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Patterns of water infiltration and soil degradation over a 120-yr chronosequence from forest to agriculture in western Kenya

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Abstract

Soil degradation is commonly reported in the tropics where forest is converted to agriculture. Much of the native forest in the highlands of western Kenya has been converted to agricultural land in order to feed the growing population, and more land is being cleared. In tropical Africa, this land use change results in progressive soil degradation, as the period of cultivation increases. Sites that were converted to agriculture at different times can be evaluated as a chronosequence; this can aid in our understanding of the processes at work, particularly those in the soil. Both levels and variation of infiltration, soil carbon and other parameters are influenced by management within agricultural systems, but they have rarely been well documented in East Africa. We constructed a chronosequence for an area of western Kenya, using two native forest sites and six fields that had been converted to agriculture for varying lengths of time.

We assessed changes in infiltrability (the steady-state infiltration rate), soil C and N, bulk density, $\delta^{13}\text{C}$, and the proportion of macro- and microaggregates in soil along a 119 yr chronosequence of conversion from natural forest to agriculture. Infiltration, soil C and N, decreased rapidly after conversion, while bulk density increased. Median infiltration rates fell to about 15% of the initial values in the forest and C and N values dropped to around 60%, whilst the bulk density increased by 50%. Despite high spatial variability in infiltrability, these parameters correlated well with time since conversion and with each other.

Our results indicate that landscape planners should include wooded elements in the landscape in sufficient quantity to ensure water infiltration at rates that prevent runoff and erosion. This should be the case for restoring degraded landscapes, as well as for the development of new agricultural areas.

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1 Introduction

The infiltrability of soil, defined as the infiltration rate resulting when water at atmospheric pressure is made freely available at the soil surface (Hillel, 1971), and soil carbon (C), as the major part of soil organic matter (SOM), are two interrelated parameters that largely determine agricultural productivity. A high infiltrability enables water to enter the soil to become available for plant uptake, allows ground water recharge and reduces the risk of erosion. Infiltrability is a reflection of soil structure and texture (Cresswell et al., 1992), of soil biological activity (Mando, 1997; Leonard et al., 2004), of soil aggregation (LeBissonnais and Arrouays, 1997) and of SOM content (Franzuebbers, 2002). Soil C enhances biological activity and thereby promotes nutrient retention and cycling. Biological activity also enhances soil aggregation (Jastrow et al., 1998), aeration, water holding capacity (WHC) and infiltrability. Soil bulk density (BD) is often correlated with both soil C and with infiltrability (Mbagwu, 1997; Mariscal et al., 2007; Arvidsson, 1998). Hence, these three parameters, infiltrability, soil C and soil BD, are particularly suitable for studying changes over time in soil fertility and production capacity (Doran and Parkin, 1992).

Whilst high parameter variability may obscure statistical significance in designed experiments, it may also provide insights into spatial and temporal processes. To avoid or reduce large scale surface runoff and erosion, the occurrence of infiltrability values that are higher than the prevailing rainfall intensities, at a spatial scale of <1 m, may be more important than the average infiltration rate for an area. Spatial variability is usually very high for infiltrability. For example, Lal (1996) reported that infiltrability varied by a factor of two within 1 m. The means and variances of infiltrability, soil C and other parameters are influenced by management in agricultural systems. Generally, the more homogeneous the management, the lower the variation.

Chronosequences, constructed from sites at different stages and durations of succession from forest to agriculture, are commonly used to describe and understand changes in soils and soil degradation (Kimetu et al., 2008; Lemenih et al., 2005a, b;

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Awiti et al., 2008). Losses of 50 % to 80 % in soil C and N have been reported from sites that have been under agriculture for 20–50 yr (Solomon et al., 2007; Lemenih et al., 2005b, a). Natural forests have higher infiltrability and soil carbon content than cultivated lands. For example, Yimer et al. (2008) reported 75 % lower infiltrability under barley cultivation (15 yr) and grazing land, as compared with forest, in Ethiopia. Omuto (2008) reported a 25 % decrease in infiltrability 10 yr after conversion from a semi-arid shrub-land to agriculture.

Much of the native forest in the highlands of western Kenya has been converted to agricultural land, and some is still undergoing conversion, in order to feed the growing population. In tropical Africa, this land use change is commonly reported to result in progressive soil degradation that increases with the duration of cultivation (Juo et al., 1995; Lemenih et al., 2005a, b; Lal, 1996). Soil degradation, defined as the loss of actual or potential productivity or utility as a result of natural or anthropogenic factors (Lal, 1993) and mediated through interrelated physical, chemical and biological processes, threatens agricultural sustainability. Among the physical processes, a deterioration of soil structure is of particular importance, since it leads to, for example, accelerated erosion. Erosion is recognized as one of the major symptoms of soil degradation that results in important on- and off-site costs (Pimentel et al., 1995). A reduction in soil organic carbon is also a key soil degradation process, especially in the low input agriculture typical of much of the tropics, where soil productivity is very dependent on SOM (Kapkiyai et al., 1998; Ouedraogo et al., 2001; Tiessen et al., 1994). Therefore, the aim of this study was to assess changes in soil parameters and their variability along a 119 yr chronosequence in Kenya, with the objectives of (i) identifying the time course of these changes, (ii) understanding the processes, and (iii) suggesting how agricultural sustainability might best be achieved.

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Tropical rains are often very intensive; rainfall intensities of $>60 \text{ mm h}^{-1}$ or even $>100 \text{ mm h}^{-1}$ are not uncommon in the area for periods up to 30 minutes (Moore et al., 1979). Such events may contribute an important part of the total annual rainfall. After 69 yr since conversion, 50 % of the cultivated area had infiltrability values below 60 mm h^{-1} , and after 119 yr the entire agricultural area had steady-state infiltrability below 100 mm h^{-1} (Table 1). As there are very few agroforestry sites in the agricultural areas that could provide high infiltrability areas, there is considerable surface runoff and erosion and hence less water available for plant growth (Stroosnijder, 2009). Erosion is known to reduce crop yield via a reduction in effective rooting depth, loss of plant nutrients and soil organic carbon, loss of land area, and direct damage to seedlings (Lal, 1998). Decreased infiltration may also lead to less groundwater recharge (Bruijnzeel, 2004; Malmer et al., 2010)

From a landscape management perspective, the implication is that wooded structures, e.g. tree lines or shelterbelts along contours (Ellis et al., 2006; Stroosnijder, 2009), woodlots or other agroforestry elements, need to be included in the agricultural system, at a scale large enough to create enough high infiltration locations to reduce runoff and erosion at both farm and landscape levels.

Soil bulk density, which reflects several characteristics and processes in soil, increased significantly and rather rapidly after conversion to agriculture. Soil bulk density is easy and cheap to measure, and thus appropriate for general descriptions of long term soil changes. However, infiltrability was more sensitive to time since conversion and therefore more appropriate for separating the smaller differences between later stages in the chronosequence, i.e. infiltrability was significantly lower ($p < 0.05$) after 119 yr than after 39 yr since conversion (Figs. 2 and 3a).

Soil C was quite high in the forest and decreased by about 40 % with cultivation, averaged over the six agricultural sites (39–119 yr). $\delta^{13}\text{C}$ increased rapidly after forest conversion to agriculture based on C_4 plants (maize and grass for grazing) from -26‰ to -18‰ , indicating that the initial degradation of forest C occurs rapidly (over the first 39 yr), but that subsequent decomposition of forest C is very slow. The low variability in

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$\delta^{13}\text{C}$ and stable $\delta^{13}\text{C}$ values after 39 yr indicates that varying between crop or grazing and tea on the same fields is not the practice. This is also supported by the farmers not mentioning it, but discussing the alternation of maize fields with grazing land (C_4 grasses). This suggests that some 40–50 % of the soil C is still of C_3 origin after 120 yr. Others have reported similar patterns of forest-derived C, for example in Ethiopia and in Brazil (Lemenih et al., 2005b; Lisboa et al., 2009).

The percentage of large macroaggregates in soil decreased with time since conversion, probably as a result of soil tillage and decomposition. Microaggregates increased with time since conversion, probably reflecting macroaggregate breakdown (Wright and Inglett, 2009). Microaggregates are relatively inert, with reported mean residence times (MRT) of 222 and 498 yr (Liao et al., 2006; Lisboa et al., 2009). Inflow to this soil pool is reported to be faster than outflow; this fact was supported by our $\delta^{13}\text{C}$ data, which also indicated a pool of relatively inert soil C (40–50 % of soil C). The slightly higher variation in soil C, $\delta^{13}\text{C}$ and in macroaggregates at sites 119 yr after conversion might indicate a difference in management, e.g. inclusion of trees in fallows or tea, in the oldest fields.

There were very strong correlations between the time since conversion and infiltrability, BD, C % and N %, as well as between these four parameters, showing that they are well-suited to describing soil changes over chronosequences from forest to agricultural land (Fig. 4, Table 2). These four parameters are furthermore cheap, easy to perform and, except for infiltrability, commonly used in agricultural soils research. In spite of admittedly weak data ($n = 5$ and farmer estimates of yield), yield correlated with time since conversion and correlated weakly ($p = 0.058$) with the first four soil parameters (Table 2). The reported yields and their decline with time since conversion are in parity with measured yield data from the same area (Ngoze et al., 2008). Although logical and easy to understand, correlations between infiltrability and the other parameters are rarely presented in research studies. This is probably due to the very high variation in infiltrability. Good correlations with infiltrability were achieved in this study, due to the large differences along the chronosequence, careful use of the double ring

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Table 1. Variability in i_c steady-state infiltrability (mm h^{-1}) for sites of different ages since conversion to agriculture, represented by the median rate and % of readings above and below particular rates.

Years since conversion	Median infiltrability (mm h^{-1})	% < 60 mm h^{-1}	% < 100 mm h^{-1}
0	341.6	8.3	16.7
39	139.6	0.0	33.3
57	68.5	33.3	83.3
69	68.5	50.0	83.3
119	46.2	54.5	100.0

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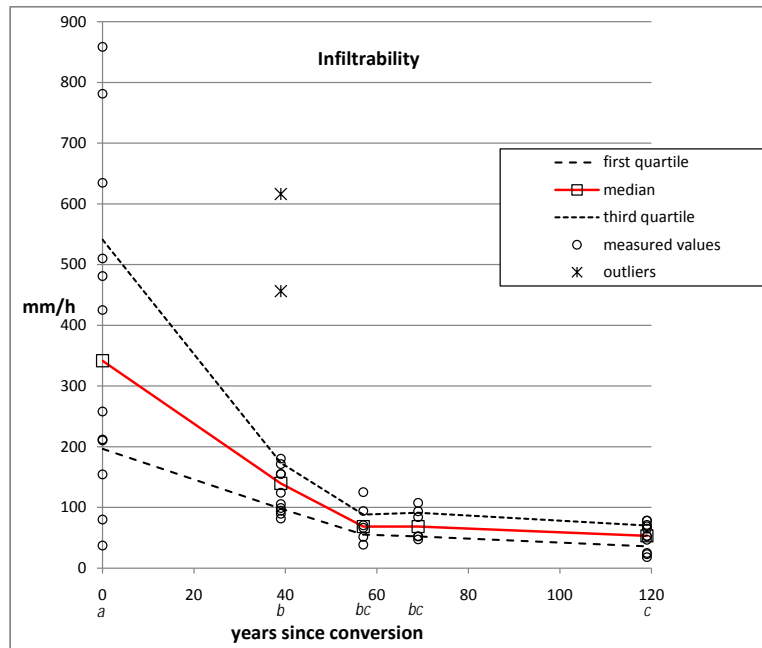


Fig. 2. Infiltrability rates along the chronosequence of years since conversion to agriculture. Letters in *italics* below x-axis represents significance. Years since conversion not followed by the same letter are significantly different ($p < 0.05$, Mood Median test).

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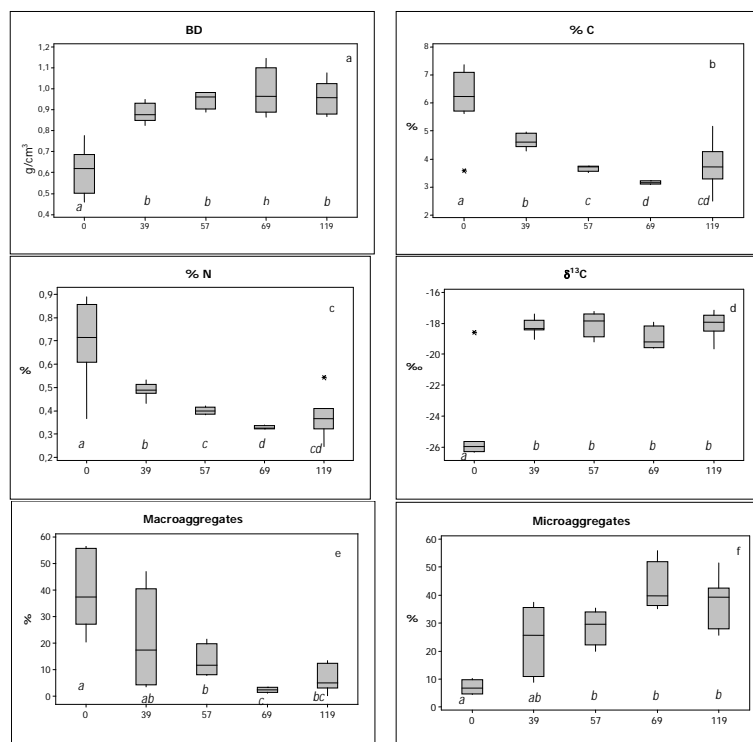


Fig. 3. Boxplots of soil parameters. **(a)** Bulk density, **(b)** soil carbon (%C), **(c)** soil N (%N), **(d)** $\delta^{13}\text{C}$, **(e)** Macroaggregates, **(f)** Microaggregates. x-axis scale is time since conversion. * represents outliers. Letters in *italics* below bars represents significance. Years since conversion not followed by the same letter are significantly different ($p < 0.05$, Mood Median test).

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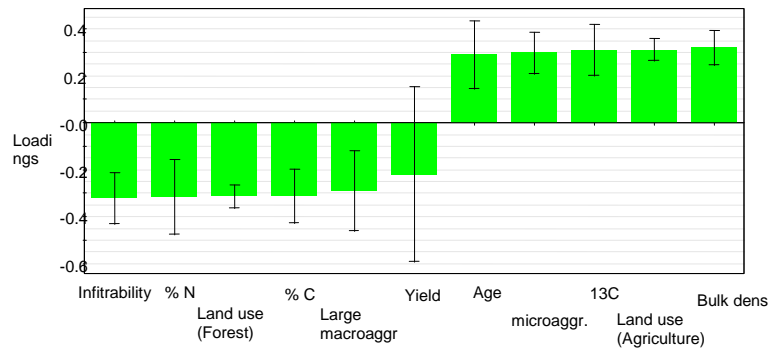


Fig. 4. Principal Component Analysis of the soil parameters, showing the loadings from the ordination on the first component. $R^2 = 0.82$.