing, the soil cores were transferred to a 1 bar pressure plate extractor. In the pressure plate extractor, moisture was removed from the samples at a pressure of 0.33 bar (pF = 2.5) and 1 bar (pF = 3). The pressure was set at 0.33 bar and samples were left to reach equilibrium for about 1–2 weeks. After equilibration, the samples were re-weighed and the pressure adjusted to 1 bar which took another 1–2 weeks to reach equilibrium. The soil samples were then oven dried at 105 ˚C and their moisture content determined. Soil bulk density was calculated by dividing the mass of the oven-dried sample (105 °C until constant weight) by the volume of the core (98.17 cm^3). Following the procedure as described by Sarkar and Haldar (2005), soil samples were crushed and passed through a 2 mm sieve and finally repacked into small cores (6.3 cm^3 volume) and saturated again. Water saturated repacked soil cores were transferred to a 15 bar pressure plate extractor (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) and the gravimetric water contents at pF = 3.7 and pF = 4.2 were determined following hydraulic equilibration. Soil water content at pF = 2.5 was used to define field capacity (FC) while the permanent wilting point (PWP) is defined as the water content at pF = 4.2. Plant available water capacity (PAWC) is the water stored between pF = 2.5 and pF = 4.2

After packing 50 g portion for texture analysis, the remaining portion was used for the determination of total soil organic carbon (SOC) and total nitrogen (TN) using the elemental combustion analyzer (model ECS 4010, Costech Analytical Technologies, Inc., Valencia, CA, USA). The samples were ground to dust size particles to obtain homogeneous composition of the sample matrix. 15 mg of the ground sample was weighed into tin cup container using analytical micro-balance and forceps. The weighed samples were loaded in the elemental combustion analyzer automatic sampler for analysis.

2.5 Statistical analysis

One-way Analysis of Variance (ANOVA) was used for determining differences in soil hydraulic properties between land use types. Tukey’s Honestly significant difference (HSD) test was used to detect differences between pairs of land use type means. All data were tested beforehand for normality using the Shapiro-Wilk test. Non-normally distributed data were transformed using the Johnson transformation package in R (Fernandez, 2015) before carrying out the ANOVA. In Johnson transformation, normality is achieved by using the Z family of distributions based on the method of the percentiles (Fernandez, 2015). Johnson transformation system consists of three types of distributions: bounded system (SB), log-normal system (SL) and unbounded system (SU). These systems are described by the equations (2–4) respectively.

$$Bounded\,form\ (SU):\ Y = \gamma + \eta log\left(\frac{\chi - \varepsilon}{\lambda + \varepsilon - \chi}\right) \tag{2}$$

$$Lognormal\,form\ (SB):\ Y = \gamma + \eta log\left(\frac{\chi - \varepsilon}{\lambda}\right) \tag{3}$$

$$Unbounded\,form\ \ (SU):\ Y = \gamma + \eta \sinh^{-1}\left(\frac{\chi - \varepsilon}{\lambda}\right) \tag{4}$$

Where:

Y is the transformed value; γ and η are shape parameters, X is continuous random variable, ε is location parameter and λ is a scale parameter. The three functions are evaluated in the package with current estimates of four parameters. The four parameters are optimized until one of the three transformation functions produces the best normality test result.

All data used in this study were transformed with exception of soil texture. Pearson correlation coefficients were calculated to identify correlations among the selected soil characteristics. All analyses were conducted using R 3.22 (R Core Team, 2015) at a significance level of $P \leq 0.05$.

3 Results

Soil texture from all land use types and depths were predominantly clayey, with the clay content increasing with depth (Table 1). All the soils for all the depths sampled were classified as clay soils based on USDA scheme for soil classification. On average, soils from the lower depths (50–100 cm) contained slightly less sand and silt and slightly higher clay content (Table 1).

