Hydrol. Earth Syst. Sci. Discuss., 8, 6993–7015, 2011
www.hydrol-earth-syst-sci-discuss.net/8/6993/2011/
doi:10.5194/hessd-8-6993-2011

Hydrology and
Earth System
Sciences
Discussions

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

G. Nyberg[1], **A. Bargués Tobella**[1], **J. Kinyangi**[2], **and U. Ilstedt**[1]

[1]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83 Umeå, Sweden
[2]Climate Change, Agriculture and Food Security, c/o ILRI, P.O. Box 30709, Nairobi 00100, Kenya

Received: 20 June 2011 – Accepted: 1 July 2011 – Published: 20 July 2011

Correspondence to: G. Nyberg (gert.nyberg@slu.se)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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, δ^{13}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.

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 (Franzluebbers, 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;

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.

2 Material and methods

2.1 Site description

The study was undertaken in the South Nandi forest (00°06′ N 35°00′ E) and in cultivated plots adjacent to it near Kaptumo, Nandi district, western Kenya (Fig. 1). South Nandi forest is one of the largest remaining fragments of the original Kakamega forest, and is one of the last remnants of virgin tropical rainforest in this area. Since 1895, parts of the forest have been cleared and converted to agriculture. The altitudes of the sites range between 1950 and 2040 m a.s.l. Mean annual temperature is about 19.6 °C, with mean annual precipitation of 2000 mm, distributed across two rainy seasons (from March to June, and from September to November). The soils of southern Nandi forest are well-drained, deep and dark to reddish brown with friable clay and a thick humic top layer, principally developed on biotite gneiss parent material. They are classified as Humic Nitosols (FAO-UNESCO, 1988). The natural vegetation is composed of Guineo-Congolian tropical rainforest species, including *Aningeria altissima, Milicia excels, Antiaris toxicaria* and *Chrysophyllum albidum,* and montane forest species, including *Olea capensis* and *Croton megalocarpus* (Solomon et al., 2007). The agricultural landscape is dominated by a mixture of maize fields and grass covered grazing land. At this altitude and latitude almost all grasses are C_4 (Tieszen et al., 1979). There are also tea fields in the landscape. Sampling was done in late March, i.e. well into the rainy season and the maize was 10 cm to 1.5 m high in the different fields depending on planting time (not all farmers plant on the same date).

2.2 Study design

The study was conducted on eight different plots of average size of 40 m^2, two of them within existing natural forest (0 yr since conversion) and six in maize (*Zea mays* L.) fields. The six maize plots had been in agricultural production after conversion for 39 (two plots), 57, 69 or 119 (two plots) years, as reported by the concerned farmers.

Thus, the chronosequence ranging from 0 to 119 yr was established using the eight study plots. The sampling sites were all within a 3 × 3 km square and had similar slope and aspect.

Crop yield estimates were obtained by interviewing farmers and recording their verbal estimates of yield as bags (approx. 90 kg) per acre (0.4 ha).

Surface soil bulk density was determined from four undisturbed samples per plot. The samples were collected using a cylindrical sampler 5 cm long and 5 cm in diameter. Dry bulk density was calculated by dividing the mass after oven drying at 70 °C by the volume of the core. Four samples for soil carbon, nitrogen and aggregate analyses were taken from the topsoil in each plot. Subsamples of the soil were analyzed for %C, δ^{13}C, %N and δ^{15}N on an Elemental Analyzer-Isotope Ratio Mass Spectrometer (EA-IRMS) that was linked to an element analyzer (Carlo Erba CHN1110). For soil particle analysis, samples were wet sieved through successively smaller mesh sizes. For each sieve, samples were shaken for 2 min (25 strokes/min) with an amplitude of 3 cm. Mesh sizes were 2 mm, 0.25 mm and 0.053 mm, which collected large macroaggregates (>2 mm), small macroaggregates (0.25–2 mm) and microaggregates (0.053–0.25 mm), respectively. The fraction that passed through all sieves, i.e. <0.053 mm, was silt and clay.

Infiltrability (Hillel, 1971) was measured using the double ring infiltrometer method (Bouwer, 1986) at six sample points per plot. The inner and the outer rings had a diameter of 20 and 30 cm, respectively. Water was carefully poured into the inner ring to avoid disturbing the soil surface, and also in the area between the inner and the outer ring, maintaining a head of 3–4 cm during the measurements.

