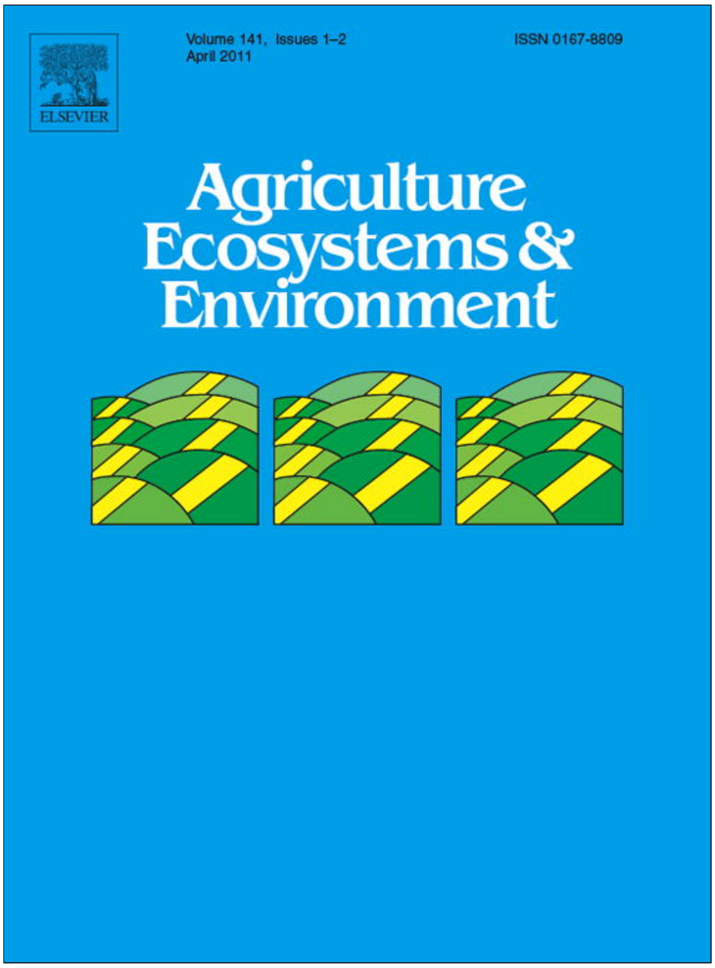
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Long-term soil quality degradation along a cultivation chronosequence in western Kenya

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ABSTRACT

Loss of agroecosystem soil functions due to soil quality (SQ) degradation impacts Africa's agricultural viability and food security. Primary forest and farm fields deforested between 1930 and 2000 were sampled along a chronosequence on two parent materials in western Kenya. Two traditional long-term management systems were sampled: continuous low-input maize (*Zea mays*; Co), and kitchen garden (Ki) polyculture with organic inputs. Physical, biological, and chemical SQ indicators were measured. Degradation in Co followed exponential decay trends for most indicators (organic matter, active C, water-stable aggregates, available water capacity, electrical conductivity, CEC, pH, Ca, Mg and Zn), as well as for yield. Organic matter quality declined linearly, suggesting degradation will continue. For both parent materials and most indicators degradation of 25–93% below initial values resulted, but with ≤40% further drop below initial values and for more indicators under Co than Ki. P, Zn and possibly K accumulated over time under Ki. The extent of degradation was influenced by parent material. In conclusion, a basic accessible set of SQ indicators was successfully used to describe soil degradation dynamics under cultivation. Results suggest that regular organic inputs can significantly reduce degradation, especially of nutrient retention and soil structure, after forest conversion.

1. Introduction

Degraded soils are becoming more prevalent in Africa due to intensive use, low inputs and poor management by growing populations (Eswaran et al., 2005). It is estimated that up to two thirds of Africa's original forest cover has been lost (Chapman et al., 2006), largely from conversion to agriculture (FAO, 2005). Extractive practices by subsistence farmers are estimated to have caused a loss of 60–80% of the original soil organic carbon in the tropics (Lal, 2006). Subsequent losses in nutrient retention and availability, soil structure, erosion resistance, drought resistance and crop yields ensue (Lal, 2006). African agriculture on a finite and often shrinking and degrading land base must produce more food, fiber and other services for rising populations, and it must do this in a way that does not further degrade these soils (Tilman et al., 2002; Lal, 2006). There is, therefore, a need to assess the status and trends of soil quality degradation, and thus for tools and indicators for monitoring and evaluation (Hurni et al., 2006).

Soil quality degradation dynamics can be difficult to assess experimentally because of the long time-scales involved. However, chronosequences, which substitute spatial history differences for time differences, have long been used in the study of soil pedological phenomena (Stevens and Walker, 1970; Huggett, 1998) and have more recently also been used as a tool to study anthropogenic management effects on soil (e.g. Solomon et al., 2007; An et al., 2008; Marin-Spiotta et al., 2009; Wang et al., 2009). Carbon and nutrient contents usually decline exponentially with long-term low-input cultivation after forest conversion to agriculture (Solomon et al., 2007; An et al., 2008; Kinyangi, 2008).

Agricultural SQ encompasses not just chemical soil fertility, but also physical and biological functions and processes of soils needed to support plant growth. Dynamic soil quality, our focus here, is also often referred to as soil health, and is the aspect of soil quality affected by human management (Karlen et al., 1997; Carter, 2002). Dynamic soil quality can be assessed indirectly by measuring a minimum dataset of representative indicators, or dynamic soil properties, while inherent soil properties, primarily controlled by soil forming properties, are useful in guiding interpretation (Larson and Pierce, 1991; Carter, 2002). Dynamic soil properties chosen to be part of such a minimum dataset of indicators for soil quality assessment must (a) be sensitive to changes in agricultural management, (b) represent a range of agrobiophysically

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important processes, and (c) when used beyond the research realm, must be easy and inexpensive to measure, and interpretations must be accessible to many users (Larson and Pierce, 1991; Mausbach and Seybold, 1998; Moebius et al., 2007). However, no widely standardized minimum dataset of SQ assessment indicators exists currently, especially for use in the tropics (Winder, 2003; Bastida et al., 2008), and methods of SQ assessment are often not accessible to farmers or even researchers and extension organizations in developing nations with minimal infrastructure (Bastida et al., 2008). The Cornell Soil Health Test was developed for broader adoption by consultants, farmers and applied researchers at reasonable cost. This minimum dataset is currently available for use in the United States (Idowu et al., 2008; Gugino et al., 2009).

Much progress has been made in elucidating nutrient and total soil organic carbon dynamics due to degradation and management effects (e.g., Lal, 2006; McLauchlan, 2006; Bationo et al., 2007; Solomon et al., 2007; Kimetu et al., 2008; Ngoze et al., 2008; Bationo et al., 2011). Improved SQ is frequently stated as the goal of such soil management- and degradation-related research in the tropics. However, relatively few studies, such as Islam and Weil (2000), Mairura et al. (2007) and Murage et al. (2000), have concurrently measured a set of SQ indicators that include some of each of physical, biological and chemical indicators, and that are all directly linked to essential agrobiophysical processes and productivity. Thus, relatively little is known about interlinked dynamics of physical, biological and chemical processes of degradation in tropical environments, especially when involving multiple, traditional management practices.

A chronosequence of land conversion from primary forest to almost 80 yr in cultivation located on the Kakamega and Nandi Forest margins in Kenya provides a unique opportunity to assess long-term SQ degradation dynamics over time using a combination of physical, biological and chemical indicators. High rainfall erosivity due to generally intense tropical rains (Moore, 1979; Angima et al., 2003), and high soil erodibility, make soils in this region particularly sensitive to degradation (deGraffenried and Shepherd, 2009). The objective of this study was to describe and assess the differences in dynamics of soil degradation over time in two contrasting traditional long-term management systems on two parent materials, using standard soil quality indicators that represent agrobiophysically meaningful soil processes, that could be accessible in developing countries, and have the potential to be included in a minimum dataset for globally standardized SQ monitoring (Moebius-Clune, 2010; Moebius-Clune et al., 2011).

2. Materials and methods

2.1. Site description

The study site is located at the margins of the Kakamega/Nandi Forest in Vihiga, Kakamega, South Nandi and North Nandi districts of western Kenya, between 0°00′N and 0°13′N latitude and between 34°45′E and 35°03′E longitude. The Kakamega/Nandi Forest is the largest remainder of the Guineo-Congolean Forest in Kenya. The water catchment area made up by these forests feeds into the Lake Victoria basin (Lung and Schaab, 2006). Poverty, government settlement plans and illegal encroachment have caused the conversion of primary forest to low-input subsistence agriculture to be the dominant form of land-use change over the last century in this area.

The rainfall distribution of the study site is bimodal, with the longer rainy season occurring from March to August, and a shorter season from September to January, thus allowing for two cereal cropping periods per year. The area receives about 1800 to 2100 mm of rainfall annually, and the mean annual temperature is 19 °C. Rainfall erosivity in the region is generally above 9000 J m^{-2} y^{-1}, and the most erosive rains usually occur at the beginning of the growing season and thus at times of minimal ground cover on cropped fields (Moore, 1979).

A chronosequence experiment, including intact primary forest sites and farms representing time points of conversion to agriculture between the approximate years of 1930–2000, was established to investigate the long-term effects of land conversion from primary forest to agriculture on soil carbon pools (Kimetu et al., 2008; Kinyangi, 2008; Ngoze et al., 2008). Farms on two chronosequences described by Kimetu et al. (2008) were selected for this study. These are on Ultisols that contain low activity kaolinite and high proportions of Fe and Al oxides (Krull et al., 2002). Nandi region soils developed on biotite-gneiss parent material and are classified as Humic Nitosols, while Kakamega region soils developed on undifferentiated basement system rock, composed predominantly of Precambrian gneisses and are classified as Ferralo-Chromic Acrisols (FAO-UNESCO, 1997; Krull et al., 2002; Solomon et al., 2007; Kimetu et al., 2008).

The Kakamega chronosequence contained three clustered forest sites and twelve collaborating farms converted from forest to agriculture in approximately 1930, 1950, 1970, and 1985 with elevation ranging from about 1600 to 1700 m ($\bar{x} = 1632$ m, $s = 36$ m) and with coarse soil textures (average sand, silt and clay ~442, 443, 115 g kg^{-1}, respectively). The Nandi sequence contained 9 forest sites, clustered in three groups, and 24 collaborating farms converted from forest in approximately 1930, 1950, 1970, 1985, 1995 and 2000, with elevation ranging from 1560 to 2028 m ($\bar{x} = 1789$ m, $s = 108$ m) and somewhat finer textures (average sand, silt and clay ~455, 370, 175 g kg^{-1}, respectively). All sites were chosen in topographically similar locations (backslope to shoulder, 2–5% slope). Most conversion years were replicated by three collaborating farms. Conversion times and cropping patterns were identified based on official and private records, Landsat imagery and farmer interviews (Kinyangi, 2008).