Table 1 Average soil particle size distribution across five land use types and five depths. Native forest (n = 39), forest plantation (n = 14), tea plantations (n = 24), croplands (n = 23) and pastures (n = 36) in the South West Mau region, Kenya.

alt-text: Table 1

Land use	Depth (cm)	Sand (%)	Clay (%)
Native forest	0–5	17.8	62.5
	5–20	17.7	63.3

	20–30	16.6	65.2
	30–50	13.4	68.2
	50–100	14.5	69.0
Forest plantation	0−5	23.1	52.1
	5–20	19.5	56.1
	20–30	19.4	57.4
	30–50	17.3	61
	50–100	14.9	64.9
Tea plantation	0−5	15.6	64.3
	5–20	13.6	67.1
	20–30	13.9	67.7
	30–50	12.3	71
	50–100	11.3	74.4
Croplands	0−5	19.8	54.8
	5–20	19.3	55.3
	20–30	18.3	56.7
	30–50	16.3	62
	50–100	15.9	64.7
Pastures	0−5	21.1	53.8
	5–20	18.6	56.7
	20–30	17.2	60.2
	30–50	14.5	62.9
	50–100	14.5	67.3

Native forest topsoil (0–5 cm) had a mean (±standard deviation) bulk density of 1.0 ± 0.2 g cm^{-3}, which was similar to that of topsoils taken from forest plantation (1.1 ± 0.2 g cm^{-3}). The mean bulk density for native forest and forest plantation were lower ($P < 0.001$) than the bulk density values for croplands (1.4 ± 0.2 g cm^{-3}), tea plantations (1.3 ± 0.3 g cm^{-3}), and pastures (1.4 ± 0.2 g cm^{-3}) (Fig. 2). A tendency towards lower bulk density for soils taken from native forest system compared to those from agricultural land uses could also be detected for the 5–20 cm soil layer though this trend across land use types was not significant ($P = 0.168$).

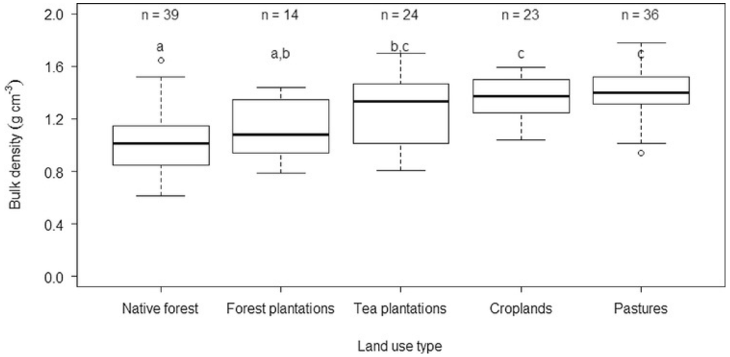

Fig. 2 Bulk density ranges for the topsoil (0–5 cm) in five different land use types in South West Mau, Kenya. The boxplot provide the median, the 25th and 75th percentile, open circles represent outliers greater than the upper whisker (maximum) or below the lower whisker (minimum). Different letters denote significant differences ($P < 0.05$).

alt-text: Fig. 2

Soils from native forest had a mean sorptivity of 196.1 ± 138.1 cm h$^{-1/2}$, forest plantations (148.5 ± 80.7 cm h$^{-1/2}$), croplands (168.6 ± 77.1 cm h$^{-1/2}$) and tea plantations (158.6 ± 69.4 cm h$^{-1/2}$), but no significant differences among those land uses were found. However, the sorptivity for the pasture soils was lower than all the other soils (55.9 ± 30.3 cm h$^{-1/2}$; $P < 0.001$).

Hydraulic conductivity was highest in native forest (63.7 ± 45.1 cm h^{-1} – ranging from 10 cm h^{-1} to 207 cm h^{-1}), which was similar to forest plantation soils (50.9 ± 48.1 cm h^{-1} – ranging from 7 to 160.6 cm h^{-1}). The mean hydraulic conductivity of native forest was higher ($P < 0.001$) than the hydraulic conductivity in soils from croplands (30.19 ± 23.9 cm h^{-1}), tea (36.14 ± 28.9 cm h^{-1}) and pastures (10.20 ± 13.6 cm h^{-1}). The hydraulic conductivity of croplands ranged from 4 cm h^{-1} to 81 cm h^{-1}, tea plantations from 8 to 90.1 cm h^{-1}and pastures from 2 to 53 cm h^{-1}.

Mean steady infiltration rate for native forest was 76.1 cm h^{-1} (ranging from 15.8 to 246.3 cm h^{-1}) and was similar to forest plantation (mean of 60.2 cm h^{-1} and ranging from 7.5 to 159.9 cm h^{-1}). The mean steady infiltration rate for croplands was 40.5 cm h^{-1}, (range of 7.2–84 cm h^{-1}). For tea plantations a mean steady infiltration rate of 43.3 cm h^{-1} (ranging from 6.1 to 93.7 cm h^{-1}) was observed, while for pastures the mean value was significantly lower with 13.8 cm h^{-1} (ranging from 1.2 to 60.3 cm h^{-1}) (Table 2).