The water level in the inner ring was measured every 3 min for one 15 min period each hour, giving 5 infiltration readings per ring every hour. Measurements continued until a constant infiltration rate was reached, or after four hours from the time measurements started.

The purpose of using a double-ring infiltrometer is for the outer space between the two rings to prevent edge effects due to non-vertical flow affecting vertical infiltration from the inner ring (Bouwer, 1986). The advantages of using the double-ring method are its simplicity, relative low cost and common use (Teixeira et al., 2003).

The steady-state infiltrability (Hillel, 2004) and sorptivity constants (defining the soil capacity to absorb water when the water flow is influenced by a matric pressure gradient) were estimated by means of curve-fitting using Philip's equation (Philip, 1957), by minimizing the squared residuals using the solver tool in Microsoft Excel.

According to Philip's equation:

$$I = st^{1/2} + i_c t$$

which, deriving (δt), gives:

$$i = \frac{s}{2t^{1/2}} + i_c$$

where:
I (mm) is the cumulative infiltration at time t
i ($\text{mm}\,\text{h}^{-1}$) is the infiltration rate at time t
s ($\text{mm}\,\text{h}^{-0.5}$) is the term defined as sorptivity
i_c ($\text{mm}\,\text{h}^{-1}$) is the term defined as transmissivity or steady-state infiltrability

2.3 Statistical analyses

Correlations were calculated between soil and site parameters using Spearman's non-parametric rank correlation (PASW). Due to the non-normal distribution and unequal variances of the data, tests of significance for differences between median values were conducted using the Mood Median Test (Minitab 16). We used Principal Component Analysis (PCA) to explore relationships between all the variables. PCA calculates new and independent latent variables (principal components) that maximize the explained variance among all variables. Since the variables had different units and ranges, they were centered and then scaled by their respective variance in the PCA. Significance of the variables was tested by Jack-Knifing, based on 95 % confidence intervals (Efron and Gong, 1983). Both explained variance (R^2) by components and predicted variance by cross-validation (Q^2) were calculated. If Q^2 did not increase when a new component was added, this component was discarded and no more components calculated. The PCA was performed using SIMCA 12.0.1 software (UMETRICS, 2009)

3 Results

3.1 Steady-state infiltrability

Infiltrability was significantly higher ($p < 0.05$) in the forest (year 0) compared with any of the agricultural fields. In the sites that had been under agriculture for 39 yr, infiltrability was significantly lower than in the forest, but significantly higher than in fields that had been under agriculture for 57–119 yr ($p < 0.05$). Thus, infiltrability decreased with time since conversion, particularly over the first 50 yr (Fig. 2). The median infiltrability after 119 yr of cultivation was only around 15 % of the median infiltrability in the forest. The variation in infiltration rates was very large in the forest, with values ranging from 37 mm h^{-1} to 859 mm m^{-1}, whilst after 119 yr of cultivation, the range was between 18 mm h^{-1} and 78 mm h^{-1} (Fig. 2). The coefficient of variation (CV = stdev/mean) was 35-80 % within plots, with higher values from the forest plots. In the forest, the median infiltrability was 342 mm h^{-1}. From 57 yr after conversion, infiltrability was below 100 mm h^{-1} and one third or more of the sampling points had values below 60 mm h^{-1}. After 119 yr, infiltrability was below 100 mm h^{-1} for all sampling points (Table 1, Fig. 2).

3.2 Bulk Density (BD)

Median soil bulk density increased over time by 52 % ($p < 0.05$) from 0.62 g cm^{-3} in the forest to 0.94 g cm^{-3} in cultivated fields (Fig. 3a). There were no significant differences in BD for any of the agricultural sites (39–119 yr). The CV for BD data was 5–25 %.

3.3 Soil C, N and δ^{13}C

Soil C and N was significantly ($p < 0.05$) lower in the cultivated fields (median 3.8 and 0.4 % respectively from 39 to 119 yr) compared with the forest (6.2 and 0.7 % respectively) (Fig. 3b and c). Median δ^{13}C was significantly lower in the C_3 dominated forest (–26 ‰), than in the cultivated fields, which all had similar values around -18 ($p < 0.05$) (Fig. 3c). The CV for C and N data ranged from 5–25 %.