Climate variability is small between sites (Kimetu et al., 2008), and farms of differing conversion times were often located within several km of each other. Site differences have been shown to be small in comparison to the differences due to the impacts of long-term cultivation (Solomon et al., 2007; Kinyangi, 2008), and thus the chronosequence can be used in examining the temporal effects of conversion (Huggett, 1998). However, care should be taken in interpreting results, as spatial effects on observed soil dynamics contribute to observed variability.

2.2. Management systems

At each farm soils from two traditional long-term management systems were sampled: kitchen gardens (Ki) and continuous maize in low-input monoculture (Co). Kitchen gardens, traditionally located close to the home and generally occupying less than 10% of total land holdings (Tittonell et al., 2005) grew diverse vegetable, fruit, legume, and grain crops in polyculture since forest conversion. Kitchen garden crops typically include various indigenous vegetables such as nightshades (*Solanum nigrum*), spiderplant (*Gynandropsis gynandra*), amaranths (*Amaranthus* spp.), cowpeas (*Vigna unguiculata*), sunhemp (*Crotalaria brevidens*), jute mallow (*Corchorus olitorius*), squashes (*Cucurbita* spp.), Ethiopian kale (*Brassica carinata*), *Asystasia shimperi*, and *Basella alba* (Guarino, 1997), as well as bananas (*Musa acuminata*), mangos (*Mangifera indica*), avocados (*Persea americana*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), tomatoes (*Lycopersicon esculentum*), and onions (*Allium cepa*). Kitchen gardens received daily cooking ashes and usually chicken dung swept out of the kitchen, which generally serves as a chicken-coop at night (Recha, 2011). Gardens also received a variety of household (banana peels, maize cobs, squash peelings, bean husks, etc.) and field harvest and processing (i.e. maize stover) residues regularly. Livestock often consume some of these residues near to the home, thus leaving their manures in kitchen gardens, or manures may be collected and added as soil amendments. Inputs were not controlled or measured, but this non-standardized treatment nevertheless provides us the opportunity to observe the effects of a soil-building and degradation-mitigating traditional management strategy.

Since forest conversion, Co fields were tilled twice per year to about 0.10–0.15 m using a hand hoe, and were reported in informal farmer interviews to have been continuously cropped with C4 cereals, primarily maize. Before the advent of maize in the 1930s, either sorghum (*Sorghum bicolor* L. Moench.) or finger millet (*Eleusine coracana* L. Gaertn.) were the primary crops in the region. Although maize-bean intercropping is common on these small traditional subsistence farms, this practice generally decreases with distance from the homestead (Tittonell et al., 2005; Recha, 2011), and Co fields were chosen specifically for their distance from the home, and history of lack of inputs and intercropping practice (Kimetu et al., 2008; Kinyangi, 2008), as a contrast to the kitchen garden polyculture system. Sporadic intercropping of beans before these plots became controlled trials in 2004 (Ngoze et al., 2008), however, cannot be ruled out. Co fields had received no or negligible fertilizer or organic amendments since conversion (Kimetu et al., 2008; Kinyangi, 2008; Ngoze et al., 2008), until 2004. From 2004 onward they received N, P and K fertilizer at rates of 120, 100, 100 kg ha^{-1}, respectively, per growing season, as part of a larger experiment described by Kimetu et al. (2008) until the 2007 long rains. Aside from recent higher fertilizer amendments, practices since 2004 were based on traditional farmer management, so these sites should be able to provide a reasonable assessment of cultivation-related degradation dynamics. Co field maize plots were 2 m × 4.5 m in size.

2.3. Field measurements

All samples were gathered in July and August of 2007. At each farm a Garmin eTrex handheld GPS was used to record location and elevation. Each plot was sampled by taking five 0 to 0.15 m samples with a soil auger (Dutch type), compositing and mixing these and sub-sampling a ~1 L volume of soil for analyses. Surface (0–0.15 m, PR15) and subsurface (0.15–0.45 cm, PR45) penetration resistance was assessed using a soil compaction tester (Dickey-John, Auburn, WI). The maximum penetration resistance within each depth range was recorded as the PR15 and PR45 value, respectively. August 2007 maize grain yield was determined for a subset of the Co plots in the Nandi region ($n = 13$). To avoid edge effects, yield was measured in subplots of 4.5 m^2, leaving one row and one plant at the end of each row in each plot.

2.4. Laboratory analysis

Soils were air-dried and passed through a 2 mm sieve prior to laboratory measurement of physical, biological and chemical soil properties, most of which are part of the Cornell Soil Health Test (Idowu et al., 2008; Gugino et al., 2009). Texture, an inherent soil property that influences interpretation of dynamic soil properties, was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) in which particles are dispersed using 3% hexametaphosphate ($(NaPO_3)_n$) and a combination of sieving and sedimentation steps is used.

Water stable aggregation (WSA) was measured by a rainfall simulation method, which closely simulates slaking processes that occur on agricultural fields during rain events. The method applies 2.5 J of energy for 300 s on 0.25–2 mm aggregates placed on a 0.25 mm mesh sieve (Moebius et al., 2007). The fraction of soil aggregates remaining on the sieve, after correcting for stones and other particles of >0.25 mm size, was regarded as the percent WSA. The ratio of stable aggregation per clay content (WSA (%)/clay (%)) was also calculated. Aggregation in tropical Ultisols is often highly influenced by Al and Fe-oxide rich kaolinitic clays (Igwe et al., 2009), and clay content varied especially among farms of the Nandi region. This index presumably returns an indicator of other-than-clay contributions to aggregation, and thus the proportional management-related contribution to aggregation. Available water capacity (AWC) was determined gravimetrically. Soil sub-samples were saturated and then equilibrated to pressures of 10 kPa and 1500 kPa on two ceramic high pressure plates (Topp et al., 1993). The gravimetric moisture content difference between these two pressures was calculated as the AWC.

Total organic matter content was gravimetrically determined by loss on ignition (OM_{LOI}). Ten gram samples were oven-dried at 105 °C overnight, weighed, ignited to equilibrium in a muffle furnace set at 350 °C for 18 h and reweighed. The lower ignition temperature was chosen to prevent errors from high loss of structural water from kaolinite clays which is generally greatest between 450 and 600 °C (Ball, 1964; Rhodes et al., 1981). Biologically active carbon (C_{act}), was estimated by reacting 2.5 g soil dried at 40 °C with very dilute potassium permanganate ($KMnO_4$) as described by Weil et al. (2003), using a hand-held colorimeter (Hach, Loveland, CO) that measures absorbance at 550 nm. This measurement is highly sensitive to soil management, and has been found to be correlated with soil biological activity, aggregation and yield (Islam and Weil, 2000; Weil et al., 2003; Mtambanengwe et al., 2006). An approximate proportion of the total organic C (C_{LOI}) made up by the C_{act} fraction was calculated as the ratio of the two numbers (C_{act}/C_{LOI}), where C_{LOI} was estimated by using a regression model of OM_{LOI} to total gravimetric organic C content as measured by dry combustion in a CN auto-analyzer. (Data are not shown, $C_{LOI} = 0.4421 \times OM_{LOI}$, $n = 28$, $r^2 = 0.79$, $p < 0.0001$, similar to correlations found by Zhang et al. (2005).) This ratio was used as an index of the lability of the total C present (Blair et al., 1995), similar to other ratios used, as reviewed by Bastida et al. (2008).

Sieved soils were suspended in water (1:2.5) and pH values, and electrical conductivity (EC), often used as an overall indicator of nutrient availability or specifically of nitrate concentration (Arnold et al., 2005; Bastida et al., 2008) were measured using a hand-held portable probe (SM802 Smart Combined Meter, Milwaukee Industries, Inc., Rocky Mount, NC). Mehlich-3 soil extracts (Mehlich, 1984) were analyzed for P, K, Mg, Ca, Zn, Cu and S concentrations by inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 730-ES, Mulgrave, Victoria, Australia) and cation exchange capacity (CEC) was calculated as the sum of K, Mg, Ca and exchangeable acidity by the Agricultural Analytical Services Laboratory, Pennsylvania State University, University Park, PA. It should be noted that the emphasis of this work was to assess degradation dynamics of soil quality via indicators, but not to establish total quantities or stocks of carbon or nutrients, and thus no bulk density analysis was included. Maize grain was weighed, moisture was determined gravimetrically, and dry weight yield (Mg ha^{-1}) was estimated.

2.5. Statistical analysis

A principal component analysis of the complete data set was conducted on the normalized measured values of all measured soil properties in JMP (Version 8.0, SAS Institute Inc., 2009). The first two components were visualized in two dimensional space, and soil property weightings in the eigenvectors were used to assess whether the observed trends could be summarized via major components. The influence of textural spatial variability on the ability to use each chronosequence to represent human-management-affected change over time was assessed using linear regression for particle size distribution vs. time (Sigma Plot, Version 11.0,

Table 1
Eigenvectors from a principal component analysis of all standardized measured values for continuous maize (Co), kitchen garden (Ki) and Forest locations from both regions.

Principal components	PC1	PC2	PC3	PC4
Cumulative variability explained (%)	42	63	73	81
Eigenvectors				
Sand	−0.01	0.36	0.22	−0.49
Silt	0.11	−0.21	−0.53	0.32
Clay	−0.12	−0.30	0.32	0.37
OM_{LOI}[a]	0.31	−0.20	0.07	−0.15
C_{act}[b]	0.33	−0.05	−0.05	−0.22
WSA[c]	0.26	−0.20	0.26	0.02
AWC[d]	0.18	0.01	−0.58	−0.11
PR15[e]	0.29	−0.17	0.10	0.07
PR45[f]	0.23	−0.28	0.21	0.12
pH	0.20	0.35	−0.05	0.11
EC[g]	0.28	0.25	0.07	0.19
CEC	0.30	−0.15	0.03	−0.25
P	0.06	0.43	−0.01	0.25
K	0.20	0.24	0.30	0.21
Ca	0.31	0.06	−0.04	−0.21
Mg	0.33	0.02	−0.02	0.00
Zn	0.14	0.29	−0.04	0.33
S	0.23	0.02	0.00	0.21

[a] OM_{LOI} = total organic matter by loss on ignition at 350 °C.
[b] C_{act} = permanganate-oxidizable, biologically active carbon.
[c] WSA = water stable aggregation.
[d] AWC = available water capacity.
[e] PR15 = penetration resistance between 0 and 15 cm.
[f] PR45 = penetration resistance between 15 and 45 cm.
[g] EC = electrical conductivity.