Table 2 Summary of *P* values for pairwise comparison of differences for various soil hydraulic properties across different land use types. Native forest (n = 39), forest plantations (n = 14), tea plantations (n = 24), croplands (n = 23) and pastures (n = 36) in the South West Mau region, Kenya.

alt-text: Table 2

Land use type	ρ Bulk density (0–5 cm)	ρ Bulk density (5–20 cm)	Sorptivity (cm h$^{-1/2}$)	Hydraulic conductivity (cm h^{-1})	Steady infiltration rate (cm h^{-1})
Pastures – Croplands	0.9	1	<0.001	0.03	<0.001
Native forest – Croplands	<0.001	0.6	1	0.001	0.01
Forest plantation – Croplands	0.03	1	0.8	0.4	0.8
Tea plantation – Croplands	0.7	1	1	0.9	1
Native forest – Pastures	<0.001	0.2	<0.001	<0.001	<0.001
Forest plantation – Pastures	0.002	1	<0.001	<0.001	<0.001
Tea plantation – Pastures	0.1	1	<0.001	0.001	<0.001
Forest plantation – Native forest	0.6	0.9	0.54	0.6	0.5
Tea plantation – Native forest	<0.001	0.2	0.9	0.03	0.008

Tea plantation – Forest plantation	0.3	0.9	1	0.9	0.8

Native forest topsoils showed the highest field capacity (0.62 ± 0.12 cm cm^{-1}), the highest wilting point (0.35 ± 0.7 cm cm^{-1}), and the highest plant available water capacity (0.27 ± 0.14 cm cm^{-1}) (Table 3).

Table 3 Mean values ± SD of field capacity, permanent wilting point and plant available water capacity for topsoils taken from sites with native forest, forest plantations, tea plantations, croplands and pastures in the South West Mau. Different letters down the columns denotes significant differences ($p < 0.05$). pF is defined as the negative logarithm of the absolute value of pressure head in centimeters.

alt-text: Table 3

Land use type	Field capacity (pF 2.5) (cm cm^{-3})	Permanent wilting point (pF 4.2) (cm cm^{-3})	Plant available water capacity (pF 2.5–4.2) (cm cm^{-3})
Native forest (n = 39)	0.62 ± 0.12 ^{a}	0.35 ± 0.073 ^{a}	0.27 ± 0.14 ^{a}
Forest plantation (n = 14)	0.47 ± 0.058 ^{a,b}	0.32± 0.01 ^{a}	0.16 ± 0.11 ^{a,b}
Tea plantation (n = 24)	0.44 ± 0.058 ^{b}	0.29 ± 0.079 ^{a}	0.14 ± 0.1 ^{b}
Croplands (n = 23)	0.47 ± 0.059 ^{b}	0.37 ± 0.044 ^{a}	0.09 ± 0.08 ^{b}
Pastures (n = 36)	0.54 ± 0.088 ^{b}	0.41 ±0.06 ^{b}	0.14 ± 0.1 ^{b}

The highest total soil organic carbon content (SOC) was recorded for topsoils of native forests with a mean (± standard deviation) of 8.1 ±2.4%, which was similar to that of soils of forest plantations with a mean of 7.4 ± 2.9%. The total SOC for native forest was significantly different from that of tea plantations, croplands and grazing ($P < 0.001$), whereas the total SOC for forest plantations did not differ from croplands, tea plantations and pastures. Similar trends were observed for total nitrogen (TN). Table 4 shows a summary of total SOC and TN for every land use type.

Table 4 Mean values ± SD of total soil organic carbon and total nitrogen for topsoils (0–5 cm) taken from sites with native forest, forest plantations, tea plantations, croplands and pastures in the South West Mau. Different letters down the columns denotes significant differences ($p < 0.05$).

alt-text: Table 4

Land use type	Total soil organic carbon (%)	Total nitrogen (%)
Native forest (n = 25)	8.11 ±2.42 ^{a}	0.49 ± 0.23^{a}
Forest plantation (n = 7)	7.40 ± 2.92 ^{ab}	0.33 ± 0.27^{a,b}
Tea plantation (n = 20)	5.84 ± 1.33 ^{b}	0.19 ± 0.099^{b}
Croplands (n = 19)	5.69 ± 1.11 ^{b}	0.21 ± 0.12^{b}
Pastures (n = 28)	6.20 ± 0.92 ^{b}	0.18 ± 0.099^{b}

Significant negative correlation between bulk density and steady infiltration rate, sorptivity and available plant water capacity was detected (Table 5). Also, significant positive correlations between steady infiltration rates, sorptivity and saturated hydraulic conductivity was found. No correlation was detected between plant available water capacity and sorptivity or steady infiltration rate.