3.4 Soil aggregates

The median percent large macroaggregates (>2 mm) decreased over time since forest conversion. The value in the forest (37.3 %) was significantly higher ($p < 0.05$) than values from sites that had been converted 57 to 119 yr ago (2.5–11.7 %) (Fig. 3e). There were no changes in small macroaggregates (0.25–2 mm; data not shown), but there was an increase in median values of microaggregates (0.053–0.25 mm) with time. In the forest, the value of 6.9 % microaggregates was significantly lower ($p < 0.05$) than that from cultivated land (25.7–39.2 %) aged 57 to 119 yr after conversion (Fig. 3f).

3.5 Correlations

All parameters except ^{13}C and ^{15}N correlated well ($p =< 0.05$) with age since conversion (Table 2). Infiltrability was negatively correlated ($p =< 0.05$) with time since conversion, BD, and the % microaggregates and positively correlated ($p =< 0.05$) with %C, %N, large macroaggregates and weakly with yield ($p =< 0.1$). Infiltrability, BD, C and N correlated strongly with each other and with time since conversion ($p < 0.05$ or $p < 0.01$) (Table 2).

3.6 Multivariate analysis

The first component of the PCA model explained 82 % of the variation in the data. The Q^2 value was 70 % for the first component. The corresponding R^2 value for component

2 was 9 %. However, since the Q^2 value was negative for the second component only the first component was retained. The PCA model demonstrated that the time since conversion from forest was important for all variables (Fig. 4). In the first component of the PCA model, time since conversion of forest related positively to bulk density, micro aggregates and ^{13}C, while infiltrability, %N and %C were negatively related to time since conversion. Yield was poorly modeled, but seemed to be negatively correlated to time since conversion, bulk density and micro aggregates.

4 Discussion

In this study we report a rapid decline in infiltrability, soil C and N after conversion of forest to agriculture in a 119 yr chronosequence. Median infiltrability is reduced to 40 % of the forest values (342 mm h^{-1}) in 39 yr of cultivation (140 mm h^{-1}) and further to 15 % after 119 yr (46 mm h^{-1}). Yimer et al. (2008) reports similar high infiltrability values from Ethiopian forests (around 450 mm h^{-1}) but an even faster decline, to 25 % after 15 yr of crop cultivation or grazing land (around 120 mm h^{-1}). Reciprocally, Ilstedt et al. (2007) in a meta-analysis report of 2–4 fold increases in infiltrability after agroforestry and afforestation measures.

A decrease in variability, especially for infiltrability, followed the decreases in average and median values. High variability in infiltrability is commonly reported (Bamutaze et al., 2010; Lal, 1996). Similar values to those reported here for the CV of infiltrability (33–81 %) were obtained by Van de Genachte et al. (1996) in a rain forest in Guyana. Infiltrability is not complicated to measure but, due to the large variation, it needs many replicate samples. The variation itself provides valuable information. In the forest, there were locations with infiltration capacity as low as in the agricultural fields. However, there were also many locations with high infiltrability, whilst such locations were largely missing in agricultural fields, especially from approximately 60 yr after conversion (Fig. 2).

Tropical rains are often very intensive; rainfall intensities of $>60\,\mathrm{mm\,h^{-1}}$ or even $>100\,\mathrm{mm\,h^{-1}}$ 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 $60\,\mathrm{mm\,h^{-1}}$, and after 119 yr the entire agricultural area had steady-state infiltrability below $100\,\mathrm{mm\,h^{-1}}$ (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 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). δ^{13}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

δ^{13}C and stable δ^{13}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 δ^{13}C data, which also indicated a pool of relatively inert soil C (40–50 % of soil C). The slightly higher variation in soil C, δ^{13}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 infiltration methodology ($n = 6$/plot). The variation reflects a natural phenomenon of spatial variability that needs to be accounted for when designing management options and landscapes.