Systat Software, Inc., 2008). Static comparison of management impacts on indicators using a mixed-model approach (including short-term organic additions that were part of this chronosequence experiment, not included here) is discussed in Moebius-Clune (2010). Curve-fitting in Sigma Plot was used to describe soil change patterns of each dynamic soil property over time in long-term continuous maize and kitchen garden management systems, separately for each parent material. The hypothesis that degradation would follow an exponential decay pattern was tested initially for each soil property. Single three-parameter exponential decay functions ($y = y_0 + a\exp^{-bx}$) were used where trends followed similar patterns as those described by Kinyangi (2008) and Kimetu et al. (2008). Linear ($y = y_0 + ax$) functions were fit to soil properties when these more closely exhibited linear dynamics over time, or when no significant linear pattern was modeled. The same curve-fitting approach was used for the Nandi maize yield data. Coefficients of determination and p-values were reported for each fit, even when non-significant, and $p \leq 0.1$ were considered to be statistically significant.

3. Results

3.1. Principal component analysis

The first four principal components (PCs) from a principal component analysis of the 18 normalized, measured soil properties explained 81% of the variability in the dataset. The first PC explained 42% of the variability, but did not clearly delineate soil properties that accounted for most of this variability (Table 1). All but the textural properties, P and Zn had component loadings between 0.18 and 0.33. Similar lack of separation was found in the remaining components (Table 1), such that PCs could not be used to explain changes in the functioning of soil processes. A two-dimensional visualization of the first two components (Fig. 1) showed general trends: older sites tended to plot lower on PC1 than younger sites, and kitchen garden sites tended to plot higher on PC2 and PC1 than continuous maize sites. However, no clear groupings

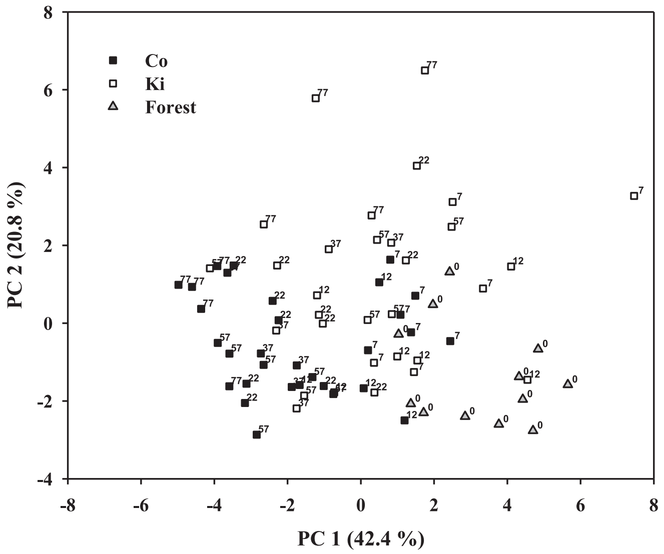

Fig. 1. Principal components 1 and 2, from principal component analysis performed on standardized properties presented in Table 1, for continuous maize (Co), kitchen garden (Ki) and Forest locations from both regions. Sampling points are labeled with number of years in cultivation.

emerged from this analysis. It was thus concluded that soil property dynamics over time in each management system needed to be assessed individually. This approach allows for development of a more process-oriented understanding of the changes occurring in the system with cultivation, than would be possible from grouping multiple soil properties into one or more composite SQ indices.

3.2. Effects of spatial variability and parent material on observed cultivation dynamics

Significant trends in spatial variability of inherent soil properties across the landscape, especially texture, can confound results when using spatial history differences to represent soil change in a chronosequence study. In the Kakamega region, no significant trends in sand, silt or clay content over conversion time points

Table 2
Means for soil biological, physical and chemical properties for the Nandi (n = 9) and Kakamega (n = 3) regions' forested sites.

	Nandi	Kakamega
Sand (%)	45A[a]	33A
Silt (%)	41A	53A
Clay (%)	14A	14A
OM_{LOI} (g kg^{-1})	168.1A	86.9B
C_{act} (mg kg^{-1})	962A	661B
C_{act}/C_{LOI}[b] (g g^{-1})	0.013A	0.017A
WSA (%)	95A	80B
WSA/clay (%/%)	8.05A	5.70A
AWC (m^3 m^{-3})	0.19B	0.24A
PR15 (kPa)	220A	200A
PR45 (kPa)	1207A	951A
pH	6.45A	6.38A
EC (dS m^{-1})	0.13A	0.06B
CEC (cmol kg^{-1})	24A	20A
P (mg kg^{-1})	9A	8A
K (mg kg^{-1})	293A	83B
Ca (mg kg^{-1})	3250A	2487A
Mg (mg kg^{-1})	465A	429A
Cu (mg kg^{-1})	2.76B	5.39A
Zn (mg kg^{-1})	16.54A	11.39A
S (mg kg^{-1})	20.38A	15.47A

[a] Means of each property followed by the same letter are not significantly different at α = 0.05, based on a Student's t-test.
[b] C_{act}/C_{LOI} = percent of total carbon made up by C_{act}.

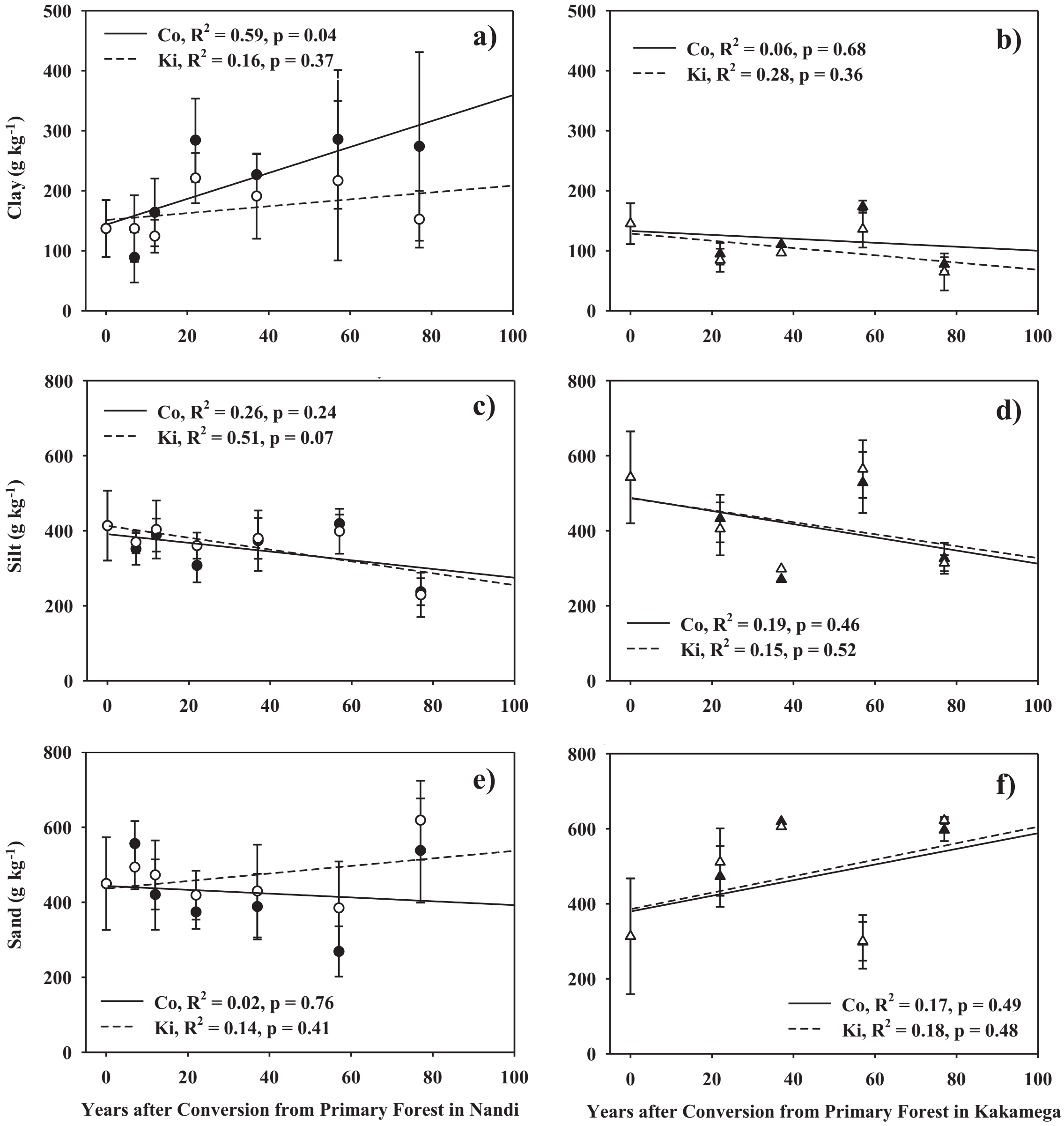

Fig. 2. Soil textural variability of sites used to make up chronosequences. At Nandi: ● = continuous maize (Co), ○ = kitchen garden (Ki); at Kakamega: = Co, △ = Ki. Error bars indicate the standard deviation at each time point.

were observed in either management system (Fig. 2), but a lot of variability was present. In the Nandi region, no significant trend existed in sand or silt contents in Ki sites, nor sand or clay contents in Co sites. Silt and clay contents exhibited statistically significant trends in opposite directions (Fig. 2a and c) in two cases: Clay content appeared to increase significantly with older conversion time points in continuous maize (Co), while silt content appeared to decrease significantly with older time points in kitchen garden (Ki) sites. This indicates that overall, textures were somewhat finer in sites representing longer times in cultivation. Also, while in Kakamega, no statistically significant textural difference between Co and Ki were found, Nandi Co plots older than 20 years had, on average, 72 g kg^{-1} higher clay content than Ki plots (Fig. 2; $p = 0.05$, ANOVA not shown). This spatial variability is taken into account in the interpretation of the results.

Sites making up the chronosequences in the two regions were developed on two different parent materials. Parent material significantly influenced the initial starting values of many soil properties under primary forest (Table 2). Several soil properties measured (WSA, OM_{LOI}, C_{act}, EC, K) were significantly higher in the Nandi forest sites than in Kakamega. The same general trend held for most other properties, except for AWC and Cu which were lower in the Nandi sites. Some patterns of soil change dynamics over time also differed between regions (Figs. 3–6). For example, WSA (Fig. 4a and b) declined exponentially in the Kakamega chronosequence, but linearly in Nandi, while WSA/clay and AWC declined exponentially in Nandi, but WSA/clay did not show statistically significant dynamics in Kakamega, and AWC more closely fit a linear trend. An exponential decay trend of pH was found in Nandi, but the trend was linear in Kakamega. Relative to their respective starting points, Nandi soil properties declined more dramatically than those in Kakamega. The effects of cultivation over time on each soil property were therefore analyzed separately by parent material.

