Diagnostic indicators of soil quality in productive and non-productive smallholders’ fields of Kenya’s Central Highlands

Evah W. Murage a, Nancy K. Karanja b, Paul C. Smithson c, Paul L. Woomer b, *

a Kenya Agricultural Research Institute, PO Box 47811, Nairobi, Kenya
b Department of Soil Science, University of Nairobi, PO Box 29053, Nairobi, Kenya
c International Centre for Research in Agroforestry, PO Box 30677, Nairobi, Kenya

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Abstract

Food security in the East African Highlands is dependent upon the productivity of lands managed by smallholders who face difficult challenges in maintaining the fertility of their soils. A study was conducted to identify indicators of soil fertility status that are consistent with farmers’ perceptions of soil fertility. Physical, chemical and biological properties of soils were measured from paired fields identified as either productive or non-productive by 12 farmers and compared to findings of a household survey on soil fertility management. Special attention was given to the potential of different soil organic matter fractions to serve as diagnostic indicators of soil fertility. Farmers’ criteria for distinguishing soil productivity included crop performance, soil tilth, moisture and colour and presence of weeds and soil invertebrates. All farmers attributed low fertility to inadequate use of organic and inorganic fertilisers (100%) and removal of crop residues (100%). Other causes included continuous cropping (83%), lack of crop rotation (66%) and soil erosion (42%). Productive soils had significantly higher soil pH, effective cation exchange capacity, exchangeable cations, extractable P and total N and P than non-productive soils. Total organic C and several estimates of soil labile C including particulate organic C (POC), three Ludox density separates of POC, KMnO4-oxidizable C and microbial biomass C were significantly greater in productive soils. Soil microbial biomass N, net N mineralisation and soil respiration were also significantly higher in productive soils. Farmers’ perceptions of soil quality were substantiated through soil chemical analyses and soil organic matter fractions provided precise information on these differences. The similarity of soil physical properties in productive and non-productive fields suggests that differences in chemical and biological indicators may have resulted, in part, from smallholders’ management and are not inherent properties of the soils. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: East African Highlands; Humic Nitisol; Soil fertility management; Soil organic carbon

1. Introduction

Soil fertility depletion results from an imbalance between nutrient inputs, harvest removal and other losses and is reaching critical proportions among smallholders in the East African Highlands. Depletion of soil organic matter (SOM) is a contributing factor in this decline (Kapkiyai et al., 1998) and several different approaches toward soil fertility replenishment are being explored (Buresh et al., 1997; Woomer et al., 1997a). Smaling et al. (1993) estimate that 112, 2.5 and 70 kg ha⁻¹ per year of N, P and K, respectively are lost from agricultural soils of Kenya. Input/output approaches to understanding nutrient dynamics in East African smallhold farming systems were further
Table 1
A profile of smallhold farming in the Central Kenyan Highlands based of a survey of 50 households in Kiambu District, Kenya (after Woomer et al., 1998)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average farm size</td>
<td>2.3 ha</td>
</tr>
<tr>
<td>Age of family farm</td>
<td>26 years</td>
</tr>
<tr>
<td>Household members</td>
<td>10 (two adult males, two adult females and six children)</td>
</tr>
<tr>
<td>Principal crops</td>
<td>maize, beans, potatoes, banana, vegetables, coffee, tea</td>
</tr>
<tr>
<td>Reported crop yields</td>
<td>maize 1420, beans 675, potatoes 3800 kg ha⁻¹</td>
</tr>
<tr>
<td>Farm animals</td>
<td>five cattle, three goats, two swine, 15 poultry</td>
</tr>
</tbody>
</table>

Farm management practices
- Apply animal manures: 96%
- Confine livestock: 92%
- Feed crop residues to livestock: 92%
- Apply fertilizers: 82%
- Combine organic and fertilizer inputs: 72%
- Produce domestic compost: 32%
- Sell organic residues: 14%

Typically, smallhold farming systems contain three enterprise areas (Woomer et al., 1998); ‘outfields’ cultivated in cereal–legume intercrops mainly intended for home consumption, ‘infields’ of market crops, and home sites where livestock are confined, manures and composts accumulated and kitchen gardens cultivated. Crop residues from these ‘outfields’ are harvested, fed to livestock and manures applied to crops intended for market. The nutrient mining of ‘outfield’ soils results in characteristic patches, plots and fields of nutrient-deficient crops. Depletion of soil organic matter exacerbates this condition (Kapkiyai et al., 1998).