5 Conclusions and recommendations

There was a sharp decline in BD, infiltrability, soil C and N after conversion of forest to agriculture. Median infiltrability values fell to about 15 % of the initial values in the forest. For infiltrability, BD, % N and % C (except for % C at 119 yr) variation was highest in the forest. Despite losing about half of the soil carbon in the forest following cultivation, 50 % of the remaining carbon consisted of organic material originating from the forest. To describe general soil changes over time, basic soil parameters, such as BD, infiltrability, soil C and N, are adequate.

Agricultural management in this area of Kenya should include tree/agroforestry components on a scale that will ensure that infiltrability at the farm and landscape scale will prevent erosion and runoff. This should apply both for restoring degraded landscapes and for new agricultural areas. The appropriate scale of these agroforestry components will depend, for example, on rainfall distribution, soil type, inclination, agroforestry type and agricultural practices. Further research is particularly required on how runoff and infiltration at the landscape scale are affected by the interaction between the spatial variability in rainfall distribution and infiltrability.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/8/6993/2011/ hessd-8-6993-2011-supplement.pdf.

Acknowledgements. This study was made possible by grants through a common research call from Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) and the Swedish International Development Agency (Sida).

References

Arvidsson, J.: Influence of soil texture and organic matter content on bulk density, air content, compression index and crop yield in field and laboratory compression experiments, Soil Till. Res., 49, 159–170, 1998.

Awiti, A. O., Walsh, M. G., and Kinyamario, J.: Dynamics of topsoil carbon and nitrogen along a tropical forest-cropland chronosequence: Evidence from stable isotope analysis and spectroscopy, Agr. Ecosyst. Environ., 127, 265–272, doi:10.1016/j.agee.2008.04.012, 2008.

Bamutaze, Y., Tenywa, M. M., Majaliwa, M. J. G., Vanacker, V., Bagoora, F., Magunda, M., Obando, J., and Wasige, J. E.: Infiltration characteristics of volcanic sloping soils on Mt. Elgon, Eastern Uganda, Catena, 80, 122–130, doi:10.1016/j.catena.2009.09.006, 2010.

Bouwer, H.: Intake rate: cylinder infiltrometer, in: Methods of soil analysis. Part 1. Physical and mineralogical methods, edited by: Klute, A., American Society of Agronomy, Inc., Madison, Wisconsin, 825–844, 1986.

Bruijnzeel, L. A.: Hydrological functions of tropical forests: not seeing the soil for the trees?, Agriculture, Ecosystems & Environment, 104, 185–228, doi:10.1016/j.agee.2004.01.015, 2004.

Cresswell, H. P., Smiles, D. E., and Williams, J.: Soil structure, soil hydraulic-properties and the soil-water balance, Aust. J. Soil Res., 30, 265–283, 1992.

Doran, J. W. and Parkin, T. B.: Defining and assessing soil quality, Defining soil quality for a sustainable environment: proceedings of a symposium, Minneapolis, MN, USA, 1992, CABI:19951904109, 3–21, 1994.

Efron, B. and Gong, G.: A leisurely look at the Bootstrap, the Jack-knife, and Cross-validation, Am. Stat., 37, 36–48, 1983.

Ellis, T. W., Leguedois, S., Hairsine, P. B., and Tongway, D. J.: Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia, Aus. J. Soil Res., 44, 117–125, 2006.

FAO-UNESCO: Soil map of the world. Revised legend, FAO World Soil Resources Reports, 60, 119 pp., 1988.

Franzluebbers, A. J.: Water infiltration and soil structure related to organic matter and its stratification with depth, Soil Till. Res., 66, 197–205, 2002.

Hillel, D.: Soil and Water: Physical Principles and Processes. (Physiological Ecology: a Series of Monographs and Treatises), Soil and Water: Physical Principles and Processes., Academic Press, New York and London., 288 pp., 1971.

Hillel, D.: Introduction to environmental soil physics, Introduction to environmental soil physics, edited by: Hillel, D., Academic Press, San Diego, xvi + 494 pp., 2004.

Ilstedt, U., Malmer, A., Elke, V., and Murdiyarso, D.: The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis, Forest Ecol. Manag., 251, 45–51, doi:10.1016/j.foreco.2007.06.014, 2007.

Jastrow, J. D., Miller, R. M., and Lussenhop, J.: Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie, Soil Biol. Biochem., 30, 905–916, 1998.