3.3. Effects of cultivation over time on soil quality dynamics

Changes in dynamic soil properties over almost 80 years indicate mostly declines after forest conversion to agriculture. Changes

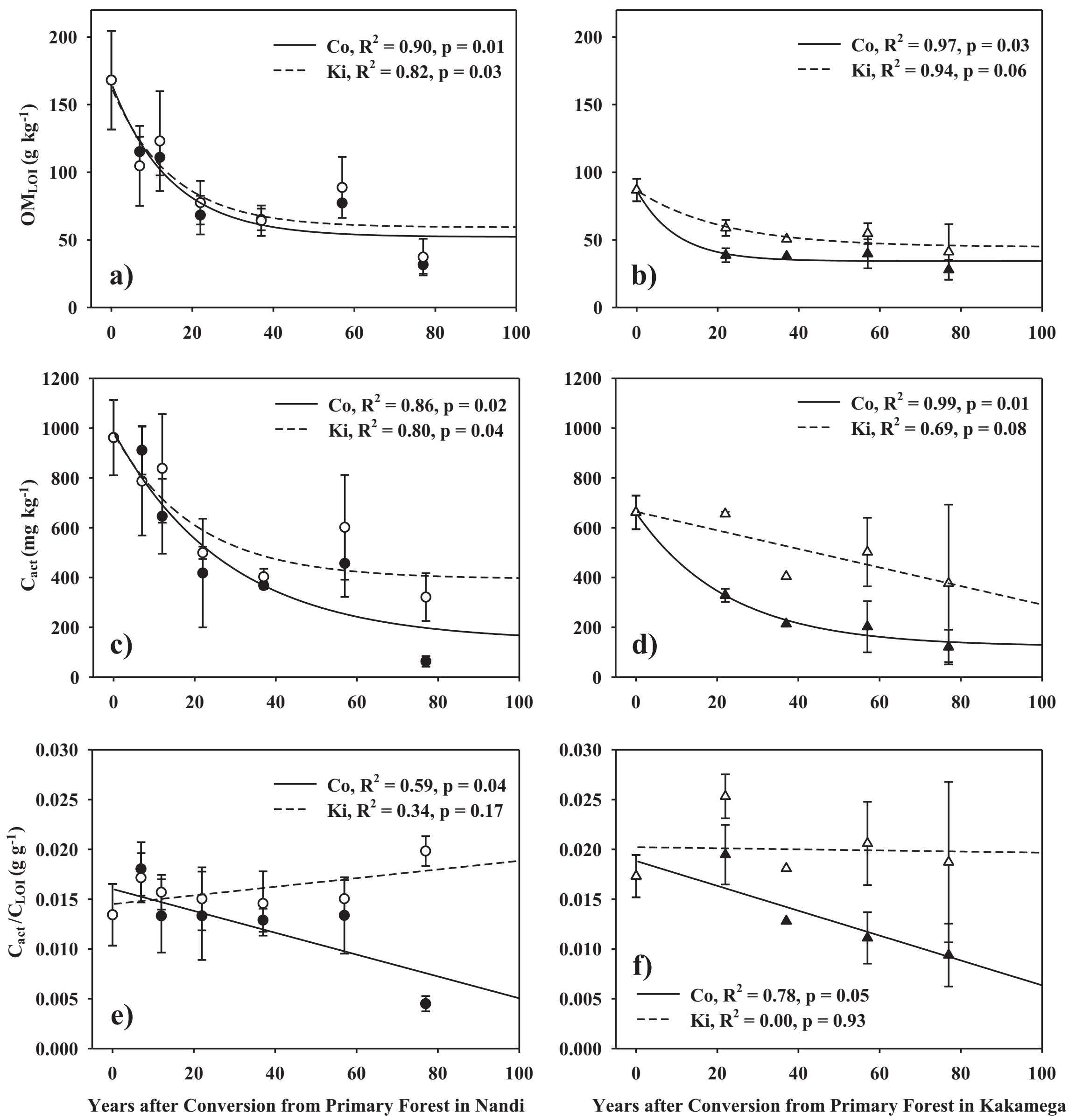

Fig. 3. Dynamics of organic fractions over time. OM_{LOI} = total organic matter by loss on ignition at 350 °C. C_{act} = permanganate-oxidizable, biologically active carbon. C_{act}/C_{LOI} = percent of total carbon made up by C_{act}. At Nandi: ● = continuous maize (Co), ○ = kitchen garden (Ki); at Kakamega: = Co, △ = Ki. Error bars indicate the standard deviation at each time point.

were seen in 14 out of 18 measured and calculated dynamic physical, biological and chemical soil properties (Figs. 3–6) and all of these (except for P) showed decreasing values over time after forest conversion to Co (filled symbols). Most decline trends followed patterns of exponential decay toward equilibrium, with the largest changes occurring in the first 22 years for most soil properties. In contrast, several measured property values were maintained or increased with time in Ki (open symbols), where fewer properties decreased in value. Some soil properties exhibited variability without significant trends over time in either parent material or management system (PR15, PR45, S, Cu; data not shown).

3.3.1. *Effect of continuous, low input maize management*

The biological indicators, total soil organic matter (OM_{LOI}, Fig. 3a and b) and biologically active C (C_{act}, Fig. 3c and d) declined exponentially under Co. In the Nandi region about 59% of the initial OM_{LOI} and 57% of the initial C_{act} in the system were lost in the first 22 years after conversion from forest, indicating an average loss of organic C_{LOI} of about 2 g kg^{-1} yr^{-1} during this time. Further declines occurred more slowly, as the system appeared to approach equilibrium. However C_{act} declined further than OM_{LOI} (93% vs. 81% of the initial amount after 77 yr in cultivation, respectively). In the Kakamega region, which had lower initial values for both indicators, about 55% of the OM_{LOI} and 50% of the total C_{act} in the system were lost in the first 22 yr after conversion from forest, indicating an average of about 1 g kg^{-1} yr^{-1} organic C_{LOI} loss during this time. Again, further declines happened more slowly, and C_{act} declined further than OM_{LOI}, (82% vs. 67% lost after 77 yr in cultivation, respectively). The C_{act}/C_{LOI} ratio (Fig. 3e and f) declined by about 67% (Nandi) and 46% (Kakamega) by 77 yr in cultivation, following an approximately linear trend on both parent materials. Linear regressions comparing these two soil properties using individual plot values (R^2 = .75, p < 0.0001 in Nandi, and R^2 = .77, p < 0.0001 in Kakamega; data not shown) also suggest that, while there is

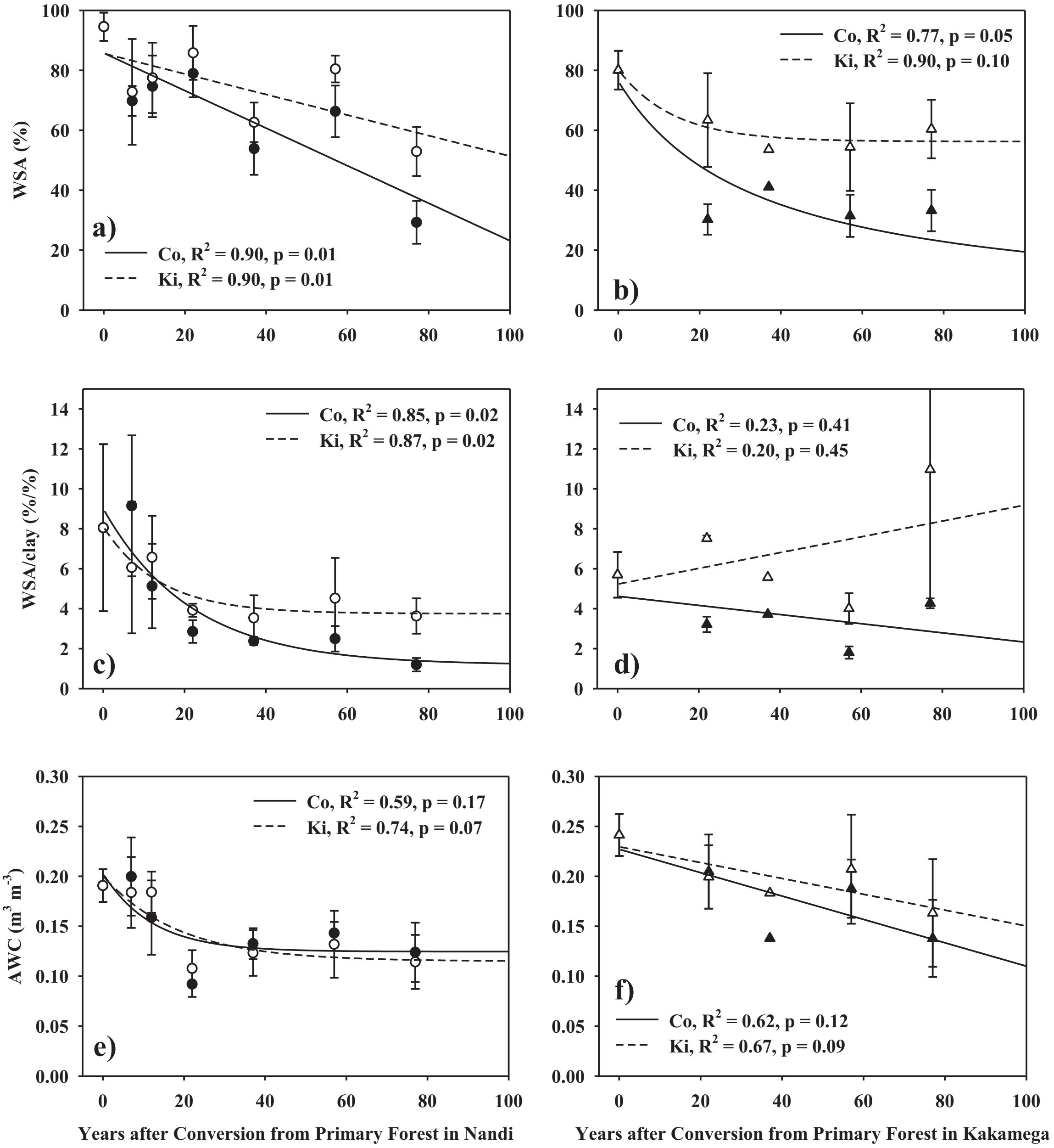

Fig. 4. Dynamics of soil structural properties over time. WSA = water stable aggregation. AWC = available water capacity. At Nandi: ● = continuous maize (Co), ○ = kitchen garden (Ki); at Kakamega: = Co, △ = Ki. Error bars indicate the standard deviation at each time point.

a relationship between them, these two soil properties represent somewhat different processes.

