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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.

## 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

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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.

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