Agriculture, Ecosystems and Environment 141 (2011) 86–99

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

B.N. Moebius-Clune[a,*], H.M. van Es[a], O.J. Idowu[b], R.R. Schindelbeck[a], J.M. Kimetu[a], S. Ngoze[a], J. Lehmann[a], J.M. Kinyangi[c]

[a] *Department of Crop and Soil Sciences, Cornell University, Ithaca, NY, United States*
[b] *Department of Extension Plant Sciences, New Mexico State University, Las Cruces, NM, United States*
[c] *CGIAR-ESSP Program on Climate Change, Agriculture & Food Security, International Livestock Research Institute, Nairobi, Kenya*

ARTICLE INFO

Article history:
Received 28 November 2010
Received in revised form 9 February 2011
Accepted 10 February 2011
Available online 5 March 2011

Keywords:
Soil quality
Chronosequence
Deforestation
Kenya
Kitchen garden
Soil degradation

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

* Corresponding author at: Department of Crop and Soil Sciences, 1001 Bradfield Hall, 306 Tower Rd, Cornell University, Ithaca, NY 14853-1901, United States.
E-mail address: bnm5@cornell.edu (B.N. Moebius-Clune).

0167-8809/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2011.02.018

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