Table 5 Pearson Correlations between the soil individual hydraulic parameters from the South West Mau region, Kenya.

alt-text: Table 5

	Bulk density (0–5 cm)	Saturated hydraulic conductivity	Plant-available water capacity	Sorptivity	Steady infiltration rate	Total soil organic carbon	Total nitrogen
Bulk density (0–5 cm)	1.00						
Saturated hydraulic conductivity	−0.43***	1.00					

Plant available water capacity	−0.43***	0.03	1.00				
Sorptivity	−0.28**	0.48***	0.006	1.00			
Steady infiltration rate	−0.47***	0.92***	0.05	0.69***	1.00		
Total organic carbon	−0.69***	0.33**	0.52***	0.03	0.27	1	
Total nitrogen	−0.44**	0.36*	0.13	0.19	0.34*	0.49***	1

Significance levels: $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

4 Discussion

Significant deforestation and agricultural land use change in the Mau Forest region of Kenya started in the last decades (Klopp and Sang, 2011). The results of this study indicate that the conversion of native forests to other land use types, resulted in significant changes in soil hydraulic properties and water retention characteristics.

Our results for soil bulk densities of samples taken from pastures, croplands or tea plantations compared to soils taken from native or forest plantations revealed significant differences. Higher topsoil bulk densities are usually attributed to compaction, structural damage and destruction of macro-pores of topsoil by overgrazing and use of machinery (Kelishadi et al., 2014; Lal, 1986; Price et al., 2010) or by intensive agricultural practices (Emadi et al., 2008). Our results are thus consistent with previous studies that reported higher bulk densities for pastures or croplands compared to native or forest plantations in Argentina (Cisneros et al., 1999), the north-eastern USA (Zhou et al., 2008), Costa Rica (Reiners et al., 1994), Iraq (Emadi et al., 2008) and Ethiopia (Selassie and Ayanna, 2013).

The intensity of land use has an impact on the soil hydraulic properties, as it has been observed in other studies (Hiernaux et al., 1999; Proffitt et al., 1995; Zimmermann et al., 2006). Hiernaux et al. (1999) observed that topsoil compaction was due to intensive, i.e. continuous grazing for nine months per year in Niger.

The observed compaction of not only soils of pastures but also of fields with croplands in this study is likely the result of livestock trampling, as pastures are often converted to cropland and *vice versa* by smallholders in Sub-Saharan Africa. In contrast, the soil compaction observed for soils of tea plantation is likely the result of site preparation and manual harvesting (Hamza and Anderson, 2005).

Our study reveals that bulk density at depth from 5 to 20 cm did not differ significantly across land use types, indicating that the influence of land use change on soil hydraulic properties is restricted to the topsoil layer, only.

The increase in bulk density with intensification of land use was mirrored by a decrease in the water infiltration capacity. This observation concurs with the findings of Nyberg et al. (2012) who found that conversion of natural forest to agricultural land uses can lead to reductions of 60% in the infiltration rate within 40 years after conversion in western Kenya. Results from our study showed higher median infiltration rates compared to results by Nyberg et al. (2012), who did their experiments only 70 km away from our study sites. The difference in the infiltration rates might be attributed to differences in parental material, which has a strong influence on soil properties. The study by Nyberg et al. (2012) was undertaken in the forest in which the parent material was biotite gneiss while in our study area, the parent material is Kericho phonolites. In Ethiopia, Yimer et al. (2008) reported that the infiltration rate under native forest was 45 cm h^{-1}, and that the infiltration rate was significantly reduced by 75%, i.e., to about 12 cm h^{-1} for croplands or pastures. Okelo et al. (2015) also reported significantly higher infiltration rate in native forest (43.5 mm h^{-1}) compared to pastures (19.3 mm h^{-1}) translating in to 56% reduction on infiltration rate and croplands (25.2 mm h^{-1}) representing 42% reduction on infiltration rate in Njoro, Kenya. These observations are in-line with our observations, as we found a 42% reduction in infiltration rates from native forests to croplands and 82% reduction from native forests to pastures. The reduction in infiltration rates after replacing native forest with croplands has also been reported by (Akintoye et al., 2012; Osuji et al., 2010; Nyamadzawo et al., 2008) in different parts of Africa. Infiltration rates of pasture soils also depend on the intensity of grazing. Proffitt et al. (1995) reported significant differences of soil infiltration rates between ungrazed fields (where pasture was mowed to stimulate grazing without trampling), low intensity grazed fields (4 dry sheep equivalent per hectare, DSE ha^{-1}) and high intensity grazed fields (8 DSE ha^{-1}), which reduced by 51% and 58%, respectively, in well-structured soils over a period of ten months at Merredin in Western Australia.