Smallholders in East Africa recognize special heterogeneity within fields and adjust land management practices accordingly (Ugen et al., 1993; Ojiem and Odendo, 1997), however, past studies have not distinguished between inherent differences of soils and those that result from past land management. The Kikuyu Red Clay is the most abundant and important agricultural soil in the Central Highlands of Kenya and its successful management greatly affects the prosperity and food security of Kenya (Siderius and Muchena, 1977). Past studies by researchers at the University of Nairobi have focused upon smallholder land-use in the Central Highlands of Kenya (Table 1) and the environmental consequences of their most common land management practices (Woomer et al., 1997b, 1998; Kapkiyai et al., 1998). The objective of this study was to characterise differences between soils from productive and non-productive fields that have resulted from smallholders’ management practices in order to identify soil quality indicators consistent with perceptions of land quality with emphasis on SOM fractions (Cambardella and Elliot, 1992; Smith et al., 1993; Blair et al., 1997) and soil biological processes (Woomer et al., 1994).

2. Methods

2.1. Site description

Twelve farms on the Kikuyu Red Clay, a Humic Nitisol (Siderius and Muchena, 1977) were randomly selected from 18 farms in Kiambu District (Kenya) identified during an earlier on-farm survey of organic resource management in the Central Kenyan Highlands (Kapkiyai et al., 1998). The natural vegetation is afromontane forest and evergreen bushland (White, 1983) that has mostly been cleared for cultivation in the mild, subhumid climate and fertile soils.
Kiambu District is adjacent to Nairobi, with ready access to its markets. A short (eight questions), formal, open-ended survey was designed that asked farmers to distinguish between productive versus non-productive sites on their farms, which crops are cultivated in productive and non-productive areas, whether or not and how crop residues, animal manure, mineral fertilizers and other soil inputs are utilized, which crops and fields are targeted for inputs, and their opinion on causes and solutions for soil fertility decline.

2.2. Soil sampling

Soils were collected in October 1996 from 12 farms in Kiambu District, Kenya (0°–0.5°S latitude and 36°30′–37°E longitude, 1350–2400 m asl). Farmers identified productive and non-productive areas after which 20 soil samples were recovered from the 0–20 cm depth in both types of fields with a small, narrow shovel. The samples were spread on a clean polythene sheet, mixed thoroughly and a 7 kg composite sample recovered. A 2 kg sub-sample was removed from the composite sample for C fractionation and biological process measurements and stored under refrigeration at 4°C. The remaining soil was air-dried, sieved to 2 mm and stored at ambient temperature for use in the various physical and chemical analyses.

2.3. Soil analyses

Soil texture was determined using a Bouyoucos hydrometer after Gee and Bauder (1986). Soil pH was determined in H$_2$O (1 : 2.5), exchangeable Ca and Mg by 1 M KCl extraction, and exchangeable K and available P by 0.5 M NaHCO$_3$+0.01 M EDTA extraction. Extractable inorganic N was measured by extraction in 2M KCl, with ammonium determination after Anderson and Ingram (1993). Nitrate was measured by Cd reduction after Dorich and Nelson (1984) followed by colorimetric determination of nitrite (Hilsheimer and Harwig, 1976). Total organic C was determined by digesting the soil at 130°C for 30 min with concentrated H$_2$SO$_4$ and K$_2$Cr$_2$O$_7$, after which C was determined colorimetrically (Anderson and Ingram, 1993). Total N and P were determined by Kjedhal digestion (Parkinson and Allen, 1975).

Particulate organic matter (POM) was recovered from soils dispersed in pH 10 water (prepared by dissolving 0.1 g NaCO$_3$ in 11 of distilled water) by end-to-end shaking for 16 h and then collected on a 53 μm mesh by wet sieving (Okalebo et al., 1993). Density fractionation of organic matter using Ludox at densities 1.13 and 1.37 Mg m$^{-3}$ was conducted by the method of Meijboom et al. (1995). Potassium permanganate oxidizable C was determined in 333 mM KMnO$_4$ according to Blair et al. (1997), with the exception that readings were taken at 24 hr instead of 1 hr reaction time. Soil microbial biomass C and N was determined by the chloroform fumigation–extraction method (Anderson and Ingram, 1993) in a closed desiccator for 24 h at 25°C. Potential anaerobic N mineralization was determined according to Anderson and Ingram (1993) following incubation of saturated soils for 7 days at 40°C. Soil respiration was determined using the potassium hydroxide trapping method of Franzluebbers et al. (1995) over a period of 24 h followed by titration with standardised HCl using phenolphthalein indicator after addition of barium chloride.