Soil physical properties also degraded over time. Kakamega sites lost 60% of their initial aggregate stability (WSA, Fig. 4a and b) in the first 22 yr under cultivation. No further losses were evident after this. In Nandi sites, WSA appeared variable, but nevertheless showed a significant linear downward trend over time, with a loss of 69% of the original stability by 77 yr under cultivation. The variability of WSA appeared to be associated with variable clay contents among farms in the Nandi region (ranging from 50 to 450 g kg^{-1}). The ratio of WSA/clay had a highly significant exponential decline trend (Fig. 4c) in Nandi sites. While WSA/clay appeared to decline in Kakamega as well, this trend was not significant (Fig. 4d). Available water capacity (AWC, Fig. 4e and f) followed closest to an exponential decay trend in Nandi (although not significant in Co) and a linear decline in the texturally more variable Kakamega sites. In both regions AWC was reduced by about 30–50% over 77 yr in cultivation.

Soil chemical properties also decreased, mostly exponentially. Electrical conductivity (EC, Fig. 5a and b) declined in the Nandi region by an order of magnitude over time, with 84% lost within the first 22 yr, 92% by 77 yr. By 22 and 77 yr, 63 and 91%, respectively, of the initial EC was lost in the Kakamega region, but the measured values for the forest site were about half of those in the Nandi region. CEC (Fig. 5c and d) declined more slowly, with 39 and 51% loss from initial CEC in the Nandi region, and 39 and 55% in the Kakamega region by 22 and 77 yr, respectively. Decreases in pH (Fig. 5e and f) followed an exponential decay trend in the Nandi region, but a strong linear trend in Kakamega, with a drop from 6.5 to 5.5 and 6.4 to 5.7, respectively, in the regions by 77 yr.

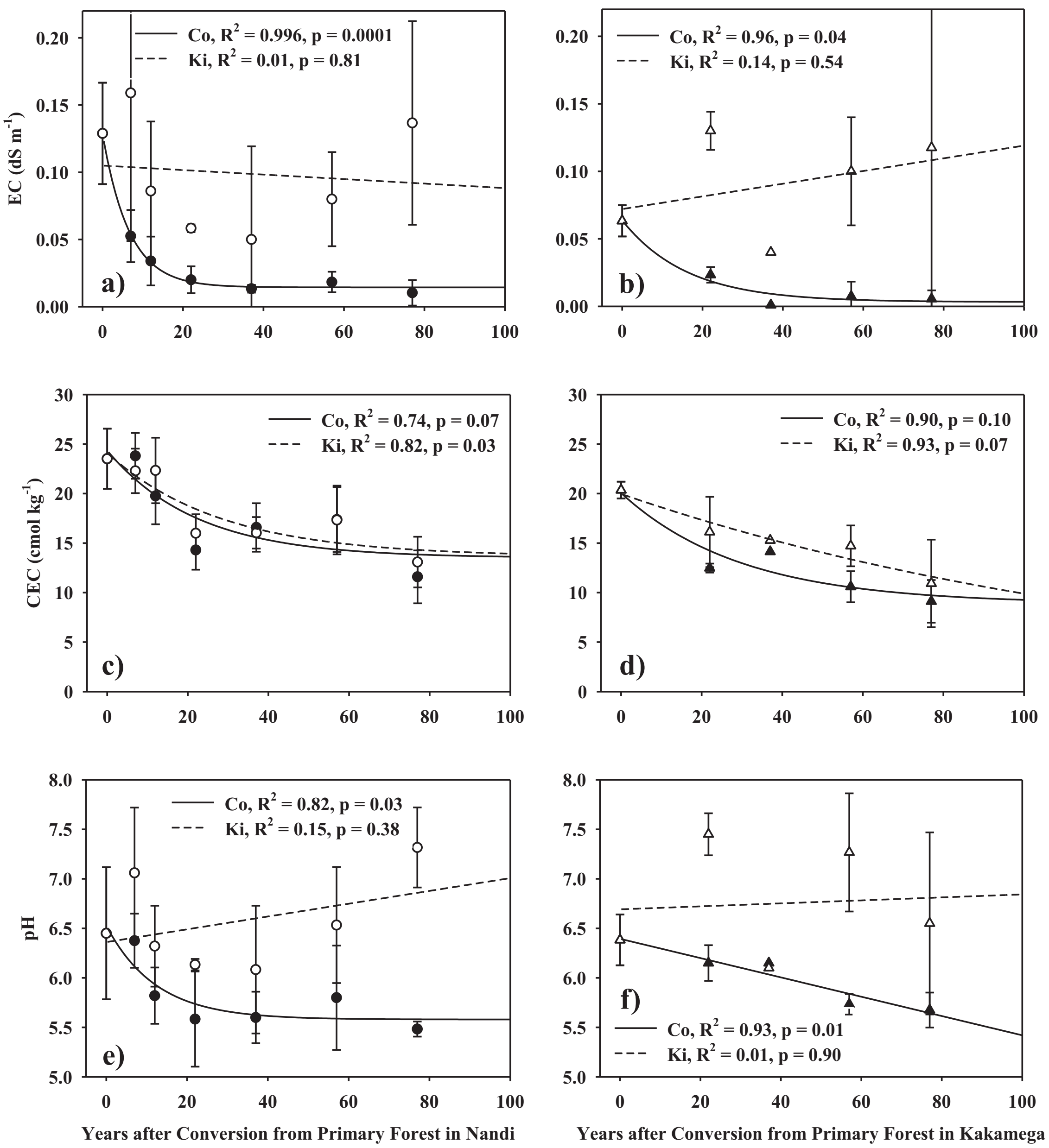

Fig. 5. Dynamics of integrative measures of nutrient availability over time. EC = electrical conductivity. At Nandi: ● = continuous maize (Co), ○ = kitchen garden (Ki); at Kakamega: = Co, △ = Ki. Error bars indicate the standard deviation at each time point.

It is important to recognize that, while P availability at both sites and K availability at Kakamega were variable without a significant decline trend over time (Fig. 6a and b), this has been influenced by recent years of P and K fertilization of these experimental plots (Kimetu et al., 2008; Ngoze et al., 2008). Kinyangi (2008) found exponential decay trends in P and K prior to this. The micronutrients Zn, Mg and Ca (Fig. 6c, d, and e) all showed exponential decay patterns in both regions.

Maize grain yields attained from a subset of the Nandi region farm sites also appeared to decrease exponentially (Fig. 7). While no yield for maize after initial forest conversion is available for comparison, yields declined by more than 50% from seven to twelve years in cultivation, and by 60–80% beyond 22 yr.

3.3.2. *Kitchen garden vs. continuous maize-management*

After forest conversion to kitchen garden management (Ki), only 7 out of 14 soil properties presented in Figs. 3–6 (open symbols) declined over time on both parent materials, and not always significantly. Exponential decay patterns were less frequent than in continuous maize cultivation, and some properties either did not follow a significant time trend or even increased over time.

Similarly to Co, the biological indicators OM_{LOI} and C_{act} declined exponentially, except for the more linear pattern of C_{act} at the Kakamega sites. However, in each region the regression curve was shifted upward in comparison to those from the Co sites, indicating slower declines to a higher equilibrium under Ki management (Fig. 3a–d). In the Nandi region only 53% (vs. 59% for Co) of the OM_{LOI} and 48% (vs. 57% for Co) of the C_{act} in the system were lost in the first 22 yr after conversion from forest. In the Kakamega region, OM_{LOI} declined only 32% (vs. 55% for Co) and C_{act} less than 10% (vs. 50% for Co) by 22 yr. By 77 yr, C_{act} under Ki management declined less than in the Co system (Nandi: 67% vs. 93%; Kakamega: 43 vs. 82%). In contrast to the Co system, C_{act} under Ki management declined less than OM_{LOI} in both parent materials (Nandi: 78% decline in

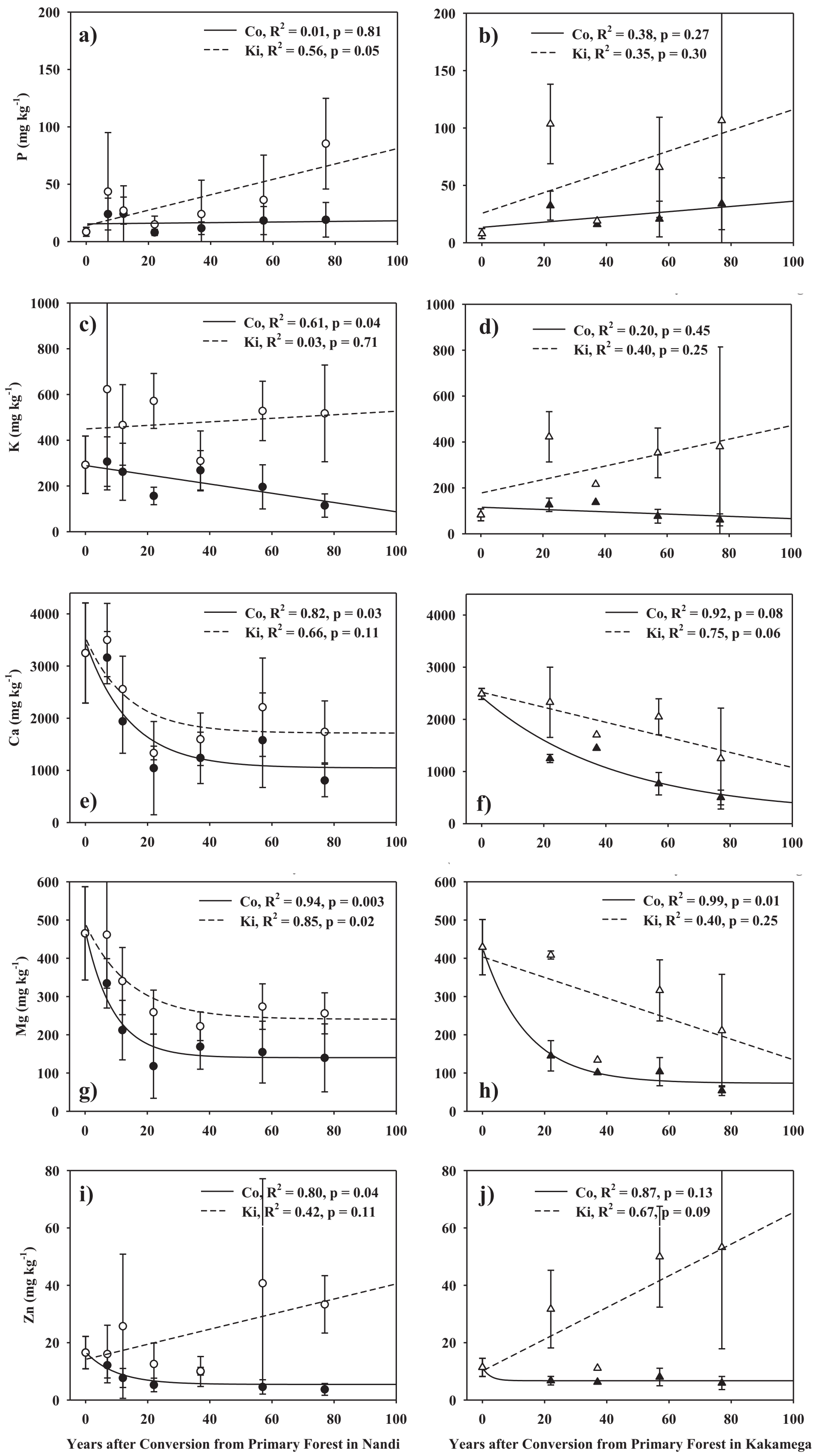

Fig. 6. Dynamics of selected nutrient availabilities over time. At Nandi: ● = continuous maize (Co), ○ = kitchen garden (Ki); at Kakamega: = Co, △ = Ki. Error bars indicate the standard deviation at each time point.