Juo, A. S. R., Franzluebbers, K., Dabiri, A., and Ikhile, B.: Changes in soil properties during long-term fallow and continuous cultivation after forest clearing in Nigeria, Agric. Ecosyst. Environ., 56, 9–18, 1995.

Kapkiyai, J. J., Karanja, N. K., Woomer, P., and Qureshi, J. N.: Soil organic carbon fractions in a long-term experiment and the potential for their use as a diagnostic assay in highland farming systems of Central Kenya, African Crop Science Journal, 6, 19–28, 1998.

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., Verchot, L., Recha, J. W., and Pell, A. N.: Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient, Ecosystems, 11, 726–739, doi:10.1007/s10021-008-9154-z, 2008.

Lal, R.: Tillage effects on soil degradation, soil resilience, soil quality, and sustainability-introduction, Soil Till. Res., 27, 1–8, 1993.

Lal, R.: Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria, 1. Soil physical and hydrological properties, Land Degrad. Dev., 7, 19–45, 1996.

Lal, R.: Soil erosion impact on agronomic productivity and environment quality, Crit. Rev. Plant Sci., 17, 319–464, 1998.

LeBissonnais, Y. and Arrouays, D.: Aggregate stability and assessment of soil crustability and erodibility, 2. Application to humic loamy soils with various organic carbon contents, Eur. J. Soil Sci., 48, 39–48, 1997.

Lemenih, M., Karltun, E., and Olsson, M.: Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia, Agric. Ecosyst. Environ., 105, 373–386, doi:10.1016/j.agee.2004.01.046, 2005a.

Lemenih, M., Karltun, E., and Olsson, M.: Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia, Agric. Ecosyst. Environ., 109, 9–19, doi:10.1016/j.agee.2005.02.015, 2005b.

Leonard, J., Perrier, E., and Rajot, J. L.: Biological macropores effect on runoff and infiltration: a combined experimental and modelling approach, Agric. Ecosyst. Environ., 104, 277–285, doi:10.1016/j.agee.2003.11.015, 2004.

Liao, J. D., Boutton, T. W., and Jastrow, J. D.: Organic matter turnover in soil physical fractions following woody plant invasion of grassland: Evidence from natural C-13 and N-15, Soil Biol. Biochem., 38, 3197–3210, doi:10.1016/j.soilbio.2006.04.004, 2006.

Lisboa, C. C., Conant, R. T., Haddix, M. L., Cerri, C. E. P., and Cerri, C. C.: Soil carbon turnover measurement by physical fractionation at a forest-to-pasture chronosequence in the Brazilian Amazon, Ecosystems, 12, 1212-1221, 10.1007/s10021-009-9288-7, 2009.

Malmer, A., Murdiyarso, D., Bruijnzeel, L. A., and Ilstedt, U.: Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations, Global Change Biol., 16, 599–604, doi:10.1111/j.1365-2486.2009.01984.x, 2010.

Mando, A.: The impact of termites and mulch on the water balance of crusted Sahelian soil, Soil Technol., 11, 121–138, 1997.

Mariscal, I., Peregrina, F., Terefe, T., Gonzalez, P., and Espejo, R.: Evolution of some physical properties related to soil quality in the degraded ecosystems of “rana” formations from SW Spain, Sci. Total Environ., 378, 130–132, doi:10.1016/j.sciotenv.2007.01.025, 2007.

Mbagwu, J. S. C.: Quasi-steady infiltration rates of highly permeable tropical moist savannah soils in relation to landuse and pore size distribution, Soil Technol., 11, 185–195, 1997.

Moore, T. R., Thomas, D. B., and Barber, R. G.: Influence of grass cover on runoff and soil erosion from soils in the Machakos area, Kenya, Trop. Agric., 56, 339–344, 1979.

Ngoze, S., Riha, S., Lehmann, J., Verchot, L., Kinyangi, J., Mbugua, D., and Pell, A.: Nutrient constraints to tropical agroecosystem productivity in long-term degrading soils, Glob. Change Biol., 14, 2810–2822, doi:10.1111/j.1365-2486.2008.01698.x, 2008.