Native forest in our study had six times higher saturated hydraulic conductivity than pastures, in line with previous studies. Price et al. (2010) reported that saturated hydraulic conductivity of forest to be approximately seven times greater than that of pasture in North Carolina, USA. In another study, carried out in Rondonia, Brazil, it was found that near surface (0–12.5 cm) saturated hydraulic conductivities were reduced by more than an order of magnitude when forests (250 mm h^{-1}) were converted to pasture land (15 mm^{-1}) (Godsey and Elsenbeer, 2002). Similar results were also reported by Zimmermann et al. (2006) for soil hydraulic conductivity at different depths under primary and cleared secondary forest, teak, pasture, and secondary forest after banana–cacao or pasture land types in the northwestern Brazil. Furthermore, these authors reported lower saturated hydraulic conductivity with increasing land use intensity.

The sorptivity of pastures, which is besides the hydraulic conductivity a core parameter determining soil water infiltration, was in our study significantly lower than that in soils of other land use types. This concurs with the findings of Kelishadi et al. (2014), who also reported lower sorptivity of pasture soils as compared to cropland soils for a study carried out in Koohrang region of central Zagros, Iran. These authors concluded that the low sorptivity of pastures was due to closure of pores and soil compaction by hoof trampling of grazing livestock which hinder movement of water in the topsoil (Kelishadi et al., 2014).

The similarities observed in soil hydraulic conductivity, bulk density, sorptivity and steady infiltration rate between native forest and forest plantations could be a result of litter cover that produces light surface permeability and acts as a filter, thereby protecting the surface against raindrop erosion and compaction (Awan, 1981). Furthermore, for native and forest plantations, the development of the tree rooting system enhances macro-pore development and maintenance.

Our study consistently found higher soil water content at field capacity, and plant available water capacity for soils taken from native forests compared to soils taken from managed land use types. This is in line with the findings of Price et al. (2010) who observed high volumetric water content at field capacity for forest soils, with values being approx. 20% higher as those for pasture soils, i.e. a comparable difference as found in our study (Table 3). Buytaert et al. (2005) also observed field capacity values of 0.64 $cm^3\ cm^{-3}$ for natural forest in tropical environment. Yu et al. (2015) also reported lower permanent wilting points for forest soils than for cropland soils as confirmed in our study. Low plant available water capacity of soils under pastures was furthermore reported by Arnhold et al. (2015) who carried out their study in Lambwe Valley, Kenya.

Even though tillage of cropland breaks up and loosens the topsoil, there is compaction in the subsoil by smearing and exertion of shear forces to the subsoil, which can form dense plow pans (Davies et al., 1993; Marshall et al., 1996; Yu et al., 2015). This results in the reduction of hydraulic conductivity, low field capacity and reduced storage capacity for plant available water compared to native forest soils (Yu et al., 2015). Also, Kodešová et al. (2011) and Li et al. (2007) showed that cultivation reduces the water retention capacity of the soil by alteration of the capillary soil-pore system and finally affects soil water flow (Horel et al., 2014). This could explain why soils used for annual cropping in our study showed strongly degraded soil hydraulic properties compared to native forest soils (Table 3). However, it is worth noting that the effect of cropland on soil water movement could also be affected by the depth of ploughing.

Our study found a reduction in saturated hydraulic conductivity and steady infiltration rate in managed land use practices in South West Mau, a region that is experiencing a high rate of forest clearance for agricultural use and settlement (Klopp and Sang, 2011; Were et al., 2013). The conversion of native forest to other land use types will likely alter the catchment’s water balance and flow component contributions. As shown by Harden (2006), the timing and distribution of infiltration as well as surface runoff have been altered by conversion of natural forests to managed land uses due to soil compaction in Andean mountains of Peru. Giertz and Diekkrüger (2003) studied two catchments with same mean annual precipitation of 609 mm (one under agricultural land use and the other one under native forest) in Benin, West Africa and reported large differences in discharge and flood peaks. The agricultural land use catchment had a surface runoff contribution of 22%, which was six times higher as that of the catchment with native forest where the contribution of surface runoff was 3% in 69 days. The authors also found that the infiltration rate in the agricultural catchment was 32% less the infiltration rate in the native forest catchment. In line with the findings by Giertz and Diekkrüger (2003), and the magnitude in which managed land use types have changed infiltration rates in our study area, we conclude that changes in land use types occurring in our study region in the last decades have already affected the hydrological regime of the landscapes and the compositions of flow components.

Omuto (2008) observed that soil physical degradation occurs in phases, which begins with deterioration of soil structure and ends in deferential loss of soil particles. Also, Nguyen et al. (2015) found that soil structure does not explain variation in soil water retention characteristics. Therefore, the low infiltration rates in pasture soils, without changes to water retention, could be due to changes in soil structure, which have not yet affected water retention.

The replacement of native forest with managed land use types such as tea plantations, croplands and pastures have also resulted in changes to soil chemical properties. Observed reductions in total topsoil SOC and TN in croplands, tea plantation and pastures in our study are consistent with both Okelo et al. (2015) and Nyberg et al. (2012). The decline in the total SOC and TN in the managed land use types was likely the result of long term removal of biomass by harvesting of crops and grazing (Nyberg et al., 2012). The high infiltration rates observed in our and other studies for soils of native forests are likely linked to high soil organic matter concentrations, but even more important, related to the well-developed macro-pore system originating from the presence of woody roots and burrowing fauna (Mapa, 1995; Wahren et al., 2009). The high surface biomass in native forest compared to managed land use types results in higher SOC in the forests and thus higher plant available water capacity. Annual tillage in the croplands coupled with the use of these fields for grazing after harvesting period results in little contribution to SOC accumulation in these soils.

The correlation results we found for saturated hydraulic conductivity and plant available water capacity are in agreement with the findings of Arnhold et al. (2015) who reported that saturated hydraulic conductivity was positively correlated to plant available water capacity. The inverse correlation between saturated hydraulic conductivity, steady infiltration and available plant water capacity with top soil bulk density agrees with the findings of Shukla et al. (2006) and Arnhold et al. (2015). The positive correlation observed between total SOC and TN are consistent with the finding of the Nyberg et al. (2012). Strong relation between steady infiltration rate, bulk density, available plant water capacity and total SOC (Table 5) shows that they are well suited for describing changes in soil hydraulic properties from native forest to managed land use types.

5 Conclusions

Our study shows that soil hydraulic properties and water retention characteristics of soils in the South West Mau were markedly different between native forest and other land use types. The other land use types had in increased soil bulk density and decreased saturated hydraulic conductivity, steady infiltration rate and water retention capacity. As the forest area of the Mau region has undergone significant land use change and deforestation, it is very likely that this has resulted in changes in landscape water fluxes, discharge patterns of rivers and groundwater recharge rates. Strongest degradation of soil hydraulic properties was found for smallholder grazing sites, likely due to severe overgrazing of these areas. To limit and possibly reverse degradation of soil hydraulic and hydrologic properties and to improve water retention at catchment scale in the Mau region, it will be necessary to create awareness among stakeholders and to consider land use change effects on regional hydrology in regional land use planning.

Uncited references

National Atlas of Kenya (1962) and Van Genuchten (1980).

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Appendix A. R code for calculating sorptivity and hydraulic conductivity from Philip’s equation

```
# constructing data vectors by reading the.csv files where the data was stored.

infil_data <- read.csv (“D:/Mau/Nonlinear/C1P1.csv”).

xdata <- infil_data$Reading.on.the.clock.

ydata <- infil_data$Infiltration.rate.cm.hr.

# examining the data by plotting.

plot (xdata,ydata).

# Fitting infiltration model (nonlinearly).

#some starting values.

S = 0.

K = 0.

#doing the fit.

fit_nonlin = nls (ydata ~ 0.5 * S * xdata ^ (−1/2) + K, start=list(S=S, K=K)).

#obtaining the fit values.

summary (fit_nonlin).
```

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Highlights

- Effects of land use on soil hydrological properties in Mau Region, Kenya, assessed.
- Forest show approx. 2 times higher soil water infiltration as croplands/pastures.
- Land use intensification resulted in degradation of soil hydraulic properties.

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