OM_{LOI}; Kakamega: 52% in OM_{LOI}). Unlike in Co, in the Ki system, the C_{act}/C_{LOI} ratio trends in both parent materials seemed to indicate maintenance or possibly increases, although these linear trends were not significant (Fig. 3e and f).

Degradation of the soil physical properties (Fig. 4), WSA and AWC, followed similar temporal patterns for the Ki as the Co systems, but, again, regression curves were shifted upward, except for AWC in the Nandi region, where the Ki curve was not distinguishable from the Co curve. Aggregation (WSA) under Ki management in Kakamega lost only 21% of its initial stability in the first 22 yr (vs. 60% for Co), and 24% by 77 yr in cultivation. In the Nandi region, WSA declined significantly under Ki management, with a loss of 44% (vs. 69% for Co) by 77 yr in cultivation, while the ratio of WSA/clay declined exponentially (Fig. 4c) with a higher equilibrium level for Ki than for Co.

Of the soil chemical properties, only CEC (Fig. 5c and d), Mg (Fig. 6g and h) and Ca (Fig. 6e and f) decreased over time in Ki. For each, the regression equilibrium was shifted upward from the respective Co trend. Electrical conductivity (EC, Fig. 5d) varied greatly, but did not show signs of decline under Ki management in either region, in contrast to the order-of-magnitude declines observed for Co. Similarly, pH (Fig. 5e and f) did not appear to decline over time under Ki management. Increases over time were observed for P, K and Zn, although due to high variability between Ki sites, linear trends were not always significant.

4. Discussion

4.1. Using soil quality indicators for monitoring

Soil quality indicators are frequently used to establish an overall index of SQ (reviewed by Bastida et al., 2008). Indexing approaches or a principal components approach (as shown in Table 1, Fig. 1) can show trends, and may provide a basis for comparing relative levels of overall SQ. However, by themselves, such indices provide little information toward a more process-oriented understanding of differences and trends in SQ. Individual indicators, on the other hand, can provide information about the relative extent of degradation of specific agrobiophysically important soil processes (Table 3), which can then inform management decisions (Moebius-Clune, 2010). The objective of this work was to use individual soil properties as SQ indicators to describe the change in relative functioning, over time in cultivation, of a wide range of such specific soil processes that are important to sustained agricultural production (Table 3).

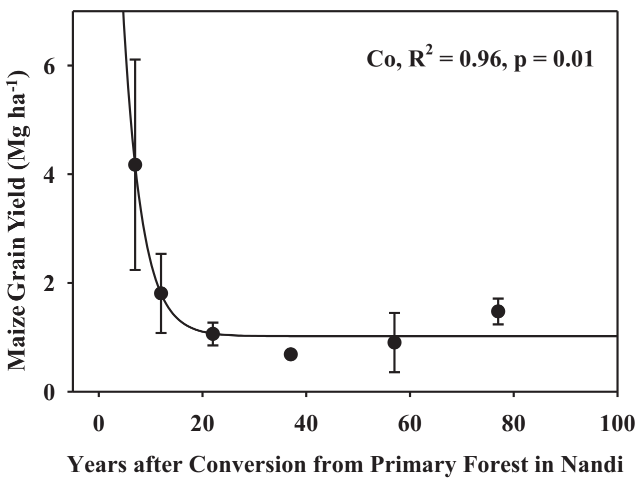

Fig. 7. Dynamics of maize grain yield over time in a subset of Co plots ($n = 13$) at Nandi. Error bars indicate the standard deviation at each time point.

Indicators were interpreted to signify higher SQ when they suggested better functioning for agricultural production and, in some cases, environmental services of the respective soil processes they represent (Table 3). For example, higher aggregate stability indicates that a soil maintains better structure, and thus better aeration, and that it is less likely to crust, such that more infiltration and less runoff and erosion will occur. For the ranges measured, all indicators, except for pH, PR15 and PR45, imply degradation in the listed soil processes when their measured values decrease. Values of pH mostly implied decreasing SQ with decreasing values, except in the optimum range between about pH 6 to 7. In a few cases, in kitchen gardens that received large quantities of cooking ash, a pH of well above 7 may also be less than ideal. Higher PR15 and PR45 values indicate harder soils, likely to reduce root proliferation, and therefore SQ. Such interpretations of indicators of SQ allow us to describe and monitor changes in SQ with respect to the changes in agrobiophysically important soil functions, processes and constraints likely to occur due to soil degradation over time and from contrasting management systems.

4.2. Effects of spatial variability and parent material on soil quality dynamics

Parent material and other inherent soil type differences, such as texture, interact with management-induced degradation and aggradation dynamics, or resilience (Carter, 2002). Textural trends and lack of trends, observed for the sites representing soil change over time, provide evidence of the validity of the chronosequence. The only statistically significant trends were observed in the Nandi region, where the increase in clay content (and concurrent decrease in silt content) with the older deforested sites is more likely to mask the strength of the observed degradation effects, but arguably does not call degradation as the driving mechanism for soil change over time into question. This is because finer textures are usually associated with increased aggregation, microbial activity, total organic matter and CEC (Sollins et al., 1996; Bronick and Lal, 2005). Thus, the decreasing values of these dynamic SQ indicators with finer textures are best explained by management-induced degradation. The variability in texture seen between the Kakamega region sites may help explain why Kakamega degradation dynamics were usually of lower statistical significance than those observed in the Nandi region. It is noted that textures in Kakamega forest sites did not significantly differ from those at sites representing 57 yr in cultivation, and thus this time point can be used as a reference point for determining the validity of observed degradation trends.

Soils on different types of parent materials often exhibit different constraints to cropping after being degraded, and degradation rates and extents may differ (Carter, 2002; Mapfumo et al., 2007; de la Rosa et al., 2009), as we observed here. For example, both regions reduced their ability to store water over time. However, the starting AWC ($0.19\,m^3\,m^{-3}$) of the forested Nandi sites was similar to the AWC attained after 57 yr of degradation under Co management in the Kakamega region (Fig. 4e and f). AWC appeared to be better-maintained by Ki vs. Co management in the Kakamega region, while Ki management did not seem to affect AWC degradation dynamics in the Nandi region, although this may be somewhat confounded by the lower clay content in old Ki plots (Fig. 2).

Despite the contrasting initial conditions for the forested soils, many soil properties degraded to similar low levels in the two parent materials after almost 80 years under cultivation, as for example with OM_{LOI}, C_{act}, WSA, CEC, pH and Zn. This suggests that the potential for soil degradation from poor soil management was greater in the Nandi region, especially when considering that the extent of degradation was likely masked by the slightly finer soil textures in older sites. Also, Kakamega soils showed a greater difference between Ki and Co degradation rates and extents, and greater accu-

Table 3
Agrobiophysically important soil processes and the indicators chosen to represent their functioning. Selected references discussing use of these indicators for the representation of soil process functioning are listed.

Soil processes	Indicators	References
Structural stability	WSA	Karlen et al. (1994), Doran and Jones (1996), Moebius et al. (2007), Gugino et al. (2009)
Runoff and erosion	WSA	"
Crusting	WSA	"
Shallow rooting	WSA, PR15	"
Aeration	WSA, PR15	"
Water infiltration and transmission	WSA, PR15	"
Plant-available water retention	AWC, OM_{LOI}	Larson and Pierce (1991), Doran and Jones (1996), Skukla et al. (2003), Gugino et al. (2009)
Drought stress tolerance	AWC, PR45	Larson and Pierce (1991), Karlen et al. (1994), Skukla et al. (2003), Hamza and Anderson (2005), Gugino et al. (2009)
Organism mobility	PR15, PR45	Hamza and Anderson (2005), Gugino et al. (2009)
Subsurface root proliferation	PR45	"
Energy storage and C sequestration	OM_{LOI}	Larson and Pierce (1991), Doran and Parkin (1994), Gugino et al. (2009)
Toxicity and pollution prevention	OM_{LOI}, pH, EC, nutrient concentrations	Tiessen et al. (1994), Doran and Jones (1996), Andrews and Carroll (2001), Arnold et al. (2005), Gugino et al. (2009)
Support of soil biological activity	C_{act}, C_{act}/C_{LOI}	Blair et al. (1995), Weil et al. (2003), Bastida et al. (2008), Mtambanengwe and Mapfumo (2008), Gugino et al. (2009)
Biologically mediated nutrient mineralization	C_{act}, C_{act}/C_{LOI}	"
Chemical buffering	CEC, pH	Karlen et al. (1994), Doran and Jones (1996), Arnold et al. (2005), Gugino et al. (2009)
Macro- and micro- nutrient retention and availability	OM_{LOI}, nutrient concentrations, EC	Tiessen et al. (1994), Doran and Jones (1996), Andrews and Carroll (2001), Arnold et al. (2005)

mulation of several nutrients under Ki management (Figs. 3–6). These findings suggest that types and effectiveness of management strategies for reclaiming degraded soils or maintaining SQ are likely to differ by parent material. However, long-term Ki management was not controlled or measured by this study, and Ki plots contained less clay than Co in Nandi, so effects of potential differences in management between the regions and of textural variability cannot be ruled out as partial drivers of the observed differences.