Omuto, C. T.: Assessment of soil physical degradation in Eastern Kenya by use of a sequential soil testing protocol, Agr. Ecosys. Environ., 128, 199–211, doi:10.1016/j.agee.2008.06.006, 2008.

Ouedraogo, E., Mando, A., and Zombre, N. P.: Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa, Agric. Ecosyst. Environ., 84, 259–266, 2001.

Philip, J. R.: The theory of infiltration: 4. Sorptiyity and algebraic infiltration equations, Soil Sci, 84, 257–264, 1957.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., and Blair, R.: Environmental and economic costs of soil erosion and conservation benefits, Science, 267, 1117–1123, 1995.

Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., and Schafer, T.: Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems, Global Change Biology, 13, 511–530, doi:10.1111/j.1365-2486.2006.01304.x, 2007.

Stroosnijder, L.: Modifying land management in order to improve efficiency of rainwater use in the African highlands, Soil Till. Res., 103, 247–256, doi:10.1016/j.still.2008.05.019, 2009.

Teixeira, W. G., Sinclair, F. L., Huwe, B., and Schroth, G.: Soil water, in: Trees, crops and soil fertility: Concepts and research methods, edited by: Schroth, G., and Sinclair, F. L., CABI Publishing, 209–234, 2003.

Tiessen, H., Cuevas, E., and Chacon, P.: The role of soil organic matter in sustaining soil fertility Nature, 371, 783–785, 1994.

Tieszen, L. L., Senyimba, M. M., Imbamba, S. K., and Troughton, J. H.: The distribution of C_3 and C_4 grasses and carbon isotope discrimination along an altitudinal and moisture gradient in Kenya Oecologia, 37, 337–350, 1979.

UMETRICS, A.: SIMCA P+®, Version, 12, 20, 2009.

Van de Genachte, G., Mallants, D., Ramos, J., Deckers, J. A., and Feyen, J.: Estimating infiltration parameters from basic soil properties, Hydrol. Process., 10, 687–701, 1996.

Wright, A. L., and Inglett, P. W.: Soil Organic Carbon and Nitrogen and Distribution of Carbon-13 and Nitrogen-15 in Aggregates of Everglades Histosols, Soil Sci. Soc. Am. J., 73, 427–433, doi:10.2136/sssaj2008.0078, 2009.

Yimer, F., Messing, I., Ledin, S., and Abdelkadir, A.: Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia, Soil Use Manage., 24, 344–349, doi:10.1111/j.1475-2743.2008.00182.x, 2008.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc

Printer-friendly Version
Interactive Discussion

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

Table 2. Correlations between soil and site parameters, including age since conversion to agriculture.

	i_c steady-state infiltrability	BD	%C	%N	Macro-aggr. %	Micro-aggr. %	δ13C	δ15N	Yield
Age	-0.982^{***}	0.788^{**}	-0.885^{***}	-0.885^{***}	-0.727^{**}	0.812^{**}	0.582	0.546	-0.889^{**}
i_c		-0.786^{**}	0.881^{***}	0.881^{***}	0.714^{**}	-0.786^{**}	−0.619	0.548	0.866^{*}
BD			-0.976^{***}	-0.976^{***}	−0.500	0.500	0.690^{**}	0.548	-0.866^{*}
%C				1.000^{***}	0.619	−0.619	−0.667	−0.619	0.866^{*}
%N					0.619	−0.619	−0.667	−0.619	0.866^{*}
Macro-aggr. %						-0.952^{***}	−0.262	-0.833^{***}	−0.577
Micro-aggr. %							0.357	0.738^{**}	−0.577
$\delta^{13}C$								0.381	0.000
$\delta^{15}N$									−0.289

i_c = steady-state infiltrability;
BD = soil bulk density;
Macro-aggr. % = % large macroaggregates (>2 mm) in soil;
Micro-aggr. % = % microaggregates (0.053–0.25 mm) in soil.
Spearman rank order correlations (plot medians),
$p < 0.1 = ^{*}$; $p < 0.05^{**}$;
$p < 0.01^{***}$ $n = 8$ for all parameters, except yield where $n = 5$.