2.4. Data analysis

Data were entered into a spreadsheet software programme with measurements as columns and the 12 farms as rows. The data were then imported into SYSTAT (Wilkinson, 1990) and pairwise t-tests were conducted between the two soil categories.

3. Results

3.1. Farmers’ diagnostic criteria of land productivity

Farmers’ criteria for distinguishing productive and non-productive fields included crop performance, ease of tillage, soil moisture retention and soil colour (Fig. 1). Indicator organisms included soil macrofauna and invading plants. The presence of earthworms and beetle larvae were regarded as positive features. Weed species were also associated with land quality, particularly Commelina benghalensis (L.) in productive fields and Digitaria scalarum (Chiov.) and Rhyncheulytrum repens (Willd.) C.E. Hubb in non-productive fields (data not presented).

Different crops were cultivated in productive and non-productive fields (Fig. 2). Farmers grew market annuals such as tomatoes (Lycopersicon esculentum
L.), potatoes (*Solanum tuberosum* L.) and green vegetables in rotation with maize (*Zea mays* L.) in the fields they considered productive. Maize and bean (*Phaseolus vulgaris* L.) intercrops were cultivated in both soil categories but more so in the productive areas. Fodder crops such as napier grass (*Pennisetum purpureum* Schumach.), lucerne (*Medicago sativa* L.), and sweet potatoes (*Ipomoea batatas* L.) were frequently established in the less productive areas.

The main causes of productivity decline identified by farmers were inadequate fertilization (100%), removal of crop residues (100%), continuous cultivation (83%), monocropping (67%) and soil erosion (42%). Solutions proposed by the farmers to overcome this condition included use of farmyard manure (100%), increased use of inorganic fertilisers (100%), crop rotation (25%) and establishment of contour strips for soil conservation (42%) (data not presented). Although most farmers identified continuous cultivation of land as being a major cause of low fertility status, only 25% of the farmers considered crop rotation a feasible solution to restore lost fertility and no farmers mentioned fallow rotations as feasible, suggesting land scarcity.

### 3.2. Soil properties in productive and non-productive soils

Soil physical and chemical properties are presented in Table 2. Mean clay and sand contents for the two soil fertility categories were not significantly different but silt content was significantly higher in productive soils compared to non-productive soils ($p < 0.001$). Productive soils contained more exchangeable cations and had higher pH than non-productive soils.

Several soil organic matter fractions were significantly greater in the productive soils than in non-productive soils (Table 3). Carbon fractions in productive versus non-productive soils were significantly greater in particulate organic C, Ludox heavy, medium and light C separates and KMnO$_4$ oxidizable C but not in non-labile C. Soil microbial biomass C and N, potential anaerobic mineralizable nitrogen and 24 h soil respiration were significantly higher in productive soils than in non-productive soils (Table 4).

### 4. Discussion

#### 4.1. Soil management decision-making by smallholders

Smallholders in the Central Kenyan Highlands recognized various categories of soil fertility upon which subsequent management decisions were made. Other studies demonstrate similar ability of East African
Table 2
Soil physical and chemical properties for a Humic Nitisol from productive and non-productive soils (0–20 cm) in 12 farms in Kiambu District, Kenya

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Farmers’ category of soil quality</th>
<th>Probabilitya</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Productive</td>
<td>Non-productive</td>
</tr>
<tr>
<td>Clay (g kg(^{-1}))</td>
<td>350</td>
<td>380</td>
</tr>
<tr>
<td>Sand (g kg(^{-1}))</td>
<td>320</td>
<td>350</td>
</tr>
<tr>
<td>Silt (g kg(^{-1}))</td>
<td>330</td>
<td>270</td>
</tr>
<tr>
<td>Exchangeable K (cmol, kg(^{-1}))</td>
<td>1.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Exchangeable Ca (cmol, kg(^{-1}))</td>
<td>13.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Exchangeable Mg (cmol, kg(^{-1}))</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Extractable NO(_3) (mg kg(^{-1}))</td>
<td>27.0</td>
<td>17.2</td>
</tr>
<tr>
<td>Effective CEC (cmol, kg(^{-1}))</td>
<td>18.3</td>
<td>11.9</td>
</tr>
<tr>
<td>Soil pH (1 : 2.5 H(_2)O)</td>
<td>6.29</td>
<td>5.56</td>
</tr>
</tbody>
</table>

a Comparison by Tukey t-test.
b ns = not significant.

depicted that farmers’ opinions considered crop vigour, invading plants, presence of earthworms and soil colour. These indicators are very similar to those identified in this study despite being derived from a semi-arid area of Tharaka Nithi District.

Table 3
Mean organic carbon content in the different organic matter pools for soils from productive and non-productive sites in selected farms in Kiambu District, Kenya

<table>
<thead>
<tr>
<th>Carbon pool</th>
<th>Soil fertility status (mg kg(^{-1}))</th>
<th>Probabilitya</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Productive</td>
<td>Non-productive</td>
</tr>
<tr>
<td>Particulate Organic C (POC, &gt;53 μm)</td>
<td>5753</td>
<td>3829</td>
</tr>
<tr>
<td>Heavy POC separate (&gt;1.37 Mg m(^{-3}))</td>
<td>222</td>
<td>103</td>
</tr>
<tr>
<td>Medium POC separate (1.13–1.37 Mg m(^{-3}))</td>
<td>453</td>
<td>252</td>
</tr>
<tr>
<td>Light POC separate (&lt;1.13 Mg m(^{-3}))</td>
<td>560</td>
<td>420</td>
</tr>
<tr>
<td>Sum of POC separates</td>
<td>1236</td>
<td>801</td>
</tr>
<tr>
<td>KMnO(_4)-oxidizable C</td>
<td>19594</td>
<td>14848</td>
</tr>
<tr>
<td>Non-KMnO(_4)-oxidizable C(^c)</td>
<td>4554</td>
<td>4420</td>
</tr>
<tr>
<td>Total soil organic C</td>
<td>24148</td>
<td>19268</td>
</tr>
</tbody>
</table>

a Comparison by Tukey t-test.
b ns = not significant.
c An estimate of non-labile soil C.

Table 4
Biological properties of a Humic Nitisol from productive and infertile soils in 12 selected farms of Kiambu District, Kenya

<table>
<thead>
<tr>
<th>Carbon pool</th>
<th>Soil fertility status (mg kg(^{-1}))</th>
<th>Probabilitya</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Productive</td>
<td>Non-productive</td>
</tr>
<tr>
<td>Soil microbial biomass C (mg kg(^{-1}))</td>
<td>145</td>
<td>103</td>
</tr>
<tr>
<td>Soil microbial biomass N (mg kg(^{-1}))</td>
<td>64</td>
<td>46</td>
</tr>
<tr>
<td>Soil microbial biomass P (mg kg(^{-1}))</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>N-mineralization (mg N kg(^{-1}) per day)</td>
<td>6.1</td>
<td>3.8</td>
</tr>
<tr>
<td>Respiration (CO(_2)) (mg C kg(^{-1}) per day)</td>
<td>61.4</td>
<td>43.7</td>
</tr>
</tbody>
</table>

a Comparison by Tukey t-test.
b ns = not significant.
arid, midland agroecosystem. Ugen et al. (1993) also found that small scale farmers' judgement of soil fertility status in Mpigi District of Uganda was based on readily observed visible and tactile soil characteristics.

Farmers in Kiambu District manage productive and non-productive soils differently. Productive sites were used for production of high value crops, often due to expectations of more favourable soil moisture conditions into the dry season. These crops included tomatoes, bananas, potatoes and green vegetables. Because of their importance to household diets, beans and maize were cultivated as intercrops in both productive and non-productive areas of the farm but more so in productive areas. Plants cultivated in poorer soils were primarily intended for livestock feed but most farmers also recognized their importance in the restoration of soil fertility. Lucerne (M. sativa) fixes atmospheric nitrogen, sweet potato (I. batatas) protects soil from erosion and napier grass (P. purpureum) is an indigenous plant used for soil regeneration by native farmers prior to European contact (Boonman, 1993). This survey and that conducted by Ugen et al. (1993) among smallholders in Uganda show that farmers' preference to grow high value crops on certain portions of their farm is governed by soil fertility status but the selection of those crops also considers social and economic factors.

Our findings reveal that farmers are more likely to allocate their limited organic resources and fertilizers to higher value crops in more productive areas of the farm than to attempt amelioration of fertility-depleted field areas. Farm ‘outfields’ thereby become mined of soil nutrients (Smaling et al., 1993) due to a conscious decision by land managers. Fertilizer application rates by farmers in Kiambu District are considerably less than that recommended by agricultural extension (FURP, 1994; Woomer et al., 1997b). Increased population density has led to land scarcity and necessitated continuous cultivation of ‘outfields’ by households, greatly restricting opportunity for fallowing and resulting in accelerated nutrient depletion (Woomer et al., 1998) and soil organic matter loss (Kapkiyai et al., 1998).

4.2. Diagnostic criteria of soil quality

Clay and sand contents did not vary between soil categories, suggesting that differences in soil properties result from past soil management rather than inherent soil properties. Silt, on the other hand, varied between soil categories (Table 2) and differences were greatest where farmers identified soil erosion as a cause of soil fertility depletion (data not presented). This observation is consistent with the general principle described by Brady (1984) that silt is usually the first mineral component of soil washed away by soil erosion.

The effective cation exchange capacity (ECEC) for productive soils was significantly greater than that of non-productive soils ($p < 0.001$). If soil ECEC and pH are mainly determined by soil organic matter content and the type and amount of clay and the clay content is not different between the soil categories, then differences in soil pH and nutrient holding capacity (Table 2) mainly arose from changes in the soil organic matter content (Table 3). In contrast, Irungu et al. (1996) failed to detect significant differences in soil pH between good and poor soils in Tharaka Nithi District, Kenya, suggesting that soil pH may not be a reliable indicator of soil fertility status in all smallhold, upland conditions. The similarity of soil physical properties in productive and non-productive fields observed in this study (Table 1) indicates that differences in chemical and biological properties (Tables 2 and 3) have resulted, in part, from land management and not inherent differences in soil.

Among soil organic carbon pools and fractions, total organic C was the most sensitive soil quality indicator suggesting that within a narrow range of soil, total soil organic C may serve as a suitable indicator of soil quality. Irungu et al. (1996) also reported similar differences between good and poor soils. Other studies in Africa report that soil organic matter fractionation may offer further insight into soil fertility changes and the sustainability of past management history (Woomer et al., 1994; Barrios et al., 1996; Kapkiyai et al., 1998). In this study, soils from productive areas contained significantly greater particulate organic C and its density separates compared to those from less productive areas. This observation agrees with Kapkiyai et al. (1998) who compared C fraction changes in different soil management strategies after 18 years of continuous cultivation in a long-term, on-station experiment also located on the Kikuyu Red Clay. It is inferred that C fractionation may provide more precise differentiation of soils and management histories under some
conditions, but the additional time and expense of conducting these procedures compared to analysis of total organic C may not be warranted in assessment of smallholds in the Central Kenyan Highlands.

Measuring differences in soil C fractions is not as useful as understanding how these differences have occurred. In our case, uncertainties of past crop and soil management histories by smallholders and past colonial estates and the paucity of soils continuing under natural vegetation (Woomer et al., 1998) provide insufficient information with which to compare these various C fractions. For example, in this study it was not possible to generate a Carbon Management Index to compare farms and soils as described by Blair et al. (1997) for lack of a suitable control condition.

The KMnO$_4$ oxidizable C was significantly different between soil categories, but the recalcitrant, non-oxidizable C was not. Blair et al. (1997) reported that labile C as estimated by the KMnO$_4$ oxidation technique was extremely sensitive to soil management in Australia. Among the different labile C pools compared in this study, the KMnO$_4$ technique emerged as one of the most convenient and reliable but serious disadvantage rests in its destructive nature, not allowing for recovery of a fraction for further characterization. Fractions inferred through KMnO$_4$ oxidation were consistently much larger than those recovered through physical procedures, suggesting that these estimates of lability are based upon different soil organic constituents and are not interchangeable.

5. Conclusions

Smallholders in the Central Highlands of Kenya are aware of the root causes of productivity decline but are often unable to devote sufficient resources to lands undergoing degradation. The internal flow of resources within the farm and allocation of scarce fertilizers are focused upon improving returns in areas viewed as having greatest potential productivity, rather than attempting to ameliorate those areas undergoing decline. This situation results in an intensification of human-induced spatial heterogeneity characterizable through several physical, chemical and biological process attributes of soil. The recognition of land management difficulties by smallholders and the documentation of consequences by scientists are important, but preliminary, steps in the development of new solutions appropriate to farmers’ needs and resources. Many adjustments by land managers are under way, particularly in shifting toward less intensive cultivation of areas undergoing decline but additional products and technologies that specifically address land rehabilitation without withdrawing lands from food production are urgently required. Several simple field indicators and soil measurements offer potential in assessing the impacts of candidate interventions as these are developed for, and adopted by, the smallhold farming sector in the Central Highlands of Kenya, particularly those cultivating the Kikuyu Red Clay, a Humic Nitisol.

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