4.3. Effects of cultivation on soil quality

Organic matter facilitates two essential categories of soil processes (Lal, 2006), organic matter stabilization and organic matter decomposition. Both were impaired as soil quality degraded biologically, physically and chemically, over time, in this study. Loss of stable organic matter resulted in destabilization of aggregates over time and thus in decreased cation retention (as represented by CEC), buffering of pH, and soil structure, which in turn decreased water storage (as represented by AWC), infiltration, root proliferation and physical access to nutrients, while increasing likelihood of surface crusting, runoff and erosion (as represented by WSA). Second, organic matter decomposition processes could not be maintained with decreasing labile carbon (as represented by C_{act}) such that less substrate was available to soil microbes that mineralize nutrients for crop growth (as represented by indicators of nutrient availability), including nitrogen (Mtambanengwe and Mapfumo, 2008), which was not directly measured in this study as it is influenced by short-term weather-related losses. Nutrient mineralization from organic matter is especially important in smallholder agriculture, which usually depends completely on organic matter-derived nutrients, because sufficient amounts of fertilizers are generally not affordable or available to farmers (Sanchez, 2002). Also, fertilizers sometimes provide limited marginal productivity gains due to von Liebig-type limitations from physical or biological constraints (Marenya and Barrett, 2009). Soil quality declines we show for this area are associated with exponential declines in grain yield even when full fertilizer rates were applied, as was shown in a subset of plots in the Nandi region in 2007 (Fig. 7), and in prior years by other researchers (Kimetu et al., 2008; Ngoze et al., 2008).

When primary forest is slashed, burned, and converted to tilled annual crop production, the organic matter-linked nutrient and carbon cycling equilibrium is disturbed and degradation commences almost immediately (Tiessen et al., 1994), as observed here. Initially, decomposition of the large forest-derived organic matter pool provided sufficient substrate for microbial activity and thus sufficient nutrients for crop growth (Kimetu et al., 2008; Ngoze et al., 2008). However, typical smallholder crop fields like the continuous low-input maize systems studied here have deficit organic matter budgets, and the resulting nutrient deficits are rarely corrected with fertilizer, particularly in fields more distant from the home (Tittonell et al., 2005). Tillage broke up existing aggregates and exposed previously stabilized organic matter to oxygen, stimulating microbial activity, and losses in aggregate stability (WSA, Fig. 4a and b, Islam and Weil, 2000; Moebius-Clune et al., 2008). Considerable amounts of suspended organic matter and topsoil were likely lost through runoff and erosion, especially on degraded fields with low structural stability, that were unable to resist slaking under erosive tropical rains (Collins et al., 2001; Roose and Barthes, 2001).

We observed an exponential decline in WSA in the Kakamega region, while the trend in Nandi was a scattered linear decrease. The WSA/clay index to some extent corrected WSA measurements in the Nandi region confounded by spatial variability in clay content among farms of different ages and thus imperfect space-to-time translation in the chronosequence. WSA and C_{act} follow a similar exponential decay trend in Kakamega, corroborating relationships between these two soil properties found by Bell et al. (1998), while in the Nandi region this holds for WSA/clay and C_{act}.

It should be noted that soil compaction (as measured by PR15 and PR45) did not show significant temporal patterns from long-term cultivation as measured (data not shown), likely in part because of variable soil moisture contents. Gravimetric moisture contents ranged from 11 to 61% between locations, and no universally appropriate conversion method to adjust penetration resistance is available. If not resulting from pedogenetic pans, surface and subsurface hardness generally result from tillage and traffic with heavy equipment, or when the soil is worked while wet

(Hamza and Anderson, 2005). Such compaction can be brought on within a single growing season by management–weather interactions, and thus between- and within-farm variability in compaction levels may be greater than any long-term trends (Moebius-Clune, 2010).

The extremely rapid initial loss rate of organic matter and active carbon (Fig. 3a–d) resulted from a combination of lower inputs and higher decomposition rates in this tropical climate (Kondo et al., 2005) after forest conversion. The rate of loss slowed as a degraded equilibrium was reached, as has been described previously by Kinyangi (2008) for this chronosequence, and for agricultural systems in general by McLauchlan (2006), among others. The overall composition of the declining organic matter changed toward more inert compounds (lower C_{act}/C_{LOI}) under a continuous low-input system. The decline trend in organic matter quality did not come to equilibrium within the timeframe represented by this chronosequence, as was also found through use of more complex and resource-intensive methodology by Solomon et al. (2007). The trend suggests that further degradation of soil organic matter quality and associated soil processes can be expected beyond 77 years in cultivation.

Cation exchange sites were also lost with the decline in organic matter, explaining the observed decreases in CEC (Fig. 5c and d), cation retention and availability (K, Mg, Ca, Zn; Fig. 6), general nutrient retention and availability (EC; Fig. 3a and b) and soil buffering ability (pH and CEC; Fig. 5c–f). As the remaining organic matter became more inert over time, it also became less able to supply nutrients through microbial decomposition. Several nutrients were below sufficiency levels, notably P (below about $30\,g\,kg^{-1}$) in most soils, but also K (below about $60–100\,g\,kg^{-1}$, depending on texture) in some of the older soils (Moebius-Clune, 2010).

In contrast, kitchen garden systems on these smallholder farms underwent a lesser degree of biological and physical degradation, and even an accumulation of some nutrients. While C_{act} decreased over time, it did so more slowly than total organic matter in the Ki management system, likely because of regular fresh organic matter and cooking-ash inputs that more closely resemble forest input dynamics. Statistically non-significant trends in the C_{act}/C_{LOI} ratio suggest maintenance or even a relative build-up of labile over non-labile organic matter under Ki management. Kitchen residue inputs apparently somewhat maintained the labile fraction, while intensive tillage for multiple crops per season in this system exposed previously aggregate-protected organic matter, thus degrading the otherwise more stable total organic matter. We thus observed maintenance or possibly increase in organic matter quality even while the overall quantity decreased.

Addition and subsequent decomposition of labile C from fresh organic matter likely contributed to better-maintained nutrient availability in Ki, despite the decreased CEC associated with the decrease in OM_{LOI}. Also, regular additions of ash are known to increase soil pH, P, K, Ca, Mg and Zn (Gorecka et al., 2006; Nyombi et al., 2006; Vandeplas et al., 2010) and apparently played a role in the better-maintained or even accumulating nutrient concentrations and pH in the Ki management system. However, even Ki management was unable to maintain the original high SQ. The stable fraction of organic matter was depleted, presumably due to intensive and frequent tillage (Hooker et al., 2005; Moebius-Clune et al., 2008). Conservation agriculture approaches involving minimal tillage could potentially further prevent degradation of biological and physical soil processes after forest conversion. While these have been studied widely in Brazil (Bolliger et al., 2006) and other regions (Hobbs, 2007), however, further studies of such approaches are required in smallholder systems of sub-Saharan Africa (Gowing and Palmer, 2008; Giller et al., 2009).

5. Conclusions

Results of this study provide insights into the dynamics of SQ degradation after forest conversion in two contrasting traditional smallholder soil management systems on two different parent materials. Continuous low-input maize cultivation caused drastic SQ degradation, with 25–93% declines over 77 yr from SQ indicator values originally measured under primary forest, and similar declines in grain yield. Most indicators followed exponential decay trends, with the greatest degradation occurring approximately within the first 22 yr. Almost all soil processes represented by the measured SQ indicators were affected, including aggregation and root proliferation, water infiltration and storage, organic matter stabilization, support of biological activity and nutrient retention, mineralization and availability. Organic matter quality trends indicate that further soil quality degradation will persist beyond 77 yr under continuous low-input maize. High-input polyculture kitchen garden cultivation showed less degradation of the soil biological and physical soil functions (up to 40% lesser drop below initial values when declines were observed). Data suggest that degradation in this management system may have reached equilibrium within 77 yr. Increases in some indicators of nutrient availability over time were found, apparently due to inputs of organic residues and cooking ashes. After 77 yr in cultivation, indicator values under Ki management remained between 12 and 2000% above respective Co management values. This indicates that agricultural SQ degradation in the tropics can be significantly reduced by better soil management, although lacking resource availability is currently a major constraint to realizing such improvements on a larger percentage of smallholder land holdings. Furthermore, the ability to measure differences in long-term degradation dynamics as a function of management differences with a basic set of SQ indicators was demonstrated. This suggests that future work on degradation dynamics and appropriate management systems could incorporate such tests to monitor and assess soil quality, and identify management systems that enhance and maintain soil quality.

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References

An, S., Zheng, F., Zhang, F., Van Pelt, S., Hamer, U., Makeschin, F., 2008. Soil quality degradation processes along a deforestation chronosequence in the Ziwuling area, China. Catena 75, 248–256.
Andrews, S.S., Carroll, C.R., 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. Ecological Applications 11, 1573–1585.
Angima, S.D., Stott, D.E., O'Neill, M.K., Ong, C.K., Weesies, G.A., 2003. Soil erosion prediction using RUSLE for central Kenyan highland conditions. Agriculture Ecosystems & Environment 97, 295–308.
Arnold, S.L., Doran, J.W., Schepers, J., Wienhold, B., Ginting, D., Amos, B., Gomes, S., 2005. Portable probes to measure electrical conductivity and soil quality in the field. Communications in Soil Science and Plant Analysis 36, 2271–2287.
Ball, D.F., 1964. Loss on ignition as estimate of organic matter and organic carbon in non-calcareous soils. Journal of Soil Science 15, 84–92.

Bastida, F., Zsolnay, A., Hernandez, T., Garcia, C., 2008. Past, present and future of soil quality indices: a biological perspective. Geoderma 147, 159–171.
Bationo, A., Waswa, B., Okeyo, J.J., Maina, F., Kihara, J.M. (Eds.), 2011. Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts. Springer. ISBN: 978-90-481-2541-8.
Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94, 13–25.
Bell, M.J., Moody, P.W., Connolly, R.D., Bridge, B.J., 1998. The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. Australian Journal of Soil Research 36, 809–819.
Blair, G.J., Lefroy, R.D.B., Lise, L., 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Australian Journal of Agricultural Research 46, 1459–1466.
Bolliger, A., Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R., de Neergaard, A., 2006. Taking stock of the Brazilian "zero-till revolution": a review of landmark research and farmers' practice. Advances in Agronomy, vol. 91. Elsevier Academic Press Inc., San Diego, pp. 47–110.
Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.
Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agronomy Journal 94, 38–47.
Chapman, C.A., Lawes, M.J., Eeley, H.A.C., 2006. What hope for African primate diversity? African Journal of Ecology 44, 116–133.
Collins, A.L., Walling, D.E., Sichingabula, H.M., Leeks, G.J.L., 2001. Suspended sediment source fingerprinting in a small tropical catchment and some management implications. Applied Geography 21, 387–412.
de la Rosa, D., Anaya-Romero, M., Diaz-Pereira, E., Heredia, N., Shahbazi, F., 2009. Soil-specific agro-ecological strategies for sustainable land use – a case study by using MicroLEIS DSS in Sevilla Province (Spain). Land Use Policy 26, 1055–1065.
deGraffenried, J.B., Shepherd, K.D., 2009. Rapid erosion modeling in a Western Kenya watershed using visible near infrared reflectance, classification tree analysis and (137)Cesium. Geoderma 154, 93–100.
Doran, J.W., Jones, A.J., 1996. Methods for Assessing Soil Quality, SSSA Special Publication, vol. 49. Soil Science Society of America, Madison, WI.
Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A.E. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America, Madison, WI.
Eswaran, H., Almaraz, R., van den Berg, E., Reich, P., 2005. An Assessment of the Soil Resources of Africa in Relation to Productivity. World Soil Resources, Soil Survey Division, USDA, Natural Resources Conservation Service, Washington, D.C.
FAO-UNESCO, 1997. Soil Map of the World, Revised Legend. ISRIC, Wageningen.
FAO, 2005. Global Forest Resources Assessment 2005: 15 Key Findings. Food and Agricultural Organization of the United Nations, Rome, Italy. Available from: <www.fao.org/forestry>.
Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Research 114, 23–34.
Gorecka, H., Chojnacka, K., Gorecki, H., 2006. The application of ICP-MS and ICP-OES in determination of micronutrients in wood ashes used as soil conditioners. Talanta 70, 950–956.
Gowing, J.W., Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. Soil Use and Management 24, 92–99.
Guarino, L. (Ed.), 1997. Traditional African vegetables. Promoting the conservation and use of underutilized and neglected crops 16. Proceedings of the IPGRI International Workshop on Genetic Resources of Traditional Vegetables in Africa: Conservation and Use. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy, ICRAF-HQ, Nairobi, Kenya.
Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., van Es, H.M., Moebius-Clune, B.N., Wolfe, D.W., Thies, J.E., Abawi, G.S., 2009. Cornell Soil Health Assessment Training Manual, Edition 2.0. Cornell University, Geneva, NY. Available from: <http://soilhealth.cals.cornell.edu/>.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems – a review of the nature, causes and possible solutions. Soil & Tillage Research 82, 121–145.
Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? Journal of Agricultural Science, 127–137.
Hooker, B.A., Morris, T.F., Peters, R., Cardon, Z.G., 2005. Long-term effects of tillage and corn stalk return on soil carbon dynamics. Soil Science Society of America Journal 69, 188–196.
Huggett, R.J., 1998. Soil chronosequences, soil development, and soil evolution: a critical review. Catena 32, 155–172.
Hurni, H., Giger, M., Meyer, K., (Eds.), 2006. Soils on the Global Agenda. Developing International Mechanisms for Sustainable Land Management. Prepared with the Support of an International Group of Specialists of the IASUS Working Group of the International Union of Soil Sciences (IUSS). Centre for Development and Environment, Bern.
Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R., Bilgili, A.V., 2008. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant and Soil 307, 243–253.
Igwe, C.A., Zarei, M., Stahr, K., 2009. Colloidal stability in some tropical soils of southeastern Nigeria as affected by iron and aluminium oxides. Catena 77, 232–237.
Islam, K.R., Weil, R.R., 2000. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agriculture Ecosystems and Environment 79, 9–16.
Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal 61, 4–10.
Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Crop residue effects on soil quality following 10 years of no-till corn. Soil and Tillage Research 31, 149–167.
Kettler, T.A., Doran, J.W., Gilbert, T.L., 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Science Society of America Journal 65, 849–852.
Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W., Pell, A.N., 2008. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11, 726–739.
Kinyangi, J., 2008. Soil Degradation, Thresholds and Dynamics of Long-term Cultivation: From Landscape Biogeochemistry to Nanoscale Biogeocomplexity. Ph.D. Dissertation. Cornell University, Ithaca, NY.
Kondo, M., Singh, C.V., Agbisit, R., Murty, M.V.R., 2005. Yield response to urea and controlled-release urea as affected by water supply in tropical upland rice. Journal of Plant Nutrition 28, 201–219.
Krull, E.S., Bestland, E.A., Gates, W.P., 2002. Soil organic matter decomposition and turnover in a tropical Ultisol: evidence from delta C-13, delta N-15 and geochemistry. Radiocarbon 44, 93–112.
Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development 17, 197–209.
Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. Evaluation for sustainable land management in the developing world. In: Conference, IBSRAM Proc. 12th. Int. Board for Soil Res. and Manage., Jatujak Thailand, Bangkok, Thailand, pp. 175–203.
Lung, T., Schaab, G., 2006. Assessing fragmentation and disturbance of west Kenyan rainforests by means of remotely sensed time series data and landscape metrics. African Journal of Ecology 44, 491–506.
Mairura, F.S., Mugendi, D.N., Mwanje, J.I., Rarnisch, J.J., Mbugua, P.K., Chianu, J.N., 2007. Integrating scientific and farmers' evaluation of soil quality indicators in central Kenya. Geoderma 139, 134–143.
Mapfumo, P., Mtambanengwe, F., Vanlauwe, B., 2007. Organic matter quality and management effects on enrichment of soil organic matter fractions in contrasting soils in Zimbabwe. Plant and Soil 296, 137–150.
Marenya, P.P., Barrett, C.B., 2009. State-conditional fertilizer yield response on western Kenyan farms. American Journal of Agricultural Economics 91, 991–1006.
Marin-Spiotta, E., Silver, W.L., Swanston, C.W., Ostertag, R., 2009. Soil organic matter dynamics during 80 years of reforestation of tropical pastures. Global Change Biology 15, 1584–1597.
Mausbach, M.J., Seybold, C.A., 1998. Assessment of soil quality. In: Lal, R. (Ed.), Soil Quality and Agricultural Sustainability. Ann Arbor Press, Chelsea, MI, pp. 33–43.
McLauchlan, K., 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. Ecosystems 9, 1364–1382.
Mehlich, A., 1984. Mehlich-3 soil test extractant – a modification of Mehlich-2. Communications in Soil Science and Plant Analysis 15, 1409–1416.
Moebius-Clune, B.N., 2010. Applications of Integrative Soil Quality Assessment in Research, Extension, and Education. Ph.D. Dissertation. Cornell University, Ithaca, NY.
Moebius-Clune, B.N., Idowu, O.J., Schindelbeck, R.R., van Es, H.M., Wolfe, D.W., Abawi, G.S., Gugino, B.K., 2011. Developing Standard Protocols for Soil Quality Monitoring and Assessment. In: Bationo, A., Waswa, B., Okeyo, J.M., Maina, F., Kihara, J.M. (Eds.), Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts. Springer. ISBN: 978-90-481-2541-8.
Moebius-Clune, B.N., van Es, H.M., Idowu, O.J., Schindelbeck, R.R., Moebius-Clune, D.J., Wolfe, D.W., Abawi, G.S., Thies, J.E., Gugino, B.K., Lucey, R., 2008. Long-term effects of harvesting maize stover and tillage on soil quality. Soil Science Society of America Journal 72, 960–969.
Moebius, B.N., van Es, H.M., Schindelbeck, R.R., Idowu, O.J., Thies, J.E., Clune, D.J., 2007. Evaluation of laboratory-measured soil properties as indicators of soil physical quality. Soil Science 172, 895–912.
Moore, T.R., 1979. Rainfall erosivity in East-Africa. Geografiska Annaler Series A: Physical Geography 61, 147–156.
Mtambanengwe, F., Mapfumo, P., 2008. Smallholder farmer management impacts on particulate and labile carbon fractions of granitic sandy soils in Zimbabwe. Nutrient Cycling in Agroecosystems 81, 1–15.
Mtambanengwe, F., Mapfumo, P., Vanlauwe, B., 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. Nutrient Cycling in Agroecosystems 76, 271–284.
Murage, E.W., Karanja, N.K., Smithson, P.C., Woomer, P.L., 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. Agriculture Ecosystems & Environment 79, 1–8.
Ngoze, S., Riha, S., Lehmann, J., Verchot, L., Kinyangi, J., Mbugua, D., Pell, A., 2008. Nutrient constraints to tropical agroecosystem productivity in long-term degrading soils. Global Change Biology 14, 2810–2822.
Nyombi, K., Esser, K.B., Zake, J.Y.K., 2006. Efforts by small-scale farmers to maintain soil fertility and their impacts on soil properties, Luwero district, Uganda. Journal of Sustainable Agriculture 27, 5–23.

Recha, J., 2011. Personal Communication. Cornell University, Ithaca, NY.
Rhodes, E.R., Kamara, P.Y., Sutton, P.M., 1981. Walkley-Black digestion efficiency and relationship to loss on ignition for selected Sierra Leone soils. Soil Science Society of America Journal 45, 1132–1135.
Roose, E., Barthes, B., 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutrient Cycling in Agroecosystems 61, 159–170.
Sanchez, P.A., 2002. Ecology – soil fertility and hunger in Africa. Science 295, 2019–2020.
Skukla, M.K., Lal, R., Ebinger, M., 2003. Tillage effects on physical and hydrological properties of a typic argiaquoll in Central Ohio. Soil Science 168, 802–811.
Sollins, P., Homann, P., Caldwell, B.A., 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma 74, 65–105.
Solomon, D., Lehmann, J., Kinyangi, J., Amelung, W., Lobe, I., Pell, A., Riha, S., Ngoze, S., Verchot, L., Mbugua, D., Skjemstad, J., Schafer, T., 2007. 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.
Stevens, P.R., Walker, T.W., 1970. Chronosequence concept and soil formation. Quarterly Review of Biology 45, 333–350.
Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic-matter in sustaining soil fertility. Nature 371, 783–785.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.
Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture Ecosystems & Environment 110, 166–184.
Topp, G.C., Galganov, Y.T., Ball, B.C., Carter, M.R., 1993. Soil water desorption curves. In: Carter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers, Boca Raton, FL, pp. 569–579.
Vandeplas, I., Vanlauwe, B., Driessens, L., Merckx, R., Deckers, J., 2010. Reducing labour and input costs in soybean production by smallholder farmers in southwestern Kenya. Field Crops Research 117, 70–80.
Wang, C.T., Long, R.J., Wang, Q.L., Jing, Z.C., Shi, J.J., 2009. Changes in plant diversity, biomass and soil C, in alpine meadows at different degradation stages in the headwater region of Three Rivers, China. Land Degradation & Development 20, 187–198.
Weil, R.R., Islam, K.R., Stine, M.A., Gruver, J.B., Samson-Liebig, S.E., 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. American Journal of Alternative Agriculture 18, 3–17.
Winder, J., 2003. Soil Quality Monitoring Programs: A Literature Review. Alberta Environmentally Sustainable Agriculture Soil Quality Monitoring Program, Edmonton, Canada.
Zhang, M., Li, Y.C., Stoffella, P.J., 2005. Comparison of analytical methods for organic matter in composts and organic mulches. Communications in Soil Science and Plant Analysis 36, 2587–2599.