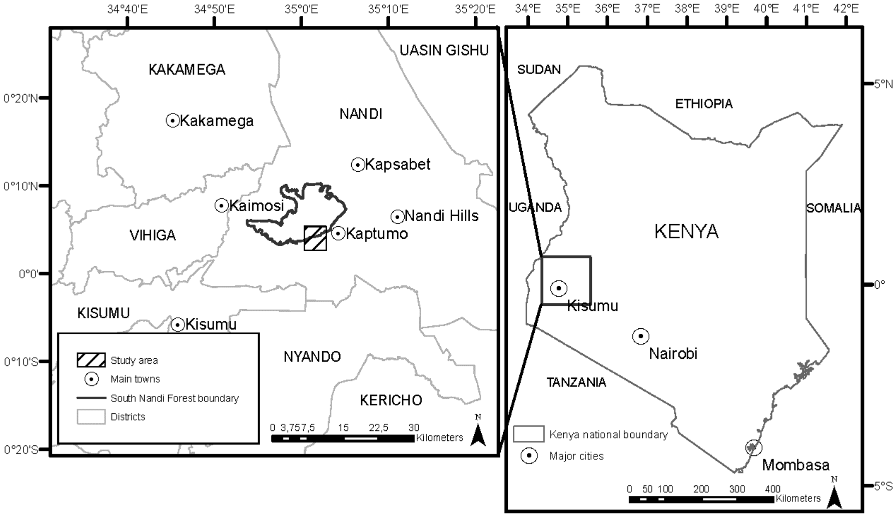

Fig. 1. Map of Kenya showing the study area near Kaptumo, Nandi province.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

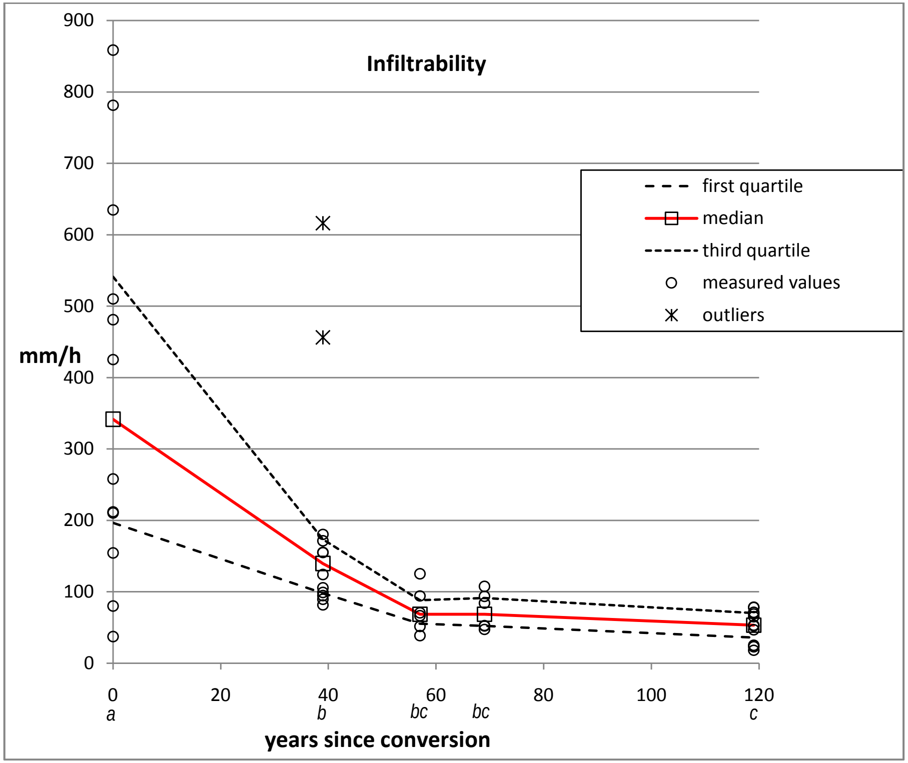

Fig. 2. Infiltrability rates along the chronosequence of years since conversion to agriculture. Letters in *italics* below x-axis represents significance. Years since conversion not followed by the same letter are significantly different ($p < 0.05$, Mood Median test).

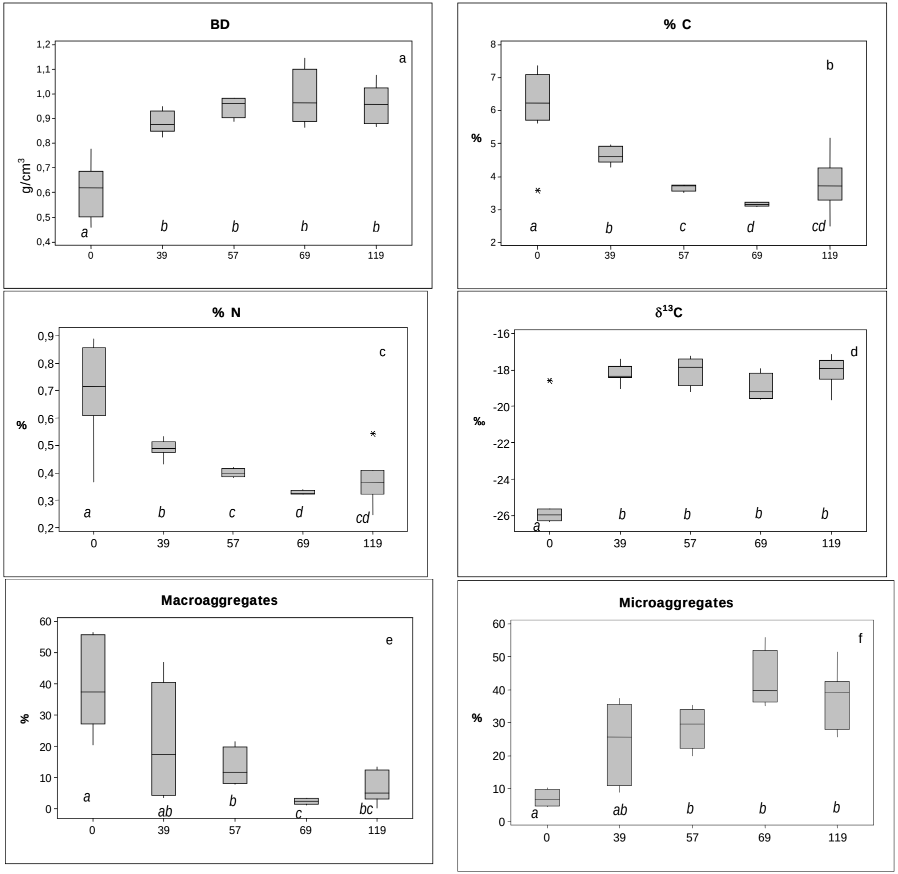

Fig. 3. Boxplots of soil parameters. **(a)** Bulk density, **(b)** soil carbon (%C), **(c)** soil N (%N), **(d)** δ^{13}C, **(e)** Macroaggregates, **(f)** Microaggregates. x-axis scale is time since conversion. * represents outliers. Letters in *italics* below bars represents significance. Years since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

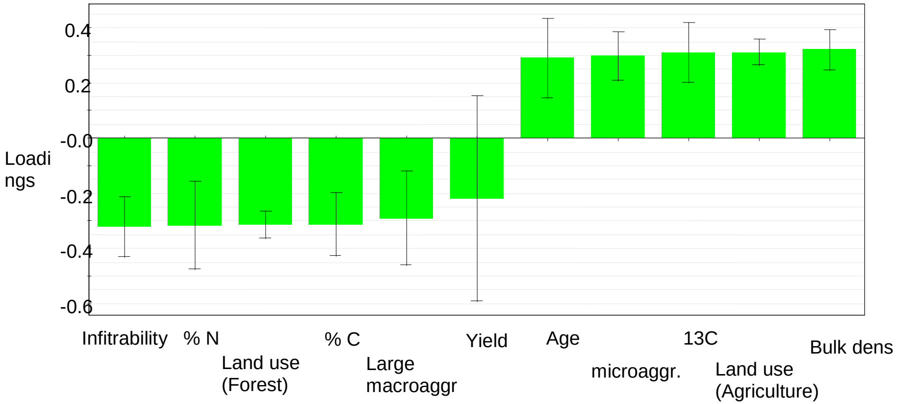

Fig. 4. Principal Component Analysis of the soil parameters, showing the loadings from the ordination on the first component. $R^2 = 0.82$.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion