APPLICATIONS OF INTEGRATIVE SOIL QUALITY ASSESSMENT IN RESEARCH, EXTENSION, AND EDUCATION

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APPLICATIONS OF INTEGRATIVE SOIL QUALITY ASSESSMENT IN RESEARCH, EXTENSION AND EDUCATION

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Declining soil quality is an emerging issue of global concern because degraded soils are becoming more prevalent due to intensive use and poor management. The degradation of agronomically essential soil functions significantly impacts agricultural viability, environmental sustainability, and food security. The Cornell Soil Health Test (CSHT) measures and interprets an integrative set of physical, biological, and chemical indicators. It was developed as a tool to be used in applied research, extension, and education to assess and monitor soil quality, aid in making management decisions, and to increase public awareness of the importance of maintaining soil quality. In this dissertation, I explore applications of integrative soil quality assessment in three projects. 1) An open inquiry unit on runoff and infiltration was designed for use in high school earth science classrooms. The unit successfully stimulated student engagement and learning about the importance of soils in their lives and the process of authentic scientific inquiry. 2) In an assessment of the effects of stover harvest and tillage, overall soil quality was found to be much lower in plow- than no-till systems, irrespective of stover treatment. Stover harvest appeared to be sustainable when practiced under no-tillage management. 3) The CSHT Framework was further developed to be easily modified by users, and applied as an assessment tool to a chronosequence experiment on smallholder farms in western Kenya. The framework showed soils degraded most in low-input maize fields, but much less so in kitchen gardens. Indicator values and interpretive scores derived from scoring

functions successfully discerned effects of long-term as well as residual short-term agricultural management differences, and were predictive of yield on smallholder farms studied. The CSHT was shown to be useful for monitoring, assessment, and in guiding on-farm management decisions. Its low infrastructure needs makes it a feasible approach to standardized soil quality testing for a variety of users internationally. In conclusion, the CSHT is potentially useful not only for applied researchers, but also for extension, non-profit, and governmental professionals to monitor soils and develop solution-oriented programs and policies that further sustainable use of soil and water management practices, locally, regionally, and potentially globally.

BIOGRAPHICAL SKETCH

Bianca Nadine Moebius-Clune was born in Bochum, Germany on March 1, 1978 to her happy first-time parents Hannelore and Eberhard Möbius. Her passion for the environment and science of the natural world originates in her childhood in Germany. She was fascinated with trees, soil, mountains, and the ocean early on. The Chernobyl accident in the Ukraine left a deep impression on her at the age of eight. Her father brought home a Geiger counter, which declared that her sandbox and all the topsoil in the garden was off limits for play. They did not harvest fruits or produce that year.

Bianca moved to Durham, NH with her family at the age of twelve. She graduated Summa Cum Laude from the University of NH in 2000 with a Bachelor of Soil Science, having spent an influential semester abroad on the island of Madagascar. There she worked on local soil conservation issues with a group of Malagasy women. She held several positions assisting in field and laboratory research at the University of NH during and after graduation, including one in the Complex Systems Research Center's Trace Gas Biogeochemistry Group. She also volunteered as an environmental educator at Sully's Hill National Game Preserve, ND, and at Curecanti National Recreation Area, CO. As an AmeriCorps volunteer, Bianca coordinated the non-profit farmer-to-farmer network Beginner Farmers of New Hampshire for a year, before continuing her education at Cornell University.

She entered an MS/PhD program in the Department of Crop and Soil Sciences to pursue work in Soil Health/Quality Assessment under Dr. Harold van Es in August, 2003. In the first year of pursuing her MS, Bianca met Dan. Dan and Bianca are happily married as of June 2008, and share the family name of Moebius-Clune.

To Dan

My partner forever

Thank you

for your

love

patience and support

encouragement

and everything else

that has

helped me come

this far…

I'm so happy

I get to keep

You!

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My minor advisor Janice provided me with excellent perspectives on the biological interactions with soil physical health, and an opportunity to discuss interdisciplinary connections. I am also deeply grateful to her for giving me the opportunity to collaborate with my (now) husband Daniel Moebius-Clune during my Masters and early PhD work. My minor advisor Barbara Crawford has been instrumental in helping me integrate my passion for education and the work I have done in high school inquiry curriculum development into my degree and dissertation. I thank her for her consistent cheerfulness and positivity.

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CSHT = Cornell Soil Health Test; SQ = soil quality

CHAPTER 2

ρ_b = bulk density; AWC = available water capacity; Decomp = cellulose decomposition rate; EEG = easily extractable glomalin concentration; K_s = saturated hydraulic conductivity; $\ln K_s = \ln(K_s + 1)$; Infilt = infiltrability; lnInfilt = ln(Infilt); NT = no till; NT-H = NT stover harvested; NT-R = NT stover returned; $Nem_{Beneficial}$ = number of beneficial nematodes; $Nem_{Parasitic}$ = number of parasitic nematodes; OM = organic matter; PMN = potentially mineralizable nitrogen; PO > 30 = pores with diam. > 30 µm; PO > 1000 = pores with diam. > 1000 µm; PR = penetration resistance PT = plow till; PT-H = PT stover harvested; PT-R = PT stover returned; SOC = soil organic carbon; TG = total glomalin concentration; WSA = water stable aggregation (0.25 - 2.00 mm)

CHAPTER 3

Avg = average, stdev = standard deviation, min = minimum score, max = maximum score

CHAPTER 4

ActC – permanganate-oxidizable biologically active carbon, AWC – available water capacity, Co – continuous low-input maize, EC – electrical conductivity, Ki – kitchen garden, LoiOM – total organic matter by loss on ignition at 350^{o}C, PR15 – penetration resistance in surface 0-15 cm of soil (kPa), PR45 – penetration resistance in subsurface 15-45 cm of soil (kPa), SQ – soil quality, WSA – water stable aggregates

CHAPTER 5

ActC – permanganate-oxidizable biologically active carbon, avgOM – average for plots receiving organic matter additions (Ch, Ma, Sa, Ti), AWC – available water capacity, Ch – charcoal amended treatment, Co – control treatment, EC – electrical conductivity, Ki – kitchen garden management, LoiOM – total organic matter by loss on ignition at 350^{o}C, Ma – manure amended treatment, Mgmt – management system, OM – organic matter, PR15 – penetration resistance in surface 0-15 cm of soil, PR45 – penetration resistance in subsurface 15-45 cm of soil, Sa – sawdust amended treatment, SQ – soil quality, Ti – *Tithonia diversifolia* amended treatment, WSA – water stable aggregates

CHAPTER 6

ActC – Permanganate-oxidizable biologically active carbon, avgOM – average for plots receiving organic matter additions (Ch, Ma, Sa, Ti), AWC – available water capacity, Ch – charcoal amended fields, CND – cumulative normal distribution

Co – control fields, CSHI – composite soil health index, CSHT – Cornell Soil Health Test, EC – electrical conductivity, Ki – kitchen garden management, LoiOM – total organic matter by loss on ignition at 350^{o}C, Ma – manure amended fields, Mgmt – management system, OM – organic matter, PR15 – penetration resistance in surface 0-15 cm of soil (kPa), PR45 – penetration resistance in subsurface 15-45 cm of soil, Sa – sawdust amended fields, SQ – soil quality, Ti – *Tithonia diversifolia* amended fields, WSA – water stable aggregation

CHAPTER 7

ActC – permanganate-oxidizable biologically active carbon, avgOM – average for plots receiving organic matter additions (Ch, Ma, Sa, Ti), AWC – available water capacity, Ch – charcoal amended fields, CND – cumulative normal distribution, Co – control fields, CSHI – composite soil health index, CSHT – Cornell Soil Health Test EC – electrical conductivity, HT – high threshold, Ki – kitchen garden management LoiOM – total organic matter by loss on ignition at 350^{o}C, LT – low threshold, Ma – manure amended fields, MT – medium threshold, OM – organic matter amended fields, PR15 – penetration resistance in surface 0-15 cm of soil, PR45 – penetration resistance in subsurface 15-45 cm of soil, Sa – sawdust amended fields, SQ – soil quality, Ti – *Tithonia diversifolia* amended fields, WSA – water stable aggregates

CHAPTER 8

CSHT = Cornell Soil Health Test; SQ = soil quality

CHAPTER 1. INTRODUCTION

Declining soil quality (SQ) is an emerging issue of increasing global concern as degraded soils are becoming more prevalent due to intensive agricultural use and poor soil management. The degradation of agronomically essential functions of the soil significantly impacts agricultural viability, environmental sustainability, and food security. Typical soil problems encountered, depending on farmer management styles and access to resources, can include loss of soil organic matter, poor nutrient retention, and availability, decreased water infiltration, excessive runoff, and erosion, soil compaction, reduced water holding capacity, drought-proneness, salinization, disease pressure, weed pressure, and usually a need for higher inputs to maintain equal or declining yields (Hillel, 1991; Magdoff and van Es, 2009; Wolfe, 2002).

Doran et al. (1994) define soil quality as "the capacity of the soil, within land use, and ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health." Soil quality generally refers to the condition of soil that is changeable in a relatively short period of time by human activity, including agricultural management practices (Carter, 2002; Karlen et al., 1997; Magdoff and van Es, 2000; Mausbach and Seybold, 1998; Wienhold et al., 2004). The terms "soil quality" and "soil health" are often used interchangeably (Harris and Bezdicek, 1994), as they are in this dissertation.

The need for SQ assessment that is available to farmers, as well as applied researchers and stakeholder organizations, such as agricultural extension services, was identified for New York State (Wolfe, 2002), and is sought for use internationally, in developed, and developing nations (Hurni et al., 2006; Lal, 1997). Soil quality can be assessed indirectly by measuring indicators, or soil properties, that are sensitive to changes in agricultural management, agronomically meaningful, and sufficiently diverse to represent the soil physical, biological, and chemical processes essential to crop growth (Doran et al., 1994; Larson and Pierce, 1991; Mausbach and Seybold, 1998). Such approaches allow for research to move beyond the current focus on soil nutrients and total organic matter dynamics that have been explored widely to date. However, while approaches to measuring air and water quality have been established and standardized, no standardized SQ assessment exists currently (Bastida et al., 2008; Winder, 2003). Furthermore, for SQ assessment to be widely adopted beyond the research domain, indicators of agricultural SQ must not only meet the criteria above. They also must be able to be readily measured and interpreted and must be accessible, easy to perform, inexpensive, and practically useful for diverse users. For adoption in developing nations, indicators must be measurable in locations with minimal infrastructure (Bastida et al., 2008).

Of the various SQ assessments developed to date, the Cornell Soil Health Test (CSHT) is the only developed assessment framework that is reasonably-priced for broader adoption by farmers, consultants, and applied researchers. Since 2006, the CSHT has been available for use by researchers and land managers, primarily in the Northeastern United States (Gugino et al., 2009; Idowu et al., 2008), similarly to the more widely available soil nutrient analysis. The CSHT is comprised of a set of physical, biological, and chemical indicators of SQ that meet the stated criteria. Measured indicator values are scored via scoring functions, and interpreted with respect to whether they constrain the soil processes they are intended to represent. The information provided by the CSHT report enables land managers to 1) identify constraints in specific soil processes on their agricultural lands, including and going beyond nutrient deficiencies, 2) implement practical management strategies that specifically target identified constraints, and 3) monitor the condition of their soils over time and in response to adopted strategies. Soil management decisions take into account land use objectives and resource availability to devise locally appropriate strategies.

This dissertation provides details of the work from three interrelated projects, which all constitute applications of integrative soil quality assessment using the CSHT and its precursors as a tool in research, extension, and education. Chapter 2, published in the Soil Science Society of America Journal in 2008 (Moebius-Clune et al., 2008), contains results on the effects of long-term maize stover removal under two tillage regimes on SQ via an expanded set of SQ indicators, using a long-term experiment in Northern New York (NY). The effects of stover removal on SQ are currently of concern because of the increasing interest in crop residues and other agricultural commodities for biofuel/bioenergy production. In Chapter 3, student engagement and learning during a newly-designed scientific inquiry unit on runoff and infiltration is reported. The inquiry unit was developed to help move authentic soil science research into high school science classrooms to increase awareness of the essential roles soils play in our lives. Chapters 4 through 7 contain reports on how the CSHT Framework was further developed and applied to a chronosequence experiment on smallholder farms in Western Kenya. In this work, the CSHT Framework's ability to measure trends in soil degradation, long- and short-term management-related constraints and differences, and its relationship with yield were evaluated. The potential for this test to be used as a management guide on smallholder farms and as an international standard for assessment and monitoring is discussed.

CHAPTER 2. LONG-TERM EFFECTS OF HARVESTING MAIZE STOVER AND TILLAGE ON SOIL QUALITY[1]

2.1. ABSTRACT

Rising concerns about greenhouse gases, increased fuel prices, and the potential for new high value agricultural products have raised interest in the use of maize stover for bioenergy production. However, residue harvest must be weighed against potential negative impacts on soil quality. This study, conducted in Chazy, NY, evaluated the long-term effects of 32 years of maize (*Zea mays* L.) stover harvest vs. stover return on soil quality in the surface layer (5 – 66 mm) under plow till (PT) and no till (NT) systems on a Raynham silt loam (coarse-silty, mixed, active, nonacid, mesic Aeric Epiaquept) using physical, chemical, and biological soil properties as soil quality indicators. Twenty-five soil properties were measured, including standard chemical soil tests, aggregate stability (WSA), bulk density (ρ_b), penetration resistance (PR), saturated hydraulic conductivity (K_s), infiltrability (Infilt), several porosity indicators (aeration pores (PO > 1000), soil water potential = $\Psi > -0.36$ kPa; air-filled pores at field capacity (PO > 30), $\Psi > -10$ kPa; available water capacity (AWC), $-1500 < \Psi < -10$kPa), total soil organic matter (OM), parasitic ($Nem_{Parasitic}$), and beneficial ($Nem_{Beneficial}$) nematode populations, decomposition rate (Decomp), potentially mineralizable nitrogen (PMN), and easily extractable (EEG) and total glomalin (TG).

[1] Moebius-Clune, Bianca N., Harold M. van Es, Omololu J. Idowu, Robert R. Schindelbeck, Daniel J. Moebius-Clune, David W. Wolfe, George S. Abawi, Janice E. Thies, Beth K. Gugino, and Robert Lucey. 2008. Long-term effects of harvesting maize stover and tillage on soil quality. Soil Sci. Soc. Am. J. 72:960-969.

Only eight indicators were adversely affected by stover harvest, and most of these effects were significant only under NT. Almost all indicators affected by stover removal were affected equally or more adversely by tillage. A total of fifteen of the 25 indicators measured were adversely affected by tillage. Results of this study suggest that, on a silt loam soil in a temperate climate, long-term stover harvest had lower adverse impacts on soil quality than long-term tillage. Stover harvest appears to be sustainable when practiced under no tillage management.

2.2. KEY WORDS

Bioenergy, soil quality, soil quality indicators, stover harvest, tillage

2.3. INTRODUCTION

Interest in bioenergy production is increasing due to rising concerns about greenhouse gas emissions, increased fuel consumption, and prices, and a need for higher-value agricultural products to improve agricultural economic viability (Energy Information Administration, 2006; Lal, 1998; Mann et al., 2002; Wilhelm et al., 2004). A feasibility study conducted by the Department of Energy (DOE) and the US Department of Agriculture (USDA) suggested that 30% of the petroleum consumed in the US could be replaced by using a potential 1 Pg annual supply of biomass (Energy Information Administration, 2006; Perlack et al., 2005).

Grains are a common source of biomass, but their use diverts products from food and feed markets (Perlack et al., 2005; Sanderson, 2006). Crop residues are a potential feedstock source for direct combustion, as well as for bio-refineries using ligno-cellulosic conversion to produce ethanol (Graham et al., 2007; Sanderson, 2006; Werblow, 2006). Maize stover, which makes up more than half of all crop residues in the US, is by far the most ubiquitous, with an annual availability of approximately 75 Tg (Perlack et al., 2005). However, harvesting crop residues has also been associated with declining soil quality and productivity (Lal, 2005).

Soil organic matter and its dynamics dictate soil structure, which in turn influences other essential physical, chemical, and biological soil processes (Carter, 2002; Six et al., 1999). Crop production potential of soils is related strongly to their organic matter content (Lal, 1998; Mann et al., 2002), which in part is controlled by organic inputs such as crop residues. The economic benefit of harvesting crop residues must therefore be weighed against the potentially negative effects that such management may have on soil quality.

However, the extent to which crop residue removal is related to soil degradation is still unclear (Mann et al., 2002; Wilhelm et al., 2004). Tradeoffs exist between the beneficial effects of residue harvest, such as faster warming of soils in spring, better seed germination and less favorable habitat for plant-pathogens, and the potential adverse effects, such as organic matter declines, higher soil temperature fluctuations and faster losses of stored soil moisture (Mann et al., 2002; Swan et al., 1996; Wilhelm et al., 2004).

Tillage also plays a role in soil organic matter dynamics. Reduced and no-tillage systems generally accumulate organic matter, and bring about higher aggregate stability, porosity, abundance of root channels and macrofauna burrows, infiltrability, water holding capacity, and biological activity (Liebig et al., 2004; Puget et al., 1999).

In quantifying the effects of residue harvest on soils, most studies have focused on aspects of organic matter or carbon dynamics, such as Dick et al. (1998), Clapp et al. (2000), Mann et al. (2002), Reicosky et al. (2002), Hooker et al. (2005), Dolan et al. (2006), Wilhelm et al. (2004), and Wilts et al. (2004), among others. Relatively few studies have explored the effects of residue harvest on other soil physical, chemical, and biological processes (Blanco-Canqui et al., 2006b; Dabney et al., 2004; Govaerts et al., 2006a; Govaerts et al., 2006b; Karlen et al., 1994).

Assessing soil quality involves a more holistic approach that goes beyond measuring soil organic carbon (SOC) and nutrient concentrations by integrating physical, chemical, and biological components and processes and explicitly considering the interactions between them (Doran and Jones, 1996; Karlen et al., 2001). Soil quality status, as affected by management, can be assessed by measuring indicators, or soil properties that are sensitive to changes in agricultural management, easy and inexpensive to measure, representative of relevant and essential soil processes and functions, and thus agronomically meaningful (Brejda et al., 2000; Doran and Parkin, 1996; Larson and Pierce, 1991).

Soil degradation from residue harvest is most likely to become significant over the long-term, but few such long-term field studies exist (Mann et al., 2002; Wilhelm et al., 2004). A 32-year long field experiment has been maintained in Chazy, NY, in which maize is grown for grain (stover returned) and silage (stover harvested) under both, no till and plow till management. This experiment provided a unique opportunity to evaluate the effects of long-term stover harvest on soil quality under two contrasting tillage systems. The objectives of this research were to: 1) evaluate the effects of long-term stover harvest on soil quality, 2) compare these long-term effects with those of tillage management, and 3) identify strategies for the sustainable use of maize stover for bioenergy production.

2.4. MATERIALS AND METHODS

2.4.1. Study site and treatments

Soils were sampled from a long-term controlled experiment under maize production, located at Chazy, NY (44°53'N, 73°28'W), on a Raynham silt loam (coarse-silty, mixed, active, nonacid, mesic Aeric Epiaquept) derived from glacio-lacustrine deposits. A randomized complete block design with sixteen 6 x 15.2 m plots was established in 1973, and planted to maize annually since then. Four treatments were replicated in four blocks: plow-till with stover returned (PT-R), plow-till with stover harvested (PT-H), no-till with stover returned (NT-R) and no-till with stover harvested (NT-H; Fig. 1). Plow till plots were moldboard plowed (to approx. 150 mm) in the autumn of each year, disked in the spring and then planted. No till plots were planted at the same time. In stover harvested (H) plots, all above-ground plant matter was harvested in the autumn of each year. In stover returned (R) plots only grain was harvested by hand at harvest maturity. Maize residues were incorporated into PT plots, and left on the surface of NT plots. Last yield measurements were obtained from this experiment in 1997. Between 1985 and 1997, grain yields in the four treatments averaged 7.9 Mg ha^{-1} for PT-H, 8.5 Mg ha^{-1} for PT-R, 8.5 Mg ha^{-1} for NT-H and 8.4 Mg ha^{-1} for NT-R. No significant differences between treatments were found.

2.4.2. Soil sampling

Soil samples were collected on 23 April of 2004, when the soil was at approximately field capacity. Samples for physical analyses were obtained from the most central non-trafficked inter-row (Fig. 2.1). One disturbed sample was taken per plot from the surface soil (5 – 66 mm depth) using a trowel, and two undisturbed soil

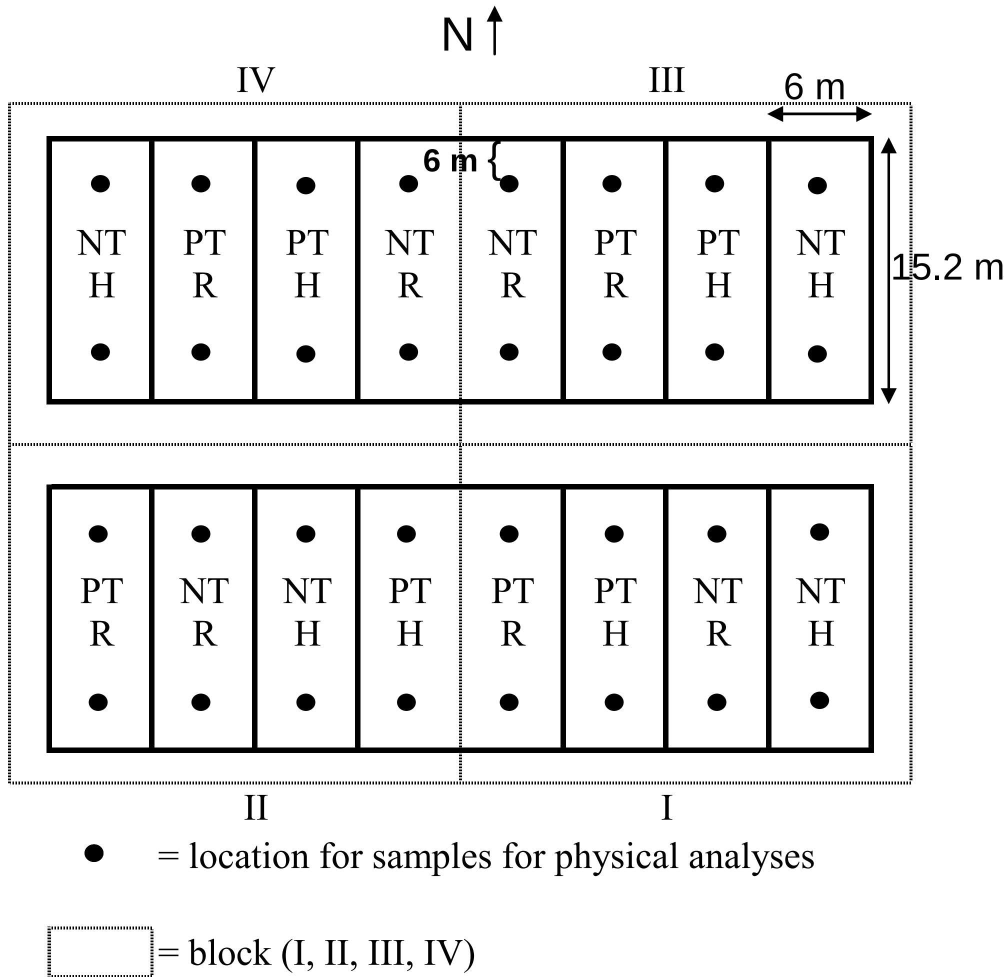

Figure 2.1 Field plot layout of experiment established in 1973 in Chazy, NY. PT = plow till, NT = no till, R = stover returned, H = stover harvested.

core samples were collected from the same depth using stainless steel rings (61 mm height, 72 mm internal diam (id), 1.5 mm wall thickness).

Samples for biological and chemical analysis were composited by mixing approximately 20 randomly collected within-inter-row soil sub-samples from the surface 0 – 15 cm of each plot in a bucket, and then sub-sampling into a plastic bag. Samples were kept in a cooler with ice, transported to the laboratory, and stored at $2^{o}C$ until analysis.

Water infiltration (Infilt) was measured on site in each plot on 28 May, 2003, using the rainfall simulation technique based on Ogden et al. (1997a). A portable rainfall simulator was placed onto an infiltration ring (241 mm id), which was inserted 75 mm into the soil, and equipped with a runoff tube at the soil surface to guide runoff water out of the ring into an external beaker. Steady infiltration rate was calculated as the difference between measured rainfall and runoff rates once steady infiltration was reached, as described by van Es and Schindelbeck (2003b).

2.4.3. Laboratory analyses

2.4.3.1 Physical properties

Undisturbed samples were prepared for laboratory analysis by attaching nylon gauze to the bottom of each ring using a rubber band. Sample soil cores were saturated ($\Psi = 0$) over the course of 24 h, and saturated hydraulic conductivity (K_s) was measured using the constant head method (Klute and Dirksen, 1986).

Macroporosity (pore diam. > 1000 μm; PO > 1000, m^3m^{-3}) was determined gravimetrically by allowing saturated core samples to drain freely for 3 h on wet cheese cloth until the average core water potential at $\Psi = -0.36$ kPa was reached (Karunatilake and van Es, 2002). Subsequently, soil cores were equilibrated to $\Psi = -10$ kPa using a sand tension table controlled with vacuum pressure regulators (Topp et al., 1993), thereby gravimetrically estimating the fraction of soil volume occupied by pores greater than 30 µm diam. (PO > 30, m^3m^{-3}).

Penetration resistance (PR, MPa) was measured immediately after equilibration at Ψ = -10 kPa, using a 30°-angle, 4 mm diam. cone micro-penetrometer, which was pushed into the soil to a depth of 50 mm at a rate of 8 mm s^{-1}, using a manual modified drill press. Penetration resistance was expressed as the force divided by the vertical projection of the cone area. Soil cores were then dried at 105°C to determine bulk density (ρ_b, g cm^{-3}) and total porosity (Culley, 1993). Residual porosity (pore diam. < 0.2 µm, m^3m^{-3}) at Ψ = -1500 kPa was determined on sub-samples using a ceramic high-pressure plate apparatus (Topp et al., 1993). Available water capacity (AWC, m^3m^{-3}) was calculated from the water loss between Ψ = -10 and Ψ = -1500 kPa.

Water stable aggregation (WSA), was measured from disturbed samples using a small rainfall simulator (Moebius et al., 2007). Samples were air-dried to friable consistency, gently crumbled through an 8 mm sieve and oven-dried at 40°C. Using stacked sieves of 2 mm and 0.25 mm and a catch pan, soil samples were shaken for 10 s on a mechanical shaker. Aggregates of 0.25 – 2 mm size were returned to 40°C to achieve consistent moisture potential, and used to determine water stable aggregation. A single layer of aggregates was spread on a 0.25 mm mesh sieve, which was placed 0.5 m below a 0.59 m diam. rainfall simulator. Simulated rainfall was used to apply 1.9 J of energy over a 300 s period, as described by Moebius et al. (2007), and WSA was determined as the fraction of soil remaining on the sieve, correcting for solid particles > 0.25 mm.

2.4.3.2 Chemical and biological properties

The pH of each sample was measured in a 1:1 suspension of soil and water using a standard pH meter (Eckert and Sims, 1995). Organic matter (OM) per unit mass of soil was determined by dry combustion (Nelson and Sommers, 1996). Plant available nutrients were extracted with Morgan's solution, a 10% sodium acetate and 3-4% glacial acetic acid solution, buffered at pH 4.8 (Morgan, 1941). Activated carbon was added to decolorize and remove organic matter from the extraction solution. After filtering, the extract was analyzed for K, Ca, Mg, Fe, Al, Mn, and Zn on an ICP (Jobin Yvon, Kyoto, Japan), and extractable NO_3-N and PO_4-P were measured using an automated rapid flow analyzer (RFA/2, Alpchem), at the Cornell Nutrient Analysis Laboratory in Ithaca, NY. All nutrient contents were calculated per mass of soil (mg kg^{-1}).

Glomalin was extracted from samples according to methods described by Wright and Upadhyaya (1998) and Clune (2007). Neutral 0.020 M $Na_3C_6H_5O_7$ (sodium citrate) was added to dry soil aggregates and mixed by vortexing. Tubes were autoclaved at 121°C, 15 psi (~103 kPa), for 30 min. Solids were pelleted by centrifuging and the supernatant removed by decanting for quantification of easily extractable glomalin (EEG). Soil solids were subjected to four more rounds of extraction by autoclaving, for 60 min in each round, in 0.05 M sodium citrate, at pH = 8.0, to extract total glomalin (TG). Extracts were stored at 4°C until quantification. Protein extracted from all samples was quantified using the Bradford assay as described in Wright and Upadhyaya (1998). Absorbance at 590 nm was measured using a Packard SpectraCount colorimetric microplate reader (Packard Instrument Co., Meriden, CT). Protein concentrations were calculated using a standard curve prepared using bovine serum albumin (BSA).

A standardized decomposition rate (Decomp) was determined using an incubation technique. Unbleached Whatman #42 cellulose filter paper (moistened, 7 cm diam.) was placed into the center of a 9 cm diam. plastic Petri dish. This was filled with soil sieved through a 2 mm mesh such that good contact between soil and paper was achieved, but without excessive compaction of the soil. Each Petri dish was covered, sealed with Parafilm, weighed, and incubated in a humid environment at 25^{o}C. The grid line intersect method (Lindsey, 1955) was used to quantify filter paper decomposition after 3, 5, and 7 weeks. Data collection ended when ≥ 90% of the paper was decomposed.

Potentially mineralizable nitrogen (PMN) was determined via a 7-day anaerobic incubation of soil samples similar to that described by Drinkwater et al. (1996) as modified from Keeney (1982). This involved KCl extractions of 8 g of 2 mm mesh-sieved fresh soil samples. Accumulation of NH_4-N and NO_3-N was measured with a Bran&Leubbe AA3 continuous flow analyzer (SEAL Analytical Inc., Mequon, WI) at the Cornell Nutrient Analysis Laboratory, Ithaca, NY.

Soil populations of plant-parasitic ($Nem_{Parasitic}$) and free-living ($Nem_{Beneficial}$) nematodes were extracted using a pie-pan modification of the Baermann funnel technique (Barker and Niblack, 1990). Nematodes were extracted from 50 cm^3 of soil, collected on a 45 µm mesh sieve (No. 325), backwashed into a beaker and adjusted to 100 ml with tap water. A 1 or 5 ml aliquot was removed from the suspension during stirring and placed in a counting dish. The nematodes were counted and identified under a dissecting microscope at 40 to 60X magnification, and expressed as the number of nematodes per 100 g of soil.

2.4.4. Data analysis

Data were analyzed for significant effects of fixed factors on indicator values using a mixed model (SAS PROC MIXED, SAS Institute, 2005), where residue, tillage, and residue x tillage interaction were fixed factors, and block, replicate and their interactions were random factors. Values of K_s were transformed to $\ln(K_s + 1)$, due to commonly found right skewing of the data (Munoz-Carpena et al., 2002; van

Es, 2002), and values of Infilt were similarly transformed to ln(Infilt). Transformed values (‘lnK_s’ and ‘lnInfilt’) were used for statistical analysis. Relevant means were compared for each indicator using Tukey’s test. All test results were deemed significant at $p \leq 0.10$.

2.5. RESULTS

Residue treatment as a main factor significantly affected the following 8 out of the 25 measured soil properties: ρ_b, AWC, K, Mg, OM, Decomp, EEG and TG (Table 2.1). Of these, all except K, Mg, and EEG were equally or more significantly affected by tillage than residue treatment. Only K was not significantly affected by tillage.

Tillage treatment as a main factor significantly affected 15 out of the 25 measured soil properties (Table 2.1). Of these, WSA, NO_3-N, Al, Mn, Zn, pH, $NemP_{arasitic}$, and PMN were affected only by tillage. Nine out of the 25 measured properties, PR, lnK_s, PO > 1000, PO > 30, lnInfilt, P, Ca, Fe, and $Nem_{Beneficial}$, were not significantly affected by either stover harvest or tillage (Table 2.1).

Overall treatment means and means separated by tillage and residue treatments are given in Table 2.2. Statistically appropriate generalizations about the overall effects of tillage and stover on soil properties could be made for all but a few properties (WSA, Mg, Decomp and TG), for which residue by tillage interactions were significant (Table 2.1).

2.5.1. Residue management effects

A relative comparison of the overall residue management treatment means ($(R_{mean} - H_{mean})/R_{mean}$) showed that soils had less organic matter under long-term stover harvest (H), by 8% relative to long-term stover return (R; Table 2.2). Stover

Table 2.1 Factor significance in a full mixed model analysis of soil physical, chemical and biological properties, significant at p = 0.10 (+), p = 0.05 (*), p = 0.01 (**), p = 0.001 (***), ns = not significant.

PHYSICAL

Factor	df num	WSA[†]	ρ_b[‡]	PR[§]	lnK_s[¶]	PO > 1000[#]	PO > 30[††]	AWC[‡‡]	lnInfilt[§§]
till	1	***	**	ns	ns	ns	ns	**	ns
residue	1	ns	+	ns	ns	ns	ns	*	ns
till*residue	1	***	ns	+	ns	ns	ns	ns	ns

CHEMICAL

Factor	df num	NO_3-N	P	K	Mg	Ca	Fe	Al	Mn	Zn	pH
till	1	+	ns	ns	*	ns	ns	*	*	*	***
residue	1	ns	ns	***	**	ns	ns	ns	ns	ns	ns
till*residue	1	ns	ns	ns	*	ns	ns	ns	ns	ns	ns

BIOLOGICAL

Factor	df num	OM[¶¶]	Nem$_{Parasitic}$[##]	Nem$_{Beneficial}$[†††]	Decomp[‡‡‡]	PMN[§§§]	EEG[¶¶¶]	TG[###]
till	1	***	***	ns	*	+	+	**
residue	1	*	ns	ns	*	ns	*	*
till*residue	1	ns	ns	ns	*	ns	ns	*

† WSA = water stable aggregates (0.25-2 mm)
‡ ρ_b = bulk density
§ PR = penetration resistance
¶ lnK_s = ln(K_s + 1), where K_s = saturated hydraulic conductivity
# PO > 1000 = drainage and aeration pores with diam > 1000 µm
†† PO > 30 = pores above field capacity with diam > 30 µm
‡‡ AWC = available water capacity
§§ lnInfilt = ln(Infilt), where Infilt = of infiltrability
¶¶ OM = organic matter
Nem$_{Parasitic}$ = parasitic nematode population
††† Nem$_{Beneficial}$ = beneficial nematode population
‡‡‡ Decomp = decomposition rate
§§§ PMN = potentially mineralizable nitrogen
¶¶¶ EEG = easily extractable glomalin concentration
TG = total glomalin concentration

Table 2.2 Means for soil physical, chemical and biological properties by tillage and residue treatment and by overall tillage and residue means.

		WSA *g g^{-1}*	ρ_b *Mg/m^{-3}*	PR *kPa*	lnK_s *ln(mm hr^{-1})*	P>1000 *mm^{-3}*	P>30 *mm^{-3}*	AWC *mm^{-3}*	ln(Infilt) *ln(cm hr^{-1})*
PHYSICAL	***R Mean***	*0.36A‡*	*1.35B*	*0.92A‡*	*2.3A*	*0.022A*	*0.114A*	*0.323A*	*1.61A*
	H Mean	*0.28A‡*	*1.42A*	*0.94A‡*	*1.4A*	*0.021A*	*0.113A*	*0.297B*	*1.11A*
No Till (NT)									
	Stover returned (R)	0.50a†	1.32b	1.08a	2.4a	0.021a	0.098a	0.357a	1.58a
	Stover harvested (H)	0.42b	1.33b	0.93a	1.9a	0.024a	0.125a	0.308b	0.83a
	NT Mean	*0.46A‡*	*1.32B*	*1.01A‡*	*2.2A*	*0.022A*	*0.111A*	*0.332A*	*1.2A*
Plow Till (PT)									
	Stover returned (R)	0.22c	1.39ab	0.77a	2.1a	0.022a	0.131a	0.291b	1.63a
	Stover harvested (H)	0.14c	1.51a	0.96a	1.0a	0.018a	0.1a	0.286b	1.39a
	PT Mean	*0.17B‡*	*1.45A*	*0.86A‡*	*1.6A*	*0.020A*	*0.116A*	*0.289B*	*1.51A*

		NO_3-N *mg kg^{-1}*	P *mg kg^{-1}*	K *mg kg^{-1}*	Mg *mg kg^{-1}*	Ca *mg kg^{-1}*	Fe *mg kg^{-1}*	Al *mg kg^{-1}*	Mn *mg kg^{-1}*	Zn *mg kg^{-1}*	pH
CHEMICAL	***R Mean***	*8.29A*	*10.11A*	*45.84A*	*181.42A‡*	*3581.21A*	*1.4A*	*7.38A*	*14.11A*	*0.41A*	*7.93A*
	H Mean	*6.22A*	*8.58A*	*25.72B*	*145.16B‡*	*3592.02A*	*1.16A*	*7.89A*	*13.22A*	*0.39A*	*7.92A*
No Till (NT)											
	Stover returned (R)	9.95a	10.25a†	47.57a	207a	3575.97a	1.12a	6.01b	13.21ab	0.49a	7.83b
	Stover harvested (H)	6.79a	7.55a	26.6b	146.18b	3379.58a	1.07a	7.44ab	11.43b	0.47a	7.79b
	NT Mean	*8.37A*	*8.9A*	*37.09A*	*176.59A‡*	*3477.77A*	*1.09A*	*6.73B*	*12.32B*	*0.48A*	*7.81B*
Plow Till (PT)											
	Stover returned (R)	6.63a	9.96a	44.1a	155.84b	3586.46a	1.69a	8.75a	15.01a	0.33a	8.04a
	Stover harvested (H)	5.65a	9.6a	24.83b	144.15b	3805.57a	1.25a	8.34ab	15.01a	0.32a	8.06a
	PT Mean	*6.14B*	*9.78A*	*34.47A*	*150B‡*	*3696.02A*	*1.47A*	*8.55A*	*15.01A*	*0.32B*	*8.05A*

		OM *%*	$Nem_{Parasitic}$ *#/100 g soil*	$Nem_{Beneficial}$ *#/100 g soil*	Decomp *% wk^{-1}*	PMN *µg g^{-1}wk^{-1}*	EEG *mg g^{-1} dry soil*	TG *mg g^{-1} dry soil*
BIOLOGICAL	***R Mean***	*4.71A*	*50A*	*408A*	*5.95A‡*	*1.6A*	*1.47A*	*5.46A*
	H Mean	*4.35B*	*68A*	*728A*	*2.54B‡*	*1.1A*	*1.11B*	*4.56B*
No Till (NT)								
	Stover returned (R)	5.39a	80ab	320a	8.93a	1.73a	1.73a	6.63a
	Stover harvested (H)	4.99a	125a	1140a	2.45b	1.65a	1.12b	4.9b
	NT Mean	*5.19A*	*103A*	*730A*	*5.69A‡*	*1.69A*	*1.42A*	*5.76A*
Plow Till (PT)								
	Stover returned (R)	4.02b	20b	495a	2.98b	1.48a	1.21b	4.29b
	Stover harvested (H)	3.71b	10b	315a	2.63b	0.55a	1.09b	4.21b
	PT Mean	*3.87B*	*15B*	*405A*	*2.8B‡*	*1.01B*	*1.15B*	*4.25B*

† means of each property followed by the same lower case letter are not significantly different at the $\alpha = 0.1$ level based on a Tukey's test of fixed effects in a mixed model. Capital letters show significance of overall tillage and residue management comparisons.

‡ means comparison is included despite significant tillage x harvest interaction.

harvest also decreased AWC (by 8%), Decomp (by 57%), and EEG and TG (by 25% and 16%, respectively). Soils under H were denser, with ρ_b increased by 5%, and K and Mg concentrations decreased by 44%, and 20%, respectively.

When comparing residue management effects within each tillage treatment, most of these properties showed significant effects of stover harvest under NT. In addition, aggregation (WSA) was significantly less stable under NT-H than NT-R. However, under PT, only K concentrations were significantly lower when stover was harvested. Other indicators were not significantly different between PT-R and PT-H, but did show similar though non-significant trends with respect to residue treatment as under NT.

2.5.2. Comparison of residue and tillage effects

Of the soil properties that were affected by both tillage and residue treatment, the majority changed more dramatically due to tillage than due to stover harvest. For example, we measured a 5% difference in ρ_b when stover was harvested, whereas tilled soils (PT) were 10% denser, relative to NT soils ((NTmean – PTmean)/NTmean). Available water capacity decreased by 13% (vs. 8% due to H), OM by 25% (vs. 8% due to H), TG by 26% (vs. 16% due to H), Mg contents by 15%, Decomp by 51%, and EEG by 19%. Other soil properties also showed significant differences between tillage treatments (Table 2.2): WSA decreased by 62% under PT relative to NT, PMN by 40%, NO_3-N by 27%, and Zn by 33%. This experiment was planted on a calcareous, alkaline soil, and overall pH was higher, i.e. more alkaline under PT (8.05) compared to NT (7.81). Higher Al by 27%, higher Mn by 18% and 85% fewer $Nem_{Parasitic}$ were also found under PT.

2.5.3. Combined effects

When indicator means were compared separately by tillage and residue treatment, two trends stood out. The most common trend was characterized by soil property means either decreasing, in the order as follows: NT-R_{mean} > NT-H_{mean} > PT-R_{mean} > PT-H_{mean}, or increasing in the same order (NT-R_{mean} < NT-H_{mean} < PT-R_{mean} < PT-H_{mean}; Fig. 2.2). These trends were observed for WSA, AWC, ρ_b, OM, TG, PMN, NO_3-N and Zn. The less common trend was characterized by decreasing means in the order as follows: NT-R > PT-R > NT-H > PT-H, which was observed for Decomp, EEG, K, and Mg (Fig. 2.3).

Table 2.3 contains the number of physical, chemical and biological soil properties affected by residue management for three agronomically relevant management comparisons tested: 1) stover returned (R) vs. harvested (H) under NT, 2) R vs. H under PT, and 3) R under PT vs. H under NT. Under NT, 7 soil properties showed significantly lower values due to stover harvest (WSA, AWC, K, Mg, Decomp, EEG, TG). In contrast, only one soil property (K) was significantly lower due to stover harvest under plow tillage. Six soil properties were significantly different between PT-R and NT-H. WSA, OM, and $Nem_{Parasitic}$ were lower in PT-R, while pH, K, Mn were higher. We also note that ten soil properties were significantly different between the two extremes of management, PT-H and NT-R. The WSA, AWC, K, Mg, OM, Decomp, EEG, and TG were lower in PT-H, while ρ_b and pH were higher.

2.6. DISCUSSION

2.6.1. Soil properties as indicators of soil quality

Soil properties were used as indicators of soil quality. They were interpreted to reflect higher soil quality when they suggested better functioning of soil processes,

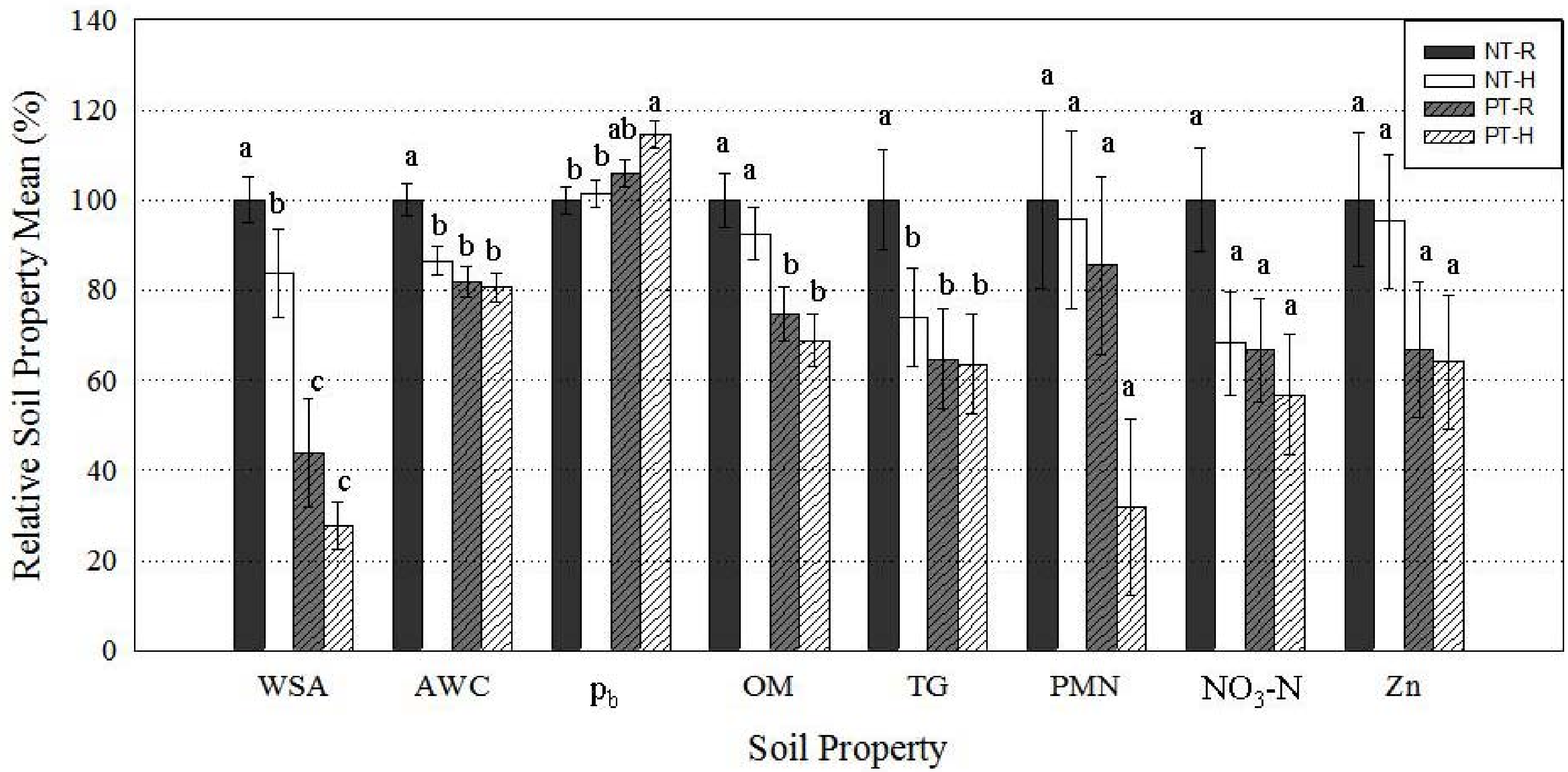

Figure 2.2 Means of soil properties, which show the trend NT-R > NT-H > PT-R > PT-H or NT-R < NT-H < PT-R < PT-H, shown relative to the NT-R treatment mean (defined as 100%). Error bars designate one standard error.

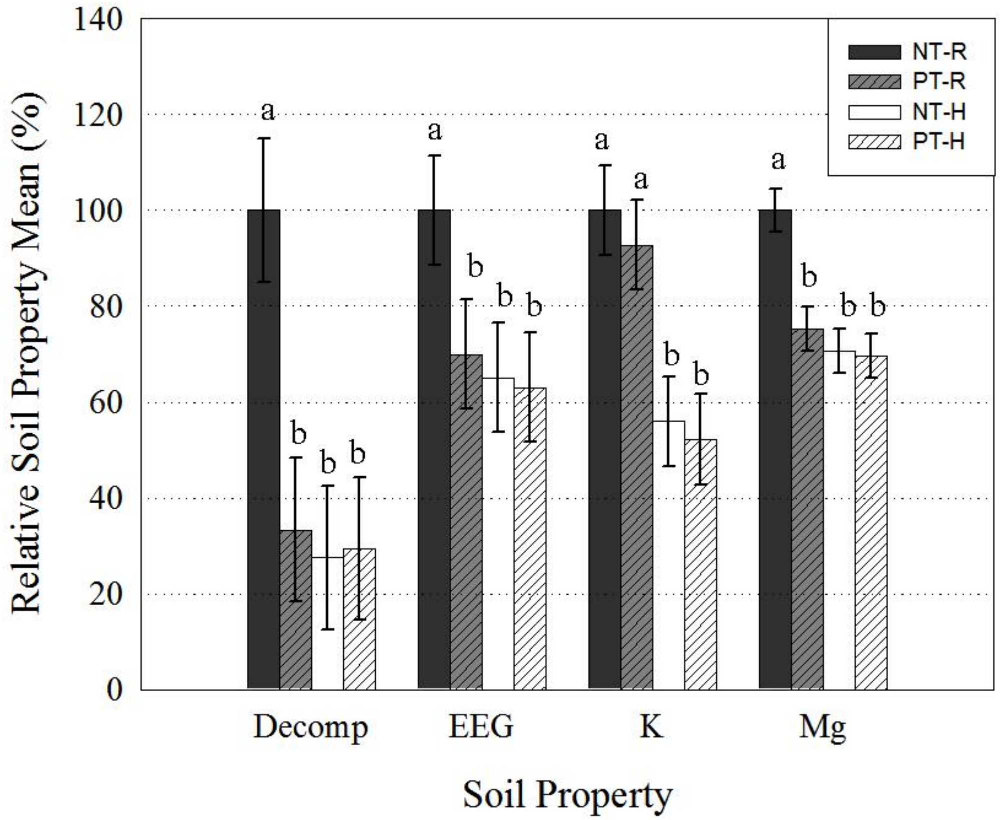

Figure 2.3 Means of those soil properties, which show the trend NT-R > PT-R > NT-H >PT-H or NT-R < PT-R < NT-H < PT-H, relative to the NT-R treatment mean (defined as 100%). Error bars designate one standard error.

Table 2.3 Comparison of management scenarios with and without stover harvest

Management Comparison	Number of Significant Differences † Physical	Chemical	Biological	Total number of differences
1. In No Till, Stover Returned (A), vs. Stover Harvested (B)	2	2	3	7
2. In Plow Till, Stover Returned (A), vs. Stover Harvested (B)	0	1	0	1
3. In Plow Till Stover Returned (A), vs. in No Till Stover Harvested (B)	1	3	2	6

with respect to crop production. Sojka and Upchurch (1999) argued that the optimization of processes may require different interpretations of soil quality indicators for the different soil functions. Our approach gets around that issue by placing the emphasis on the value of the information itself, rather than broader interpretation within an evaluation framework or index. Indicators identify soil constraints and relative differences between management scenarios and thus help select management solutions.

The 25 soil properties measured in this experiment represent a wide range of physical, chemical and biological soil processes (Andrews et al., 2004; Doran and Parkin, 1994; Karlen et al., 1994; Larson and Pierce, 1991) that are essential for crop growth. Represented processes include physical root proliferation and movement of soil organisms (ρ_b, PR); chemical buffering (pH); organic matter decomposition (pH, Decomp); macro- and micro- nutrient mineralization, retention and availability (pH, PMN, Decomp, nutrient concentrations); toxicity and pollution prevention (nutrient concentrations, OM, pH); pest suppression ($Nem_{Parasitic}$ and $Nem_{Beneficial}$); energy and carbon storage (OM, TG, EEG); soil structural stability and runoff/erosion prevention (WSA); aeration (WSA, ρ_b, PO > 1000, PO > 30); water retention (AWC); and water infiltration and transmission (lnInfilt, lnK_s, WSA).

Some measured soil properties were too variable or narrow in range to reflect management-induced changes. Penetration resistance, lnK_s and PO > 1000 were considered highly variable in other studies (Moebius et al., 2007; Munoz-Carpena et al., 2002; van Es, 2002), as were PO > 30 and lnInfilt in this experiment. Free-living nematodes generally increase under higher OM contents and decomposition rates (Ferris and Bongers, 2006), however, these processes are slow early in the season. Counts of $Nem_{Beneficial}$ thus may not have shown differences among treatments because of sample timing. Phosphorus, Fe and Ca (high due to calcareous soil type) showed neither treatment effects (Table 2.2), nor deficiencies or toxicities (CCE, 2007).

Remaining soil properties were sensitive to management, and were thus used as indicators of soil quality. Their values were interpreted based on mechanisms and trends discussed by Andrews and Carroll (2001), Arshad and Martin (2002), and Larson and Pierce (1991) among others, to assess the effects of residue and tillage management on soil quality. These indicators fit into two groups for the purpose of assessing the effects of treatments on soil quality. Some generally imply improved soil quality when their values increase; these include WSA, AWC, OM, Decomp, PMN, EEG, TG, N, K, Mg, and Mn. No toxic or excessive levels (CCE, 2007) occurred in our data. Other indicators generally imply improved soil quality when their values decrease; these include ρ_b, Al, and $Nem_{Parasitic}$. For the alkaline Raynham silt loam used in this experiment, pH was also included in this category, as lower pH soils are closer to neutral for this site, and therefore closer to ideal for maize growth.

2.6.2. Residue management effects

Several indicators reflected a decrease in soil quality after 32 years of stover harvest. However, under PT, only K was significantly different between R and H. Residue management treatments resulted in greater soil quality differences under NT (Table 2.2).

The most significant overall differences between residue treatments were found in the K and Mg contents ($\alpha \leq 0.01$, Table 2.1). Potassium contents in maize stover generally range from 7.5 to 24.9 g K kg^{-1}, and Mg contents from 1.2 to 3.3 g Mg kg^{-1} (DairyOne, 2006; Mubarak et al., 2002). Thus, presumably, long-term harvest resulted in the nutrient deficit we observed. Average K contents found under H (Table 2.2) were classified as "low" (CCE, 2007), while those found under R were classified as “medium.” However, Mg was in the “very high” range (CCE, 2007) for both residue management treatments. Thus, the difference in K was agronomically meaningful, while that in Mg was not.

Decomp was significantly higher under NT-R than under the other treatments (Fig. 2.3). Deng and Tabatabai (1996) found the same trends in cellulase activity. Decomposition of cellulose filter paper is indicative of cellulase activity (Sharrock, 1988) and of the capacity of the soil microbial community to decompose high-cellulose plant residues. Microbial communities that can decompose cellulosic residues are favored in environments where there is continuous input of such materials, e.g. when crop residues are returned and remain on an undisturbed surface.

Both EEG and TG were highest under NT-R. The EEG and TG fractions of glomalin are measures of heat-stable soil proteins that can be extracted by autoclaving soil in a citrate buffer. Some authors have proposed that glomalin is produced by arbuscular mycorrhizal fungi (e.g., Wright and Upadhyaya, 1998), however, Clune (2007) found that it is more likely derived from fresh residues and accumulated soil organic matter from various sources.

Overall, stover harvest resulted in denser (ρ_b) soils that were less ideal for rooting, and stored less water (AWC). Higher soil density was presumably the result of lower aggregation and structural stability (WSA), which in turn may have resulted from lower organic matter fractions (OM, EEG and TG). Blanco-Canqui (2006a; 2006b) found similar trends in ρ_b, soil organic carbon (SOC) and WSA, as well as inverse relationships between ρ_b and SOC, and positive correlations between WSA and SOC, as a result of residue harvest in a one-year study under no till management. Impacts of stover harvest were significant in only some of these indicators under NT, but not in any of them under PT, consistent with observations in similar climates by

Dick et al. (1998), Clapp et al. (2000), Reicosky (2002) and numerous studies reviewed by Wilhelm et al. (2004).

It has been suggested that root residues play a larger role in increasing SOC than shoot residues, because roots are continuous sources of C inputs via exudates and fine root turnover, are more recalcitrant due to their composition, and are better protected within aggregates (Puget and Drinkwater, 2001). Hooker et al. (2005) found that, overall, when residues were returned, 85 to 88% of the carbon added to soil over a 28 yr period was lost, while only 59 to 72% was lost when residues were harvested. They suggested that more rapid cycling of above- vs. below-ground biomass back to the atmosphere may mean that long-term annual return of residues does not significantly add to long-term soil C storage. Similarly, our data suggest that soil quality declines were small in response to long-term stover harvest, especially when roots were disturbed under plow-till management.

2.6.3. Comparison of residue and tillage effects

Intense soil mixing from conventional tillage causes rapid loss of soil organic matter and degrades soil structure (Moorman et al., 2004). Campbell et al. (1991) found no difference in SOC for conventionally tilled plots when spring wheat straw was harvested or returned for 30 yrs, suggesting that intensive tillage combined with incorporating residues may stimulate organic matter decomposition. This may explain why significant negative effects of stover harvest were more strongly expressed under NT.

Overall, OM was significantly reduced by stover harvest, but tillage effects were greater. NT soils were also less dense before tillage. It should be noted that even immediately after tillage, in June, PT soils were not significantly less dense (Moebius et al., 2007), and they subsequently resettled throughout the season. The NT soils were capable of holding more water, and were likely to be more resistant to erosion and drought conditions. They had higher WSA values, with a factor of 3.6 between treatments of highest (NT-R) and lowest (PT-H) soil quality (Table 2.2, Fig. 2.2). These impacts on soil processes were also observed in the field during sampling. It was noted that soil in plots under PT were crusted, sealed, cracked, compacted, and lacking aggregation, suggesting erosion was taking place, while this was not observed for soils under either residue management in NT soils. Higher aggregate stability under NT has also been reported in reviews by Amezketa (1999) and Carter (2002), among others. In a similar experiment by Hooker et al. (2005), SOC in the top 15 cm was not significantly affected by residue harvest within tillage treatments, but tillage effects were significant regardless of residue management.

While several indicators showed statistically significant differences due to tillage, only some of these may be agronomically meaningful, because others were either at sufficient or normal levels (e.g., Al, Mn, Mg) or not at damage threshold densities (e.g., $Nem_{Parasitic}$) across the experiment, irrespective of treatment.

Measured Zn levels (Table 2.2) span the "medium" range (CCE, 2007). The lower pH (closer to neutral) found under NT-H, in this calcareous, alkaline soil indicates better buffering, presumably due to higher organic matter content and increased biological activity. Thus both lower Zn availability and higher, more alkaline pH measured under PT could be agronomically meaningful.

The higher available NO_3-N and higher potential mineralization of N (PMN) may also be agronomically significant. Soil mineral N is highly dynamic throughout the season, with most mineralization from organic matter in humid temperate climates occurring in the early to late spring, thus accumulating just before the rapid growth stage of maize (van Es et al., 2007). The static NO_3-N observed in April was 36% higher under NT than under PT. Early season differences, before much N-mineralization had likely occurred, in conjunction with higher mineralization potential and higher organic matter under NT, suggest that the NT system is likely capable of supplying more seasonal N than the PT system. Potentially mineralizable N, available N and Zn, increased with treatments following the same trend as other agronomically significant indicators such as ρ_b, AWC, WSA, OM and TG (Fig. 2.2). Overall, the trend exhibited by all indicators illustrated in Fig. 2.2 suggests that declines in soil quality were far greater in response to tillage than to stover harvest, consistent with findings of Hasche et al. (2003), Wilhelm et al. (2004), Wilson et al. (2004), and Hooker et al. (2005).

Hooker et al. (2005) also showed that, in NT systems, relic C3-C from forest vegetation had a much longer half-life, meaning that old C decomposed much faster in plowed systems, while residue inputs hardly affected this process. Recently introduced maize-derived C4-C, on the other hand, was more influenced by residue management than by tillage (Hooker et al., 2005), showing the same trend as the indicators Decomp, K, Mg, and EEG in our experiment (Fig. 2.3), which relate to processes involving newly added C. It is arguably more important to retain relic C3-C within already established soil aggregates, than to add new C4-C, while losing a larger quantity of relic C (Six et al., 1999).

2.6.4. Management strategies for sustainable use of maize residue

This experiment allows for three explicit, practical and relevant comparisons between H vs. R management scenarios and the evaluation of their relative soil quality impacts (Table 2.3). These are: 1) the effect of a change to stover harvest under PT, 2) the effect of the same change under NT, and 3) the effect of a change to stover harvest concurrently with a transition from PT to NT.

The K deficit under PT-H, brought about by harvesting large quantities of biomass for 32 years, could be remedied with appropriate amendments, and would thus not harm long-term soil quality. However, residue harvest under PT resulted in the lowest overall soil quality of all treatments (Fig. 2.2 and 2.3), and could thus be considered the least sustainable stover harvest option. Soil quality was, comparatively, more seriously degraded with stover harvest under NT management, as shown by seven significant differences in indicator values, but overall soil quality under NT-H was still considerably higher than when stover was harvested under plow-till.

A third option for a plow-till grower is to offset the negative effects of stover harvest by making the transition to NT management. Six indicators showed significant differences in this comparison. The PT-R soils had higher K and Mn, and fewer $Nem_{Parasitic}$. However, the aspects of soil quality improved by PT-R were not agronomically meaningful, since K deficits can be readily addressed by fertilizing, and differences in Mn and $Nem_{Parasitic}$ would not affect crop production. The NT-H soils had a lower (more neutral) pH, higher OM (by 24%), and higher WSA (by 91%) than PT-R. In addition, it is noted that most non-significant trends (e.g., for ρ_b, AWC, and TG; see Fig. 2.2) are similarly more favorable for NT-H. Overall, these results suggest that simultaneously converting to NT while initiating stover harvest may alleviate most concerns related to soil quality degradation, and may even improve some aspects of soil quality.

This experiment did not allow for erosion to be measured directly, although WSA represents this process indirectly. Erosion is a concern when residues are harvested at the landscape scale and on slopes (Govaerts et al., 2006a; Graham et al., 2007; Lal, 2005; Lindstrom, 1986; Nelson, 2002; Wilson et al., 2004) and thus remediative practices should be considered. Partial residue harvest was not addressed in this study, but is discussed at length by Graham et al. (2007), among others. Other options, such as cover cropping or harvesting of perennial crops, were explored by Lemus and Lal (2005), McLaughlin and Walsh (1998), and Tilman et al. (2006) among others.

In a similar set of treatments in the semi-arid, sub-tropical highlands of Mexico, NT-H actually resulted in the lowest soil quality (Govaerts et al., 2006a), likely due to more easily erodible soil types, higher intensity rains and faster degradation of organic matter in this climate. However, in a temperate climate, erosion from plowed plots has been found to be significantly greater than from NT plots, whether residues were harvested or not (Dabney et al., 2004; Hasche et al., 2003).

2.7. CONCLUSIONS

Results of this study provided insights into the effects of long-term removal of maize stover on soil quality, relative to the effects of tillage, in a temperate humid climate. Adverse effects were observed from 32 years of stover harvest for 8 of 25 soil quality indicators (ρ_b, AWC, Mg, K, OM, Decomp, EEG, and TG). Tillage, in contrast, adversely affected 15 indicators (ρ_b, AWC, Mg, OM, Decomp, EEG, TG, WSA, N, Al, Mn, Zn, pH, $Nem_{Parasitic}$, and PMN). Most indicators that were affected by stover harvest (all except K, Mg and EEG) were affected equally or more strongly by tillage.

Not tilling significantly improved many soil processes, as measured through soil quality indicators, irrespective of residue treatment. Stover return provided additional (although smaller) soil quality benefits, especially with respect to several organic-matter-dependent soil processes. This resulted in improved soil structure and stability, water storage capacity, carbon storage, cellulose decomposition potential, and nutrient availability.

Stover harvest had a greater effect on soil quality under a NT system compared to PT, but overall soil quality was much lower in the PT systems. This suggests that: 1) the beneficial effects of stover return are greater under NT, presumably because the organic residues decompose more slowly, and 2) despite its relative impact on soil quality, stover harvest is more sustainable under NT than under PT. This study did not, however, evaluate the effects of stover removal on erosion, which may be a concern in some maize cropping systems.

2.8. ACKNOWLEDGEMENTS

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CHAPTER 3. MOVING AUTHENTIC SOIL RESEARCH INTO HIGH SCHOOL CLASSROOMS: STUDENT ENGAGEMENT AND LEARNING[2]

3.1. ABSTRACT

Currently, most high school curricula do not effectively employ scientific inquiry-based teaching and learning about the nature of science, nor do they include explicit lessons in soil science. Soils impact most aspects of our lives. They provide for a large number of human needs and play key roles in many natural disasters. Effective inquiry-based teaching can facilitate students in developing deep and applied understandings of human-environmental connections, and, vice versa, soil science-related topics can provide a concrete model system for learning inquiry skills. This article describes student engagement and learning resulting from an inquiry-based instructional unit collaboratively designed by a New York high school earth science teacher and a Cornell University soil science graduate student. The unit is based on authentic soil research methods. The activities engaged students in an open inquiry to learn about the concepts of water runoff from soils, infiltration into soils, and how scientists do their work. Students selected their own research questions related to runoff and infiltration, designed and conducted investigations in the classroom, and prepared presentations for their peers in their preferred presentation format. Students peer-reviewed final projects in a conference setting. The designed unit was field-tested

[2] Moebius-Clune, B.N., I.H. Elsevier, B.A. Crawford, N.M. Trautmann, R.R. Schindelbeck and H.M. van Es. Moving authentic soil research into high school classrooms: student engagement and learning. To be submitted to the Journal of Natural Resources and Life Sciences Education.

in three earth science classes. Pre- and Post-test grades, final project grades, a student survey and observations of student attitudes were used to assess student engagement and learning. Pre- to Post-test gain revealed that students learned significant amounts of unit-related science content. The mean grade for final projects was lower than that for Post-tests. Some students struggled with the open-ended and complex nature of the final projects, suggesting the need for more teacher-scaffolding. Students reported on surveys that they learned essential inquiry skills, such as designing a research experiment, engaging in teamwork as scientists do, learning from their peers and relating the concepts to real world issues. There was evidence that students were motivated, in that students enthusiastically reported enjoying the unit and the final project. One third of the students reported increased excitement about science. We conclude that this and similar inquiry-based units should be more commonly used in science classrooms, to enable students to learn how to think critically, develop collaborative team work skills, take ownership of their learning and be substantively engaged in authentic tasks applicable in later life.

3.2. KEY WORDS

Soil science; open inquiry; curriculum unit; runoff; infiltration

3.3. INTRODUCTION

Two gaps have been identified in current high school science education. First, most high school curricula do not effectively employ scientific inquiry-based teaching, and, second, explicit lessons in soil science content are rare. There is also a lack of interest in science by students, particularly in middle and high schools. Effective inquiry-based teaching can capture student interest and facilitate students in developing important skills, such as critical and logical thinking, and a deep and applied understanding of human-environmental connections. Soil science-related topics, while being important in their own right, can provide a concrete and relevant model system for learning inquiry skills. This article addresses both gaps.

Life, as we know it, could not exist without soil. Agriculture, the profession perceived to be most directly related to soil-topics, is being practiced by a shrinking percentage of the population. The average child is thus no longer growing up with an awareness of the importance of soil, as there are few other concrete ways for students to learn this. A group of 16 incoming freshman in Arts and Sciences majors at Cornell University, taking part in a New Student Reading project on John Steinbeck's The Grapes of Wrath, for example, stated that they felt no connection to agriculture (Crawford, 2009, personal communication). In higher education there has been a noticeable decline in undergraduate enrollment in soil science courses and majors, which may well be related to the limited emphasis on soil science in K-12 science classes (Collins, 2008).

Yet, the skin of the earth plays many critical roles in our ecosystems that need to be addressed in science education. Beyond providing a medium to build on, and growing the plants that provide us with food, fiber and building materials, soil mediates atmospheric composition directly and indirectly. It transmits, filters and stores water that we use daily. The below-ground parts of the water cycle that take place in the soil are often difficult for students to grasp. Students may lack an understanding of the soil beneath their feet, as a three-dimensional volume with pore spaces that can hold, move or fail to absorb water. When soils are misunderstood or improperly managed, they can lose their essential functions.

Degrading soils can, for example, pollute surface waters, or fail to take up enough rain water, such that erosion and flooding result. A rising world population is resulting in increased use of marginal farmland, encroachment on essential ecosystems, depletion of aquifers and more frequent occurrence of disasters from severe weather. It is essential that future citizens (today's high school students) develop a deep understanding of the basic functions of environmental systems, so that they will be equipped to make wise decisions about future environmental problems that arise (National Research Council, 2000).

To this end, it is an important goal of science education for all students to become "scientifically literate": to learn how to think critically and independently, reason scientifically, evaluate carefully the validity of claims and multi-media information available, logically use evidence as the basis for conclusions and decisions, and communicate scientific ideas effectively in varied settings (AAAS, 1989; National Research Council, 1996; National Research Council, 2000; Shipman, 2004). These goals are difficult to attain in the traditional classroom where the teacher's role is that of the main authority, and where students have limited opportunities to take charge of their own learning (Crawford, 2008). Students must have the chance to practice the skills that create scientific knowledge; in other words they must learn to do scientific inquiry (AAAS, 1989; National Research Council, 1996; National Research Council, 2000; Reeves et al., 2007; Rutledge, 2005).

Scientific inquiry is "what scientists and engineers do" (Shipman, 2004), as they develop scientific knowledge by asking new questions, designing experiments or organized ways of making observations of the natural world, and coming to conclusions by interpreting the results (Capps and Crawford, 2009). Scientific inquiry is characterized by critical thinking, logic, creativity, and collaboration. It is a self-correcting endeavor, because interpretations are open to public scrutiny and must be verifiable by further experimentation or observation. Essential features of inquiry, as discussed in the National Science Education Standards, include the learner being 1) involved in scientifically oriented questions, 2) giving priority to evidence in responding to questions, 3) using evidence in developing explanations, 4) connecting explanations to scientific knowledge, and 5) communicating and justifying explanations (National Research Council, 2000).

Inquiry-based teaching is instruction that reflects the nature of science and scientific inquiry and integrates these characteristics into classroom content and dynamics (Anderson, 2002; National Research Council, 1996; National Research Council, 2000). Inquiry-based classrooms are thus student-centered, rather than teacher-centered. Students collaborate in teams and engage in authentic activities (Backus, 2005; National Research Council, 1996), defined as either relating to students' lives, or being similar to what a scientist or other professional might encounter (Crawford et al., 1999). In open or full inquiry, students choose their own scientific questions, in guided inquiry student are given a question but design and conduct their own experiments (National Research Council, 2000). Students use their evidence to develop answers to their questions and debate and write about the relevance of their findings to real world issues.

An inquiry-based classroom allows both students and teachers to take on non-traditional roles (Crawford, 2000). The teacher facilitates student activities and discussions where necessary, guides and mentors student progress, and models the behaviors and attitudes of a scientist by being a collaborator with the students, an innovator, and experimenter and an active learner. Students take on roles of apprentices, experimenters, learners and collaborators, but, within their research teams also take on some of the roles traditionally reserved for the teacher, such as teacher, leader and planner. The skills needed for collaborative work are not learned individually, or abstractly, but by experiencing and developing them (Brown et al., 1989). Collaborative work in the classroom thus will teach students skills needed in the adult workplace. This approach tends to engage students substantively in their own learning, as defined by Nystrand and Gamoran (1991) to mean that they develop personal sustained commitment to understand and interact with the content matter for its inherent interest.

While inquiry usually takes more time than traditional teaching, and is often messy, it leads to a deeper understanding of the subject matter and the nature of science (Brown and Campione, 1994), and gives students ownership of their discoveries and the confidence and motivation to be curious and seek answers (Crawford, 2000). In a study by Schneider et al. (2002), students who had been taught through project-based science outperformed students taught with more traditional methods on the National Assessment of Educational Progress (NAEP). This assessment was developed by the National Center for Education Statistics as a national measurement tool of student achievement in subject areas including science. Thus, students taught using inquiry-based teaching approaches may perform better on science achievement tests in addition to gaining skills, such as reasoning, critical and creative thinking, and problem solving that are laid out in the National Science Education Standards (AAAS, 1993; National Research Council, 1996).

Despite the focus of the science content standards on inquiry, and the development of teaching standards promoting inquiry-based teaching (AAAS, 1993; National Research Council, 1996; National Research Council, 2000), there are few actual examples of effective inquiry-based teaching at the K-12 education levels. Inquiry-based instruction is still uncommon in classrooms for many reasons. It is a complex and sophisticated way of teaching that demands significant professional development (Capps and Crawford, 2009; Crawford, 2000; Crawford, 2007). Many teachers are inadequately prepared in science generally (Krajcik et al., 2000), lack effective inquiry-based teaching materials, feel pressure from time constraints due to high-stakes testing and are unfamiliar with how science is practiced (Deboer, 2004)..

This article simultaneously addresses the lack of soil science content and the lack of inquiry teaching materials for high school settings. Facilitated by the NSF GK-12 sponsored Cornell Science Inquiry Partnerships program, a graduate student researcher (the first author) and a high school earth science teacher (the second author) collaboratively designed and implemented a scientific inquiry unit in which students explore water runoff from and infiltration into soil, and the ways that human activities affect these soil-water dynamics. We adapted an experimental set-up from authentic research methods used at Cornell University to investigate runoff and infiltration (van Es and Schindelbeck, 2003a), such that it could be cheaply and easily implemented in the classroom. Our objectives were to describe 1) the field testing of the unit, 2) findings about student learning of soil science concepts and science inquiry skills, and 3) student attitudes and engagement while undertaking this unit.

3.4. MATERIALS AND METHODS

3.4.1. Unit development and field testing

For classroom instruction, we developed and field-tested a 3-week-long unit on runoff and infiltration over the course of two consecutive years. In the first year, we used portable research equipment from Cornell University (van Es and Schindelbeck, 2003a). We involved three earth science classes of mostly tenth-graders in an outdoor, guided inquiry unit, in which students were given a question and the experimental set-up.

In the second year, we modified the methods, using materials more readily available to teachers. Thus, we built multiple, smaller, indoor experimental set-ups (conceptually pictured in Fig. 3.1), using everyday equipment and materials, such as an electric drill, carpet knives, pins, milk jugs, plastic buckets, rubber stoppers, tubing, and a variety of soil materials with varying runoff and infiltration characteristics, all easily accessible to teachers. We revised the worksheets to include a more open-ended inquiry approach (Moebius and Elsevier, 2008). Forty-eight students from three earth science classes worked in teams to build some of the equipment, asked their own research questions, and designed their experiments with the available equipment. We added two further components: a final project and a conference-like peer review session. These components served to help students gain a more complete perspective on the process of developing scientific knowledge. Table 3.1 shows the sequence of lessons in this revised second year of unit development.

The students built rain-makers by adding a volumetric scale to the outside of a 1 gallon milk jug, and then poking small holes into the bottom. Rain-makers were capped at the top using rubber stoppers with movable tubes, such that the amount of rainfall per unit time could be held approximately constant (Ogden et al., 1997a; van Es and Schindelbeck, 2003a). We built soil microcosms by drilling drainage holes into the bottoms of 2-5 gallon plastic buckets, and a hole on the side of each bucket to hold a tube for diverting runoff out of the bucket (Fig. 3.1). In preparation for their experiments, students filled buckets with the soil materials they had chosen via their research proposals, up to the level of the runoff tube before making measurements.

Throughout the unit, students completed a series of worksheets to guide their inquiry, some individually, and some in teams. Students also completed journal entries, in which they answered a series of questions. These questions addressed the

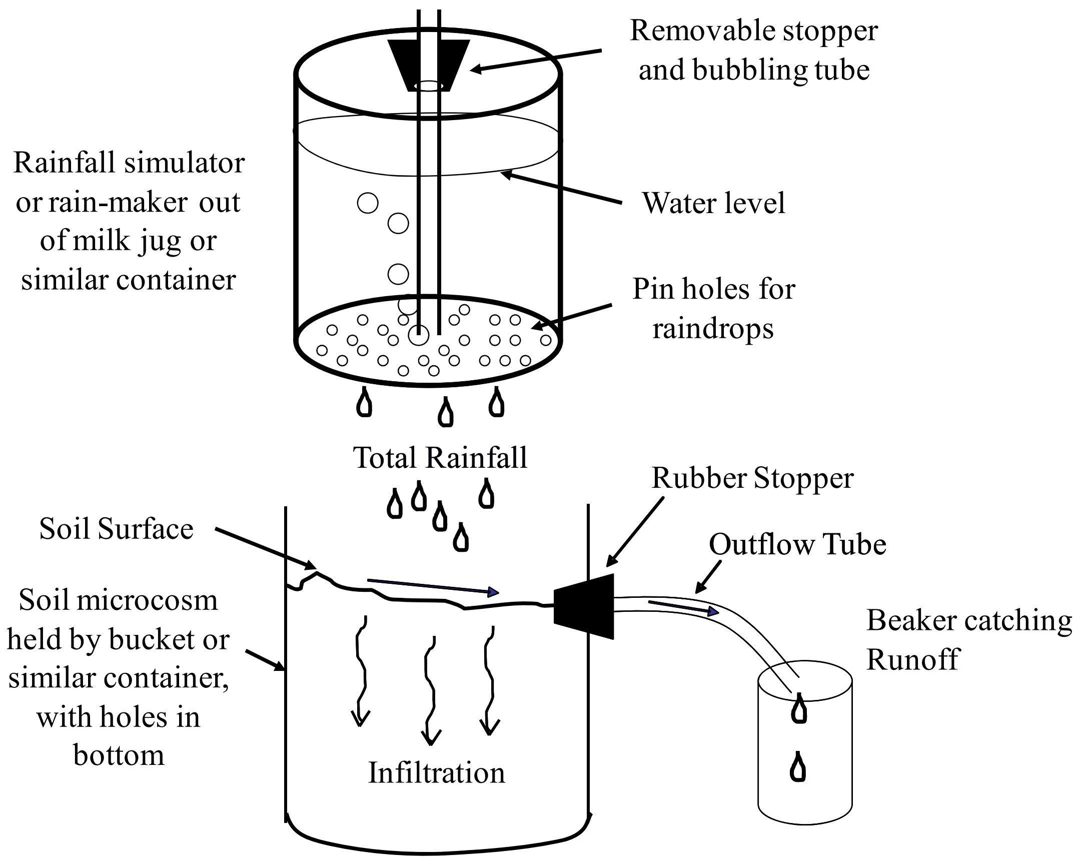

Figure 3.1 Conceptual diagram of experimental runoff and infiltration measurement set-up.

Table 3.1 Sequence of lessons in inquiry unit as field tested.

Day	Class Content
Day 1	Pre-test.
Day 2	Split classes into teams. Teams build rain-makers. Discussion of importance of precision & accuracy in tools/measurements.
Day 3	Introduction: Sponge as soil exercise, demo of rain-maker and sample experimental setup. Students share ideas/observations from journal entries. Hand out methods reading. Homework: students read methods and write in journals about what jobs these methods could be divided into in their team.
Day 4	Discussion to split methods into jobs to be performed by team members.
Day 6	Brainstorm what is in soil, discuss some runoff/infiltration related soil issues. Students rotate through about a dozen different soil materials and make observations to help visualize and decide on questions/hypotheses. In teams, students pick questions, write hypotheses, and start their research proposals. Teacher collects proposals to provide feedback. Hand out assessment rubric to students and announce project.
Day 7	Teams finish writing their research proposals, incorporating written and/or verbal feedback and information from instructors and class discussion. Teams receive final approval from instructors.
Day 8	Instructors provide all materials. Teams set up their experiments and make as many measurements as are possible in allotted time.
Day 9	Teams calculate total runoff, total infiltration, percentages, averages, and draw bar graphs of their results.
Day 10	Students finish or fix calculations and bar graphs and analyze their data, guided by the provided worksheet. Instructors discuss final project and rubric. Homework: students start their final projects.
Day 12	About one full class worth of time allotted over several days for students to work on final projects, and consult with the teacher. Homework: students finish projects.
Day 13	Hold short discussion of the role of conferences in science. Classroom conference during which each student is required to review at least three projects of their peers.
Day 14	Post-test and Student Survey.

experiment performed in class and made connections to real-world issues, similar to those suggested on the unit website (Moebius and Elsevier, 2008).

The teacher's roles included giving short lectures, referred to as "lecturettes" by Shipman (2004), as necessary, to introduce each day's activities, summarize learning, draw connections to real-world events and scientific processes, or clear up common misunderstandings. Other roles of the teacher were those of mentor and collaborator, etc. as described by Crawford (2000). To help students develop their final projects, they received a list of final project options, including writing a research report or a letter to a curious friend, or designing a poster or cartoon etc., and the option to propose their own idea for the project. Students also received a list of required project components and an assessment rubric by which their projects were then graded (Fig. 3.2). After students finished their final projects, a class conference was held, during which students read and answered questions about several of their peer's final projects posted around the classroom. All teaching materials were updated using student feedback and experience from the second year field-testing of this unit and were made available online (Moebius and Elsevier, 2008).

3.4.2. Student assessment and survey

We administered a Pre- and Post-test to all students (Appendix A). The tests included questions related to water runoff and infiltration, taken from old Regents exams (NY State Education Department, 2009), and questions we designed. Most Post-test questions were identical to those on the Pre-test. Final projects were graded using the provided rubric. We also administered a student survey (Appendix B), in which students reported agreement or disagreement with a series of statements designed to assess their self-reported ability to carry out various aspects of scientific

CATEGORY	Points: 4	3	2	1
Required Elements present?	All required elements are present.	One required element is missing.	Two required elements are missing.	Several required elements are missing.
Question/ Purpose	The question is clearly identified and stated.	The question is identified, but is stated in an unclear manner.	The question is partially identified, and is stated in an unclear manner.	The question is wrong or not stated.
Experimental Hypothesis	Independent and dependent variables are accurate and the predicted results are stated, the explanation is clear and accurate based on what has been studied.	The variables and the predicted results are stated but explanation is unclear or not quite logical.	The variables and the predicted results are stated, but not explained.	No hypothesis has been stated.
Procedures	Procedures are reported clearly, accurately and in logical order.	Procedures are reported mostly accurately, and somewhat clearly but may lack logical order or are difficult to follow.	Procedures are reported but do not accurately report the steps of the experiment or are missing important pieces.	Procedures are missing.
Drawings/ Diagrams	Clear, accurate diagrams are included and make the experiment easier to understand. Diagrams are labeled neatly and accurately.	Diagrams are included and are labeled neatly and accurately.	Diagrams are included and are labeled, but important labels are missing or inaccurate.	Some needed diagrams are missing.
Results	Concise, clear and accurate statement of what the results were.	Accurate statement of what the results were.	Statement of results included.	Missing statement of results.
Graphs	Clear, accurate graphs illustrate the results well and are labeled neatly and accurately.	Clear, accurate graphs are included and are labeled.	Graphs are included and are labeled but may be missing important labels or have some inaccuracies.	Graphs are missing OR mostly inaccurate.
Calculations	Example calculations are shown and the results are correct and labeled appropriately.	Some calculations are shown and the results are correct and but labels are not clear.	Example calculations are shown but results are inaccurate and/or significantly mislabeled.	No calculations are shown.
Analysis	The relationship between the variables is discussed and logically analyzed. Predictions are made about what might happen if part of the experiment is changed or the experimental design changed.	The relationship between the variables is discussed and logically analyzed, no further predictions are made.	The relationship between the variables is discussed but not analyzed, no predictions are made based on the data.	The relationship between the variables is not discussed.
Error Analysis	Experimental errors, their possible effects, and ways to reduce errors are discussed.	Experimental errors and their possible effects are discussed.	Experimental errors are mentioned.	Experimental errors are not mentioned.
Scientific Concepts	Report illustrates an accurate and thorough understanding of scientific concepts and relevance/implications of results to real-life situations.	Report illustrates an accurate understanding of most scientific concepts and relevance/implications of results to real-life situations.	Report illustrates a limited understanding of scientific concepts underlying and relevance/implications of results to real-life situations.	Report illustrates inaccurate or lacking understanding of scientific concepts and relevance/implications of results to real-life situations.
Appearance, Organization, Language	Typed and uses headings and subheadings to visually organize the material. Contains almost no errors.	Neatly handwritten or typed and uses headings and subheadings to visually organize the material. Contains one or two errors.	Neatly written or typed, but formatting does not help visually organize the material. Contains errors.	Looks sloppy, with cross-outs, multiple erasures and/or tears and creases. Contains multiple errors.
Total Points Earned out of 48 possible:				

Figure 3.2 Final project grading rubric for runoff and infiltration investigation.

insights into her students' learning, behavior and attitudes, beyond the quantitative inquiry, their perceptions of learning from peers, and the extent to which they enjoyed the unit.

3.4.3. Education research design and data sources

The research design used a mixed methods approach, including quantitative Pre- and Post- science content tests and responses to a partially open-ended student questionnaire, which elicited their reactions to the new unit (Creswell, 1998; Miles and Huberman, 1994). Additional data included students' final projects and the authors' journal entries written after each lesson. At the end of the unit we also solicited feedback from the teacher regarding necessary unit design changes and observations of student attitudes, engagement and abilities. The teacher shared her data, as she had known these students and observed them during regular class and laboratory work for 8 months prior to teaching this unit.

3.4.4. Data analysis

Identical Pre- and Post-test questions were used to calculate a Pre- and Post-test grade (%) for each student (n = 48) and descriptive statistics for the total test score, for the subset of Regents-only questions, and for the subset of non-Regents-only questions. A one-tailed paired t-test of students' Pre- and Post-test grades was used to determine whether overall test scores had improved for each grouping of test questions (gain). We ranked questions from most to least net student improvement. Descriptive statistics for final project grades (n = 27), as well as regression r^2 values for final project grades vs. test scores and test gains were determined.

The Wilcoxon signed-rank test (Darlington, 1996) was used to assess average agreement or disagreement with each of the survey statements. Average rank scores were compared to the neutral H_o of X = 2.5, and a table of Wilcoxon p's was used to determine statistical significance (Darlington, 1996). Open-ended survey questions ("I especially liked" and "Suggestions for improvement") were analyzed by coding (Creswell, 1998; Strauss and Corbin, 1990). Categories were determined from student responses while reading their comments. The number and percentage of students fitting into each category was determined.

3.5. RESULTS AND DISCUSSION

3.5.1. Pre- and Post-tests

Pre- vs. Post-test results (Table 3.2, Fig. 3.3) indicate that the average student performed better on the Post-test. These results suggest that most students learned a significant amount of science content material. A large number of students may have known some of the material well enough to excel at the Pre-test (average of 62%, and maximum of 98%), in part because the high school is in an agricultural area and thus more students are likely to be somewhat knowledgeable about the concepts addressed by this unit. However, even with relatively high Pre-test scores, total test score average increased by 17%, while the standard deviation, i.e., the gap between most and least knowledgeable students, decreased.

Regents Pre-test scores were higher than non-Regents scores, and percent gains were greater in the non-Regents questions (20%) than for Regents questions (15%). There may be several reasons for this: Many students have a keen ability to read and eliminate multiple choice options, allowing for better Regents Pre-test scores, while others come without these skills. Conversely our own questions applied more directly to unit activities, allowing for greater improvement on non-Regents questions.

Table 3.2 Pre- and Post-test score (%) outcomes, n = 48.

		Pre-test	Post-test	Gain
Total Test				
	Avg †	62	80	17***‡
	stdev †	21	12	19
	min †	10	40	-24
	max†	98	100	71
Regents				
	Avg	65	82	15***
	stdev	23	16	21
	min	0	31	-31
	max	100	100	77
Non-Regents				
	Avg	55	75	20***
	stdev	27	16	30
	min	0	25	-50
	max	100	100	94

† Avg = average, stdev = standard deviation, min = minimum score, max = maximum score

‡ All gains were significant with a one-tailed paired t-test at $\alpha < 0.0005$ (***).

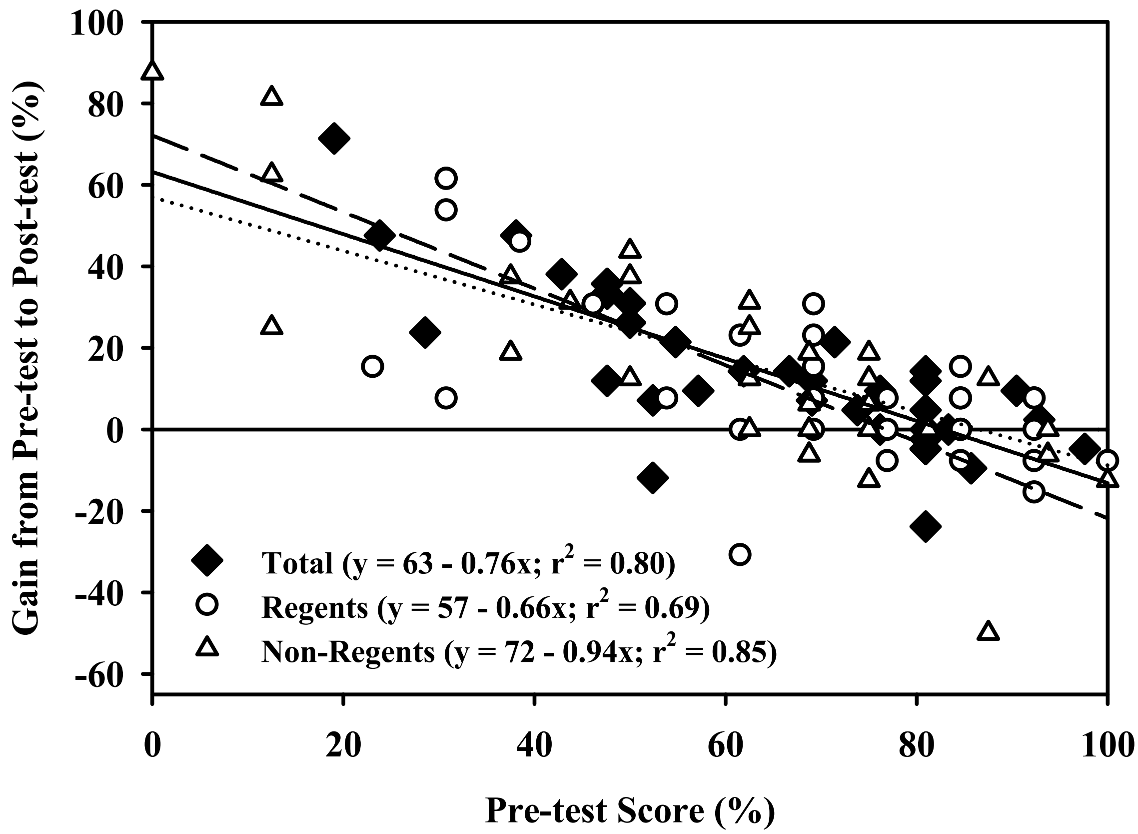

Figure 3.3 Gain from Pre-test to Post-test vs. Pretest Score, with linear regressions for total scores (solid line), regents scores (dotted line) and non-regents scores (dashed line).

A net 20 to 33% of students improved their answer to each of 7 out of the 17 questions on the Post-test (Table 3.3). Three out of the four non-Regents short answer questions were among the most improved questions. Two of these asked for a real world implication of water runoff and infiltration, one required an understanding of the water cycle. These questions required fairly simple short answers. The fourth short-answer question tested students' knowledge of observation and inference. This required a more sophisticated answer than any of the other questions, and seemed to be a difficult concept for the students to grasp. These concepts would need more discussion in class.

One might underestimate the importance of these findings, and expect students to gain more understanding in any unit that is taught. However, these results are quite significant, as the experienced teacher in this study said, "If a quarter of your students have improved on anything, then you've done a really good job in education."

Several questions resulted in lower improvement rates. Only 6 - 18% of the students improved their answers to each of the remaining 10 questions. One explanation is that Regents questions used vocabulary that we neglected to define during this unit (such as "permeability" and "impermeable"). Some questions required especially careful reading, or a mixing of concepts that may have been more difficult. It should be noted also that we did not prepare students for specific types of test questions during this unit.

Overall, 6 to 33% of students improved their understanding of every question asked on the test, with all but two questions showing improvement by 10% or more of the students. Most remaining students began with the right answers, whether from guessing or from prior knowledge is hard to tell, and thus could not have improved. However, seven out of 48 students (15%) picked enough wrong answers on the Post-test to receive lower Post-test scores than Pre-test scores (Fig. 3.3). This may be

Table 3.3 Total increase from all classes in the net % of students that improved their answer for each question (Gain) from Pre- to Post-test (Appendix A), given in order from highest to lowest improvement by question. Letters designate short answer questions we designed, numbers designate Regents questions.

Test Question #	**Net % Students with Gain**	**Question topic**
9	33	Choosing condition causing increased surface runoff
B	28	Giving example of positive effect of infiltration
A	24	Naming 3 places where runoff goes
8	24	Choosing situation with greatest surface runoff
11	24	Choosing graph relating particle size and infiltration
C	22	Giving example of negative effect of runoff
12	20	Relating particle size and infiltration
7	18	Choosing condition to produce most runoff
2	16	Relating runoff and infiltration in graph
D	16	Defining difference between observation and inference
1	14	Relating infiltration to saturation and permeability
6	14	Choosing runoff results with defined surface characteristic
5	12	Applying relationship between runoff and infiltration numerically
10	12	Choosing probability of flooding related to runoff
13	10	Relating infiltration to type of particle size mix
4	8	Relating infiltration to multiple concepts (particle size, slope, permeability)
3	6	Relating slope and permeability to infiltration

attributed to apathy sometimes found in high school students, or changes in health .status. Seven students (15%) with pretest scores of less than 30% improved by more than 50% (Fig. 3.3), showing that this unit had the potential to significantly improve student understanding of the subject matter.

3.5.2. Final projects

Interestingly, final project scores on average were much lower than Post-test scores (Avg of 61%, with a stdev of 14%, min of 31% and max of 81%), despite a clearly laid out grading rubric (Fig. 3.2) that students received far in advance. This indicates that this kind of exercise is much more challenging for students than a standardized test, even for the academically strong students. The final project was a difficult task, demanding organization, critical thinking, reasoning, synthesis, evaluation and expression of concepts based on an understanding of the nature of science, on a much higher level than multiple choice or short answer questions would.

Final project scores were found to be bimodally distributed. The teacher noted she has seen bimodal distributions when there is either a lack of effort or extra effort on the part of some of the students. The distribution of final scores is normal (Shapiro-Wilk test, $p = 0.44$, JMP Statistical Software, Version 7) when the eight students with the grades in the highest range (75 - 81%) were not included, suggesting that these eight put in extra effort beyond the remaining students. Even the projects prepared by students with the greatest effort nevertheless only met 75 - 81% of the criteria. On the lower end of the spectrum (grades of 31 - 46%) a number of projects had obviously been given very little effort.

Learning to communicate about scientific findings is often best achieved by a collaborative effort and authentic audience (Hand et al., 2004). A peer review session of draft projects might possibly have motivated the students who contributed little effort to take the rubric and final project more seriously, by providing a more authentic process and audience during project preparation. Discussion and feedback might have allowed students to develop a better ability to understand and communicate their findings in general, so that they would be more able to deliver projects that met the criteria. Assessing their peers' projects would also have allowed students to grapple with the grading rubric from the other side, before using it to finalize their own projects.

Interestingly, there was no significant correlation between the final project scores and any Pre- or Post-, total or partial test scores, with r^2 values of non-significant linear regressions ranging from <0.001 to 0.077. However, final project scores correlated inversely and significantly, though not highly, with gain in total test score ($r^2 = 0.18$, $p = 0.04$) and gain in Regents-only test scores ($r^2 = 0.22$, $p = 0.02$). The most likely explanation for decreasing final project score with increasing gain is that students who had high Pre-test scores, and therefore small gains (Fig. 3.3) were usually the academically stronger students, who were more likely to be able to complete a project that required complex and sophisticated communication.

However there were a number of students that did not fit this pattern. Some students earned high grades for both Pre- and Post-tests, yet their final project scores were among the lowest. Others had low test scores and low or negative gains, but relatively high project scores. One student managed to earn a better-than-average final project score, and improved on the test by 38%, among the larger gains. Another student who earned a high final project score had a very low Pre-test score, and only marginally improved on the Post-test.

One student in particular, had a low Pre-test score of 52%, received an even lower score on the Post-test, but had one of the highest final project scores. She is generally a poor test-taker and is therefore considered to be a poor student. The teacher commented, however, that this student knew how to read the rubric and meet the criteria. Considering this student's skills, she demonstrated better understanding of the material and what was asked of her with respect to the final project. She thus would have the potential to perform better in a work-situation than many of her peers who were better test-takers, but lacked either motivation or similar synthesis skills.

In conclusion, test scores had relatively little to do with whether a student did well on the final project. This finding may be attributed to the fact that standardized tests and short-answer questions are often poor measures of what students really understand about science. They are also a poor measure of critical thinking, the ability to synthesize data, and to communicate complex information. Students need to not only learn definitions for the vocabulary associated with the science content, but they need to understand the underlying concepts of these words well enough to use them effectively in reading, learning, applying and communicating about these concepts (Brown et al., 1989). Unfortunately, due to the current emphasis on high-stakes standardized testing, there is often little time left in the high school environment for teaching students the arguably more important skills of higher level thinking and communicating.

3.5.3. Student surveys

The results of the student surveys reveal that on average students enjoyed the unit, learned or improved useful skills and their understanding of these environmental science concepts, and were able to relate the concepts to real world issues. Furthermore, some students reported that their interest in science overall was increased. Quantitative student survey results are presented in Table 3.4. Results from qualitative, open-ended survey responses to "I especially liked…" are presented in Table 3.5, "Suggestions for improvement" in Table 3.6.

Table 3.4 Student responses to survey questions, where 1 = strongly disagree, 2 = disagree, 3 = agree, 4 = strongly agree. Significance (p) of the difference of the average student response from a neutral (neither disagree or agree) average of 2.5 was determined by a Wilcoxon signed ranks test.

Survey Question	Average	Std Dev	p	% of students who agreed	the average student…
1. After doing this soil inquiry, I think I could design other research experiments.	3.0	0.6	3.9E-07	85	...agrees
2. I learned to do the kind of teamwork that is required of research scientists.	3.2	0.4	1.3E-12	98	...agrees
3. The runoff and infiltration unit helped me understand real world issues related to soil and water.	3.0	0.6	4.7E-07	85	...agrees
4. I am more excited about science than before.	2.3	0.6	7.7E-10	33	… disagrees
5. I learned something from the other people in my research team	2.7	0.7	3.6E-02	58	...agrees
6. This experiment was more difficult than most labs.	2.1	0.8	3.4E-07	21	… disagrees
7. I enjoyed this research experiment more than most labs.	3.2	0.7	1.6E-09	88	...agrees
8. I feel good about the final project I handed in.	3.1	0.6	1.2E-09	90	...agrees
9. I learned something from seeing other people's final projects.	2.9	0.7	6.2E-07	73	...agrees
10. During this soil inquiry, I was bored more than in most classes.	1.8	0.7	1.8E-08	15	… disagrees
11. I enjoyed doing my final project.	2.8	0.7	5.1E-04	69	...agrees

Table 3.5 Coded qualitative, open-ended survey data – written responses by students (n = 48) to “I especially liked …”

Response category	No. students	% of students
Inquiry design	3	6
Hands-on work	11	23
Using equipment	19	40
Working with soil	5	10
Data analysis	2	4
Final project	4	8
Communicating science	4	8
Group-work aspects	4	8
Real world connection	1	2
Enhanced understanding	5	10
No answer	8	17

Table 3.6 Coded qualitative, open-ended survey data – written responses by students (n = 48) to “Suggestions for improvement …”

Response category	No. students	% of students
No suggestions	22	46
More time	10	21
Change set-up	7	15
Not challenging/interesting enough	3	6
Decrease lecturing	2	4
Improve explanations	4	8
Change requirements	3	6

Two statements that students overwhelmingly agreed with were that they enjoyed this research experiment more than most laboratory exercises, and that they learned to do the kind of teamwork that is required of research scientists. The teacher was surprised by how highly the teamwork statement scored. She had perceived that the team work did not go smoothly. Teams got confused, had personal issues to iron out, spilled soil and water, and made mistakes, some of which they did not recognize until later. However, it appears that in the end, students valued the importance of learning to work with their peers.

On average, students agreed that the unit helped them understand real world issues related to soil and water, one main goal we had set out to reach. Students also believed that after doing this soil inquiry they could design other research experiments. This positive attitude will be useful for those who decide to go into the sciences, and to others who will have a better understanding of the process by which scientific knowledge is developed. These results, as well as observations of student progress and interactions made by the teacher and the graduate student, indicate strongly that students were substantively engaged by the unit, as defined by Nystrand and Gamoran (1991), in part, because it contained authentic tasks, and they were able to pursue their own questions. We observed that even students who usually don't actively participate were enthusiastically engaged in coming up with a good question and experimental design.

Many students showed visible excitement with their results. For example, one student shouted in the middle of the experiment, "Look, look at how much runoff we're getting from the compacted soil!" Students even asked to be able to repeat the experiment in an attempt to get better data, when they realized they had made a mistake in their initial trial. Multiple students expressed the wish for more time to run the experiment so that they could get better data, both, during the unit and in the survey (Table 3.6). Backus (2005) found similar student engagement when students were eager to repeat a lab without procedures, incorporating peer-suggestions for improved methods.

While most students did not find this experiment more difficult than most labs, 21% of students did. Despite the presence of a large number of students who generally misbehaved in the classroom or did not seem to care about school in general, and a number of students who already knew much of the Regents-related material, most students reported not being more bored than in most classes (i.e. disagreed with #10, Table 3.4). Only seven students agreed with this survey statement. Interestingly, one of the students who reported being more bored, also, counter-intuitively, suggested more time in class. Five of these students nevertheless agreed (some strongly) with enjoying this experiment more than most labs, and 5 of these students still agreed that this unit helped them understand real world issues related to soil and water. On the other hand, we got numerous enthusiastically circled 1's (strongly disagree) to being more bored, and one student even added a 0 to emphasize how strongly they disagreed with this statement. This same student added an infinity symbol instead of circling the 4 for strongly agreeing that they enjoyed doing the final project. Students on average (69% of students) enjoyed doing their final project. Ninety percent of students reported they felt good about the final project they handed in at the conclusion of the unit.

More than half of the students (58%) agreed with the statement that they learned from the people in their research team. Most students (90%) agreed that they learned something from seeing other people's final projects, and several commented on this. The teacher observed a high level of engagement and seriousness while students were reviewing each others' projects during the class room conference. She noted that this was unprecedented in these three classes. Even several students who had neglected to finish a final project on time presented their graphs and analysis of the data via their worksheets, and were engaged in the process of reviewing others' projects. Students really took answering all review questions, mostly concerning observations and inferences made by their fellow students, seriously.

Overwhelmingly, students displayed enthusiasm and appreciation for this unit. Two students wrote notes on the backs of their surveys saying how much they enjoyed this project. As has been highlighted in some studies (Crawford, 2000; Crawford et al., 1999), it is important to allow students to choose their own questions, a characteristic of open or full inquiry (National Research Council, 2000). This was reiterated by a comment one of the students left on the back of her survey, asking "Isn't it obvious that people learn better when they make up and do a project themselves?"

Excitement about science at the high school level is often lost already, as research shows that this drops between 4th and 8th grade (Linn et al., 2000; Schmidt et al., 1999). While students, on average, disagreed with the statement that they were more excited about science than before (presumably because they either remained as excited about it as before or the unit did not change their mind), 33% of students did agree with this statement. To have had an impact on the overall interest in science of 33% of the students in these classes is, we think, an accomplishment, considering the small amount of time spent with this kind of teaching.

Students had the opportunity to write comments about what they especially liked (Table 3.5), and their suggestions for improvement (Table 3.6). Once again, in both open comment sections students' enthusiasm for various aspects of the unit was clear. In the "I especially liked:" section, only 17% of students gave no response. Whether they described it as "doing all the hands-on stuff" or "conducting the experiment" or "using the rain-makers," the majority of students commented that they enjoyed an aspect of conducting the experiment, such as the hands-on nature of the unit (23%) or some aspect of working with the equipment (40%), or working with soil (10%). Inquiry-related aspects such as inquiry design, communicating science, doing the final project, and group-work-related aspects were each mentioned by 6 to 8% of the students. Data analysis was mentioned as a highlight by two students, and 10% of students reported enhanced understanding.

Only 56% of students gave suggestions for improvement (Table 3.6). Most suggested more time should be given for the experiment itself, while suggestions to improve the set-up were given by 15% of students. Four students suggested improved explanations, two thought we should decrease lecturing time (in favor of more time for the experiment) and three students commented that the unit was not challenging or interesting enough (without specific suggestions).

A few students suggested changes in requirements and one suggested that the teacher "keep people on track." This is one of the traditional roles of the teacher, which we exercised to a lesser extent than average during this unit. Some suggestions for improvement were indicative of some interpersonal issues within teams, as were initially also present in the focus team performing inquiry that was described by Crawford et al. (1999). While many team-members were self-motivated and substantively engaged in their inquiries, some students did not take on this responsibility in the three weeks allotted for this unit. These kinds of dynamics, if explicitly discussed as authentic skills needed in science, would likely be improved over time as was the case in Crawford et al.'s (1999) focus team after about 8 weeks.

3.5.4. Future improvements of unit

The instructional team made several revisions to the unit, based on student suggestions and results from the field testing of the unit. For example students suggested a better or smaller experimental set-up. We took this suggestion seriously, because it was logistically difficult to provide and store about 70 to 130 L of wet soil per class. We also recognized that smaller amounts of soil and set-up size would likely improve the ability of teams to design better experiments. Improved experimental set-ups could be built with smaller soil microcosms (for example quart size yoghurt containers or two quart sherbet containers instead of 2-5 gallon buckets), and smaller rain-makers (two-quart soda or milk bottles or similar). Each team could thus replicate their experiment more appropriately, while using less soil than was necessary for the non-replicated experimental setup used during field testing.

One class period for the experiment was not enough time. Giving students two or possibly more periods would allow them to perform an initial trial run, reflect on needed improvements, and then gather better, replicated data. Especially if explicit discussion about the relevance of such method revisions is included in these classes, the authenticity and student involvement would likely grow (Bell et al., 2003).

We noticed while grading final projects that many students were still not making appropriate inferences, and were not making effective use of the rubric that we had laid out. The difference between an observation and an inference was explicitly reviewed before the conference that culminated the unit. However, we think that this apparently difficult concept needed to be reviewed earlier and repeated several times. Students needed the opportunity to practice applying this concept in their final project drafts, and to receive explicit feedback before submitting a final version. Several studies and reviews have shown how important explicit, as opposed to implicit, instruction is in helping students gain a better understanding of the nature of science (Abd-El-Khalick and Lederman, 2000a; Abd-El-Khalick and Lederman, 2000b; Bell et al., 2003).

A day of peer-review and teacher-feedback for drafts of final projects, including explicit discussion of the importance of peer-review, could be beneficial for student learning in this unit, as discussed above. Berkenkotter (1981) noted that "school writing stifles the development of audience representation because it precludes its necessity." This has been empirically supported by Hand et al. (2004) and Nystrand and Gamoran (1991) among others, in that written work by students was consistently of higher quality when written for audiences other than the teacher. Teachers are generally perceived as the experts who merely check for correctness, which is not very relevant or inspiring for a student. Instead, writing for peers or an otherwise interested audience that is reading to interact with the students' thoughts, is more authentic, and thus has been shown to help motivate and engage students. Incorporating the peer-review process into the middle of the unit might allow students to develop a much deeper understanding of the content, in a substantively engaging way, as they have to clarify their own understanding in order to explain it better to their peer audience (Hand et al., 2004). This process gives them an authentic experience that is very much like what they might encounter in the professional world later on. Suggested changes for the unit are reflected in the unit materials available for download online (Moebius and Elsevier, 2008).

3.6. CONCLUSIONS

Group collaboration and communication about scientific ideas in an inquiry setting, both verbally and in writing, are the backbone of science in the professional world. We showed here that students were more likely to take ownership of their learning and be substantively engaged when given authentic tasks to teach skills applicable in later life, as also shown in other studies (Backus, 2005; Crawford, 2000). The findings from this educational study strongly suggest inquiry-based teaching is an effective pedagogical approach for engaging and challenging a classroom of students with a large range of content knowledge and skill levels. In an inquiry setting, academically weaker students have the opportunity to learn from their peers through collaboration, while stronger students have the opportunity to get a deeper understanding of the subject matter and the nature of science by tutoring their peers. Even the weaker students have the opportunity to shine by providing an idea or skill that nobody else on their team may have, while all students have the opportunity to practice essential interpersonal skills.

Our unit engaged students in authentic tasks that guided their thinking and learning by undertaking scientific inquiry. Using an authentic and concretely relevant soil-related topic as a model system for this inquiry helped students make connections to real-world essential environmental concepts that affect the relationship between humans and the natural world, and allowed them to develop an in-depth, rather than superficial understanding of these. They had fun, while practicing interpersonal skills needed in the work place. Students not only valued their own accomplishments, but also those of their class mates as they took part in directing conversation and choosing what aspects of runoff and infiltration they wanted to learn more about. While this unit may be logistically more difficult to set up than average classroom activities, it has the potential to engage students in critical and independent thinking, problem solving and analysis. More importantly, students who usually did not make an effort to participate were substantively engaged in this unit. We conclude that this and similar inquiry-based units should be used more commonly in science classrooms. This will enable students to build their confidence with and excitement about science inquiry endeavors, while expanding their critical thinking and collaborative team work skills that are vital in today's work places.

3.7. ACKNOWLEDGEMENTS

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CHAPTER 4. ASSESSMENT OF LAND DEGRADATION ALONG A CHRONOSEQUENCE IN WESTERN KENYA USING AN INTEGRATIVE SET OF SOIL QUALITY INDICATORS[3]

4.1. ABSTRACT

The loss of agronomic soil functions due to soil quality (SQ) degradation significantly impacts Africa's agricultural viability and food security. We measured physical, biological and chemical soil properties as indicators of SQ, along a degradation gradient of an agricultural chronosequence experiment at the Kakamega and Nandi Forest margins in Kenya. In 2007, we sampled primary forest and fields on farms converted from forest between 1930 and 2000. On each farm two traditional long-term management systems were sampled: 1) continuous maize (*Zea mays*) in low-input monoculture (Co), and 2) a kitchen garden (Ki), where organic wastes are added regularly and diverse crops are grown in polyculture. Physical soil properties (water stable aggregates (WSA), available water capacity (AWC), and field penetration resistance in surface (PR15) and subsoil (PR45)), biological properties (permanganate oxidizable active C (ActC) and total organic matter by loss-on-ignition (LoiOM)) and chemical properties (electrical conductivity (EC), pH and P, K, Mg, Ca, Zn, Cu, S) were measured. Using these as indicators, we assessed SQ degradation differences and trends over time in Co and Ki systems on two parent materials.

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[3]Moebius-Clune, B.N., H.M. van Es, O.J. Idowu, R.R. Schindelbeck, J.M. Kimetu, S. Ngoze, J. Lehmann, and J.M. Kinyangi. Assessment of land degradation along a chronosequence in western Kenya using an integrative set of soil quality indicators. To be submitted to one of following: Soil Science Society of America Journal, Geoderma, Agriculture Ecosystems and Environment.

Exponential decay, quadratic or linear functions fit to each indicator showed significant and dramatic soil degradation over time for most indicators under Co. While SQ degraded in Ki, it did not degrade as much, and some nutrients accumulated over time. Trends in the two parent materials were similar. However, Nandi forest soils started at a higher SQ, degraded to similar low values as Kakamega forest soils with respect to some indicators, but inherent soil type differences influenced other indicator levels. Our findings indicate that appropriate management practices can minimize soil degradation after forest conversion. In conclusion, use of an integrative set of SQ indicators demonstrates physical, biological and chemical degradation after converting forest to agricultural production, with less degradation taking place in kitchen gardens.

4.2. KEY WORDS

Africa; Cornell Soil Health Test; chronosequence; deforestation; Kenya; kitchen garden; maize; soil degradation; smallholder agriculture; soil health; soil quality; soil quality assessment and monitoring; subsistence agriculture;

4.3. INTRODUCTION

Civilizations have risen and fallen on the basis of their soil's condition (Hillel, 1991; Montgomery, 2007; Yaalon and Arnold, 2000). The first Green Revolution bypassed Africa, so an estimated quarter of its rapidly rising population is currently food-insecure, and degraded soils are becoming more prevalent due to intensive use and poor management (Eswaran et al., 2005; Lal, 2009). 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, and subsequently losses in nutrient retention and availability, soil structure, erosion resistance, drought resistance and crop yields (Lal, 2006). Thus, African agriculture faces many challenges. It must not only produce more food for rising populations, and do this on a finite and often shrinking and degrading land base, but it must do so in a way that does not further degrade the soils its population ultimately depends on for food, fiber and other services (Lal, 2006; Lal, 2007; Tilman et al., 2002). There is therefore a need to assess the status and trends of soil degradation, and thus for indicators and tools for monitoring and evaluation (Hurni et al., 2006).

Agricultural SQ, often referred to as soil health, encompasses the chemical, physical and biological functions and processes of soils needed to support plant growth (Doran et al., 1994). Soil quality can be assessed indirectly by measuring indicators, or soil properties, that are sensitive to changes in agricultural management and are agronomically meaningful (Doran et al., 1994; Larson and Pierce, 1991; Mausbach and Seybold, 1998). However, no widely-standardized SQ assessment exists currently, especially for use in the tropics (Bastida et al., 2008; Winder, 2003). Additionally, methods of SQ assessment are often not accessible to researchers and extension organizations in developing nations with minimal infrastructure (Bastida et al., 2008). Of those SQ indices and assessment frameworks that have been developed to date, most have been primarily used for research purposes. The Cornell Soil Health Test, however, was developed for broader adoption by consultants, farmers and applied researchers at reasonable cost, and is currently available for use in the United States (Gugino et al., 2009; Idowu et al., 2008).

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 (Huggett, 1998; Stevens and Walker, 1970) and have more recently also been used to study anthropogenic management effects on soil (e.g., An et al., 2008; An et al., 2009; Marin-Spiotta et al., 2009; Solomon et al., 2007; Wang et al., 2009). Carbon and nutrient availability have usually been shown to decline exponentially with long-term low-input cultivation after forest conversion to agriculture (An et al., 2008; Kinyangi, 2008; Solomon et al., 2007). Also, much progress has been made in elucidating nutrient and total soil organic carbon dynamics due to degradation and management effects (Bationo et al., 2007a; Bationo et al., 2007b; Fofana et al., 2008; Kimetu et al., 2008; Lal, 2006; Lynam et al., 1998; McLauchlan, 2006; Ngoze et al., 2008; Solomon et al., 2007; Vanlauwe et al., 2006, among others). Improved SQ is frequently stated as the goal of such soil management- and degradation-related research in the tropics. However, relatively few, such as Islam and Weil (2000), Mairura et al. (2007) and Murage et al. (2000) among others, have measured an integrative set of physical, biological and chemical SQ indicators, that are directly linked to essential agronomic processes and productivity, when assessing the impacts of management in the tropics. Thus, relatively little is known about interlinked dynamics of physical, biological and chemical processes in such environments, especially when involving multiple, traditional management practices.

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 dominant form of land-use change over the last century in this area: the conversion of primary forest to low-input subsistence agriculture. A chronosequence of land conversion from primary forest to almost 80 yr in cultivation, located on the Kakamega and Nandi Forest margins in Kenya, provided a unique opportunity to assess long-term SQ degradation over time using a combination of physical, biological and chemical indicators of SQ. The objective of this study was to describe soil degradation dynamics over time in two contrasting traditional long-term management systems on two parent materials, and to do this using a basic set of measurements that would be accessible in developing countries, and that have the potential to be included in a minimum dataset for globally standardized SQ monitoring.

4.4. MATERIALS AND METHODS

4.4.1. Site description

The site used in this study is located at the margins of the Kakamega/Nandi Forest in Vihiga, Kakamega, South Nandi and North Nandi districts of western Kenya, between $0^{o}00'$N and $0^{o}13'$N latitude and between $34^{o}45'$E and $35^{o}03'$E longitude. Long rains of the bimodally-distributed rainfall occur from March to August, and short rains from September to January, thus allowing for two cereal cropping seasons per year in this region. The area receives about 1800 – 2100 mm of rainfall annually, and the mean annual temperature is 19^{o}C.

A chronosequence experiment, including intact primary forest sites and farms representing time points of conversion to agriculture between the years of about 1930 to 2000, was established to investigate the long-term effects of land conversion from primary forest to agriculture on soil carbon (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 sites are on Ultisols that contain low activity kaolinite and high proportions of Fe and Al oxides (Krull et al., 2002), and developed on two parent materials: undifferentiated basement system rock in the Kakamega region, and biotite-gneiss in the Nandi region (Kimetu et al., 2008).

The Kakamega chronosequence contained three clustered forest sites and 12 farms converted from forest to agriculture in 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 ~ 47, 40, 13% respectively). The Nandi sequence contained 9 forest sites, clustered in three groups, and 24 farms converted from forest in 1930, 1950, 1970, 1985, 1995 and 2000, with elevation ranging from 1560 to 2028 m ($\bar{x}$ = 1789 m, s = 108 m) and slightly finer textures (average sand, silt and clay 47, 36, 17% respectively). Most conversion years were replicated by three 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 (Kinyangi et al., 2008; Solomon et al., 2007), and thus time can be substituted by space (Huggett, 1998) in examining the effects of conversion. However, spatial effects on observed soil dynamics cannot be ruled out.

4.4.2. 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, received household organic wastes and cooking ash, and grew diverse fruit and vegetable crops in polyculture since forest conversion. Co fields were tilled twice a year to 0.10 – 0.15 m using a hand hoe, continuously cropped with maize, and had received no or negligible fertilizer or organic amendments since conversion (Kinyangi, 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 described by Kimetu et al. (2008) until the 2007 long rains. Maize plots measured 2 x 4.5 m^2.

4.4.3. 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 field was sampled by taking five 0 – 0.15 m cores with a soil auger, 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.

4.4.4. Laboratory analysis

Soils were air-dried and passed through a 2 mm sieve prior to laboratory measurement of additional physical, biological and chemical soil properties, most of which are part of the Cornell Soil Health Test (Gugino et al., 2009; Idowu et al., 2008). Texture, an inherent, but influential soil property, was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) in which 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 (Ogden et al., 1997b). The method applies 2.5 J of energy for 300 s on 0.25 to 2 mm aggregates placed on a 0.25 mm mesh sieve. 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, as described by Moebius et al. (2007). The ratio of aggregation per percentage point of clay (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 may give an idea of 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 in soils between these two pressures was calculated as the AWC.

Total organic matter content was determined by loss on ignition (LoiOM). 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 450-600°C (Ball, 1964; Rhodes et al., 1981). Biologically active carbon (ActC), was estimated by soil reaction with very dilute potassium permanganate ($KMnO_4$) as described by Weil et al. (2003). A hand-held colorimeter (Hach, Loveland CO) was used to determine absorbance at 550 nm, which has an inverse linear relationship with increasing ActC. 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; Mtambanengwe et al., 2006; Weil et al., 2003). An approximate proportion of the total C made up by the ActC fraction was calculated as the ratio of the two numbers (ActC/LoiC), where LoiC was determined by using a regression model of LoiOM to total C content as measured by dry combustion in a CN auto-analyzer. (Data are not shown, LoiC (%) = 0.4421 * LoiOM (%) , $n = 28$, $r^2 = 0.79$, $p < 0.0001$, 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 electrical conductivity (EC), often used as an overall indicator of nutrient availability (Bastida et al., 2008), and pH 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 contents 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.

4.4.5. Statistical analysis

Curve-fitting in Sigma Plot (Version 11.0, Systat Software, Inc., 2008) was used to describe soil change patterns over time in the long-term continuous maize and kitchen garden management systems. Single, three-parameter exponential decay functions ($y = y_o + a \exp^{-bx}$) were used where trends followed similar patterns as those described by Kinyangi et al. (2008) and Kimetu et al. (2008). Linear ($y = y_o + ax$) or quadratic ($y = y_o + ax + bx^2$) functions were fit to soil properties exhibiting different dynamics over time.

4.5. RESULTS

4.5.1. Effects of cultivation and parent material over time

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 4.1). Several soil properties measured significantly higher in the Nandi than at the Kakamega chronosequence sites (WSA, LoiOM, ActC, EC, K). The same trend held for most other properties, except for AWC and Cu which were lower in Nandi sites. Some patterns of soil change dynamics over time also differed between regions (Figs. 4.1 through 4.4). For example, WSA (Figs. 4.2a and b) declined exponentially in the Kakamega chronosequence, but linearly in Nandi, while WSA/clay declined exponentially in Nandi, but did not significantly decline in Kakamega.

Final equilibriums reached after degradation in continuous maize (Co) in Nandi appeared higher than at Kakamega for LoiOM, EC, CEC, Ca and Mg, but lower for AWC (Figs. 4.1 through 4.4). Relative to their respective starting points, Nandi soil properties declined more dramatically than those in Kakamega, and kitchen garden management (Ki) promoted larger differences in measured variables above Co in the Kakamega than in the Nandi region. Because of this large effect, we analyzed effects of cultivation over time separately by parent material.

Soil changes over almost 80 years were mostly declines after forest conversion to agriculture. Changes were seen in 14 out of 21 measured physical, biological and chemical soil properties (Figs. 4.1 through 4.4) 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. Fewer

Table 4.1 Means for soil biological, physical and chemical properties for the Nandi (n = 9) and Kakamega (n = 3) regions' forested sites. Means of each property followed by the same letter are not significantly different at α = 0.05, based on a Student's t-test.

	Nandi	Kakamega
LoiOM† (g kg^{-1})	168.1 A	86.9 B
ActC‡ (mg kg^{-1})	962 A	661 B
ActC/LoiC§ (g g^{-1})	0.013 A	0.017 A
WSA¶ (%)	95 A	80 B
WSA/clay (%/%)	8.05 A	5.70 A
AWC# (m^3 m^{-3})	0.19 B	0.24 A
PR15†† (kPa)	220 A	200 A
PR45‡‡ (kPa)	1207 A	951 A
pH	6.45 A	6.38 A
EC§§ (dS m^{-1})	0.13 A	0.06 B
CEC (meq/100 g)	24 A	20 A
P (mg kg^{-1})	9 A	8 A
K (mg kg^{-1})	293 A	83 B
Ca (mg kg^{-1})	3250 A	2487 A
Mg (mg kg^{-1})	465 A	429 A
Cu (mg kg^{-1})	2.76 B	5.39 A
Zn (mg kg^{-1})	16.54 A	11.39 A
S (mg kg^{-1})	20.38 A	15.47 A

† LoiOM = total organic matter by loss on ignition at 350^{o}C.
‡ ActC = permanganate-oxidizable, biologically active carbon.
§ ActC/LoiC = percent of total carbon made up by ActC.
¶ WSA = water stable aggregation.
# AWC = available water capacity.
††PR15 = penetration resistance between 0-15 cm.
‡‡ PR45 = penetration resistance between 15-45 cm.
§§ EC = electrical conductivity.

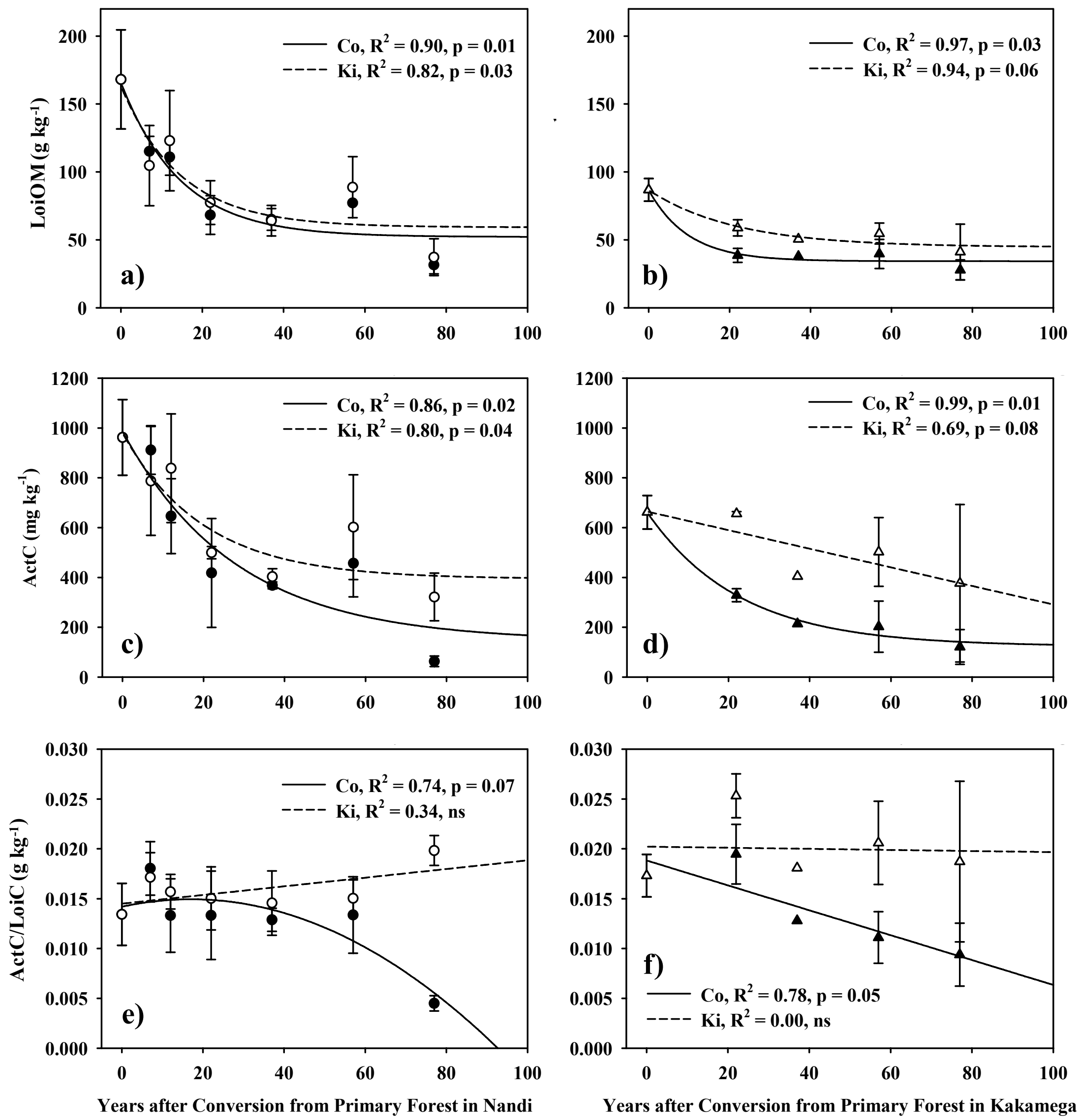

Figure 4.1 Dynamics of organic fractions over time. At Nandi: ● = Co, ○ = Ki; at Kakamega: ▲= Co, Δ = Ki.

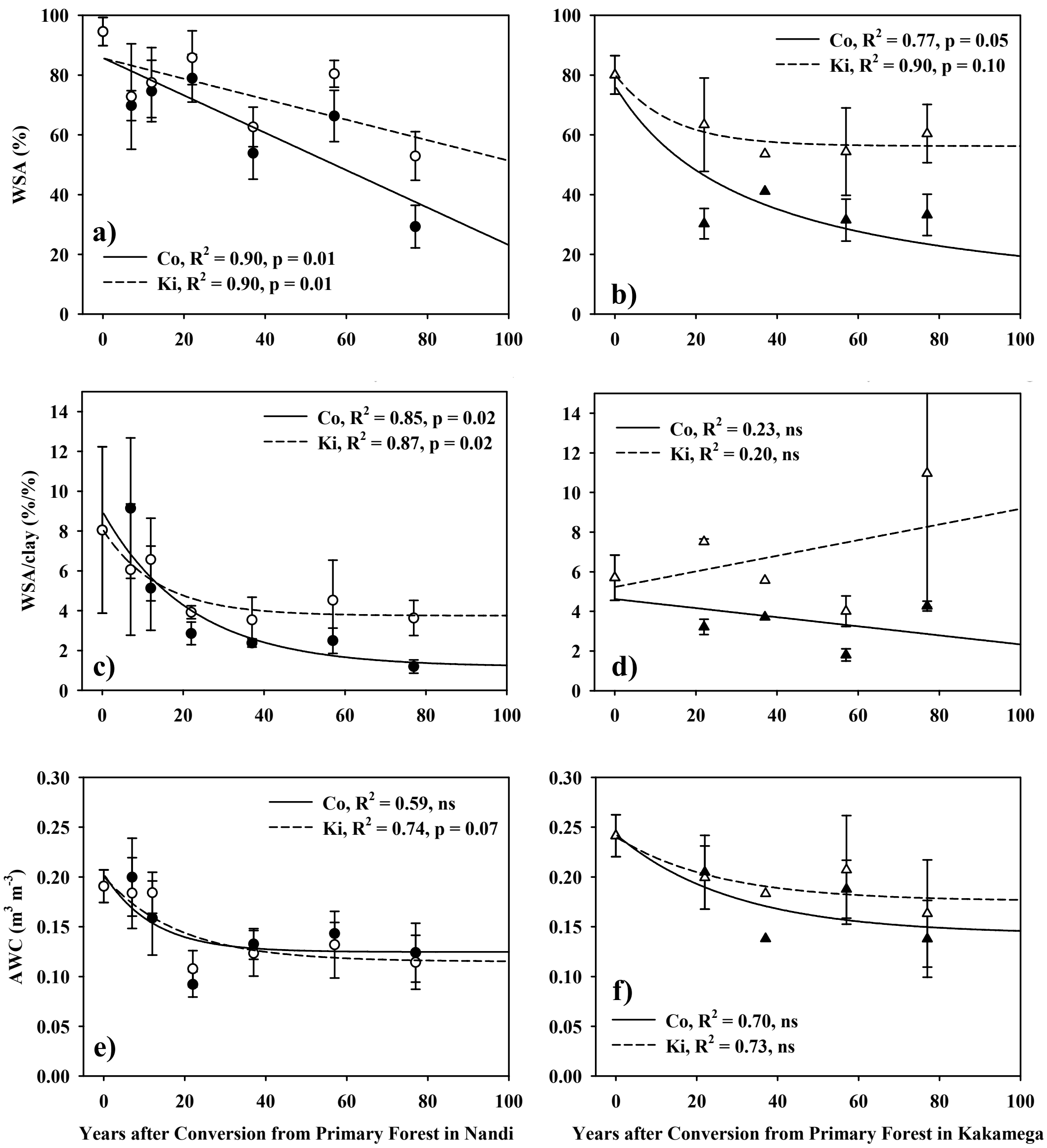

Figure 4.2 Dynamics of soil structural properties over time. At Nandi: ● = Co, ○ = Ki; at Kakamega: ▲= Co, Δ = Ki.

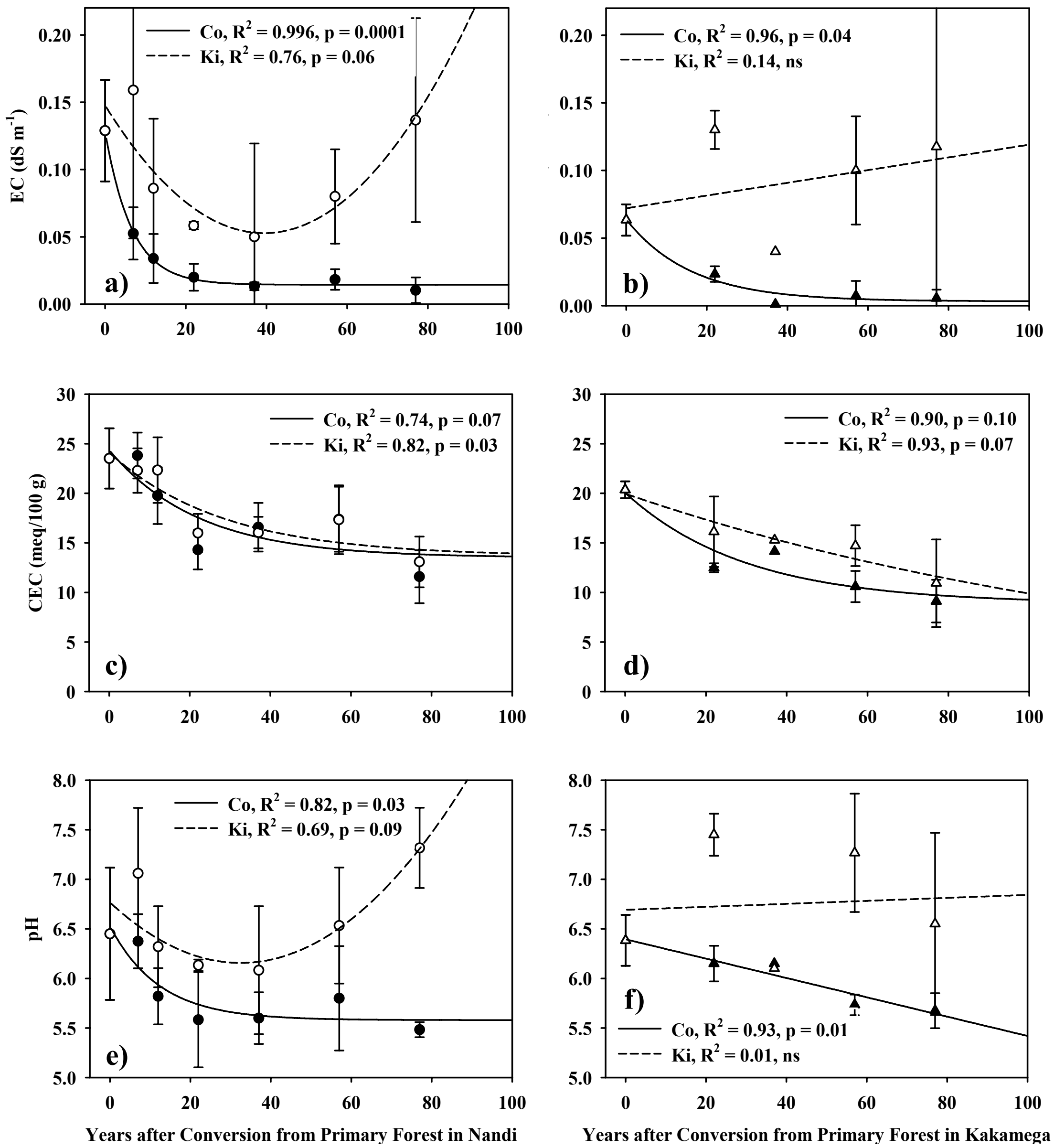

Figure 4.3 Dynamics of measures of nutrient availability over time. At Nandi: ● = Co, ○ = Ki; at Kakamega: ▲= Co, Δ = Ki.

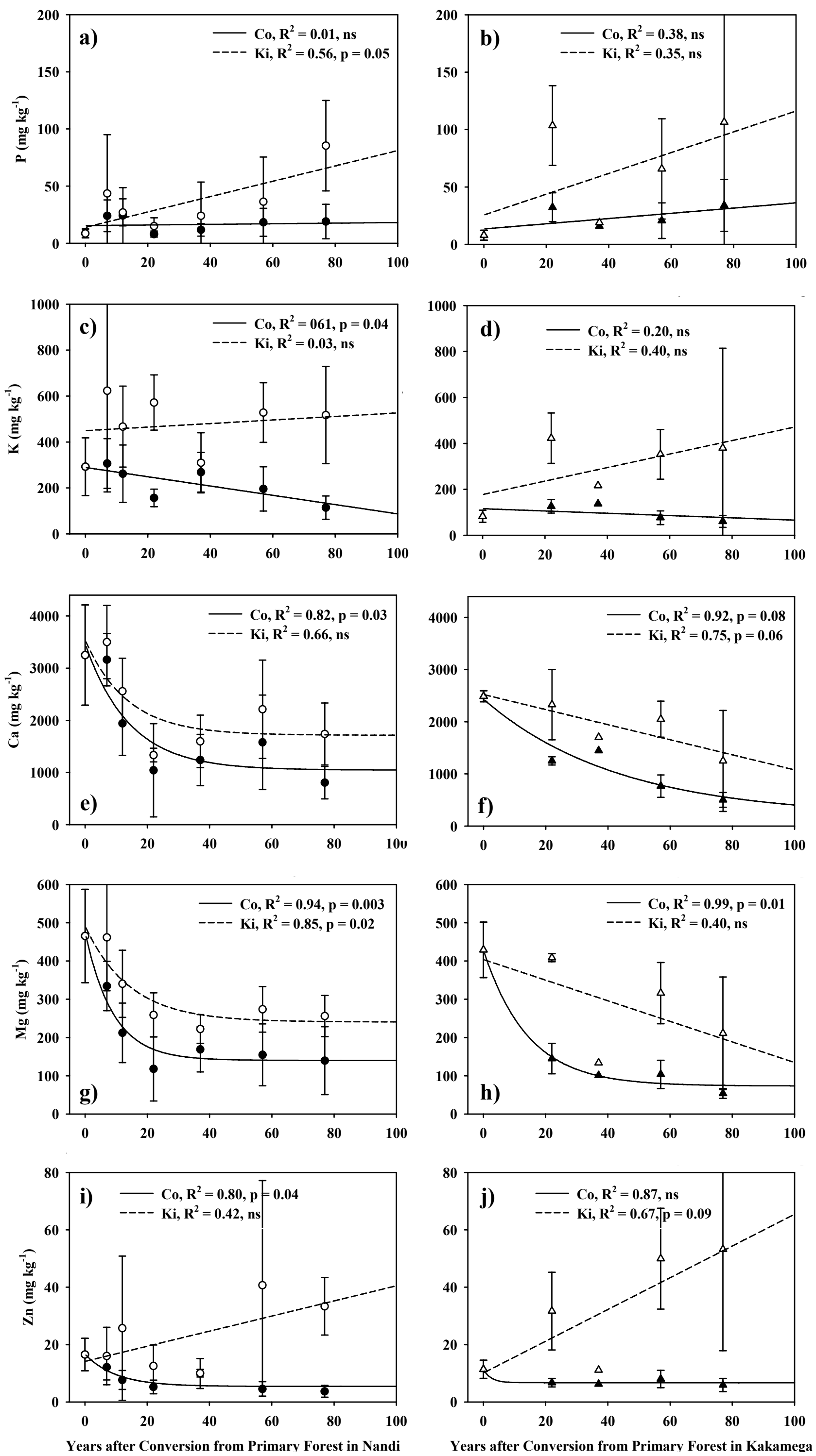

Figure 4.4 Dynamics of selected nutrients over time. At Nandi: ● = Co, ○ = Ki; at Kakamega: ▲= Co, Δ = Ki.

properties decreased in value in Ki (open symbols), whereas other measured property values were maintained or increased with time. Some soil properties exhibited variability without significant trends over time in either parent material (textural properties, PR15, PR45, S, Cu; data not shown).

4.5.1.1 Effect of continuous, low input maize management

The biological properties, total soil organic matter (LoiOM, Figs. 4.1a and b) and biologically active C (ActC, Figs. 4.1c and d) declined exponentially under Co. In the Nandi region about 59% of the initial LoiOM and 57% of the initial ActC in the system were lost in the first 22 years after conversion from forest, indicating an average loss of organic C of about 2 g kg^{-1} yr^{-1}. Further declines occured more slowly, as the system appeared to reach equilibrium. However ActC declined further than LoiOM, where 93% of the initial amount was lost by 77 yr in cultivation, in contrast to 81% of LoiOM lost. In the Kakamega region, which had lower starting values for both LoiOM and ActC, about 55% of the LoiOM and 50% of the total ActC 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 loss. Again, further declines happened more slowly, and ActC declined further than LoiOM, losing 82% by 77 yr in cultivation, in contrast to 67% of LoiOM lost. The ActC/LoiC ratio thus declined with a very different pattern (Figs. 4.1e and f) and did not appear to occur until after 57 yr in the case of Nandi sites, while it followed closer to a linear decline trend in the case of Kakamega sites.

Soil physical properties also degraded over time. Aggregates in Kakamega sites lost 60% of their initial stability (WSA, Figs. 4.2a 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 the variability in the mostly higher clay contents between farms located in the Nandi region (ranging from 5 to 45%). The ratio of WSA/clay had a highly significant exponential decline trend (Figs. 4.2c) in Nandi sites. While WSA/clay appeared to decline in Kakamega as well, this trend was not significant (Fig. 4.2d). Available water capacity (AWC, Figs. 4.2e and f) showed exponential decay trends in both regions, although these were not significant because of the small range of this property and the measurement- and among-farm-variability. Both regions lost about 30-50% of their AWC over time.

Soil chemical properties also decreased over time, mostly exponentially. Electrical conductivity (EC, Figs. 4.3a 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. Reductions were less sharp in the Kakamega region as the original starting point was about half of that in the Nandi region, but still 63% and 91% of the initial EC was lost by 22 and 77 yr, respectively. CEC (Figs. 4.3c and d) declined more slowly, with 39 and 51% loss from initial values in the Nandi region, and 39 and 55% in the Kakamega region by 22 and 77 yr, respectively. Decreases in pH (Figs. 4.3e 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.

It is important to recognize that, while P content at both sites and K content at Kakamega were variable without a significant decline trend over time (Figs. 4.4a and b), this has been influenced by recent years of experimental P and K fertilization of these 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 (Figs. 4.4c, d, and e) all showed exponential decay patterns in both regions, which were significant in all, except Zn in the Kakamega region.

4.5.1.2 Comparison of effect of kitchen garden- with maize-management

After forest conversion to kitchen garden management (Ki), only 8 out of 14 soil properties presented in Figs. 4.1 through 4.4 (open symbols) declined over time on both parent materials, and not always significantly. Declines followed exponential decay patterns less frequently than with continuous maize cultivation, while other properties either increased over time or did not follow a significant time trend.

The biological properties LoiOM and ActC declined exponentially, except for the linear pattern of ActC 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 under Ki management (Figs 4.1a through d). In the Nandi region only 53% (vs. 59% for Co) of the LoiOM and 48% (vs. 57% for Co) of the ActC in the system were lost in the first 22 yr after conversion from forest. In the Kakamega region, LoiOM declined only 32% (vs. 55% for Co) and ActC <10% (vs. 50% for Co) in 22 yr. By 77 yr, Ki ActC declined less than in the Co system (Nandi: 67% vs. 93%; Kakamega: 43 vs. 82%). In contrast to the Co system, ActC under Ki management declined less than LoiOM in both parent materials (Nandi: 78% decline in LoiOM; Kakamega: 52% in LoiOM). The ActC/LoiC ratio trends in both parent materials seemed to indicate maintenance or possibly increases, although not significant, in the Ki system (Figs 4.1e and f).

Degradation of the soil physical properties (Fig. 4.2), WSA and AWC, followed similar patterns for the Ki as the Co systems, but again, regression curves were shifted upward, except for AWC in the Nandi region. Aggregation (WSA) in Kakamega lost only 21% (vs. 60% for Co) of its initial stability in the first 22 yr, 24% by 77 yr in cultivation. In the Nandi region, WSA declined significantly, but along a slower linear downward trend, with a loss of 44% (vs. 69% for Co) by 77 yr in cultivation, while the ratio of WSA/clay declined exponentially (Fig. 4.2c), again with a higher equilibrium base level for Ki than for Co. While WSA/clay appeared to increase in Kakamega, this trend was not significant. The equilibrium AWC reached after exponential decline in Kakamega was also higher in Ki, with about 30% (vs. 43% in Co) of the original AWC lost by 77 yr (Fig. 4.2f). In Nandi the curve did not shift significantly from Co to Ki management.

Of the soil chemical properties, only CEC (Figs. 4.3c and d), Mg (Figs. 4.4g and h) and Ca (Figs. 4.4e and f) decreased over time for Ki. For each, the regression equilibrium was shifted upward from the respective Co trend. Electrical conductivity (EC, Fig. 4.3d) varied greatly, but did not show signs of decline in either region, in contrast to the order-of-magnitude declines observed for Co. Similarly, pH (Figs. 4.3e and f) did not appear to decline over time for Ki. Linear, though not always significant, increases over time were observed for P, K and Zn.

4.6. DISCUSSION

4.6.1. Using soil quality indicators for monitoring

We used soil properties as indicators of soil quality. Soil quality is the capacity of the soil to function (Doran and Parkin, 1994) physically, biologically and chemically. Indicators were chosen to represent a wide range of such functions and specific processes that are important to sustained agricultural production (Table 4.2).

Indicators were interpreted to signify higher SQ when they suggested better functioning of soil processes for agricultural production. For the ranges measured, all indicators, except for pH, PR15 and PR45, imply degradation in the soil functions noted above when their measured values decrease. Values of pH mostly implied decreasing SQ with decreasing values, except in the few cases in kitchen gardens with

Table 4.2 Soil functional processes, and the indicators chosen to represent these. Selected references that discuss use of these indicators are listed.

Soil Processes	Indicators	References
Structural stability	WSA	(Andrews et al., 2004; Arshad et al., 1996; Gugino et al., 2009; Karlen et al., 1994; Moebius et al., 2007)
Runoff and erosion	WSA	"
Crusting	WSA	"
Shallow rooting	WSA, PR15	"
Aeration	WSA, PR15	"
Water infiltration and transmission	WSA, PR15	"
Plant-available water retention	AWC, LoiOM	(Gugino et al., 2009; Larson and Pierce, 1991; Lowery et al., 1996; Skukla et al., 2003)
Drought stress tolerance	AWC, PR45	(Gugino et al., 2009; Hamza and Anderson, 2005; Karlen et al., 1994; Larson and Pierce, 1991; Skukla et al., 2003)
Organism mobility	PR15, PR45	(Gugino et al., 2009; Hamza and Anderson, 2005)
Subsurface root proliferation	PR45	"
Energy storage and C sequestration	LoiOM	(Doran and Parkin, 1994; Gugino et al., 2009; Larson and Pierce, 1991)
Toxicity and pollution prevention	LoiOM, pH, EC, nutrient concentrations	(Andrews and Carroll, 2001; Arnold et al., 2005; Gugino et al., 2009; Smith and Doran, 1996; Tiessen et al., 1994)
Support of soil biological activity	ActC, ActC/LoiC	(Bastida et al., 2008; Blair et al., 1995; Gugino et al., 2009; Mtambanengwe and Mapfumo, 2008; Weil et al., 2003)
Biologically mediated nutrient mineralization	ActC, ActC/LoiC	"
Chemical buffering	pH	(Arnold et al., 2005; Gugino et al., 2009; Karlen et al., 1994; Smith and Doran, 1996)
Macro- and micro- nutrient retention and availability	LoiOM, Nutrient concentrations, EC	(Andrews and Carroll, 2001; Arnold et al., 2005; Smith and Doran, 1996; Tiessen et al., 1994)

a pH above 7. 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 changes in SQ with respect to the changes in agronomically important soil functions, processes and constraints likely to occur due to soil degradation over time and due to contrasting management systems.

4.6.2. Effects of parent material on soil quality dynamics

Parent material and related, inherent soil type differences, sometimes referred to as inherent soil quality, affect degradation and aggradation of dynamic soil quality, which is management-induced (Carter, 2002). Different types of parent materials often exhibit different constraints to cropping after being degraded, and degradation rates and extents may differ (Carter, 2002; de la Rosa et al., 2009; Mapfumo et al., 2007) as we observed here.

For example, while both regions reduced their ability to store water over time, the starting AWC (0.19 m^3m^{-3}) of the forested Nandi sites was similar to the equilibrium AWC attained after degradation under Ki in the Kakamega region (Figs. 4.2e and f). This suggests that a crop on a recently converted soil in Nandi will not stand up to drought stress as well as a crop on a degraded Kakamega soil under Ki management, and not even much better than a degraded Kakamega soil under Co management. AWC was maintained better by Ki management in the Kakamega region, whereas Ki management did not seem to affect AWC degradation dynamics in the Nandi region. This may indicate that a given management practice can be effective at maintaining SQ in some soil types but not in others.

Despite the contrasting initial conditions in forest soils, many soil properties degraded to similar low levels in the two parent materials after almost 80 years under cultivation, as for example with ActC, WSA, Zn and pH. This indicates that the potential for losses in soil quality from poor soil management was greater in the Nandi region. This is further supported by other differences found between the two regions: Kakamega soils showed a greater difference between Ki and Co degradation rates and extents and greater accumulation of several nutrients under Ki management (Figs. 4.1 through 4.4). This suggests that types and effectiveness of management strategies for reclaiming degraded soils will likely differ by parent material.

4.6.3. Effects of cultivation over time on soil quality

Organic matter provides two essential categories of functions, as has been described by Lal (2006), among others, both of which were impaired as soil quality degraded over time. 1) Organic matter stabilization in aggregates improves cation retention (as represented by CEC), and buffering of pH, and well-established soil structure enhances water storage (as represented by AWC), infiltration, root proliferation and physical access to nutrients, while decreasing surface crusting, runoff and erosion, as represented by WSA. 2) Organic matter decomposition on the other hand, is important because labile carbon, as represented by ActC, provides substrate to soil microbes, which thus mineralize nutrients for crop growth, as represented by the various indicators of nutrient availability. The latter is especially important in smallholder agriculture, which usually depends completely on organic matter-derived nutrients, because fertilizers are not affordable or available to farmers (Sanchez, 2002).

When a 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 (Hölscher et al., 1997; Tiessen et al., 1994), as observed here. Initially, decomposition of the large forest-derived organic matter pool provides sufficient nutrients for crop growth and microbial activity. However, in the typical smallholder grain fields, such as the continuous low-input maize systems studied here, the minimal crop residues that may be returned to the soil make up a much smaller quantity of organic matter than would be returned to the soil in a forested system. Smallholder farmers rarely correct the resulting nutrient deficit with fertilizer, particularly in fields more distant from the home (Tittonell et al., 2005). In addition, tillage breaks up existing aggregates and exposes previously stabilized organic matter to oxygen, which stimulates microbial activity. This brings on rapid decomposition and losses in aggregate stability as was measured here (WSA, Figs. 4.2a and b) and by others previously (e.g., Islam and Weil, 2000; Liebig et al., 2004; Moebius-Clune et al., 2008).

We observed an exponential decline in WSA in the Kakamega region, while the trend in Nandi was a scattered linear decrease. In the Nandi chronosequence, the WSA/clay index allowed us to more closely isolate the exponential decrease in aggregation that is due to time-dependent decreases in biological activity and aggregate maintenance in these soils. This effect is masked in the Nandi WSA measurements by the spatial variability in clay content between farms of different ages that results from the imperfect space-to-time translation in the chronosequence (Huggett, 1998). The same does not appear to be the case for Kakamega, where WSA and ActC follow a similar exponential trend. We note that the degradation trend of the WSA/clay ratio over time in the Nandi region is also exponential, and quite similar to the exponential decline observed for ActC. Others have similarly found ActC to be related to aggregate stability (Bell et al., 1998).

It should be noted that compaction (as measured by PR15 and PR45) did not change significantly as a result of time in cultivation, probably because tillage in this region is done by hand hoeing (data not shown). 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; Soane and van Ouwerkerk, 1995; Yao-Kouame and Yoro, 1991).

Greater exposure to intense tropical rains after forest clearing, combined with lower evapotranspiration, further increases organic matter decomposition and exports through runoff and leaching from the system (Kondo et al., 2005). Thus, further losses in soil structure, nutrient retention and availability and soil quality in general result, as was the case along this chronosequence. The extremely rapid initial rate of loss of organic matter we measured (LoiOM, Figs. 4.1a and b) resulted from this combination of lower inputs and higher decomposition rates and losses 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. Microbial habitat and labile, microbially-available organic matter, as measured by ActC (Islam and Weil, 2000; Mtambanengwe and Mapfumo, 2008; Weil et al., 2003) declined exponentially, similarly coming to an equilibrium. We also saw a change in the overall composition of the declining organic matter, leaving behind relatively more inert organic matter (lower ActC/LoiC). It should be noted that the decline trend in organic matter quality did not come to equilibrium within the timeframe of this chronosequence, as was also found by use of more complex methodology by Solomon et al. (2007).

Cation exchange sites were also lost with the loss of organic matter, explaining the observed decreases in CEC (Figs. 4.3c and d), cation availability (K, Mg, Ca, Zn; Fig. 4.4), general nutrient availability (EC; Figs. 4.3a and b) and soil buffering ability (pH; Figs. 4.3e and f). As the remaining organic matter became more inert over time, it became less apt to supply substrate for micro-organisms, and therefore also less able to provide a supply of nutrients through decomposition. As most of the initial organic matter decomposed, the soil was effectively mined for nutrients, while also losing other functions important to crop production.

We observed extreme degradation of soil quality under continuous, low-input maize cultivation with respect to most of the essential soil processes, only some of which had been reported previously (Kinyangi, 2008). Similar degradation patterns have been observed at other tropical sites after deforestation (Tiessen et al., 1994). Soil quality declines in this area are, not surprisingly, associated with exponential declines in grain yield (Kimetu et al., 2008; Ngoze et al., 2008).

In contrast, kitchen garden systems on these smallholder farms underwent a much lesser degree of degradation of biological and physical processes, and even an accumulation of some nutrients. While ActC decreased over time, it did so more slowly than total organic matter in either the Co or Ki systems, likely because of daily fresh organic matter inputs that much more closely resemble forest input dynamics. Increasing (though non-significant) trends in the ActC/LoiC ratio, especially in the Nandi region, imply a relative build-up of labile over non-labile organic matter under Ki, and thus an increase in organic matter quality even while the overall quantity decreased. This can likely be attributed to the rapid mineralization of fresh organic inputs (Bol et al., 2000; Jenkinson and Ayanaba, 1977), stimulated further by frequent tillage in the Ki system. Addition and subsequent decomposition of labile C from fresh organic matter may partially explain the increasing or more slowly decreasing dynamics of available nutrient contents under Ki management. Regular additions of ash are also known to increase pH, P, K, Ca, Mg and Zn (Augusto et al., 2008; Cabral et al., 2008; Gorecka et al., 2006) and apparently played a role in our findings in the Ki system.

However, additions under Ki management do not appear to be sufficient to maintain the soil at its original high SQ. The stable fraction of organic matter is depleted despite regular additions. Kitchen gardens are intensively used for both perennial and annual crops. They thus experience higher foot-traffic and tillage than the more outlying maize fields, and certainly greater disturbance than the original primary forest. Tillage has been shown to negatively impact SQ more than residue inputs in temperate regions (Hooker et al., 2005; Moebius-Clune et al., 2008). Hooker et al. (2005) found 85-88% losses of organic matter added via maize residues over three decades, and showed that relic C3-C from forest vegetation decomposed much faster under plow-till than no-till, while residue additions did not influence this process. These dynamics are likely to hold with even faster decomposition in the tropics (Tiessen et al., 1994), and would help explain the high total organic matter losses for the Ki system. Therefore, while nutrient supply for Ki appears to be mostly maintained over time through higher inputs, total organic matter and essential functions that it maintains, such as biological activity, water storage and aggregate stabilization still decline after conversion from forest, although not as much as under continuous low-input maize.

4.7. CONCLUSIONS

Results of this study provide insights into the dynamics of SQ degradation after forest conversion to two very different traditional smallholder soil management systems. Continuous low-input maize cultivation caused drastic SQ degradation, with 50-93% declines from original indicator values measured under primary forest. Almost all soil processes represented by the measured SQ indicators were affected, including aggregation and root proliferation, water intake and storage, carbon storage, support of biological activity and nutrient retention, mineralization and availability. High-input polyculture kitchen garden cultivation showed significantly less degradation of the soil biological and physical soil functions, and actually caused aggradation of some soil chemical indicators due to high inputs of organic debris and cooking ashes. This indicates that agricultural SQ degradation in the tropics can be minimized by appropriate management. Conservation agriculture approaches involving minimal tillage could potentially further prevent such drastic degradation of especially the biological and physical soil functions after forest conversion. However, while these have been studied widely in Brazil (Bolliger et al., 2006) and other regions (Hobbs, 2007) further studies of such approaches are required in smallholder systems of sub-Saharan Africa (Gowing and Palmer, 2008). The demonstrated ability to measure differences in degradation as a function of management differences with a basic set of SQ indicators suggests that future work on degradation dynamics and appropriate management systems could incorporate such tests to monitor and assess soil quality.

4.8. ACKNOWLEDGEMENTS

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CHAPTER 5. ASSESSMENT OF SHORT- AND LONG-TERM ORGANIC MATTER MANAGEMENT IN KENYAN SMALLHOLDER SYSTEMS USING AN INTEGRATIVE SET OF SOIL QUALITY INDICATORS[4]

5.1. ABSTRACT

The loss of agronomic soil functions due to improper soil management leads to degradation of soil quality (SQ) and adversely impacts Africa's agricultural viability and food security. Physical, biological and chemical soil properties that have been used as indicators of SQ were measured in six management systems in an agricultural chronosequence experiment at the Kakamega and Nandi Forest margins in Kenya. Farms were converted to agriculture from forest between 1900 and 2000. On each farm two traditional long-term management systems were sampled: 1) continuous maize (*Zea mays*) fields in low-input monoculture (control, Co), and 2) kitchen gardens (Ki) in high-input polyculture. Additionally, four short-term maize experimental plots on each farm had received several types of organic matter (OM) amendments, added at 18 t ha^{-1} C split over 3 growing seasons, between 2005 and 2006: *Tithonia diversifolia* (Ti), manure (Ma), charcoal (Ch), and sawdust (Sa). Sampling took place 16 months after last organic amendments had been added. Physical soil properties (water stable aggregates (WSA), available water capacity (AWC), and field penetration resistance in surface (PR15) and subsoil (PR45)),

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biological properties (permanganate oxidizable active C (ActC) and total loss-on-ignition organic matter C (LoiOM)) and chemical properties (electrical conductivity (EC), pH and P, K, Mg, Ca, Zn, Cu, S) were measured. These were used as indicators to assess SQ differences between management systems on two parent materials. Soil quality was much higher in Ki than in Co, with higher WSA, AWC, LoiOM, ActC, pH, EC, CEC and nutrient contents. Sixteen months after short-term OM additions to previously low-input systems had ceased, soil quality on average remained slightly improved over Co, with significantly higher WSA, EC, P and K, and, depending on parent material, higher pH and organic matter quality (ActC/LoiC). However, Kakamega soils were compacted by increased tillage when organic matter was incorporated. Differences between types of short-term OM amendments were small and significant only for several chemical indicators due to the short duration of amendment additions. In conclusion, integrative SQ assessment, with a fairly basic set of indicators, can help identify soil constraints, complex management effects on multiple soil functions, and effects of inherent soil type differences.

5.2. KEY WORDS

Soil quality; soil quality assessment and monitoring; soil health; soil degradation; smallholder agriculture; kitchen garden; maize; Kenya; Africa; deforestation

5.3. INTRODUCTION

Civilizations have risen and fallen on the basis of their soil's quality (Hillel, 1991; Montgomery, 2007; Yaalon and Arnold, 2000). The first Green Revolution bypassed Africa, and an estimated quarter of its rapidly rising population is currently food-insecure. Moreover, degraded soils are becoming more prevalent due to intensive use and poor management (Eswaran et al., 2005; Lal, 2009). Extractive practices by subsistence farmers are estimated to have caused a loss of 60-80% of the original soil organic carbon in the tropics, and subsequently losses in nutrient retention and availability, soil structure, erosion resistance, drought resistance and crop yields (Lal, 2006). African agriculture thus faces many challenges. It must produce more food for rising populations on a finite and shrinking land base, and must do so in a way that does not further degrade these soils (Lal, 2006; Lal, 2007; Tilman et al., 2002). Sanchez and Swaminathan (2005) summarize the recommendations of the Hunger Task Force to meet the Millennium Development Goal of halving world hunger by 2015, noting that to increase agricultural productivity of food-insecure farmers, "restoring soil health is often the first entry point."

Agricultural soil quality (SQ), also referred to as soil health, encompasses the chemical, physical and biological functions and processes of soils needed to support plant growth (Doran et al., 1994). Soil quality can be assessed indirectly by measuring indicators, or soil properties, that are sensitive to changes in agricultural management and agronomically meaningful (Doran et al., 1994; Larson and Pierce, 1991; Mausbach and Seybold, 1998).

Much progress has been made in elucidating the nutrient and total soil organic carbon dynamics due to management practices (Bationo et al., 2007b; Bationo A et al., 2007; Fofana et al., 2008; Kimetu et al., 2008; Lal, 2006; Lynam et al., 1998; Ngoze et al., 2008; Tittonell et al., 2005; Vanlauwe et al., 2006 among others). The effects on nutrient contributions from low vs. high quality organic matter, for example, are becoming better understood (Kimetu et al., 2008; Palm et al., 2001), but how and to what extent these amendments contribute to other essential soil processes is less well understood. Improved SQ is frequently stated as the goal of soil management-related research in the tropics. However, relatively few, such as Islam and Weil (2000), Mairura et al. (2007) and Murage et al. (2000) among others, have measured an integrative set of physical, biological and chemical SQ indicators, that are directly linked to essential agronomic processes and productivity.

Many questions remain about how to effectively improve soil quality, as for example discussed by (Gowing and Palmer, 2008; Graves et al., 2004; Pretty et al., 2006). The diversity of agricultural crops, resource availabilities, climates and soil types in Africa don't allow for blanket recommendations, and thus potential solutions must be studied locally or regionally (Lal, 1997). This requires an ability to assess the influences of management changes on soil quality (Hurni et al., 2006; Lal, 1997), which would be greatly facilitated by access to standardized SQ tests that help growers make in decisions about management changes (Barrios et al., 2006).

However, no widely-standardized SQ assessment framework exists currently, especially for use in the tropics (Bastida et al., 2008; Winder, 2003). Furthermore, methods of SQ assessment are often not accessible to researchers and extension organizations in developing nations with minimal research or agricultural service infrastructures (Bastida et al., 2008). The Cornell Soil Health Test, was developed for broad adoption by consultants, farmers and applied researchers at reasonable cost (Gugino et al., 2009; Idowu et al., 2008), primarily to aid in assessing management effects on soil quality and making management decisions based on measured soil constraints.

A series of farms located on the Kakamega and Nandi forest margins in Kenya was converted from primary forest between 1900 and 2000. This chronosequence experiment allows exploration of the effects of long-term and short-term management strategies on a combination of physical, biological and chemical indicators of soil quality in this region. The goal of this study was to accomplish its objective using basic measurements comprising the Cornell Soil Health Test, which would be accessible in developing countries, and have the potential to be included in a minimum dataset for globally standardized SQ monitoring. The objective was to evaluate the extent and nature of traditional long-term and residual short-term organic matter management effects on SQ.

5.4. MATERIALS AND METHODS

5.4.1. Site description

The site used in this study 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. Long rains of the bimodally-distributed rainfall occur from March to August, and short rains from September to January, thus allowing for two cereal cropping seasons per year in this region. The area receives about 1800 – 2100 mm of rainfall annually, and the mean annual temperature is 19°C.

A chronosequence experiment, including intact primary forest sites and farms representing time points of conversion to agriculture between the years of about 1900 to 2000, was established to investigate the long-term effects of land conversion from primary forest to agriculture (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 farms are on Ultisols, which contain low activity kaolinite and high proportions of Fe and Al oxides (Krull et al., 2002), and developed on two parent materials: undifferentiated basement system rock in the Kakamega region, and biotite-gneiss in the Nandi region.

The Kakamega chronosequence contained 12 farms converted from forest to agriculture in 1930, 1950, 1970, 1985, and 1995 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 ~ 47, 40, 13% respectively). The Nandi sequence contained 27 farms converted from forest in 1900, 1930, 1950, 1970, 1985, 1995 and 2000, with elevation ranging from 1538 to 2028 m ($\bar{x}$ = 1761 m, s = 109 m) and somewhat finer textures (average sand, silt and clay 43, 38, 19% respectively). Most conversion years were replicated by three 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).

5.4.2. Management systems

At each farm, soils from two traditional long-term management systems were sampled: kitchen gardens (Ki) in high-input polyculture and continuous maize in low-input monoculture (used as the control; Co). Kitchen gardens, traditionally located close to the home, regularly received household organic wastes and cooking ash, and were used grow diverse fruit and vegetable crops since the time of forest conversion. Co plots were tilled twice a year to 0.10 to 0.15 m using a hand hoe, continuously cropped with maize, and had received no or negligible fertilizer or organic amendments since conversion (Kinyangi, 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 described by Kimetu et al. (2008).

On continuously cropped maize fields, four experimental short-term organic matter input systems were established in 2005 (Kimetu et al., 2008). For three consecutive growing seasons (long rains and short rains in 2005 and long rains in 2006, 16 months prior to our sampling), 6 t C ha^{-1} per season were added in the form of *Tithonia diversifolia* leaves (Ti), cattle manure (Ma), wood charcoal (Ch), and sawdust (Sa), for a total of 18 t C ha^{-1}. These plots received the same N, P and K fertilizer as Co plots (Kimetu et al., 2008). All plots received inorganic fertilizer until the 2007 long rains. Maize plots measured 2 x 4.5 m^2.

5.4.3. Field measurements

All samples were gathered in July and August of 2007. At each farm a handheld GPS (Garmin eTrex) was used to record location and elevation. Each plot was sampled by taking five 0 to 0.15 m cores with a soil auger, compositing and mixing these and sub-sampling a ~1 L volume of soil for analyses. Surface (0 to 0.15 m, PR15) and subsurface (0.15 to 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.

5.4.4. Laboratory analysis

Soils were air-dried and passed through a 2 mm sieve prior to laboratory measurement of additional physical, biological and chemical soil properties, most of which are part of the Cornell Soil Health Test (Gugino et al., 2009; Idowu et al., 2008). Texture, an inherent and influential soil property, was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) that involves a combination of sieving and sedimentation steps.

Water stable aggregation (WSA) was measured by a rainfall simulation method, which closely simulates slaking processes that occur on agricultural fields during rain events (Ogden et al., 1997b). The method applies 2.5 J of energy for 300 s on 0.25 to 2 mm aggregates placed on a 0.25 mm mesh sieve. 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, as described by Moebius et al. (2007). 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 in soils held between these two pressures was calculated as the AWC.

Total organic matter content was determined by loss on ignition. Ten-g samples were oven-dried at 105°C overnight, weighed, ignited to equilibrium in a muffle furnace 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 (ActC), was estimated by soil reaction with very dilute $KMnO_4$ as described by Weil et al. (2003). A hand-held colorimeter (Hach, Loveland, CO) was used to determine absorbance at 550 nm, which has an inverse linear relationship with increasing ActC. 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; Mtambanengwe et al., 2006; Weil et al., 2003). An approximate proportion of the total C made up by the ActC fraction of organic matter was calculated as the ratio of the two numbers (ActC/LoiC), where C was determined by using a regression of LoiOM to total C content, similar to correlations found by Zhang et al. (2005). (Data not shown, C measured by dry combustion in a CN autoanalyzer, C(%) = 0.4421 * LoiOM(%) , $n = 28$, $r^2 = 0.79$, $p < 0.0001$.) This ratio was used as an index of the lability of the total C present (Blair et al., 1995), similar to other ratios used in the literature as reviewed by Bastida et al. (2008).

Sieved soils were suspended in water (1:2.5) and electrical conductivity (EC), often used as an overall indicator of nutrient availability (Bastida et al., 2008), and pH 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 contents by inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 730-ES, Mulgrave, Victoria) 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.

5.4.5. Statistical analysis

To test differences between management systems, a multivariate Hotelling T^2 test, was conducted using MatLab v.1.5.2 (The MathWorks, Inc., 2007). Each possible paired comparison ([Ki] – [Co], [Ki] – [Ma] … [Sa] – [Ti], etc.) of the multivariate, normalized, standardized data was tested against the H_o that the difference-matrix equals zero. The tests were controlled for false discovery rate at a global $\alpha = 0.05$ as described by Wilks (2006).

To further quantify how specific measured soil properties differed between management systems, mixed models in JMP v.7.0 (SAS Institute, Inc., 2007) were used. Some measured values were transformed (natural log of EC, P, K, Zn) prior to analysis, in order to prevent violating mixed model assumptions. Fixed factors used in mixed models, as appropriate, were years since conversion (Time), parent material, management (Mgmt) and the Time by Mgmt interaction. Farm was used as a random factor to account for variability among farms. Statistical significance of fixed factors was reported to $\alpha = 0.1$, while LS means from Tukey's tests were reported at $\alpha = 0.05$.

5.5. RESULTS

5.5.1. Management effects by parent material

The multivariate Hotelling T^2 test showed that kitchen garden (Ki) fields and long-term low-input maize control plots (Co) across the entire region differed significantly from each other and all other treatments (Table 5.1). In addition Ma plots differed from Ch and Sa plots, but no other short-term organic matter amended systems differed significantly from each other. Management as a main factor in the mixed model, based on data from all farm sites, significantly affected 17 out of 20 soil properties (all except AWC, PR15 and silt; Table 5.2).

Sites making up the chronosequences in the Nandi and Kakamega regions were developed on two different parent materials. Moebius-Clune (Chapter 4) showed that parent material significantly influenced the initial starting values under primary forest and degradation trends of many soil properties in Ki and Co. Parent material was also a significant main factor for 13 of the 20 soil properties (Table 5.2). Because of this large effect, the specific effects of management on soil properties were explored separately for each parent material. Time was a significant main factor for 11 out of the 20 soil properties.

Management was a significant factor for 14 out of 20 soil properties in the Nandi region (all except AWC, PR15, PR45, Silt, LoiOM and Cu), and for 16 out of 20 soil properties in Kakamega (all except PR15, sand, silt, Cu and S; Table 5.3). The Time*Mgmt interaction was significant for only two soil properties in Kakamega (WSA and EC), where few recently converted farms were available for sampling, but for 11 soil properties in the Nandi region, where a large number of 7 and 12 year old farms were included. Thus, analyses of management effects via two relevant linear contrasts (Table 5.4) and LS means by management system (Table 5.5) were presented

Table 5.1 Differences between pairs of treatments based on multivariate Hotelling T^2 test, controlled for false discovery rate at a global α = 0.05 (Wilks, 2006).

	Co†	**Ch‡**	**Ma§**	**Sa¶**	**Ti#**
Ki††	***‡‡	***	***	***	***
Co		***	***	***	***
Ch			**	ns	ns
Ma				***	ns
Sa					ns

† Co = control treatment.
‡ Ch = charcoal amended treatment.
§ Ma = manure amended treatment.
¶ Sa = sawdust amended treatment.
# Ti = *Tithonia diversifolia* amended treatment.
†† Ki = kitchen garden management.
‡‡ p-values are <0.001 (***), <0.01 (**), ns = not significantly different.

Table 5.2 Factor significance in mixed model analysis of soil physical, biological and chemical properties measured on farm samples.

PHYSICAL AND BIOLOGICAL		WSA¶	AWC#	PR15††	PR45‡‡	Sand	Silt	Clay	LoiOM†	ActC‡	ActC/LoiC§
All Data	**Parent Material**	***§§	ns	ns	*	ns	ns	**	***	***	ns
	Mgmt	***	ns	ns	**	*	ns	***	***	***	***
	Time	**	ns	ns	*	**	ns	***	***	***	**
	Mgmt*Time	**	ns	ns	ns	*	ns	*	ns	*	**

CHEMICAL		pH	EC¶¶	CEC	P	K	Ca	Mg	Cu	Zn	S
All Data	**Parent Material**	ns	*	***	**	***	***	***	***	ns	**
	Mgmt	***	***	***	***	***	***	***	+	***	***
	Time	ns	***	**	ns	ns	*	ns	ns	ns	*
	Mgmt*Time	*	*	ns	*	*	ns	ns	ns	*	ns

† LoiOM = total organic matter by loss on ignition at 350°C.
‡ ActC = permanganate oxidizable biologically active carbon.
§ ActC/LoiC = percent of total carbon made up by ActC.
¶ WSA = water stable aggregation.
# AWC = available water capacity.
†† PR15 = penetration resistance between 0-15 cm.
‡‡ PR45 = penetration resistance between 15-45 cm.
§§ p-values are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), ns = not significantly different.
¶¶ EC = electrical conductivity.

Table 5.3 Factor significance in mixed model analysis of soil physical, biological and chemical properties measured on farm samples by parent material.

PHYSICAL AND BIOLOGICAL		WSA	AWC	PR15	PR45	Sand	Silt	Clay	LoiOM	ActC	ActC/LoiC
Nandi	**Mgmt**	***†	ns	ns	ns	*	ns	**	ns	+	***
	Time	*	*	***	***	***	ns	***	***	***	*
	Mgmt*Time	**	+	ns	ns	*	ns	**	ns	*	***
Kakamega	**Mgmt**	***	*	ns	*	ns	ns	*	***	***	***
	Time	+	ns	ns	ns	ns	ns	ns	*	+	ns
	Mgmt*Time	+	ns	ns	ns	ns	ns	ns	ns	ns	ns

CHEMICAL		pH	EC	CEC	P	K	Ca	Mg	Cu	Zn	S
Nandi	**Mgmt**	***	***	+	***	***	***	***	ns	***	***
	Time	ns	***	*	ns	ns	*	ns	ns	ns	ns
	Mgmt*Time	*	*	ns	+	+	ns	ns	ns	**	ns
Kakamega	**Mgmt**	***	***	***	*	***	***	***	ns	***	ns
	Time	ns	ns	ns	ns	ns	ns	ns	ns	+	*
	Mgmt*Time	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

† p-values are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), ns = not significantly different.

Table 5.4 Significance of two linear contrasts (kitchen garden (Ki) vs. all maize plots (Maize); control (Co) vs. average short-term organic matter addition treatment (OM) in mixed model analysis of soil physical, biological and chemical properties measured on farm samples.

PHYSICAL AND BIOLOGICAL		**WSA**	**AWC**	**PR15**	**PR45**	**Sand**	**Silt**	**Clay**	**LoiOM**	**ActC**	**ActC/LoiC**
Nandi	**Ki vs. maize**	***†	ns	ns	ns	*	ns	**	*	**	***
	Co vs. avgOM	*	ns	ns	+	*	ns	**	ns	ns	*
Kakamega	**Ki vs. maize**	***	***	ns	ns	ns	*	**	***	***	***
	Co vs. avgOM	+	ns	ns	***	ns	ns	ns	ns	ns	ns
CHEMICAL		**pH**	**EC**	**CEC**	**P**	**K**	**Ca**	**Mg**	**Cu**	**Zn**	**S**
Nandi	**Ki vs. maize**	***	***	ns	ns	***	***	***	ns	***	***
	Co vs. avgOM	+	*	ns	***	***	ns	ns	ns	ns	ns
Kakamega	**Ki vs. maize**	***	***	***	ns	***	***	***	ns	***	*
	Co vs. avgOM	ns	***	ns	***	***	ns	ns	ns	ns	ns

† p-values are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), ns = not significantly different.

Table 5.5 LS means for soil physical, biological and chemical properties by parent material and management system.

PHYSICAL AND BIOLOGICAL		WSA %	AWC $m^3 m^{-3}$	PR15 kPa	PR45 kPa	Sand $g\ kg^{-1}$	Silt $g\ kg^{-1}$	Clay $g\ kg^{-1}$	LoiOM $g\ kg^{-1}$	ActC $mg\ kg^{-1}$	ActC/LoiC %
Nandi - All Farms											
	Ki	74 A	0.15 A	228 A	1328 A	440 A	380 A	180 B	86.5 A	610 A	1.63 A
	Co	64 B	0.15 A	177 A	1219 A	400 B	380 A	220 A	83.2 A	525 A	1.32 B
	Ti	67 B	0.14 A	217 A	1308 A	420 AB	380 A	200 AB	82.4 A	569 A	1.51 AB
	Ma	69 B	0.15 A	212 A	1326 A	430 AB	380 A	200 AB	80.7 A	548 A	1.50 AB
	Sa	68 B	0.15 A	189 A	1290 A	430 AB	370 A	210 AB	81.4 A	550 A	1.42 B
	Ch	66 B	0.14 A	216 A	1305 A	430 AB	380 A	190 AB	82.9 A	542 A	1.38 B
Kakamega - All Farms											
	Ki	56 A	0.18 A	261 A	1735 AB	490 A	410 A	100 B	50.6 A	490 A	2.16 A
	Co	37 B	0.16 AB	110 A	1333 B	460 A	400 A	140 AB	37.1 B	218 B	1.30 B
	Ti	41 B	0.15 AB	294 A	1858 A	490 A	390 A	130 AB	38.8 B	263 B	1.47 B
	Ma	42 B	0.15 B	190 A	1864 A	470 A	380 A	150 A	38.1 B	260 B	1.55 B
	Sa	41 B	0.16 AB	228 A	1866 A	480 A	390 A	140 AB	37.6 B	246 B	1.44 B
	Ch	42 B	0.16 AB	232 A	1839 AB	490 A	380 A	130 AB	38.6 B	242 B	1.38 B

CHEMICAL		pH	EC (dS m-1)	CEC (meq/100g)	P $mg\ kg^{-1}$	K $mg\ kg^{-1}$	Ca $mg\ kg^{-1}$	Mg $mg\ kg^{-1}$	Cu $mg\ kg^{-1}$	Zn $mg\ kg^{-1}$	S $mg\ kg^{-1}$
Nandi - All Farms											
	Ki	6.63 A	0.072 A	18.84 A	24 A	481 A	2321 A	333 A	2.02 A	16.82 A	15.10 A
	Co	5.86 B	0.020 B	18.38 A	15 B	209 D	1821 B	216 C	1.93 A	6.92 B	13.17 B
	Ti	5.94 B	0.026 B	18.64 A	25 A	313 BC	1893 B	219 C	1.93 A	8.75 B	13.39 B
	Ma	6.02 B	0.030 B	18.83 A	29 A	371 AB	1827 B	264 B	1.99 A	8.90 B	13.87 AB
	Sa	5.95 B	0.023 B	17.71 A	26 A	259 CD	1805 B	228 BC	1.89 A	6.74 B	13.14 B
	Ch	6.03 B	0.027 B	17.70 A	28 A	287 BC	1978 B	232 BC	1.94 A	8.17 B	13.33 B
Kakamega - All Farms											
	Ki	6.77 A	0.077 A	13.85 A	49 A	296 A	1721 A	268 A	4.64 A	31.54 A	16.35 A
	Co	5.67 B	0.007 C	11.02 B	26 B	97 C	754 B	88 B	4.46 A	6.22 B	15.85 A
	Ti	5.80 B	0.019 B	10.95 B	43 AB	150 B	834 B	99 B	4.31 A	5.82 B	14.83 A
	Ma	5.84 B	0.023 B	10.75 B	51 A	177 B	806 B	112 B	4.70 A	6.56 B	15.18 A
	Sa	5.71 B	0.016 B	10.78 B	44 AB	134 BC	766 B	95 B	4.52 A	6.55 B	15.10 A
	Ch	5.68 B	0.019 B	10.85 B	40 AB	125 BC	819 B	92 B	4.41 A	5.82 B	15.12 A

† Means of each property followed by the same letter are not significantly different at $\alpha = 0.05$, based on a Tukey's test of fixed effects in the mixed model. Means comparisons were included even for those properties which showed significant treatment by conversion year interaction.

for both regions across the whole sequence, but for the Nandi region a similar analysis of LS means was presented separately for new and old farms (7 or 12 yr and > 20 yr out of forest, respectively; Table 5.6). It should be noted that kitchen gardens had somewhat coarser textures in both regions since they were generally located closer to the hill top than maize fields.

5.5.1.1 Long-term management systems

Out of 20 soil properties, 13 in the Nandi and 15 in the Kakamega region showed significant differences between Ki and average maize management (all except PR15, PR45, P and Cu in both, silt in Kakamega and AWC, sand, CEC in Nandi; Table 5.4). The starkest differences between management systems were found between long-term, low-input Co and Ki LS means (Table 5.5).

In the Nandi region, compared to Co plots, Ki had higher WSA by 16%, ActC/LoiC by 23%, EC by 260%, P by 60%, K by 130%, Ca by 28%, Mg by 54%, Zn by 143%, S by 15%, and pH by 0.87 pH units (Table 5.5). The extent of the management difference between Ki and Co increased over time for almost all indicators (all except PR15 and S; Table 5.6). Fewer soil properties (mostly soil chemical properties) were significantly different between newer Ki and Co fields. In new vs. old farms, Ki had higher PR15 (100% vs. ns), pH (0.56 vs. 0.91 pH units), EC (136% vs. 391%), P (21% vs. 108%), K (77% vs. 180%), Mg (39% vs. 73%) and S (26% vs. ns). In old farms, Ki additionally had significantly higher WSA by 22%, LoiOM by 12%, ActC by 43%, ActC/LoiC by 44%, Ca by 46% and Zn by 221% (Table 5.6).

In the Kakamega region, kitchen garden management had an even larger effect on almost every soil property affected in Nandi. In comparison to Co plots, Ki had significantly higher WSA by 51%, LoiOM by 36%, ActC by 125%, ActC/LoiC by

Table 5.6 Significance of management as a factor, and LS means for soil physical, biological and chemical properties in new (7 and 12 yr) and old (> 20 yr) farms in Nandi by management system in a mixed model.

PHYSICAL AND BIOLOGICAL		WSA %	AWC m3 m-3	PR15 kPa	PR45 kPa	Sand g kg^{-1}	Silt g kg^{-1}	Clay g kg^{-1}	LoiOM g kg^{-1}	ActC mg kg^{-1}	ActC/LoiC %
Nandi - New Farms											
	Mgmt Factor	ns†	+	*	ns	ns	ns	ns	ns	ns	ns
	Ki	75 A‡	0.18 A	236 A	1235 A	490 A	380 A	130 A	112.2 A	799 A	1.63 A
	Co	72 A	0.18 A	118 B	1030 A	490 A	390 A	120 A	114.5 A	795 A	1.58 A
	Ti	74 A	0.17 A	131 AB	1126 A	500 A	370 A	120 A	110.8 A	831 A	1.71 A
	Ma	76 A	0.17 A	133 AB	1080 A	510 A	370 A	120 A	107.6 A	778 A	1.64 A
	Sa	75 A	0.19 A	147 AB	1087 A	510 A	360 A	130 A	110.8 A	848 A	1.73 A
	Ch	72 A	0.17 A	174 AB	1146 A	510 A	370 A	120 A	110.1 A	799 A	1.65 A
Nandi - Old Farms											
	Mgmt Factor	***	ns	ns	ns	***	ns	***	*	***	***
	Ki	72 A	0.12 A	223 A	1380 A	410 A	380 A	220 B	67.9 A	472 A	1.63 A
	Co	59 B	0.13 A	215 A	1334 A	330 B	370 A	290 A	60.5 B	329 B	1.13 B
	Ti	62 B	0.12 A	278 A	1429 A	370 AB	380 A	250 AB	61.5 AB	377 B	1.35 AB
	Ma	63 B	0.13 A	267 A	1497 A	370 AB	380 A	250 AB	60.9 AB	381 B	1.39 AB
	Sa	63 B	0.12 A	215 A	1428 A	370 AB	370 A	260 A	59.6 B	330 B	1.18 B
	Ch	62 B	0.12 A	243 A	1409 A	360 AB	390 A	250 AB	62.9 AB	353 B	1.17 B

CHEMICAL		pH	EC (dS m-1)	CEC (meq/100g)	P mg kg^{-1}	K mg kg^{-1}	Ca mg kg^{-1}	Mg mg kg^{-1}	Cu mg kg^{-1}	Zn mg kg^{-1}	S mg kg^{-1}
Nandi - New Farms											
	Mgmt Factor	***	***	ns	*	*	ns	**	ns	+	*
	Ki	6.65 A	0.092 A	22.02 A	23 AB	465 A	2915 A	390 A	1.88 A	15.10 A	16.34 A
	Co	6.09 B	0.039 B	22.04 A	19 B	263 B	2550 A	280 B	1.65 A	9.31 A	12.96 B
	Ti	6.07 B	0.050 B	22.04 A	33 AB	355 AB	2620 A	278 B	1.72 A	13.04 A	13.84 AB
	Ma	6.11 B	0.057 B	22.25 A	37 A	399 AB	2500 A	334 AB	1.79 A	11.94 A	14.48 AB
	Sa	6.12 B	0.045 B	21.36 A	34 AB	296 AB	2570 A	291 B	1.69 A	9.98 A	13.32 B
	Ch	6.32 AB	0.057 B	20.55 A	35 AB	346 AB	2824 A	300 AB	1.71 A	10.87 A	13.53 AB
Nandi - Old Farms	**Mgmt Factor**	***	***	*	*	***	***	***	ns	***	*
	Ki	6.60 A	0.059 A	16.50 A	25 A	496 A	1872 A	290 A	2.13 A	17.86 A	14.26 A
	Co	5.69 B	0.012 B	15.68 AB	12 B	177 D	1280 B	168 C	2.13 A	5.55 B	13.30 AB
	Ti	5.82 B	0.016 B	16.10 AB	21 AB	280 BC	1345 B	174 BC	2.09 A	6.34 B	13.05 AB
	Ma	5.93 B	0.018 B	16.27 A	24 A	346 AB	1322 B	211 B	2.14 A	7.00 B	13.41 AB
	Sa	5.80 B	0.014 B	14.97 B	21 AB	231 CD	1227 B	179 BC	2.03 A	4.91 B	13.01 B
	Ch	5.80 B	0.015 B	15.58 AB	23 AB	245 BCD	1337 B	180 BC	2.10 A	6.46 B	13.18 AB

† p-values are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), ns = not significantly different.
‡ Means of each property followed by the same letter are not significantly different at α = 0.05, based on a Tukey's test of fixed effects in the mixed model

66%, pH by 1.10 pH units, EC by 1000%, CEC by 26%, P by 89%, K by 205%, Ca by 128%, Mg by 204%, and Zn by 407% (Table 5.5). A linear contrast of Ki vs. Co (not shown) also showed significantly higher PR45 (30%) and AWC (13%) in Ki than in Co.

5.5.1.2 Short-term management interventions

Out of 20 soil properties, 9 in the Nandi and 5 in the Kakamega region showed significant differences between Co and an average of all organic matter additions (avgOM, Table 5.4). Compared to Co plots, avgOM plots had higher WSA (by 6% in Nandi, by 12% in Kakamega), higher PR45 (by 7% in Nandi, by 39% in Kakamega), higher EC (by 33% in Nandi, by 175% in Kakamega), higher P (by 85% in Nandi, by 70% in Kakamega) and higher K (by 55% in Nandi, by 51% in Kakamega). In the Nandi region avgOM plots also had higher ActC/LoiC (by 10%) and pH (by 2%). Because most differences were small and there was a lot of variability between farms (farm as a random factor accounted for 24-95% of the variability in the mixed models), only a few of these differences (such as EC in Kakamega and K in both regions) were significant when comparing types of organic matter inputs to Co in the more conservative Tukey's test shown in Table 5.5. Several other soil properties in the organic matter amended maize systems showed similar increased trends as those found in kitchen garden management, although these were not statistically significant.

Differences between the four short-term organic matter amendments were explored with another mixed model, which, to achieve greater power, did not include Co or Ki measurements. Short-term organic amendment type was a significant factor for 7 soil properties on Nandi farms, and for 3 on Kakamega farms (Table 5.7). A Tukey's test showed Ma amended plots to have highest K, Mg, Cu and Zn among the

Table 5.7 Significance of short-term organic amendment management as a factor in a mixed model analysis of soil physical, biological and chemical properties measured on farm samples by parent material.

Indicator	Nandi	Kakamega
WSA	ns†	ns
AWC	+	ns
PR15	ns	ns
PR45	ns	ns
LoiOM	ns	ns
ActC	ns	ns
Act/C	+	ns
pH	ns	ns
EC	ns	ns
CEC	**	ns
P	ns	ns
K	***	*
Ca	+	ns
Mg	***	+
Cu	+	**
Zn	***	ns
S	+	ns

† p-values are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), ns = not significantly different.

Table 5.8 LS means for soil properties for which a Tukey's test of fixed effects in the mixed model found significant differences between type of short-term OM amendment 16 months after each was applied.

		CEC (meq/100g)	**K** mg kg^{-1}	**Mg** mg kg^{-1}	**Cu** mg kg^{-1}	**Zn** mg kg^{-1}
Nandi	**Ti**	18.49 AB†	304 B	217 B	1.94 A	8.43 A
	Ma	18.68 A	361 A	263 A	2.00 A	8.58 A
	Sa	17.56 B	252 C	226 B	1.90 A	6.50 B
	Ch	17.55 B	279 BC	230 B	1.95 A	7.88 A
Kakamega	**Ti**	10.96 A	150 AB	99 A	4.31 B	5.81 A
	Ma	10.75 A	177 A	112 A	4.70 A	6.55 A
	Sa	10.78 A	134 AB	95 A	4.52 AB	6.54 A
	Ch	10.85 A	125 B	92 A	4.41 B	5.81 A

† Means of each property followed by the same letter are not significantly different at $\alpha = 0.05$.

four amendments, and highest CEC in Nandi (Table 5.8). The management by time interaction in the Nandi region was significant for several soil properties, including ActC and ActC/LoiC, and a Tukey's test (not shown) of the four amendments on old Nandi farms revealed highest ActC and ActC/LoiC were found in Ma plots, followed by Ti (Table 5.6).

5.6. DISCUSSION

5.6.1. Using indicators for soil quality monitoring and assessment

We used soil properties as indicators of soil quality. Soil quality is the capacity of the soil to function (Doran and Parkin, 1994) physically, biologically and chemically. Indicators were chosen to represent a wide range of such functions and processes that are important to sustained agricultural production (e.g. Chapter 4, Andrews et al., 2004; Gugino et al., 2009; Idowu et al., 2008; Karlen et al., 1994; Larson and Pierce, 1991; Moebius-Clune et al., 2008; Weil et al., 2003). Represented processes include: physical root proliferation and movement of soil organisms in the surface (PR15) and subsurface (PR45); chemical buffering (pH); macro- and micro-nutrient retention and availability (pH, CEC, EC, nutrient concentrations, LoiOM); toxicity and pollution prevention (nutrient concentrations, LoiOM, pH); energy and carbon storage (LoiOM, ActC, ActC/LoiC); support of soil biological activity and nutrient mineralization (ActC, ActC/LoiC); soil structural stability, runoff/erosion/crusting prevention, aeration and water infiltration and transmission (WSA, PR15); and water retention (AWC, LoiOM).

Indicators were interpreted to signify higher SQ when they suggested better functioning of soil processes for agricultural production. For the ranges measured, all indicators, except for pH, PR15, PR45 and soil textural variables, suggest improvements in the soil processes as given above when their measured values increase. Values of pH mostly suggest increasing soil quality with increasing values, except in the few cases in kitchen gardens that had pH values above 7. Higher PR15 and PR45 values indicate harder soils, a decrease in root proliferation, and therefore a decrease in soil quality. Texture is a necessary inherent soil property that enables soil quality interpretation, but is rarely changed by management, and does not exhibit management related changes in the Nandi and Kakamega regions. Such interpretation of indicators of soil quality allows us to describe changes in SQ with respect to the changes in agronomically important soil functions and constraints occurring due to degradation over time and due to contrasting management systems.

5.6.2. Long-term management effects on soil quality

Organic matter facilitates two essential categories of functions (Lal, 2006), both of which can be impaired when soil quality is not managed appropriately: First, organic matter stabilization in aggregates improves cation retention (as represented by CEC), and pH buffering, and, in well-established soil structures, enhances water storage (as represented by AWC), infiltration, root proliferation and physical access to nutrients, while decreasing surface crusting, runoff and erosion, as represented by WSA. Tillage in continuous cropping systems breaks up existing aggregates, exposing organic matter that was stabilized under the natural ecosystem to oxygen and microbial activity, and bringing on rapid decomposition and loss in aggregate stability (e.g., Chapter 4, Islam and Weil, 2000; Liebig et al., 2004; Moebius-Clune et al., 2008). Second, organic matter decomposition is important because labile C, as represented by ActC, provides substrate for soil microbes. These soil biota produce exudates that help bind soil particles into stable aggregates, as represented by WSA, and mineralize nutrients for crop growth, as represented by the various indicators of nutrient availability. The latter is especially important in smallholder agriculture, which usually depends entirely on organic matter-derived nutrients, because fertilizers are not affordable or available to most farmers (Sanchez, 2002).

Because organic amendment availability to smallholder farmers is limited, fields closer to the homestead, such as the kitchen gardens sampled here, are preferentially amended with what little is available, such as cooking ashes, plant remains, and manure (Mtambanengwe and Mapfumo, 2008). On the other hand, typical smallholder grain fields, such as the continuous low-input maize system sampled here, do not generally receive such inputs. The small quantities of crop residues that are returned to the soil are not adequate to maintain soil quality in these systems. This explains why these fields were found to have the lowest soil quality of all management systems studied. Nutrient gradients resulting from varying soil management practices in small holder agriculture have been widely documented throughout Africa, and higher nutrient and organic C status has been found closer to the farm homestead (Fofana et al., 2008; Prudencio, 1993; Tittonell et al., 2007; Tittonell et al., 2005) as was the case in this study. The effects of such management differences on indicators of physical and biological soil constraints have not been addressed sufficiently in the literature so far.

We found that the different management of Ki fields resulted in vastly better overall soil quality in this system. Aside from much higher nutrient availability and pH, Ki soils also had better aggregation, and thus likely improved infiltration and lower runoff and erosion potentials, which would contribute to higher nutrient availability by decreasing nutrient and organic matter losses. They were able to store marginally more water in the Kakamega region, and thus would likely be more drought resistant. Ki soils in the Kakamega region and on the older Nandi farms, where management differences were more established, had higher total and labile OM (despite their lower clay contents, due to their upland position in the toposequence), and higher quality organic matter (ActC/LoiC) and thus likely had higher biological activity, and higher nutrient supplying capacity throughout the cropping season. Kitchen gardens are thus likely to produce better yields due to improved overall soil function, not just due to increased nutrient availability, as has been found in similar comparisons by Vanlauwe et al. (2006) and Mtambanengwe and Mapfumo (2008), among others.

On the other hand Ki sites had somewhat higher subsoil compaction (PR45). Although only marginally statistically significant (linear contrast in the Kakamega region, $\alpha = 0.05$), high PR45 was likely agronomically constraining in some individual fields. Typical Ki management involves more foot traffic and tillage than in Co, because of more intensive crop and amendment management and more frequent planting and harvesting. Increased pH in most kitchen gardens brought them closer to ideal cropping conditions than the respective Co field, but some individual kitchen gardens had a pH of up to 7.8, likely from adding too much ash from cooking fires (Gorecka et al., 2006). These higher-than-optimal pH values suggest that cooking ash distribution could be improved on the individual farm scale, as explored further by Moebius-Clune (Chapter 7).

5.6.3. Short-term management effects on soil quality

Residual effects of adding several types of organic matter to continuously cropped fields further from the home were small 16 months after they were applied, but several of the measured indicators do suggest beneficial effects of added OM on several soil processes. This highlights the importance of using an integrative, multi-indicator assessment to determine management-induced changes to SQ.

Using a standard loss on ignition technique, we did not find the significant increases in total soil organic C that Kimetu et al. (2008) measured via CN analyzer just after organic amendments were added. The tropical, warm, moist climate in western Kenya is conducive to rapid degradation of higher quality (low C:N ratio) organic matter and probably even sawdust with higher C:N ratios (Larson et al., 1972; Palm et al., 2001). It is thus likely that C added by amending soils with Ma, Ti and Sa decomposed beyond detection in the 16 months between the last OM application and sampling for this assessment. Even in more temperate climates, increases in stable soil organic matter generally take much longer than three seasons to achieve (Carter, 2002; Wander et al., 1994).

Due to the recalcitrance of charcoal (frequently referred to as biochar) in soil, it is unlikely that the C added with Ch amendments decomposed within 16 months (Kuzyakov et al., 2009; Lehmann and Rondon, 2006; Nguyen et al., 2008), but the loss on ignition technique cannot measure increases in soil black carbon content. Oxidation at 375^{o}C is a method frequently used in the literature to oxidize all but black carbon (Gustafsson et al., 1997). Much higher temperatures, such as those used in CN auto-analyzer analyses, are then used to determine the content of black C (charcoal) in soil. This explains why our results did not show the total organic C increases from charcoal applications previously measured (Kimetu et al., 2008), which are likely to still be present.

Increased CEC due to organic amendments observed previously (Kimetu et al., 2008) was also no longer detectable 16 months after the last organic amendments were added, except for the slightly elevated CEC in Ma plots on the older farms in the Nandi region. We did, however, measure several small but significant residual physical, biological and chemical soil quality differences, such as elevated pH and ActC/LoiC in Nandi and higher aggregation and nutrient availability (WSA, EC, available P and K) in averaged organic-amended systems as compared to Co in both regions. Phosphorus levels in avgOM plots were as high as those in Ki, while Co plots had lower P, although they received the same fertilizer as avgOM plots. This suggests that, while OM differences were not detectable, adding organic matter helped maintain higher P availability 16 months later.

Results of the Hotelling T^2 test suggested that Ch and Sa amended soils differed significantly from those amended with Ma, but none differed from those amended with Ti. While not all of the specific differences were large enough to be statistically significant in a mixed model analysis of each indicator, it appeared that the larger differences were related to nutrient contents. Manure plots, often followed by Ti, differed from Ch and Sa plots due to significantly higher CEC, K, Mg, Cu and Zn in one or both parent materials. This can be explained by the higher concentrations of these nutrients contained in the organic materials applied, and the large quantity of biomass applied in order to attain a total of 6 t C ha^{-1} (Kimetu et al., 2008). Trends suggest higher residual availability of several other nutrients in Ma plots as well, and higher ActC in Ma and Ti amended systems in both parent materials. No other biological or physical differences were detected between the amended soils 16 months after OM application.

Organic matter amended systems had higher subsurface hardness (PR45) in both the Nandi and Kakamega regions, although this difference was less significant in the Nandi soils. Similar, but mostly statistically non-significant trends were observed in the more intensively cultivated kitchen gardens. Compaction levels created on the Kakamega farms are especially noteworthy. The subsoil was not only significantly harder, but also came close to the 2000 kPa threshold often cited as an impediment to root penetration (Tekeste et al., 2007). This compaction results from increased tillage and foot traffic during OM incorporation: 6 instead of 2 tillage passes per year when the soil was wet, because this is when it is easier to hoe by hand. While adding OM provided some lasting benefits to aggregation, biological activity and especially nutrient availability, the method and timing of OM incorporation caused agronomically significant compaction.

5.6.4. Effects of parent material on soil quality dynamics

Parent material and related inherent soil type differences, sometimes referred to as inherent soil quality, affect degradation and aggradation of dynamic soil quality (Carter, 2002), which is management-induced. The effect of inherent soil characteristics is an essential component to consider in developing appropriate management strategies for smallholder agriculture. Different types of parent materials often result in different inherent constraints and potential constraints developed due to degradation (Carter, 2002; de la Rosa et al., 2009; Mapfumo et al., 2007). Our data indicate greater differences between the Co and Ki systems in Kakamega than in Nandi soils across the majority of measured indicators. Kakamega soils were also much more sensitive than Nandi soils to subsurface compaction (PR45). Similar effects of soil type on compaction development have been reported previously by Yao-Kouame and Yoro (1991) and Tekeste et al. (2007), among others. This suggests that effectiveness of management strategies for reclaiming degraded soils or maintaining newly cultivated soils differs based on parent material.

5.6.5. Soil quality management as a long-term strategy

Our data corroborate the notion that soil quality management needs to be a long-term strategy (Magdoff and van Es, 2009). Soil biological and physical characteristics 1) showed small differences between different types of short-term organic matter inputs and between these and non-amended Co plots after three seasons of relatively large OM additions, and 2) were not yet significantly different between the two long-term strategies, Co and Ki, on newer farms. However, biological and physical indicators showed that there were highly significant effects of OM additions on aggregation and organic matter fractions of soils on older farms, where the two contrasting, long-term management systems had been in place for over 20 yr. While most soil chemical properties were affected within the first 7 to 12 years of contrasting management, effects on chemical soil fertility increased over time as well.

The long lag in the response time of biological and physical properties to Ki vs. Co management may in part be due to the severe limitations in OM available to these smallholder farmers (Lal, 2006). Small amounts of OM added were able to maintain Ki at higher overall SQ levels than Co, but did not prevent them from degrading after forest conversion. Since the quantities of organic additions were likely small, differences did not become detectable until they had been in place for over 20 yr. Amendments on the order of 6 t ha^{-1} per season (which are usually not available to smallholders), such as the experimental Ti, Ma, Sa and Ch amendments added to plots in this study, caused small but detectable increases in soil aggregation and quality of available organic matter (ActC/LoiC) in much less time. Further differences SQ from applying different high vs. low quality organic matter would likely become discernable after more long-term additions. For example, it would be expected that long-term additions of more stable materials (Sa and Ch) would increase total soil organic matter and AWC more rapidly than more easily degradable materials (Ti and Ma). However three seasons were not long enough to bring about measurable changes.

Unlike the slow rates of SQ change observed in other indicators, soil compaction developed much more quickly, responding significantly to merely 3 seasons of imprudent management. In light of the many adverse effects of compaction on other soil functions (Hamza and Anderson, 2005; Soane and van Ouwerkerk, 1995), this result suggests that compaction should be regularly monitored. While short-term additions can positively influence SQ, growers should aim to make management changes that can be implemented not just once, but consistently over the long term. This will help achieve the kinds of soil quality improvements that only longer-term proactive management appears to be able to bring about.

5.7. CONCLUSIONS

Results of this study provide insights into the effects of contrasting, traditional, long-term soil management strategies used by smallholder farmers and short-term management interventions on soil quality. Biological, physical, and chemical indicators of SQ suggest that, with long-term management, much higher soil quality, specifically higher soil aggregation, water storage, C storage, substrate for biological activity and nutrient retention, mineralization and availability, can be maintained better in high-input polyculture kitchen gardens than in continuous low-input maize fields. Sixteen months after short-term organic matter additions, SQ in previously low-input maize fields remained slightly improved, except for the compaction caused by imprudent management. Amended soils had somewhat higher aggregation and nutrient availability, and sometimes slightly higher-quality organic matter, suggesting the potential for marginally higher biological activity and nutrient supplying capacity in amended soils. The fact that SQ was improved by short- and especially long-term management, indicates that, despite rapid organic matter turnover in the tropics, there is great potential to reverse SQ declines, and therefore improve crop production in degraded soils through targeted management strategies. Strategies that can be maintained in the long-term by farmers in such smallholder systems need to be identified to bring about such aggradation. Parent material and associated inherent SQ limitations and differences must be taken into consideration when devising management strategies to reverse SQ declines. The inadvertent compaction caused while managing soil with the goal of improving SQ, in particular, makes the case for implementing basic SQ assessment. The demonstrated ability to measure management differences with a fairly basic set of SQ indicators suggests that future work on appropriate management systems could be enhanced by incorporating such tests to assess and monitor soil quality.

5.8. ACKNOWLEDGEMENTS

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CHAPTER 6. DEVELOPMENT AND EVALUATION OF SCORING FUNCTIONS FOR INTEGRATIVE SOIL QUALITY ASSESSMENT AND MONITORING IN WESTERN KENYA[5]

6.1. ABSTRACT

Agricultural viability and food security depend heavily on the quality of managed soils, but widely-standardized soil quality (SQ) assessment protocols are largely non-existent, especially for use in the tropics. The Cornell Soil Health Test (CSHT) is composed of a set of inexpensive, agronomically meaningful, low-infrastructure-requiring indicators of SQ to help target management strategies that will help to alleviate yield-limiting soil constraints. Soils were sampled from primary forest and fields on farms converted from forest between 1900 and 2000, along an agricultural chronosequence experiment at the Kakamega and Nandi Forest margins. On each farm, soils were sampled from two traditional, long-term management systems (continuous low-input maize (*Zea mays*, control, Co), and diversely cropped high-input kitchen gardens (Ki)) and short-term experimental maize plots that received several types of organic matter (OM) inputs 16 months prior to sampling. Maize grain, stover, and total biomass yields were measured in 2005 and 2007. Measured SQ

[5] Moebius-Clune, B.N., H.M. van Es, O.J. Idowu, R.R. Schindelbeck, J.M. Kimetu, S. Ngoze, J. Lehmann, and J.M. Kinyangi. Development and evaluation of scoring functions for integrative soil quality assessment and monitoring in western Kenya. To be submitted to one of following: Soil Science Society of America Journal, Geoderma, Agriculture Ecosystems and Environment, Soil and Tillage Research.

indicators included physical indicators (water stabile aggregation (WSA), available water capacity (AWC), and field penetration resistance in the surface (PR15) and subsoil (PR45)), biological indicators (permanganate oxidizable active C (ActC) and total organic matter by loss-on-ignition (LoiOM)) and chemical indicators (electrical conductivity (EC), pH, P and K). From these data, a set of scoring functions, as well as a composite soil health index (CSHI), were developed using cumulative normal distribution functions. The scoring functions succeeded in differentiating management related constraints in essential, agronomically-related soil processes. For most SQ indicators, old farms were more frequently constrained than new farms. Decreasing CSHI values and increasing number of constraints over time confirmed soil degradation under Co, and to a lesser extent under Ki. Indicator scores and values and the CSHI predicted up to 32% of the variability in yield components via simple linear regression and up to 47% of the variability via multiple linear regression (MLR), with ActC as the most reliable single predictor of yield. Up to 65% of the variability in yield could be explained by accounting for variability between farms. The number of constrained indicators predicted up to 85% of the variability in yield components. Our findings indicate that the developed CSHT scoring functions 1) successfully assessed soil constraints resulting from management practices and 2) are predictive of crop productivity. The CSHT may provide a practical framework from which to develop standardized soil quality assessment and monitoring.

6.2. KEY WORDS

Soil quality; soil quality assessment and monitoring; scoring function; soil health; soil degradation; low-input agriculture; smallholder agriculture; kitchen garden; maize; Africa; deforestation

6.3. INTRODUCTION

6.3.1. Need for soil quality testing in Africa

Africa's agricultural viability and food security depend heavily on the quality of its soils. Agricultural soil quality (SQ), often referred to as soil health, encompasses the chemical, physical and biological functions and processes of soils that support crop growth (Doran et al., 1994). Declining SQ is becoming more prevalent in Africa due to intensive land use and poor soil management that often results from over-population and poverty (Eswaran et al., 2005; Lal, 2009).

Sanchez and Swaminathan (2005), in a summary of Hunger Task Force recommendations, note that to increase agricultural productivity of food-insecure farms, "restoring soil health is often the first entry point." Furthermore, the World Soils Agenda developed by the International Union of Soil Scientists lists as the first two agenda items 1) assessment of status and trends of soil degradation at the global scale and 2) definition of impact indicators and tools for monitoring and evaluating soil condition (Hurni et al., 2006). There is thus a need for international standards for measuring and interpreting SQ to enable 1) on-farm assessment of SQ constraints limiting food production, 2) applied extension research on locally-adapted management options, and 3) regional to international scale SQ assessment and monitoring.

While approaches to measuring air and water quality are widely established and standardized, similarly widely-standardized SQ assessment protocols are still largely non-existent (Bastida et al., 2008; Winder, 2003). Furthermore, methods to assess SQ are often not accessible to researchers, extension organizations and especially farmers in developing nations due to constraints in available infrastructure (Bastida et al., 2008). A clear need exists for methodologies and frameworks that are applicable in disparate circumstances to support action and enable international comparability of data (Riley, 2001).

6.3.2. Indicator choice and interpretation through scoring functions

Soil quality cannot be measured directly, but soil properties that influence the functioning of soil processes important in crop production can be used as indicators of agricultural SQ (Doran and Parkin, 1996; Larson and Pierce, 1991). For SQ assessment to be widely adopted beyond the research domain, indicators of agricultural SQ must be standardized, scientifically and agronomically relevant, represent relevant physical, biological and chemical processes, and be sensitive to changes in agricultural management. But they must also be easy and inexpensive to measure, and interpretations must be accessible to many users (Doran et al., 1994; Larson and Pierce, 1991; Mausbach and Seybold, 1998). Furthermore, standardized indicators to be adopted in developing nations, it is desirable that minimal infrastructure and investment be required (Chapter 7, Bastida et al., 2008).

Once indicators have been chosen, criteria and thresholds must be set by which to assess performance levels relative to standards, as discussed by Arshad and Martin (2002), among others. This is usually accomplished through linear or non-linear scoring functions, which normalize measured indicator values to a predefined range, (Andrews et al., 2002; Andrews et al., 2004; Glover et al., 2000; Hussain et al., 1999; Karlen et al., 1994; Masto et al., 2008). While linear scoring can be simpler to accomplish, non-linear scoring has been found to be more sensitive to management and is also more representative of system functions (Andrews et al., 2002; Masto et al., 2008). To integrate the information and provide a measure of the overall soil condition, a set of individually scored indicators are sometimes grouped into subgroups by soil function and then weighted, to calculate a single index of overall

SQ, as initially proposed by Karlen et al. (1994). A large number of such soil indices has been developed and successfully used by different researchers over the past few decades to describe differences and assess changes in soil functions in diversely managed experimental cropping systems, as reviewed by Bastida et al. (2008). Many have derived their basic structure from work by Karlen et al. (1994) and most of this work has been done in developed countries.

Several needs have not yet been addressed. First, there is very little standardization among chosen SQ indicators, field sampling protocols, laboratory methodologies, scoring functions and overall SQ indices used (Bastida et al., 2008). Second, most attention has been on comparing overall SQ between management systems, and less effort expended on identifying the level to which soil functions, and the processes that control these functions, are constrained. While various soil quality indices correlate well with endpoint outcomes, such as yield (e.g. Andrews et al., 2004; Masto et al., 2008), yield limitations due to specific soil processes and constraint levels have received little attention in these studies. Assessment of which vital soil processes are constrained can help land managers target specific management practices at alleviating such yield limiting factors (Chapter 7), similarly to fertilizing in response to identified nutrient constraints.

6.3.3. The Cornell Soil Health Test as a framework for standardized soil quality testing

The Cornell Soil Health Test (CSHT) was designed for field-by-field SQ assessment to aid management decisions. Since 2006, the CSHT has been offered to land managers, primarily in the Northeastern United States (Gugino et al., 2009; Idowu et al., 2008), similarly to widely available soil nutrient analyses. The CSHT is made up of a set of management-sensitive physical, biological and chemical indicators of SQ that meet the criteria described above (Chapter 5, Idowu et al., 2008; Idowu, 2009). Indicator measurements are interpreted via scoring functions and assessed with respect to whether they constrain the soil processes they represent. The information provided by the CSHT report enables farmers to 1) identify constraints in specific processes in their agricultural soils, including and beyond nutrient deficiencies, 2) implement practical management strategies that specifically target these constraints, and 3) monitor the condition of their soils over time. This test may provide a good framework for standardized SQ assessment and monitoring in developing nations and globally, but requires broader testing and an interpretative framework that can serve a variety of regions and infrastructure capacities.

A chronosequence of land conversion to agricultural production from primary forest, located on the Kakamega and Nandi forest margins in Kenya, provided a unique opportunity to "test the Test" in a tropical environment on small-holder farms. It has been well established that severe soil degradation and declines in productivity have occurred along this chronosequence since forest clearing (Chapter 4, Kinyangi, 2008; Ngoze et al., 2008; Solomon et al., 2007), and that productivity can be increased by short-term applications of fertilizers and organic amendments (Kimetu et al., 2008; Ngoze et al., 2008).

The goal of this study was to develop a set of scoring functions for use with the Cornell Soil Health Test in the Kenyan Highlands and to evaluate (i) the CSHT's ability to discern differences in soil constraints due to short- and long-term management differences in farm fields along this chronosequence, ii) the CSHT's ability to monitor soil quality change over time in two traditional long-term management systems, and (iii) the relationship of CSHT results with crop yield.

6.4. MATERIALS AND METHODS

6.4.1. Site description

The site used in this study is located at the margins of the Kakamega/Nandi Forest in Vihiga, Kakamega, South Nandi and North Nandi districts of western Kenya, between $0^{o}00'$N and $0^{o}13'$N latitude and between $34^{o}45'$E and $35^{o}03'$E longitude. Long rains of the bimodally-distributed rainfall occur from March to August, and short rains from September to January, thus allowing for two cereal cropping seasons per year in this region. The area receives about 1800 – 2100 mm of rainfall annually, and the mean annual temperature is 19^{o}C.

A chronosequence experiment, including intact primary forest sites and farms representing time points of conversion to agriculture between the years of about 1900 to 2000, was established to investigate the long-term effects of land conversion from primary forest to agriculture on soil C (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 sites are on Ultisols that contain low activity kaolinite and high proportions of Fe and Al oxides (Krull et al., 2002), and developed on two parent materials: undifferentiated basement system rock in the Kakamega region, and biotite-gneiss in the Nandi region (Kimetu et al., 2008).

The Kakamega chronosequence contained three clustered forest sites and 12 farms converted from forest to agriculture in 1930, 1950, 1970, 1985, and 1995 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 ~ 47, 40, 13% respectively). The 1995 farms were not used in time dynamics evaluation, since these appeared to be spatial outliers with a shallow gravelly restricted horizon that was not an effect of time in cultivation. The Nandi chronosequence contained 9 forest sites, clustered in three groups, and 27 farms converted from forest to agriculture in 1900, 1930, 1950, 1970, 1985, 1995 and 2000, with elevation ranging from 1538 to 2028 m ($\bar{x}$ = 1761 m, s = 109 m) and somewhat finer soil textures (average sand, silt and clay 43, 38, 19% respectively). The farms converted in 1900 were similarly spatial outliers, and were not used in time dynamics evaluations. They were more distant, of lower elevation and of higher clay content than remaining farms in this region. Most conversion years were replicated by three 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 (Kinyangi et al., 2008; Solomon et al., 2007), and thus time can be substituted by space (Huggett, 1998) in examining the effects of conversion. However, spatial effects on observed soil dynamics cannot be ruled out.

6.4.2. 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 (used as control; Co). Kitchen gardens, traditionally located close to the home, received household organic wastes and cooking ashes, and grew diverse fruit and vegetable crops in polyculture since forest conversion. The Co plots were generally tilled twice a year to 0.10 to 0.15 m using a hand hoe, continuously cropped with maize, and had received no or negligible fertilizer or organic amendments since conversion (Kinyangi, 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 (Kimetu et al., 2008).

On continuously cropped maize fields, four experimental short-term organic matter input systems were established in 2005 by Kimetu et al. (2008). For three consecutive growing seasons (long rains and short rains in 2005 and long rains in 2006, 16 months prior to our sampling) 6 t C ha^{-1} per season were added in the form of *Tithonia diversifolia* leaves (Ti), cattle manure (Ma), wood charcoal (Ch), and sawdust (Sa), for a total of 18 t C ha^{-1}. These plots received the same N, P and K fertilizer as Co plots (Kimetu et al., 2008). All plots received inorganic fertilizer until the 2007 long rains. Maize plots measured 2 x 4.5 m^2.

6.4.3. Field measurements

Maize total biomass, grain and stover yields were determined at the end of the long rainy season in 2005, after the first set of amendments in a subset of the plots in Nandi (n = 74), and, in 2007, in a subset of the plots in both the Nandi and Kakamega regions (n = 89). To avoid edge effects, yields were measured in subplots of 4.5 m^2, leaving one row and one plant at the end of each row in each plot. Fresh plant material was weighed, moisture was determined gravimetrically, and dry weight yield (kg ha^{-1}) was estimated.

All soil samples were gathered in July and August of 2007. At each farm a handheld GPS (Garmin eTrex) was used to record location and elevation. Each plot was sampled by taking five 0 to 0.15 m cores with a soil auger, compositing and mixing these and sub-sampling a ~1 L volume of soil for analyses. Surface (0 to 0.15 m, PR15) and subsurface (0.15 to 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 (Idowu et al., 2008).

6.4.4. Laboratory analysis

Soils were air-dried and passed through a 2 mm sieve prior to laboratory measurement of additional physical, biological and chemical soil properties, most of which are part of the Cornell Soil Health Test (Gugino et al., 2009; Idowu et al., 2008). Texture, an inherent, but influential soil property, was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) that involves a combination of sieving and sedimentation steps.

Water stable aggregation (WSA) was measured by artificial rainfall, which closely simulates slaking processes that occur on agricultural fields during rain events (Ogden et al., 1997b). The method applies 2.5 J of energy for 300 s on 0.25 to 2 mm aggregates placed on a 0.25 mm mesh sieve. 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, as described by Moebius et al. (2007). 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 in soils between these two pressures was calculated as the AWC.

Total organic matter content was determined by loss on ignition (LoiOM). Ten gram samples were oven-dried at 105^{o}C overnight, weighed, ignited to equilibrium in a muffle furnace set at 350^{o}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^{o}C (Ball, 1964; Rhodes et al., 1981). Biologically active carbon (ActC), was estimated by soil reaction with very dilute $KMnO_4$ as described by Weil et al. (2003). A hand-held colorimeter (Hach, Loveland, CO) was used to determine absorbance at 550 nm, which has an inverse linear relationship with increasing ActC. 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; Mtambanengwe et al., 2006; Weil et al., 2003).

Sieved soils were suspended in water (1:2.5) and electrical conductivity (EC), and pH 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 and K by inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 730-ES, Mulgrave, Victoria, Australia) at the Agricultural Analytical Services Laboratory, Pennsylvania State University, University Park, PA.

6.4.5. Scoring curve development for indicator interpretation

Non-linear scoring functions to interpret measured indicator values were developed for the chronosequence similarly to the scoring functions developed for the Cornell Soil Health Test offered in the Northeastern United States (Gugino et al., 2009) based on initial work done by Karlen et al. (1994) and Andrews et al. (2004). Scoring functions interpret the level to which represented soil functional processes (specific processes that control soil function, Table 6.1) are constrained.

Three types of scoring functions were developed: "less is better" (PR15 and PR45), "optimum range" (pH), and "more is better" (remaining indicators, Karlen et al., 1994). Scores (S) for each indicator range from 0 to 100, where $0 \leq S \leq 30$ is considered to indicate soil constraints, $30 < S < 70$ is an intermediate range, and $70 \leq S \leq 100$ indicates optimal soil functioning.

Scoring functions developed from this dataset (n = 227) are intended to provide a solid framework for soil quality interpretation, and are designed for easy

Table 6.1 Soil processes represented by measured indicators and scoring functions used to evaluate soil quality status.

Indicator	Soil Functional Processes	Type of Function	Scoring Function (0-100)†	Sources Scoring Function Parameter Development
PHYSICAL				
Aggregate Stability (WSA, %)	Structural stability, crusting, runoff, erosion, aeration, infiltration, shallow rooting	More is better	CND(49, 19)*100‡; CND(58, 19)*100	average local conditions
Available Water Capacity (AWC, m^3 m^{-3})	Plant-available water retention, drought stress tolerance	More is better	CND(0.16, 0.04)*100; CND(0.13, 0.04)*100	average local conditions
Surface Hardness (PR15, kPa)	Surface rooting, water infiltration and transmission	Less is better	(1-CND(1150, 175))*100	Cass (1999), Schuler et al. (2000) and Tekeste et al. (2007)
Subsurface Hardness (PR45, kPa)	Subsurface root proliferation, drought stress tolerance	Less is better	(1-CND(1500, 250))*100; (1-CND(1600, 300))*100	Cass (1999), Schuler et al. (2000) and Tekeste et al. (2007)
BIOLOGICAL				
Total Organic Matter (LoiOM, g kg^{-1})	Energy storage, C sequestration, water and nutrient retention	More is better	CND (58, 29)*100; CND(59, 29)*100	average local conditions
Active Carbon (ActC, mg kg^{-1})	Soil biological activity and biological nutrient mineralization	More is better	CND(427, 214)*100; CND(333, 214)*100	average local conditions
CHEMICAL				
pH	Toxicity, chemical buffering, nutrient availability	Optimum	$S = -63.1*(pH)^2 + 844.5*(pH) – 2716.5$	Gugino et al. (2009)
Electrical Conductivity (EC, dS/m)	Nutrient Availability (Salinity not an issue in this region)	More is better	CND(0.10, 0.025)*100	Arnold et al. (2005), Smith and Doran (1996), Glover et al. (2000), Milwaukee Instruments Inc. (2003)
Extractable Phosphorus (P, mg kg^{-1})	P Availability (P pollution not an issue in this region)	More is better	CND(33.5, 5.75)*100	Landon (1991), Kleinman et al.(2001), Schmisek et al. (1998)
Extractable Potassium (K, mg kg^{-1})	K Availability	More is better	CND(107.5, 24.25)*100; CND(68.5, 14.75)*100	Landon (1991), Texas A&M University (2004)

† For indicators that were scored separately by soil textural category, the function for soils with clay < 15% is listed first, followed by the function for soils with clay >15%.
‡ CND(m,s) = cumulative normal distribution, where m = mean, s = standard dev.

modification for other purposes and increased sensitivity of locally-appropriate analyses (Hussain et al., 1999). For some indicators (WSA, AWC, PR45, LoiOM, ActC, K), separate scoring curves were developed for samples above and below 15% clay content, as measured values cannot be interpreted without accounting for effects of particle size distributions (e.g., Dexter, 2004; Moebius et al., 2007). The majority of the Nandi soils (62%) were in the > 15% clay category. The majority of the Kakamega soils (60%) were in the < 15% clay category.

Where absolute thresholds have not been established, they can be tentatively set based on average local conditions (Arshad and Martin, 2002). This approach was used by modeling the distribution of each indicator based on a Gaussian distribution function (Fig. 6.1):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, -\infty < x < \infty \qquad [1]$$

with the parameter μ estimated by the sample mean (m) and the parameter σ by the sample standard deviation (s). Average local conditions were defined as those from the medium-aged farms between 12 and 77 yr since forest conversion. The average age of datasets used in the two textural categories was about 40 yr, with n = 69 in the > 15% clay dataset, and n = 93 in the < 15% clay dataset. The cumulative normal distribution function, CND(m,s), is the integral of Equ. [1] and gives the probability (between 0 and 1) that a member of the distribution is ≤ x. Such a CND(m,s) was developed for scoring WSA, AWC, LoiOM and ActC (Fig. 6.2, Table 6.1) by using the appropriate mean (m) from the textural category, and the overall standard deviation (s) of the medium-aged farm sample dataset, and then normalizing to a scoring range from 0 to 100:

$$CND(x,m,s) = 100\,\frac{1}{2}\left(1 + \mathrm{erf}\left[\frac{(x-m)}{s\,\sqrt{2}}\right]\right), -\infty < x < \infty \qquad [2]$$

where erf is the so-called error function.

The influence of the remaining soil properties on crop growth has been quantitatively established in the literature, such that approximate thresholds, critical values or ranges and therefore scoring functions could be defined for P, K, pH, EC, PR15 and PR45 (Fig.6.2, Table 6.1). A quadratic function (Table 6.1, where score = S when $0 \leq S \leq 100$, and score = 100 where S > 100, and score = 0 where S < 0) was used to score pH values. For all but pH, we again used the shape of a CND(m,s), where m was assigned to be the midpoint between high and low thresholds (similar to the baseline value as defined by Karlen et al. (1994), receiving a score of 50 in our rating system), and s was half of the difference between the mean and each threshold.

Penetration resistance scoring curves were based upon literature thresholds discussed by Cass (1999), Schuler et al. (2000) and Tekeste et al. (2007), among others. Seedling emergence, which is affected by surface hardness, starts to be limited at thresholds in excess of just above 1000 kPa. Therefore, we assigned PR15 values of below 800 kPa scores approaching 100, and values above 1500 kPa scores approaching 0, to result in a scoring curve of CND(1150, 175). Subsurface compaction prevents good aeration and water drainage and causes extensive root impedance at 2000 kPa and extreme limitations well below 3000 kPa, more so in dense clays, which tend to have fewer large pores, and become relatively harder as they dry. We assigned PR45 values of below 1000 kPa scores approaching 100. For heavier soils (> 15% clay) values of 2000 kPa approach a score of 0, resulting in a CND(1500, 250), and for soils with lower clay content (< 15% clay) values of 2200kPa approach a score of 0, resulting in a CND(1600, 300).

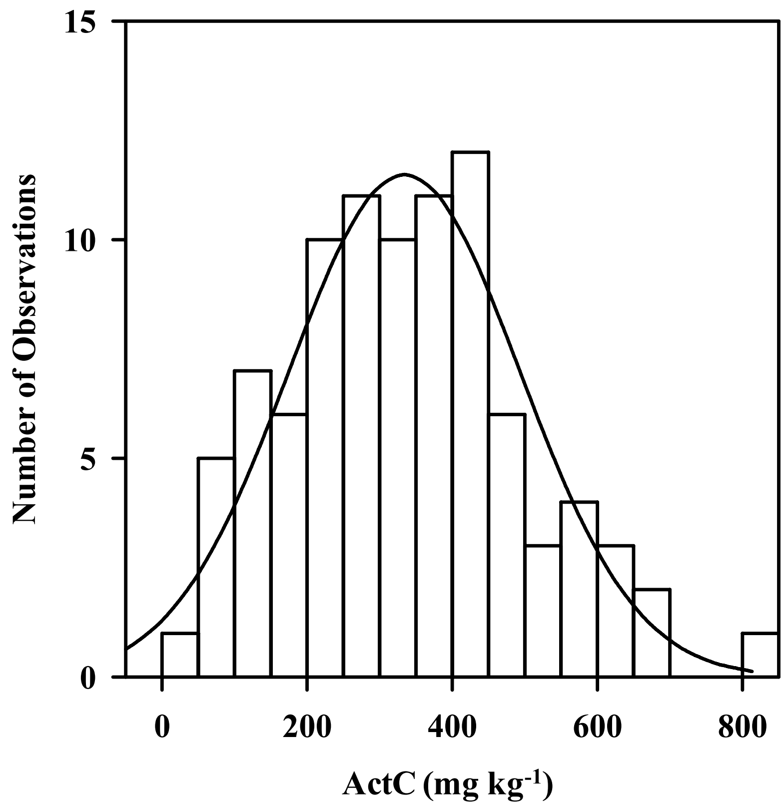

Figure 6.1 Sample histogram and fitted normal curve N ~ (334, 160) of distribution of ActC in soils that have more than 15% clay.

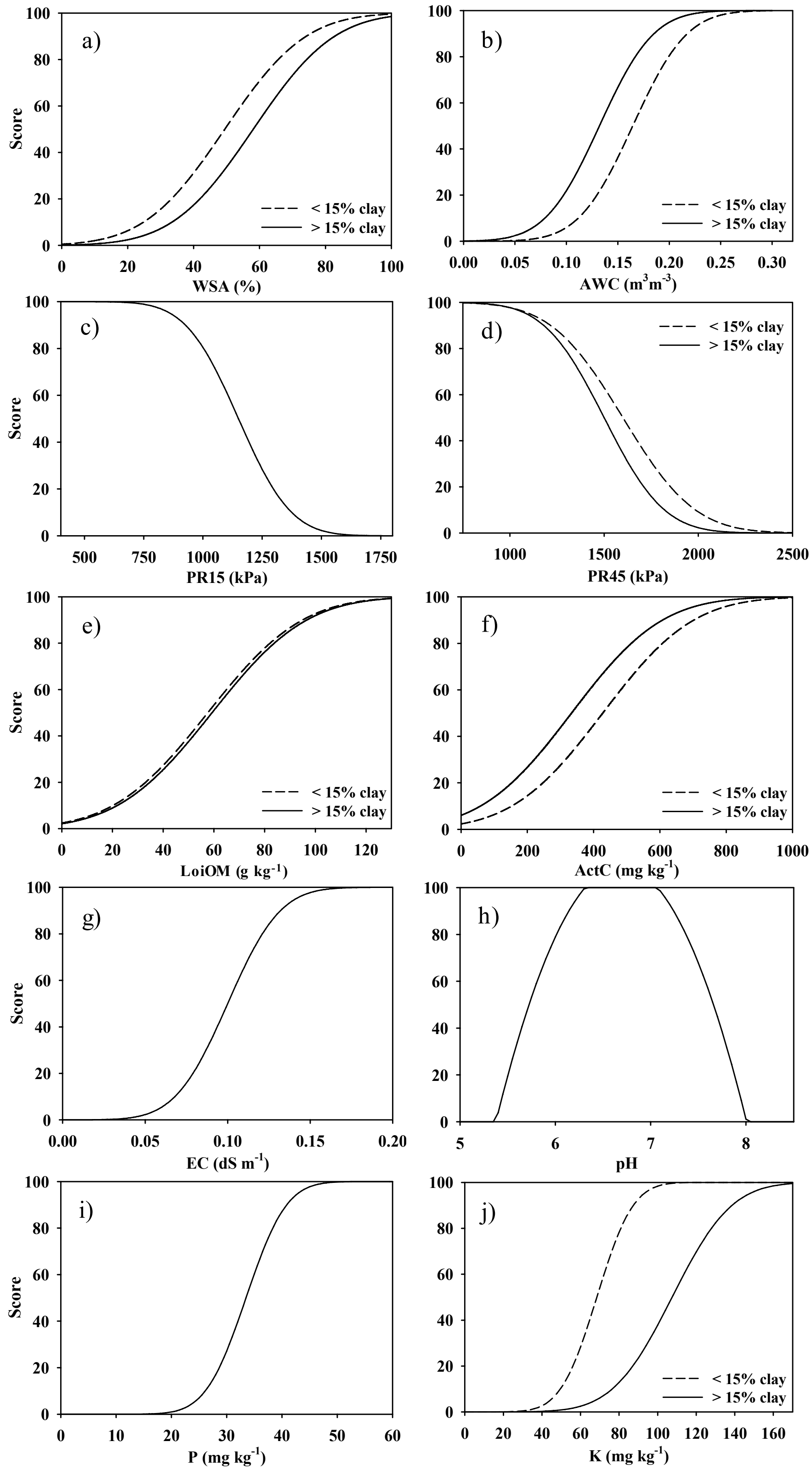

Figure 6.2 Scoring curves developed to interpret measured soil quality indicators.

Electrical conductivity (EC) indicates decreasing nutrient availability at values below about 0.40 dS m^{-1} (in 1:2.5 soil:water suspension equivalence) while above 0.4 dS m^{-1} salinity may limit crop growth, although this depends on crop type (Arnold et al., 2005; Bastida et al., 2008; Shaw, 1999). There were no salinity constraints at the sites tested. Therefore, we scored electrical conductivity as an integrative indicator of nutrient availability only, using a "more is better function" that would not be appropriate in semi-arid or arid regions. The highest EC value measured was 0.31 dS m^{-1}. EC is well-correlated with plant-available nitrate concentration (Arnold et al., 2005; Smith and Doran, 1996) where an EC of 0.01 indicates <1.4 mg kg^{-1} nitrate-N, and therefore a constraint. Acceptable ranges between these thresholds vary in the literature, and depend on soil type, climate, and crop. For this assessment, the specific thresholds given in the EC probe manual (Milwaukee Instruments Inc., 2003) were used, which is similar to the ascending portion of the EC scoring function by Glover et al. (2000). Values below 0.05 were considered to indicate nutrient deficiency and received a score approaching 0, while values of above 0.15 were considered to be sufficient and received a score approaching 100, resulting in a CND(0.10, 0.025).

The P scoring curve was approximated based on threshold values given in Bray and Olsen test values by Landon (1991), converted to Mehlich III values using regression equations (Kleinman et al., 2001; Schmisek et al., 1998). Values below 22 mg kg^{-1} P approach a score of 0, values above 45 mg kg^{-1} P approach a score of 100, to result in a CND(33.5, 5.75). No P values that would be considered "excessive" and raise environmental concerns were observed in this study. Therefore, an optimum scoring function as developed by Andrews et al. (2004) and Idowu et al. (2008) was not necessary for this region. We similarly approximated K scoring curves, basing high scores on the midpoint of the adequate range given by the Zimbabwe Ministry of Agriculture, Harare (Landon, 1991) and assuming no need for extractant conversion

(Texas A&M University, 2004). Finer textured soils (> 15% clay) approached a score of 0 below 59 mg kg^{-1} K, and a score of 100 above 156 mg kg^{-1}, resulting in a CND(107.5, 24.25). Coarser textured soils (< 15% clay) approached a score of 0 below 39 mg kg^{-1} K, and a score of 100 above 98 mg kg^{-1}, resulting in a CND(68.5, 14.75). The NORMDIST function in Excel (Microsoft Office, 2007) was used to evaluate the cumulative normal probability and score all measured values.

The composite soil health index (CSHI) was calculated as the average of the ten individual indicator scores obtained from the scoring functions, and is thus a linear unweighted combination of the scores. A simple unweighted index was chosen, because no compelling scientific justification existed to weight indicators differentially, and an unweighted index is more user-friendly. Andrews et al. (2002; 2004) found weighting unnecessary for reliably reflecting endpoint outcomes, although weighted functions have sometimes been found to be more sensitive to management and endpoint outcomes (Masto et al., 2008). Values of the CSHI were qualitatively interpreted to indicate very low soil quality at CSHI < 40, low at 44 < CSHI < 55, medium at 55 < CSHI < 70, high at 70 < CSHI < 85 and very high at CSHI > 85. All scoring functions are shown in Fig. 6.2, with a summary of development information given in Table 6.1.

6.4.6. Statistical analysis

The ability of scoring functions to distinguish differences in degree of soil constraints between management systems by parent material was evaluated using mixed model analysis of the scores for each indicator in JMP (Version 7.0, SAS Institute, Inc., 2007). Fixed factors used in the mixed models were time since conversion (Time), Management System (Mgmt), and the Time by Mgmt interaction. Farm was used as a random factor to account for variability among farms.

Changes in frequencies of encountered soil constraints over time in the long-term, low-input continuous maize (Co) and kitchen garden (Ki) management systems, were described by grouping samples by conversion age into three categories for each parent material: forest samples (0 yr), new farms (< 30 yr) and old farms (> 30 yr). The percentage of total samples scoring high (≥ 70), medium (between 30 and 70) and low (≤ 30, constrained) for each indicator were calculated for each time interval. Linear functions ($y = y_o + ax$) in Sigma Plot (Version 11.0, Systat Software, Inc., 2008) were used to describe dynamics over time of the composite soil health index (CSHI) and the number of constrained indicators.

Using JMP (Version 7.0, SAS Institute, Inc., 2007), simple linear regression (SLR) and backward multiple linear regression (MLR, $p = 0.10$ for removal) were used to predict yield components using a) indicator values and scores and b) composites (CSHI and the number of constrained indicators). A mixed model approach was also used to predict yield components from the CSHI and by MLR using Farm as a random factor in the model.

6.5. RESULTS AND DISCUSSION

6.5.1. Effect of long-term management on soil constraints

Management System (Mgmt) was a significant factor for 7 out of 10 SQ indicators in the Nandi region (all except PR15, PR45 and LoiOM), for 6 out of 10 indicators in the Kakamega region (all except AWC, PR15, pH and P), and for the overall composite soil health index (CSHI) in both parent materials (Table 6.2). Data were analyzed separately by parent material, which was a significant factor for almost all indicator scores and values, as discussed in Chapter 5. Time was a significant

Table 6.2 Factor significance in mixed model analysis of scores for each indicator measured on farm samples.

		WSA†	AWC‡	PR15§	PR45¶	LoiOM#	ActC††	pH	EC‡‡	P	K	CSHI§§
Nandi	**Mgmt**	***¶¶	*	ns	ns	ns	**	***	***	**	+	***
	Time	*	ns	*	***	***	***	ns	ns	ns	ns	***
	Mgmt*Time	**	*	**	ns	*	***	ns	ns	***	ns	**
Kakamega	**Mgmt**	***	ns	ns	*	***	***	ns	***	ns	***	***
	Time	ns	ns	ns	ns	+	*	ns	ns	ns	+	ns
	Mgmt*Time	*	ns	ns	ns	ns	ns	ns	ns	ns	+	ns

† WSA = water stable aggregation.
‡ AWC = available water capacity.
§ PR15 = penetration resistance between 0-15 cm.
¶ PR45 = penetration resistance between 15-45 cm.
# LoiOM = total organic matter by loss on ignition at 350^{o}C.
†† ActC = permanganate oxidizable biologically active carbon.
‡‡ EC = electrical conductivity.
§§ CSHI = composite soil health index.
¶¶ p-values of <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different.

factor for many indicators, even without 0 yr (forest) time points, which could not be included in mixed models, as discussed separately below. The Time*Mgmt interaction was significant for only two indicators in the Kakamega region, but for seven indicators in the Nandi region, mainly because SQ of Ki in 7 and 12 yr old Nandi farms did not yet differ significantly from maize plots, in contrast to most older farms (Chapter 5).

Management differences were presented by Mgmt in terms of LSmeans of indicator scores averaged across time (Table 6.3). Organic amendments available to smallholder farmers are limited, and so kitchen gardens are preferentially amended with what is available, such as cooking fire ashes, plant remains, and manure (Mtambanengwe and Mapfumo, 2008). Such inputs add plant nutrients to the soil and also aid in maintaining soil structure and biological activity. Conversely, continuous low-input cultivation degrades soil structure and biological activity, and mines soil nutrients (Carter, 2002; Lal, 2006; Sanchez, 2002). Fields further from the home, represented by Co management, generally receive few or no inputs, but are nevertheless continuously tilled and cropped. Also, Ki fields are generally polycultures, while Co fields were generally managed as maize monocultures. Thus, the starkest difference in SQ was found between these two contrasting management systems.

Kitchen gardens, on average, had significantly higher scores than Co in the Nandi region for WSA, ActC, pH, EC, P, K and CSHI, and in Kakamega for WSA, LoiOM, ActC, EC, K and CSHI (Table 6.3). In Nandi, the average kitchen garden rated high for overall soil quality, as it had no constraints (score ≤ 30), and all but AWC, EC and P were in the optimal range (score ≥ 70). On average, Nandi Co plots were constrained in EC and P, had less than optimal ($30 < \text{score} < 70$) WSA, AWC,

Table 6.3 LS means of scores derived from scoring functions for each management scenario, separated by parent material. Means comparisons were included even for properties that showed significant Mgmt*Time interaction (Table 6.2). Scores are color coded as for a Cornell Soil Health Test Report. Green = high (70-100), yellow = medium (> 30 to < 70), red = low (0-30).

	Nandi							Kakamega						
	Ki	Co	Ma	Ch	Sa	Ti	Co vs. avgOM	Ki	Co	Ma	Ch	Sa	Ti	Co vs. avgOM
WSA	80a	66b	72ab	70b	71b	70b	*	57a	22b	32b	31b	29b	30b	*
AWC	50a	59a	55a	49a	54a	50a	*	65a	56a	50a	54a	54a	51a	ns
PR15	100a	100a	100a	100a	100a	100a	ns	94a	100a	95a	100a	92a	92a	ns
PR45	70a	74a	69a	69a	71a	72a	ns	45ab	71a	39b	42ab	41b	47ab	***
LoiOM	72a	71a	70a	72a	69a	71a	ns	41a	24b	25b	25b	24b	26b	ns
ActC	77a	68b	73ab	70ab	68b	74ab	ns	65a	24b	27b	27b	27b	29b	ns
pH	82a	57b	73ab	65ab	62b	62b	+	65a	50a	60a	47a	50a	59a	ns
EC	39a	2b	5b	7b	4b	4b	ns	48a	0b	0b	0b	0b	0b	ns
P	40a	16b	45a	47a	39ab	37ab	***	54a	43a	82a	65a	73a	68a	*
K	100a	88b	97ab	98ab	96ab	97ab	**	96a	62b	100a	87a	90a	93a	***
CSHI	71a	60c	66ab	65bc	64bc	64bc	**	63a	45b	51b	48b	48b	49b	+
	High	Medium						Medium	Low					

† Means followed by same letter are not significantly different at α = 0.05, based on Tukey's test of fixed effects in mixed model.
‡ Significance of linear contrasts of Co vs. the average of plots receiving organic matter amendments (avgOM), p < 0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different.

ActC and pH, and thus had lower overall SQ (medium CSHI rating). With these identified constraints, Co plots would thus have decreased soil structural, biological and nutrient supply functions. In the Kakamega region, average Ki indicator scores were mostly below optimum (except for PR15 and K), although no constraints were identified. The CSHI score rated medium (Table 6.3). The average Co plot, by contrast, was constrained in WSA, LoiOM, ActC and especially EC, and had less than optimal levels for all indicators, except soil hardness. Thus, Co plots in the Kakamega region, again, had a much lower overall soil quality (low CSHI) than Ki. However, the lower PR45 score in Ki (significant with a linear contrast, not with Tukey's test) suggests that agronomically limiting subsurface compaction may be a concern. This would constrain deep root proliferation in Kakamega, which was the only soil function that was significantly more constrained in Ki than in Co. Kitchen gardens are used intensively for both perennial and annual crops and experience higher foot-traffic and more frequent tillage than the outlying maize fields. These activities could explain their greater compaction (Hamza and Anderson, 2005) relative to Co plots in the Kakamega region's soil type.

6.5.2. Effect of short-term management on soil constraints

Residual effects of short-term additions of organic matter to continuously cropped fields were small 16 months after they were applied, largely because fresh organic matter degrades quickly in tropical environments (Bol et al., 2000; Jenkinson and Ayanaba, 1977) and presumably-recalcitrant charcoal additions were not detected by the loss on ignition method (Chapter 5). Tukey's test did not demonstrate any statistically significant differences between Co and each organic matter amendment type for most indicator scores (Table 6.3), and similarly for indicator values (Chapter 5). Only Ma plots in the Nandi region had a significantly higher overall CSHI value than Co. This was due to a significantly higher P score, and non-significant trends for higher WSA, ActC, EC and pH scores. However, linear contrasts of Co vs. an average of the organic matter amended plots (avgOM, Table 6.3) showed that, in Nandi, Co plots had significantly lower scores for WSA, pH, P, K, and the overall CSHI, and in Kakamega Co plots had significantly lower scores for WSA, P, K and CSHI. These results suggest that residual effects of organic matter still had a positive effect on soil structural, buffering and nutrient retention processes 16 months after they were applied.

Organic matter amended (avgOM) plots in Kakamega were close to being constrained by subsurface compaction (PR45), while subsurface hardness in Co was within the optimal range. Similar trends were observed in Nandi, however, there, these differences were not agronomically significant, hence indicator scores did not reflect these differences, while indicator values did (Chapter 5). Compaction in avgOM plots presumably resulted from the method and timing of organic matter application (Hamza and Anderson, 2005), which involved two additional intensive tillage passes and increased foot traffic per season, made worse by applying when the soil was wet (for easier hand-hoeing).

6.5.3. Effect of time under cultivation on soil constraints in two long-term management systems

The frequency of observed constraints in soil functions for forests (0 yr), new farms (< 30 yr) and old farms (> 30 yr) across the two chronosequences was investigated. Similar patterns in most physical (Fig. 6.3), biological (Fig. 6.4) and chemical (Fig. 6.5) indicator scores were observed. After conversion from primary forest to Co, the percent of fields scoring in the optimal range decreased for most

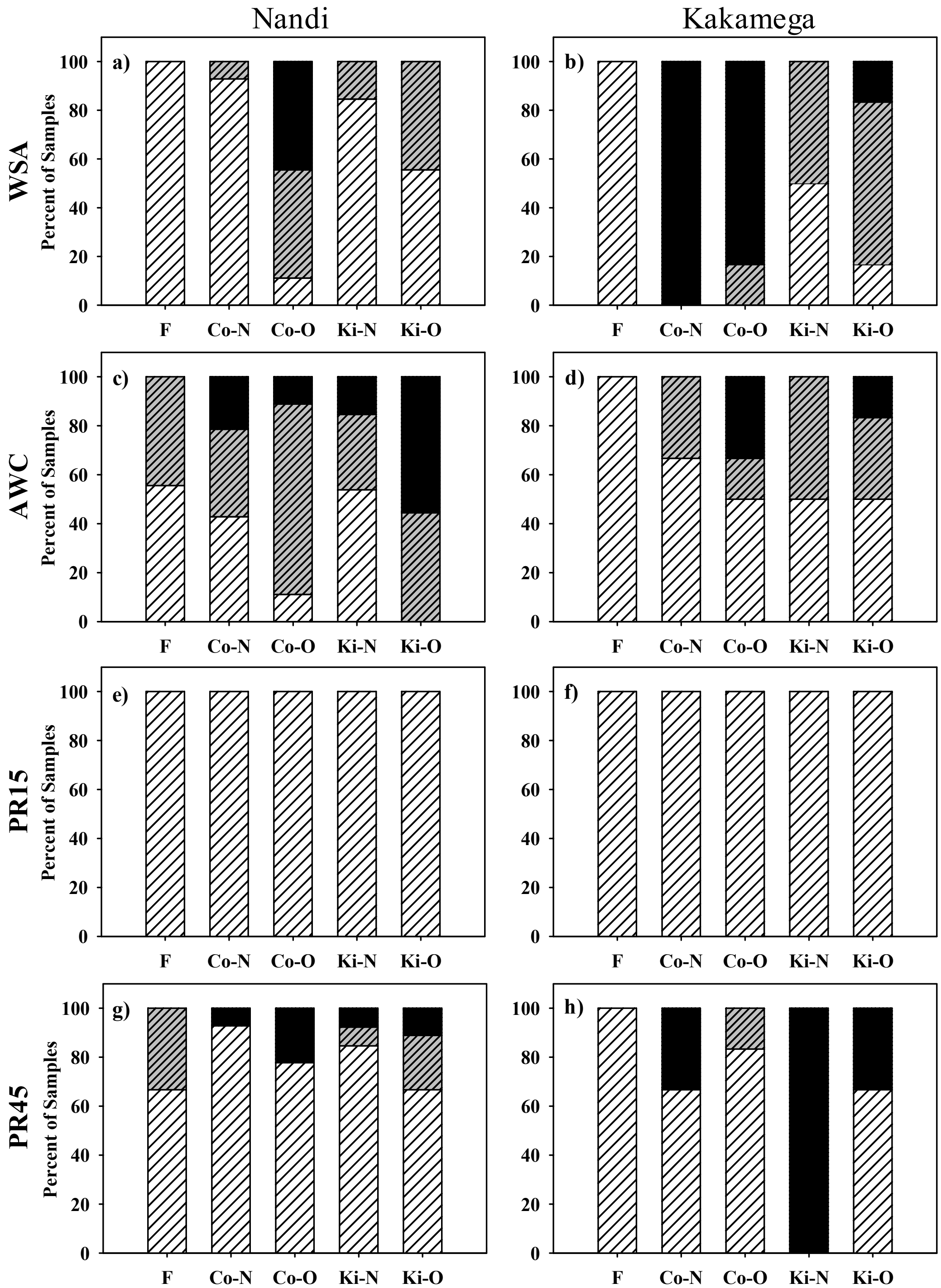

Figure 6.3 Changes in physical indicators over time in control fields (Co) vs. kitchen gardens (Ki) - percent of samples rated optimal (≥ 70, white), less-than-optimal (between 30 and 70, gray), and constrained (≤ 30, black) for each indicator, by parent material and conversion category. F = Forest (0 yr, Nandi n = 9, Kakamega n = 3), N = New Farms (<30 yr, Nandi n = 14, Kakamega n = 3; 2 for Co; Ki), O = Old Farms (>30 yr, Nandi n = 9, Kakamega n = 6).

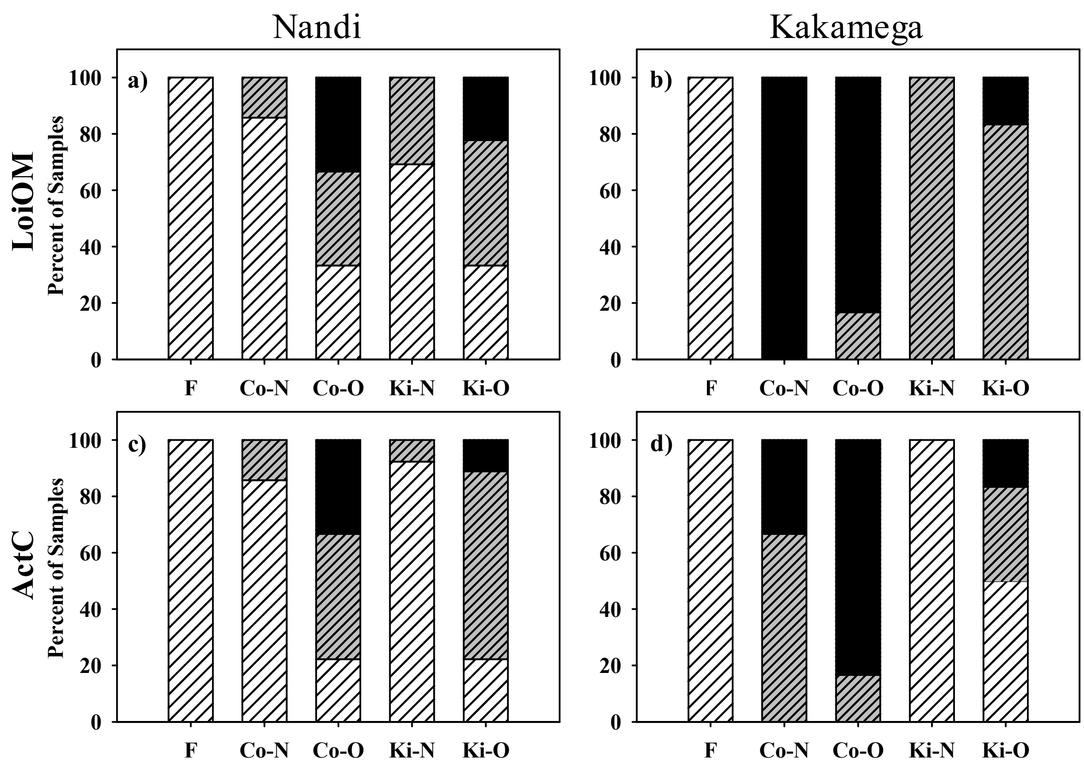

Figure 6.4. Changes in biological indicators over time in control fields (Co) vs. kitchen gardens (Ki) - percent of samples rated optimal (≥ 70, white), less-than-optimal (between 30 and 70, gray), and constrained (≤ 30, black) for each indicator, by parent material and conversion category. F = Forest (0 yr, Nandi n = 9, Kakamega n = 3), N = New Farms (<30 yr, Nandi n = 14, Kakamega n = 3;2 for Co; Ki), O = Old Farms (>30 yr, Nandi n = 9, Kakamega n = 6).

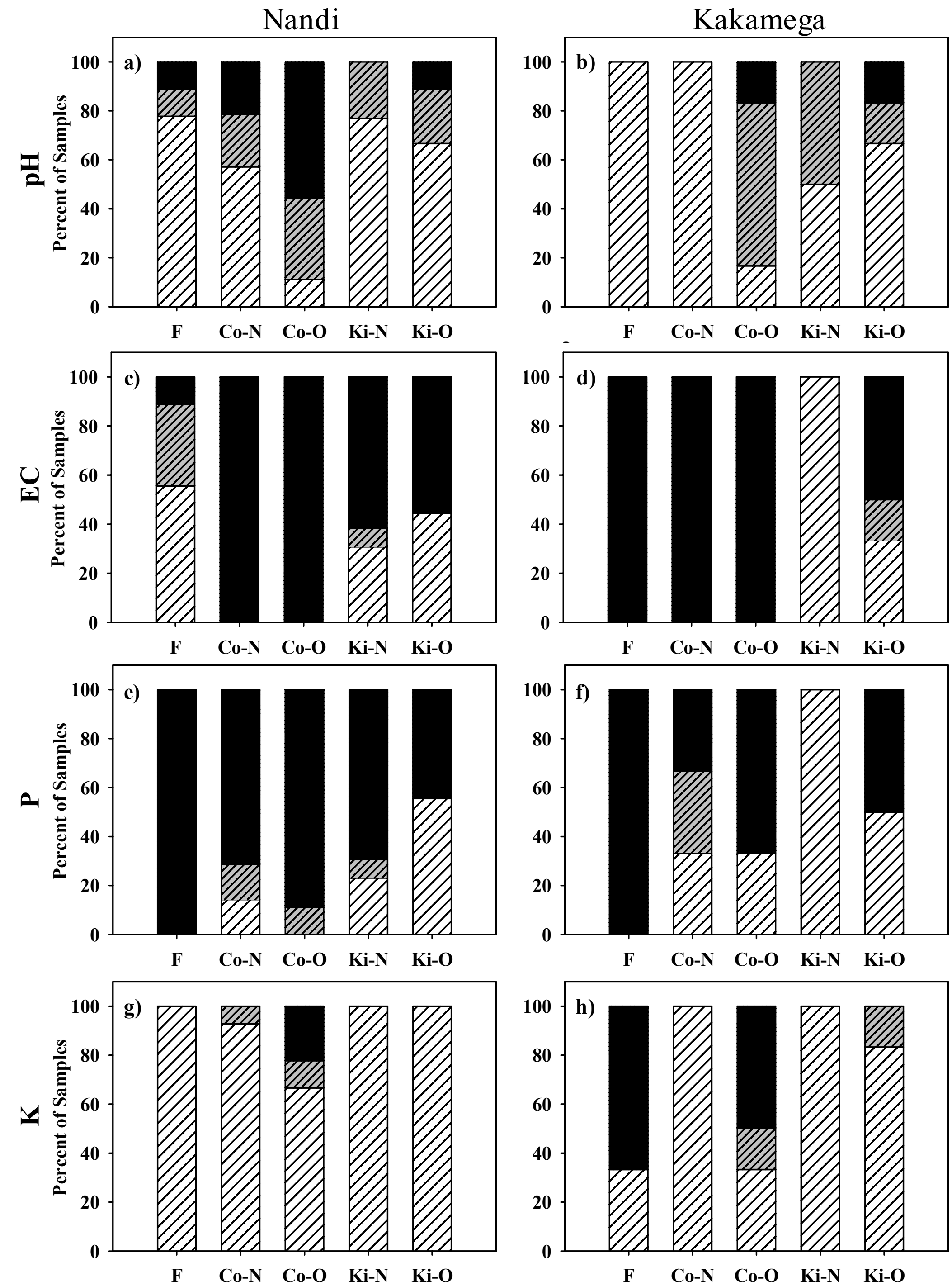

Figure 6.5. Changes in chemical indicators over time in control fields (Co) vs. kitchen gardens (Ki) - percent of samples rated optimal (≥ 70, white), less-than-optimal (between 30 and 70, gray), and constrained (≤ 30, black) for each indicator, by parent material and conversion category. F = Forest (0 yr, Nandi n = 9, Kakamega n = 3), N = New Farms (<30 yr, Nandi n = 14, Kakamega n = 3;2 for Co; Ki), O = Old Farms (>30 yr, Nandi n = 9, Kakamega n = 6).

indicators, and the percent of fields receiving less-than-optimal and/or constrained scores generally increased over time. In the Nandi region the most frequent constraints that developed on old farms (Co-O bars) were in WSA, pH, and especially EC (with 44%, 55%, and 100% of old farms being constrained; Figs. 6.3a, 6.5a and 6.5c, respectively). In the Kakamega region the most frequent constraints on old farms were in WSA, LoiOM, ActC and EC (with 83%, 83%, 83% and 100% of old farms being constrained; Figs. 6.3b, 6.4b, 6.4d, and 6.5d, respectively).

A larger number of old than new farms were constrained in P in both parent materials (Figs. 6.5e and 6.5f), but forest soils were the most frequently P-limited (100% in both parent materials) because these soils, as many tropical soils in East Africa, have genetic P deficiencies (Ngoze et al., 2008). Similarly, in the Kakamega region only old farms were K constrained (50%, Fig. 6.5h), and 67% of forest soils were also constrained. The greater availability of P and K on farms than in forests is likely due to recent experimental fertilizer applications to these fields, rather than good retention of these nutrients. The lower P and K availability in old compared to new farms is likely linked to decreasing CEC, LoiOM, and ActC (Chapter 4), and thus lowered ability to mineralize and retain plant-available nutrients (Lal, 2006).

Overall, kitchen gardens developed constraints after forest conversion less frequently, as can also be interpreted from overall SQ differences reflected in their CSHI values (Fig. 6.6). The only exception to this was for PR45, which was more frequently constrained in Ki in Kakamega due to compaction from soil management (Fig. 6.3h). Availability of P and K in Ki remained at the same as levels available in forests, and even increased in some cases.

The number of constrained indicators increased significantly over time in Co systems in both parent materials (Figs. 6.7a and 6.7b) – from about two to six

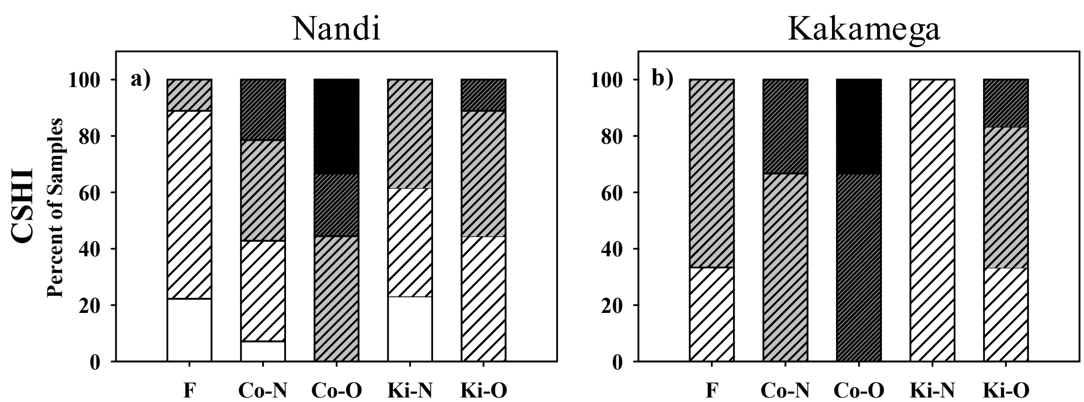

Figure 6.6 Changes in the CSHI over time in control fields (Co) vs. kitchen gardens (Ki). Percent of samples rated very high (≥ 85, white), high (between 70 and 80, white with pattern), medium (between 55 and 70, light gray), low (between 40 and 55, dark gray) and very low (≤ 40, black), by parent material and conversion category. F = Forest (0 yr, Nandi n = 9, Kakamega n = 3), N = New Farms (<30 yr, Nandi n = 14, Kakamega n = 3;2 for Co; Ki), O = Old Farms (>30 yr, Nandi n = 9, Kakamega n = 6).

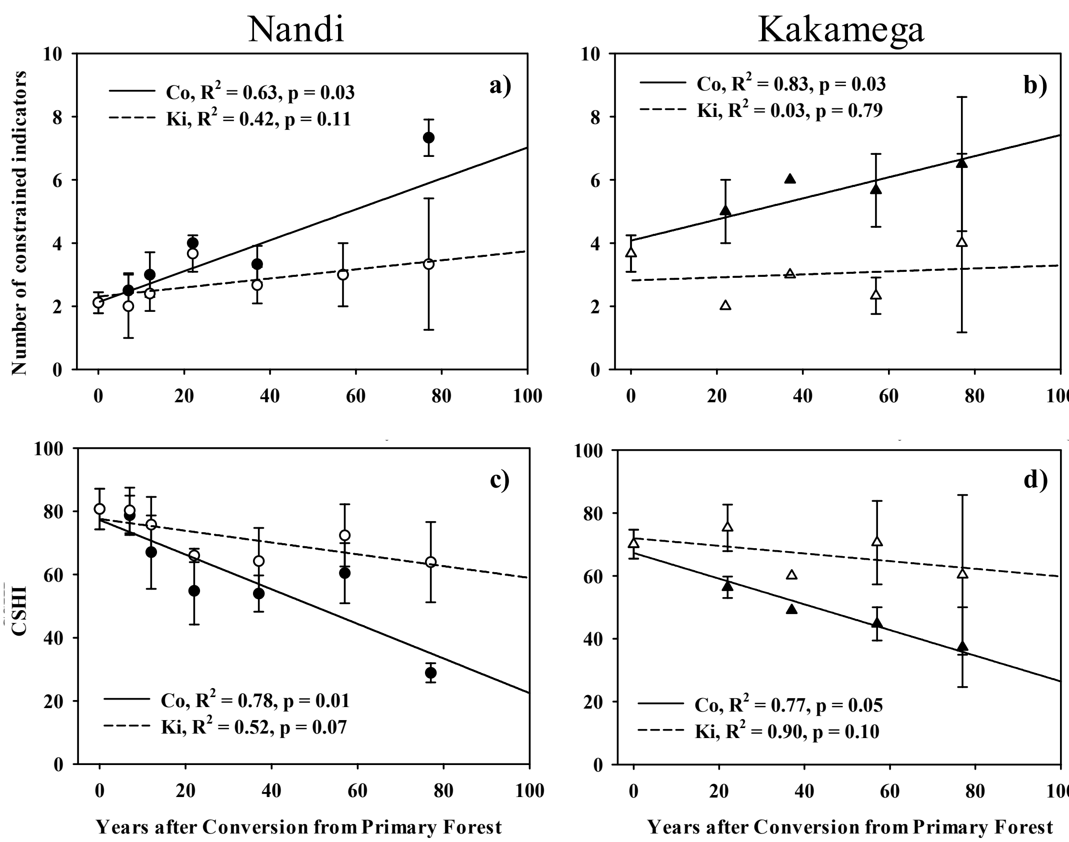

Figure 6.7 Changes in number of constrained indicators and CSHI over time.

constraints in Nandi, and from about four to six constraints in Kakamega. Accordingly, the overall CSHI decreased significantly over time in both parent materials, by about 50 in Nandi and by just over 40 in Kakamega (Figs. 6.7c and 6.7d). Time since conversion explained 77-78% of the variability in the CSHI averaged by years under cultivation. While similar patterns were observed in Ki, the regression slopes were smaller because the rates of change over time were slower. Only the linear regression fit to the decrease in Ki-CSHI in Nandi was marginally significant ($p = 0.07$, Fig. 6.7).

The concept of SQ monitoring, as applied above, has been discussed as a necessary next step for sustaining local, regional and global SQ (Arshad and Martin, 2002; Barrios et al., 2006). However the programs in place in Europe, North America, Australia and New Zealand in which various soil properties are monitored, share neither a common set of indicators, nor standardized laboratory methods, nor an interpretive framework. No such programs appeared to be in place in developing countries as of 2003 (Winder, 2003).

6.5.4. Effect of soil quality on yield

One of the most compelling reasons to monitor SQ and then address identified constraints is the continuing decline in crop reliability and productivity associated with soil degradation (Lal, 2009). An integrative agricultural SQ test should, therefore, demonstrate a relationship with yield. Soil quality degradation in the Kenyan highlands has been associated with exponential decreases in grain yield (Kimetu et al., 2008; Ngoze et al., 2008). While, in many cases, nutrients are a major limiting factor to biomass and grain production (Ngoze et al., 2008), other factors are also agronomically constraining, especially on older farms, although constraints do differ by individual farms and fields (Figs. 6.4 through 6.7).

A series of simple linear regression (SLR) models were developed by using indicator values or scores alone as predictors of maize grain-, stover- and total biomass yield in 2005 and 2007 (Table 6.4). Coefficients of determination (R^2 values) of statistically significant SLR models were very low (0.04 to 0.18 for grain yield; 0.04 to 0.31 for stover; 0.05 to 0.28 for total biomass). This may be expected for such a diverse data set, where there are interactions between different constraints and where variability in farmer management and soils presumably preclude highly linear responses. Notably, the direction response consistently showed increasing crop productivity with increasing functionality, as per the developed scoring functions (Figure 6.2). In 34 out of 60 cases, measured indicator values were better predictors of yield components (especially of grain yield) than indicator scores derived from scoring functions, while indicator scores were better predictors in 15 pairs. Indicator scores of WSA were consistently better predictors than values.

ActC was the second best single predictor of grain yield in 2005 closely following pH, and the best in 2007, explaining 16 and 13% of the variability in grain yield, respectively. Furthermore, ActC values and scores were the best single indicator predictors of stover and total biomass yield in both years, explaining 26 - 31% of the variability in yield. Comparable relationships of ActC with yield have been found by Weil et al. (2003) and Mtambanengwe et al. (2006). These results supports the idea that higher ActC leads to increased nutrient supply to the crop through microbially mediated decomposition (Weil et al., 2003). Such an organic-matter-derived nutrient supply is especially important in smallholder farming systems where synthetic fertilizers are often not available, and organic sources alone provide the necessary nutrients (Sanchez, 2002).

Table 6.4 Simple linear regression of each indicator value and score as a predictor for each yield component, by year.

	Indicator Value		Indicator Score		Indicator Value		Indicator Score		Indicator Value		Indicator Score	
	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p	R^2	p
	Grain Yield 2005, n = 74				**Stover Yield 2005, n = 75**				**Total Biomass 2005, n = 74**			
WSA	0.01	ns†	0.04	+	0.23	***	0.28	***	0.13	**	0.19	***
AWC	0.05	+	0.01	ns	0.06	*	0.02	ns	0.07	*	0.01	ns
PR15	0.00	ns	0.00	ns	0.01	ns	0.01	ns	0.01	ns	0.01	ns
PR45	0.02	ns	0.02	ns	0.01	ns	0.02	ns	0.02	ns	0.02	ns
LoiOM	0.09	*	0.06	*	0.25	***	0.25	***	0.22	***	0.20	***
ActC	0.16	***	0.11	**	0.29	***	0.31	***	0.28	***	0.26	***
pH	0.18	***	0.14	***	0.18	***	0.14	**	0.22	***	0.17	***
EC	0.15	***	0.12	**	0.26	***	0.24	***	0.24	***	0.22	***
P	0.13	**	0.13	**	0.07	*	0.08	*	0.11	**	0.12	**
K	0.05	*	0.02	ns	0.18	***	0.03	ns	0.14	**	0.03	ns
	Grain Yield 2007, n = 90				**Stover Yield 2007, n = 89**				**Total Biomass 2007, n = 89**			
WSA	0.01	ns	0.02	ns	0.08	**	0.09	**	0.05	*	0.07	*
AWC	0.07	*	0.06	*	0.11	**	0.10	**	0.12	**	0.11	**
PR15	0.03	ns	0.02	ns	0.04	*	0.02	ns	0.05	*	0.02	ns
PR45	0.03	ns	0.02	ns	0.09	**	0.12	***	0.08	**	0.09	**
LoiOM	0.09	**	0.08	**	0.22	***	0.23	***	0.21	***	0.21	***
ActC	0.13	***	0.11	**	0.27	***	0.28	***	0.26	***	0.26	***
pH	0.09	**	0.07	*	0.08	**	0.07	*	0.11	**	0.09	**
EC	0.12	***	0.03	ns	0.24	***	0.06	*	0.23	***	0.06	*
P	0.00	ns	0.03	+	0.00	ns	0.01	ns	0.00	ns	0.02	ns
K	0.07	**	0.04	+	0.24	***	0.07	*	0.21	***	0.07	*

† p-values for models are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different.

Standard multiple linear regression (MLR) models yielded better predictions than single indicators, explaining 15 - 38% of grain-, 30 - 47% of stover- and 29 - 40% of total biomass yield variability, without accounting for farm-variability (Table 6.5). When accounting for variability among farms (about 15 - 53% of the variability in the data), predictions improved further. Mixed MLR models explained 38 - 65% of grain, 56 - 65% of stover, and 56 - 63% of total biomass yield variability, as they were able to account for spatial soil and weather variation and farmer management effects that frequently affect yields.

With the exception of the MLR models for grain yield in 2005 and the mixed MLR model for total biomass in 2005, all models included ActC as a factor. Most 2007 standard MLR models included WSA. Most 2005 standard models included P, which may be explained by the fact that fields had only received one season of fertilizer application for the 2005 long rainy season. Thus, inherently low P-availability in these tropical soils may have affected yields more significantly in 2005 than in 2007, after four seasons of fertilization. In five out of six standard MLR models, indicator values were better predictors of yield components, but in four out of six mixed MLR models indicator scores were better predictors. These results suggest that scoring functions could likely be improved further to represent agricultural productivity yet better, by using more controlled studies, where possible.

The CSHI, without accounting for between-farm variability, was a better predictor of maize grain yield than any of the individual indicator scores, but not better than individual indicator values or MLR models (Table 6.6). In 2005, the CSHI was a better predictor of stover and biomass yield than any of the SLR models, but in 2007, ActC values and scores were better predictors. When accounting for between-farm variability (15 - 42% of variability in the data), the predictive ability of CSHI improved dramatically, explaining up to 56% of grain, 53% of stover and 54% of the

Table 6.5 Coefficients of determination (R^2) and significant factors for standard backward multiple linear regression (MLR) and mixed MLR, using farm as a random factor in each model, and using either indicator values or scores, by year.

		Standard MLR		**Mixed MLR**		
	Yield Component & Yr	**R^2**	**Significant Factors**	**R^2**	**Significant Factors**	**Variability explained by farm (%)**
Indicator Values	**Grain '05**	0.38	PR45, K, P, pH	0.61	K	53
	Grain '07	0.16	WSA, ActC	0.38	ActC, K,WSA	18
	Stover '05	0.42	P, WSA, ActC	0.58	AWC, EC, ActC, PR15	25
	Stover '07	0.40	K, pH, PR15, LoiOM, ActC	0.65	K, ActC, LoiOM	43
	Total Biomass '05	0.40	P, ActC	0.57	LoiOM, P, PR15	25
	Total Biomass '07	0.35	K, WSA, pH, ActC	0.60	K, ActC	36
Indicator Scores	**Grain '05**	0.30	PR45, P, pH	0.65	pH, PR15, AWC	52
	Grain '07	0.15	WSA, ActC	0.39	ActC, P	21
	Stover '05	0.47	PR45, P, AWC, EC, ActC	0.61	ActC, EC, AWC, PR45	25
	Stover '07	0.30	WSA, ActC	0.56	ActC, K	29
	Total Biomass '05	0.39	P, ActC	0.63	ActC, P, AWC, PR15	35
	Total Biomass '07	0.29	WSA, ActC	0.56	ActC, K	31

Table 6.6 Coefficients of determination (R^2), slope and model significance (p_1) for simple linear regression (standard SLR) using CSHI as a single predictor of yield. Coefficients of determination (R^2), significance of CSHI as a factor (p_2), and variability explained by farm as random factor for a mixed model used to predict yield.

	Standard SLR			Mixed SLR		
Yield Component & Yr	**b†**	**R^2**	**p_1‡**	**R^2**	**p_2‡**	**Variability explained by farm (%)**
Grain '05	0.05	0.17	***	0.57	*	42
Grain '07	0.04	0.12	***	0.37	**	20
Stover '05	0.12	0.32	***	0.46	***	15
Stover '07	0.08	0.25	***	0.53	***	29
Total Biomass '05	0.18	0.29	***	0.53	**	27
Total Biomass '07	0.12	0.25	***	0.54	***	29

† b = slope of regression in Mg ha^{-1} per CSHI point.
‡ p-values for models are <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different.

variability in total biomass yield (Table 6.6), which is comparable to the performance of the mixed MLR models (Table 6.5). Simple regressions of CSHI and yield suggest that a 10 point increase in the CSHI would lead to an increase of approximately 0.4 to 0.5 Mg ha^{-1} dry grain. This is especially significant as farm sizes in this region range between only about 0.25 and 2.0 ha (Jayne et al., 2003). That same increase of 10 points in the CSHI would also lead to an increase of approximately 0.8 to 1.2 Mg dry stover, suggesting considerable potential to increase animal fodder production or carbon additions to soils.

The number of indicators whose values suggested soil constraints to yield (Fig. 6.8) was an even better predictor of grain yield, explaining 51% of the variability in 2007, without accounting for between-farm variability. The regression analysis suggested that removing one constraint could increase grain yields by approximately 0.25 Mg ha^{-1}. In 2005, regression analysis would similarly explain about 50% of the variability in grain yield with one outlier removed. The number of constrained indicators was a very effective predictor of stover and total biomass yield, explaining 72 - 85% of the variability in yield. This level of predictability suggests that thresholds for identifying soil constraints were defined closely to relative effects on productivity. The regression analyses suggest that eliminating one soil constraint could improve stover yields by 0.60 - 0.75 Mg ha^{-1} and total biomass by 0.78 - 0.94 Mg ha^{-1}.

Mixed MLR and the number of soil constraints (SLR) predicted crop productivity better than CSHI scores. This corroborates the perspective that information about the status of specific soil constraints is more important than information on overall soil quality. This is especially the case when the goal is to change soil management to address constraints associated with specific soil processes (Table 6.1), rather than broad soil functions such as “supporting plant growth” and

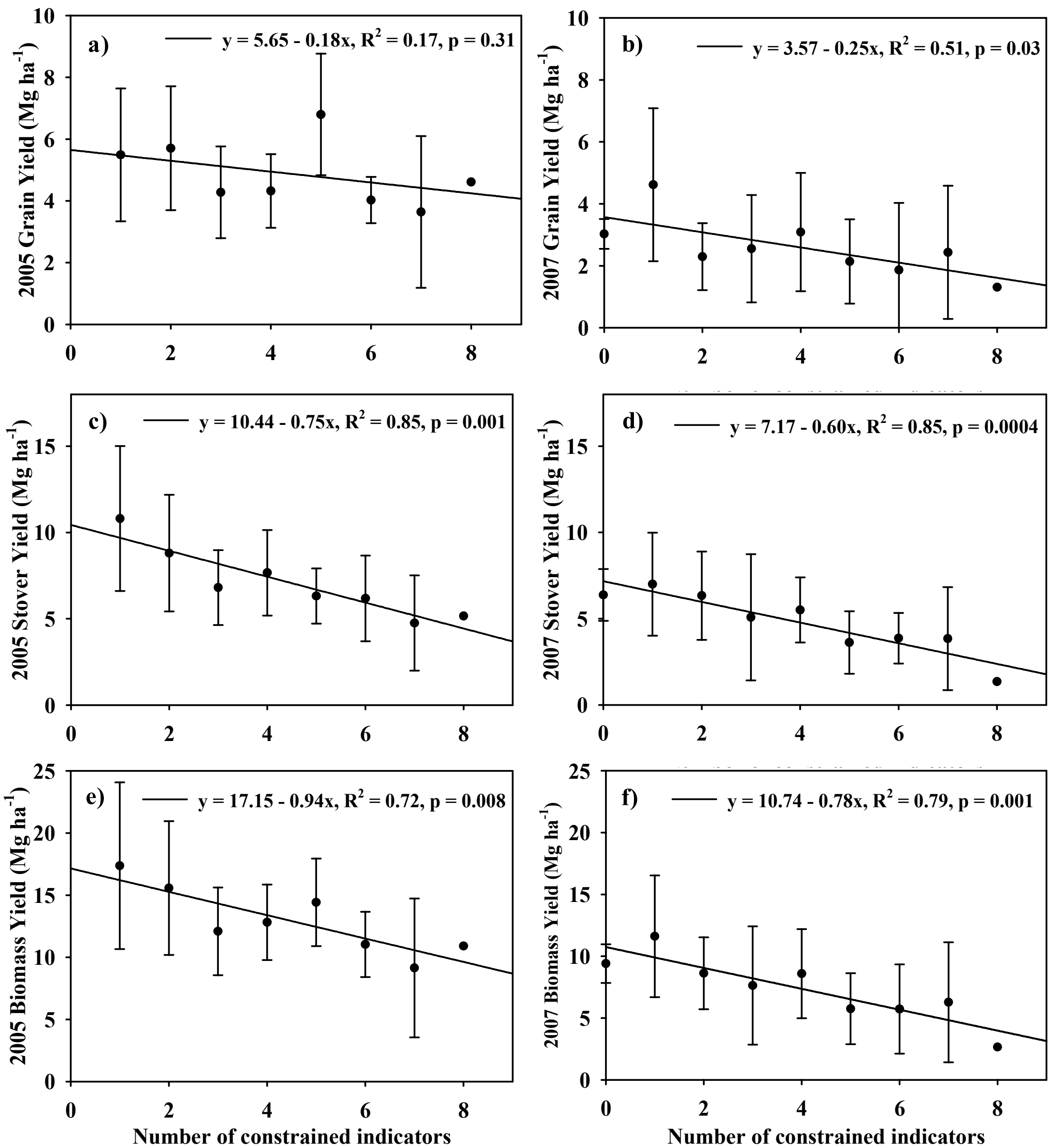

Figure 6.8 Relationship between various yield components and number of indicators suggesting soil constraints.

“facilitating water transfer and absorption” which have been the common foci in SQ assessments thus far (e.g. Glover et al., 2000; Hussain et al., 1999; Karlen et al., 1994).

Severe constraints in one soil factor can prevent full yield potential from being expressed even when all other factors are optimal, but constraints in different processes are rarely independent of each other. Considering the large amount of variability and interaction inherent in our data set, the predictive ability of models presented in Tables 6.4 - 6.6 is quite high, and indicates that the CSHT contains relevant indicators that are able to flag constraints to crop productivity. Accounting for farm variability dramatically increased yield predictability, which indicates that yield is very responsive to management in an individual field, since only year-to-year variability in weather and farmer management would confound responses across the chronosequence.

6.6. CONCLUSIONS

Soil quality management requires an integrative approach wherein the importance of specific physical, biological and chemical processes that control soil functions are recognized. We developed scoring functions appropriate for interpreting a set of standardized SQ indicators with respect to the status of agronomically important soil processes for Ultisols in western Kenya. The development of a standardized integrative SQ test by which soil constraints can be assessed enables widespread assessment and monitoring of SQ. The CSHT appears to be suitable for these purposes. The scoring functions developed for use with the Cornell Soil Health Test in this region of Kenya succeeded in assessing and differentiating management-related constraints. Both, differences between traditional long-term management systems, and intentional and unintentional changes in constraints due to short-term management changes were detected. Our findings suggest that the CSHT can be successfully used to monitor SQ changes over time, using multiple strategies, including monitoring changes in 1) indicator values (Chapter 4), 2) the frequency and number of soil constraints under a given management strategy at different time intervals across a region, and 3) the overall SQ by using the composite soil health index (CSHI). Indicator values and scores, as well as the CSHI, and the number of soil constraints at a site were good predictors of crop productivity, which is an essential endpoint measure for farmers. Because the CSHT provides a standardized framework, based on tests that require minimal infrastructure (Chapter 7), it has the potential to be used by governmental and non-governmental agencies for local, regional, national and potentially international SQ monitoring. In conclusion, selected indicators were useful tools for assessing soil constraints, monitoring SQ, and targeting management strategies to alleviate yield-limiting soil constraints and improve productivity in smallholder systems in western Kenya and potentially elsewhere, when scoring functions are locally adapted.

6.7. ACKNOWLEDGEMENTS

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CHAPTER 7. IDENTIFYING AND MANAGING SOIL CONSTRAINTS TO CROP PRODUCTIVITY ON DEGRADED TROPICAL SMALLHOLDER FARMS USING THE CORNELL SOIL HEALTH TEST[6]

7.1. ABSTRACT

Africa's agricultural viability and food security depend heavily on the quality of its soils. While approaches to measuring air and water quality are widely established, similarly widely-standardized agricultural soil quality (SQ) assessment protocols are largely non-existent and not available to smallholder farmers in the tropics. The Cornell Soil Health Test (CSHT), developed for the Northeastern United States, is composed of a set of inexpensive, simple, agronomically meaningful indicators of SQ. We assessed the usefulness of this tool on smallholder farms that are part of a chronosequence experiment of forest conversion to agricultural production in western Kenya. The CSHT successfully identified constraints in agronomically essential soil processes that occur as a result of soil degradation or differences in land management. Crop yield was found to significantly increase with decreasing number of identified constraints. The developed framework can help farmers target management strategies to alleviate such constraints. A large proportion of smallholder farms were found to have the option available to re-allocate resources from a field

[6] Moebius-Clune, B.N., H.M. van Es, O.J. Idowu, R.R. Schindelbeck, J.M. Kimetu, S. Ngoze, J. Lehmann, J.E. Thies and J.M. Kinyangi. Identifying and Managing Soil Constraints to Crop Productivity on Degraded Tropical Smallholder Farms using the Cornell Soil Health Test. To be submitted to Soil Use and Management or Journal of Soil and Water Conservation.

receiving excess inputs to fields that are constrained from lack of inputs. The CSHT provides a practical and scientifically-sound framework for developing standardized, inexpensive soil quality assessment tools using basic tests that require little infrastructure investment. The CSHT can be used feasibly for SQ monitoring, applied research on locally-relevant SQ management options and in helping smallholder communities make informed management decisions to improve and sustain their crop productivity.

7.2. KEY WORDS

soil quality testing; soil health test; soil constraints; low-input agriculture; subsistence agriculture; smallholder agriculture; Kenya; Africa; tropics

7.3. INTRODUCTION

7.3.1. Need for soil quality testing in developing countries

Africa's agricultural viability and food security depend heavily on the quality of its soils. Agricultural soil quality (SQ), also referred to as soil health, encompasses the chemical, physical and biological functions and processes of soils needed to support crop growth (e.g., Doran et al., 1994). Declining SQ is becoming more prevalent in Africa due to intensive land use and poor soil management, often the result of poverty and over-population (Eswaran et al., 2005; Lal, 2009).

Sanchez and Swaminathan (2005), in a summary of Hunger Task Force recommendations, note that to increase agricultural productivity of food-insecure farmers, "restoring soil health is often the first entry point." Braimoh and Vlek (2006) found, for example, that soil quality was the most important determinant of maize yield in Ghana. However, few decision makers in Africa have access to diagnostic tools to help them identify the major soil constraints limiting food production. This minimizes their ability to target limited resources and specific management toward alleviating existing constraints. Farmers, farm consultants and researchers need access to affordable, but scientifically defensible, SQ assessments to be able to explore viable, locally-adapted management options (Lal, 1997). While approaches to measuring air and water quality are widely established and standardized, similarly widely-standardized SQ assessment protocols are still largely non-existent (Bastida et al., 2008; Winder, 2003), due to global diversity of soils and land uses. Furthermore, constraints in available infrastructure often make methods of SQ assessment inaccessible to researchers and extension organizations in developing nations (Bastida et al., 2008).

7.3.2. Soil quality indicators for informed management

Soil quality cannot be measured directly, but soil properties that influence the proper functioning of soil processes important in crop production can be used as SQ indicators (Doran and Parkin, 1996; Larson and Pierce, 1991). Criteria and thresholds for relevant indicators must then be set to facilitate assessment of soil performance levels with respect to sustaining crop productivity (Arshad and Martin, 2002). For SQ assessment to be widely adopted beyond the research domain, indicators of agricultural SQ must be standardized, scientifically and agronomically relevant, sufficiently diverse to represent the physical, biological and chemical processes essential to crop growth, sensitive to changes in agricultural management, and measuring and interpreting them must be accessible, easy, inexpensive and practically useful (Doran et al., 1994; Larson and Pierce, 1991; Mausbach and Seybold, 1998). For adoption of standardized indicators in developing nations, it is also important that minimal infrastructure be required to support measurement of quantitative SQ indicators (Bastida et al., 2008).

A large number of overall SQ indices have been developed from minimum datasets of indicators by different researchers over the last decades, as reviewed by Bastida et al. (2008). These indices have been used to assess broad soil functions in diversely managed experimental cropping systems. Attention has been focused largely on comparing overall SQ between management systems. Less attention has been paid to evaluating the degree to which specific soil processes are constrained, and identifying management changes to alleviate these constraints and thus improve yields. Furthermore, few of these tests serve land managers directly, as is common for soil nutrient testing.

Of those SQ indices and assessment frameworks that have been developed to date, only one, the Cornell Soil Health Test (CSHT), is available to the public for practical, useful SQ assessment. Since 2006, the CSHT has been offered to land managers, primarily in the Northeastern United States (Gugino et al., 2009; Idowu et al., 2008), similarly to more widely available soil nutrient analyses. The CSHT is comprised of an integrative set of physical, biological and chemical indicators of SQ that meet the above-stated criteria. Measured indicator values are assessed via scoring functions and interpreted with respect to whether they constrain the soil processes they represent. The information provided by the CSHT report enables farmers to 1) identify constraints in specific soil processes on their agricultural lands, including and beyond nutrient deficiencies, 2) implement practical management strategies that specifically target these constraints and 3) monitor the condition of their soils over time.

7.3.3. The Cornell Soil Health Test as a potential framework for standardized soil quality testing

Cornell Soil Health Test indicator values are sensitive to long-term changes due to use of degrading soil management practices in smallholder systems, suggesting that this set of indicators may be useful for SQ monitoring over time (Chapter 4). Indicator values and scores have been shown to be sensitive to differences in management practices, both in the Northeastern United States and in western Kenya (Chapters 5 and 6, Idowu et al., 2008; Idowu, 2009). This integrative test may thus provide a useful framework for providing standardized SQ assessment, and further to provide management guidelines to smallholder farmers. A chronosequence of land conversion from primary forest to agriculture, located on the Kakamega and Nandi Forest margins in western Kenya, provided a unique opportunity to demonstrate the usefulness of this test in a tropical environment involving smallholder farmers. The objectives of this study were to 1) use a version of the Cornell Soil Health Test to demonstrate its usefulness for (i) assessing the level of soil degradation on smallholder farms, (ii) assessing the effects of different management practices on SQ, and (iii) making changes in soil management to alleviate identified soil constraints, and 2) evaluate the overall feasibility of using CSHT indicators in environments beyond those in which it was developed.

7.4. MATERIALS AND METHODS

7.4.1. Site and management systems

The smallholder farms sampled during this study are located on Ultisols developed on two different parent materials at the margins of the Kakamega and Nandi Forests in western Kenya, between $0^{o}00'$N and $0^{o}13'$N latitude and between

$34^{o}45$'E and $35^{o}03$'E longitude. These farms are part of a chronosequence experiment being used to investigate the long-term effects of land conversion from primary forest to agriculture, between 1900 and 2000 (Chapter 4, Kimetu et al., 2008; Kinyangi, 2008; Ngoze et al., 2008), and were described in detail in Chapter 6. Rainfall ranges between 1800 – 2100 mm per annum and has a bimodal distribution. The mean annual temperature is $19^{o}C$. The Kakamega chronosequence contained 12 farms, converted from forest to agriculture between 1930 and 1995, with coarse soil textures (average sand, silt and clay ~ 47, 40, and 13% respectively). The Nandi chronosequence contained 27 farms converted between 1900 and 2000, with somewhat finer textured soils (average sand, silt and clay 43, 38, and 19% respectively).

At each farm, two traditional long-term management systems were sampled: kitchen gardens (Ki) and continuous maize in low-input monoculture (used as control; Co). Kitchen gardens, traditionally located close to the home, have received household organic wastes and cooking ash, and have grown diverse fruit and vegetable crops in polyculture since forest conversion. Co plots were tilled twice a year to 0.10 – 0.15 m using a hand hoe and continuously cropped with maize. They had received no or negligible fertilizer or organic amendments since conversion (Kinyangi, 2008), until 2004.

On continuously cropped maize fields, four experimental short-term organic matter input systems were established in 2005 (Kimetu et al., 2008). For three consecutive growing seasons (long rains and short rains of 2005 and long rains of 2006, 16 months prior to our sampling) 6 t C ha^{-1} per season were added in the form of *Tithonia diversifolia* leaves (Ti), cattle manure (Ma), wood charcoal (Ch), or sawdust (Sa), for a total of 18 t C ha^{-1}. From 2004 until 2007 all maize systems received N, P and K fertilizer at rates of 120, 100, 100 kg ha^{-1}, respectively, per growing season, as described by Kimetu et al. (2008). Maize plots measured 2 x 4.5 m^2.

7.4.2. Field and laboratory measurements

Maize grain and stover yields were determined gravimetrically in 4.5 m^2 subplots at the end of the long rainy season in 2007 (Chapter 6). In July and August of 2007 soil samples were taken from 0 to 0.15 m with a soil auger, composited by plot, mixed, and sub-sampled for analyses. Surface (0 to 0.15 m, PR15) and subsurface (0.15 to 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 (Gugino et al., 2009).

Air-dried, 2 mm sieved soils were assessed for additional physical, biological and chemical soil properties, most of which are part of the Cornell Soil Health Test (Gugino et al., 2009; Idowu et al., 2008). Texture, an inherent, but influential soil property, was assessed using a simple and rapid quantitative method developed by Kettler et al. (2001) consisting of a combination of sieving and sedimentation steps.

Water stable aggregation (WSA) was measured by a rainfall simulation method, which closely simulates slaking processes that occur on agricultural fields during rain events (Ogden et al., 1997b). The method applies 2.5 J of energy for 300 s on 0.25 to 2 mm aggregates placed on a 0.25 mm mesh sieve. The fraction of soil aggregates remaining on the sieve, after correcting for particles of > 0.25 mm size, was regarded as the percent WSA, as described by Moebius et al. (2007). 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 difference in gravimetric moisture content in soils between these two pressures was calculated as the AWC.

Organic matter content was determined by loss on ignition. Ten-g samples were oven-dried at 105°C overnight, weighed, ignited to equilibrium in a muffle furnace at 350°C for 18 h and reweighed. A lower ignition temperature was chosen to prevent errors from high loss of structural water from kaolinite clays which is generally greatest highest 450 - 600°C (Ball, 1964; Rhodes et al., 1981). Biologically active carbon (ActC), was estimated by soil reaction with very dilute $KMnO_4$ as described by Weil et al. (2003). A hand-held colorimeter (Hach, Loveland, CO) was used to determine absorbance at 550 nm, which has an inverse linear relationship with increasing ActC. This measurement has been shown to be correlated with soil biological activity, soil aggregation and crop yield (Islam and Weil, 2000; Mtambanengwe et al., 2006; Weil et al., 2003).

Sieved soils were suspended in water (1:2.5) and electrical conductivity (EC), and pH 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 and K by inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 730-ES, Mulgrave, Victoria, Australia) by the Agricultural Analytical Services Laboratory (Pennsylvania State University, University Park, PA).

7.4.3. Interpretive soil health report development

Effective use of soil health information requires a practical framework for easy interpretation and application by farmers and advisors. A soil health report card was thus designed in Excel (Microsoft Office, 2007), using combined quantitative (indicator values and ratings) and qualitative (listed constraints and color coding) information to facilitate integrative assessment and identification of soil constraints to crop productivity (Idowu et al., 2008).

Measured indicator values were rated using scoring functions to interpret the level to which the soil processes represented may be constrained. The agronomically essential processes represented by each indicator and scoring function parameters are listed in Table 7.1. Non-linear scoring functions were developed similarly to the scoring functions for the Cornell Soil Health Test offered in the Northeastern United States (Gugino et al., 2009), and used to interpret measured indicator values for the land conversion chronosequence, as described in detail in Chapter 6.

Scores (S) for each indicator range from 0 to 100. The Cornell Soil Health Test report is color coded as follows: red for $0 \leq S \leq 30$ indicating soil constraints, yellow for $30 < S < 70$ in the intermediate range, and green for $70 \leq S \leq 100$ indicating optimal soil functioning. An example of a report is provided in Fig. 7.1. A linear unweighted combination of the scores provides a composite soil health index (CSHI). Values of the CSHI are qualitatively interpreted to indicate very low soil quality at < 40, low at < 55, medium at < 70, high at < 85 and very high above 85 (Idowu et al., 2008). Scoring functions developed for this dataset are intended to provide a solid framework and general scoring ranges, rather than providing final scoring functions to be applied in future SQ assessments in Africa. These tests and scoring functions are designed to be modified easily by users, so that more locally-appropriate interpretations can be made, where necessary.

7.4.4. Data analysis

The level of soil degradation for new (7 yr) vs. old (77 yr) farms in the Nandi region was demonstrated by linear contrasts of indicator scores obtained in mixed model analysis in JMP (Version 7.0, SAS Institute, Inc., 2007). Impact of assessed constraints on crop productivity was evaluated using simple linear regression (SLR), by using the number of constrained indicators to predict grain and stover yields across the chronosequence farms in both the Nandi and Kakamega regions. Effects of management practices on soil constraints in the Kakamega region were demonstrated

Table 7.1 Soil processes represented by measured indicators and scoring functions used to evaluate soil quality status.

Indicator	Soil Functional Processes	Type of Function	Scoring Function (0-100)†	Sources Scoring Function Parameter Development
PHYSICAL				
Aggregate Stability (WSA, %)	Structural stability, crusting, runoff, erosion, aeration, infiltration, shallow rooting	More is better	CND(49, 19)*100‡; CND(58, 19)*100	average local conditions
Available Water Capacity (AWC, $m^3\ m^{-3}$)	Plant-available water retention, drought stress tolerance	More is better	CND(0.16, 0.04)*100; CND(0.13, 0.04)*100	average local conditions
Surface Hardness (PR15, kPa)	Surface rooting, water infiltration and transmission	Less is better	(1-CND(1150, 175))*100	Cass (1999), Schuler et al. (2000) and Tekeste et al. (2007)
Subsurface Hardness (PR45, kPa)	Subsurface root proliferation, drought stress tolerance	Less is better	(1-CND(1500, 250))*100; (1-CND(1600, 300))*100	Cass (1999), Schuler et al. (2000) and Tekeste et al. (2007)
BIOLOGICAL				
Total Organic Matter (LoiOM, %)	Energy storage, C sequestration, water and nutrient retention	More is better	CND (58, 29)*100; CND(59, 29)*100	average local conditions
Active Carbon (ActC, mg kg^{-1})	Soil biological activity and biological nutrient mineralization	More is better	CND(427, 214)*100; CND(333, 214)*100	average local conditions
CHEMICAL				
pH	Toxicity, chemical buffering, nutrient availability	Optimum	$S = -63.1*(pH)^2 + 844.5*(pH) – 2716.5$	Gugino et al. (2009)
Electrical Conductivity (EC, dS/m)	Nutrient Availability (Salinity not an issue in this region)	More is better	CND(0.10, 0.025)*100	Arnold et al. (2005), Smith and Doran (1996), Glover et al. (2000), Milwaukee Instruments Inc. (2003)
Extractable Phosphorus (P, mg kg^{-1})	P Availability (P pollution not an issue in this region)	More is better	CND(33.5, 5.75)*100	Landon (1991), Kleinman et al.(2001), Schmisek et al. (1998)
Extractable Potassium (K, mg kg^{-1})	K Availability	More is better	CND(107.5, 24.25)*100; CND(68.5, 14.75)*100	Landon (1991), Texas A&M University (2004)

† For indicators that were scored separately by soil textural category, the function for soils with clay < 15% is listed first, followed by the function for soils with clay >15%.

‡ CND(m,s) = cumulative normal distribution, where m = mean, s = standard dev.

CORNELL SOIL HEALTH TEST				
Name of Farmer	NA		**Sample ID:**	Average of 1930 farms
Location	Nandi Region		**Agent:**	NA
Field/Treatment	Co		**Soil Texture Model:**	> 15% clay
Tillage	hand hoeing		**Date Sampled:**	7/1/2007
Crops Grown	continuous maize		**Conversion Yr:**	1930

	Indicators	**Value**	**Score**	**Constraint**
PHYSICAL	**Aggregate Stability (%)**	**22**	**8**	**Aeration, Infiltration, Rooting**
PHYSICAL	**Available Water Capacity (m^3m^{-3})**	**0.12**	**44**	**possibly Water Retention**
PHYSICAL	**Surface Hardness (kPa)**	**300**	**100**	
PHYSICAL	**Subsurface Hardness (kPa)**	**1650**	**27**	**Subsurface Pan/Deep Compaction**
BIOLOGICAL	**Total Organic Matter (%)**	**3.2**	**17**	**Energy storage, C Sequestration, Water Retention**
BIOLOGICAL	**Active Carbon (mg kg^{-1})**	**63**	**10**	**Soil Biological Activity**
CHEMICAL	**pH**	**5.50**	**17**	**Toxicity, Nutrient Availability**
CHEMICAL	**Electrical Conductivity (dS m^{-1})**	**0.010**	**0**	**Low Nutrient Availability**
CHEMICAL	**Extractable Phosphorus (mg kg^{-1})**	**28**	**20**	**Low P Availability**
CHEMICAL	**Extractable Potassium (mg kg^{-1})**	**105**	**45**	
	Composite Soil Health Index	**(OUT OF 100):**	**29**	VERY LOW

Soil Textural Class: loam

SAND (%): 55 **SILT (%): 29** **CLAY (%): 16**

Figure 7.1 Example of Cornell Soil Health Test report, providing the value of each measured indicator, a score (color coded red for 0 ≤ S ≤ 30 indicating soil constraints, yellow for 30 < S < 70 in the intermediate range, and green for 70 ≤ S ≤ 100 indicating optimal soil functioning), identified constraints, and a composite soil health index (CSHI).

using mixed model analysis of the scores for each indicator. Fixed factors used in the mixed models were time since conversion, management system, and the time by management interaction. Farm was used as a random factor to account for variability between farms. To support an analysis of within-farm resource distribution, the percentage of fields that 1) scored above a high threshold of 97.72 (two standard deviations above the mean), and 2) were located on a farm which contained fields scoring below a medium (< 70) or low (< 30) threshold, was calculated for each indicator for both the whole dataset and for Ki. The percentage of farms with such scenarios was also calculated.

7.5. RESULTS AND DISCUSSION

7.5.1. Identifying constraints: soil degradation on smallholder farms and impact on yield

A comparison of indicator values and scores for new (7 yr) vs. old (77 yr) low-input continuous maize fields sampled in the Nandi region of western Kenya is shown in Table 7.2. Fields that had been under cultivation for only 7 yr had high soil quality, with only two constraints (in red, with ratings of 30 or below): low P and overall nutrient availability, as measured by EC. Constraints in P availability are common among Ultisols containing low-activity kaolinite clays in this region, and are often found in forest soils. EC can be limiting in forests, but is also one of the most rapidly degrading indicators measured in this region (Chapters 4 and 6).

Continuous long-term cultivation with minimal inputs of fertilizers or organic amendments severely degrades soil structure and biological activity, and mines soil nutrients (Chapter 4, Carter, 2002; Lal, 2006; Sanchez, 2002). Notably, the old fields sampled in this region have very low soil quality. The only indicator that was virtually

Table 7.2 Effects of soil quality degradation from continuous low-input cultivation on indicator values, scores and CSHI.

	Young (7 yr)		Old (77 yr)		p
PHYSICAL	**Value**	**Score**	**Value**	**Score**	
Aggregate Stability (WSA, %)	**68**	**83**	**22**	**8**	***†
Available Water Capacity (AWC, m^3m^{-3})	**0.17**	**81**	**0.12**	**44**	+
Surface Hardness (PR15, kPa)	**90**	**100**	**300**	**100**	ns
Subsurface Hardness (PR45, kPa)	**1000**	**98**	**1650**	**27**	ns
BIOLOGICAL					
Total Organic Matter (LoiOM, %)	**11.5**	**97**	**3.2**	**17**	**
Active Carbon (ActC, mg kg^{-1})	**885**	**99**	**63**	**10**	***
CHEMICAL					
pH	**6.20**	**95**	**5.50**	**17**	***
Electrical Conductivity (EC, dS/m)	**0.060**	**5**	**0.010**	**0**	***
Extractable Phosphorus (P, mg kg^{-1})	**30**	**30**	**28**	**20**	ns
Extractable Potassium (K, mg kg^{-1})	**307**	**100**	**105**	**45**	ns
Composite Soil Health Index (CSHI, out of 100)	**High:**	**79**	**Very Low:**	**29**	*

† Significance of linear contrasts of indicator scores on new (n = 6, 7 yr in cultivation) vs. old (n = 3, 77 yr in cultivation) farms in the Nandi region shown by p-values of <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different, corrected for false discovery rate at global $\alpha = 0.05$ (Wilks, 2006).

unaffected by cultivation was surface hardness, which can be explained by the lack of use of heavy machinery. Apparently manual tillage of these soils did not significantly harden their surface over time. However, soil aggregates became significantly less stable, and thus more prone to erosion, slaking, runoff, crusting and poor aeration, which are concerns with the intense tropical rains common to the region. Additionally, the ability of older fields to store water decreased (low AWC and LoiOM). Although the difference in subsurface hardness ratings between new and old fields was not statistically significant, the level of subsurface compaction measured is likely to be agronomically significant on those old farms which contributed to the low average rating. Old farms also had low nutrient availability and low pH. Active carbon, which supports the soil microbial community in mineralizing nutrients from organic matter over time, was also low for the older fields. The interaction between nutrient constraints and reduced root extension into deeper soil horizons likely creates yield-limiting conditions in these fields.

This level of degradation is indicative of unsustainable management practices, and also significantly decreases crop productivity. Moebius-Clune (Chapter 6) concluded that CSHT measurements strong predictors of crop productivity. The strong relationship between the number of identified constraints and grain and stover yields across the Kakamega and Nandi fields is shown in Fig. 7.2. Results of regression analyses suggest that eliminating a single constraint could, on the average, improve grain yields by approximately 0.25 Mg ha^{-1} and stover yields by about 0.60 Mg ha^{-1}. This would represent a significant increase in yield for a subsistence farmer who depends on the field's productivity for the family's food, fodder and fuel supply, especially considering that typical farm sizes in this region range between 0.25 and 2.0 ha (Jayne et al., 2003).

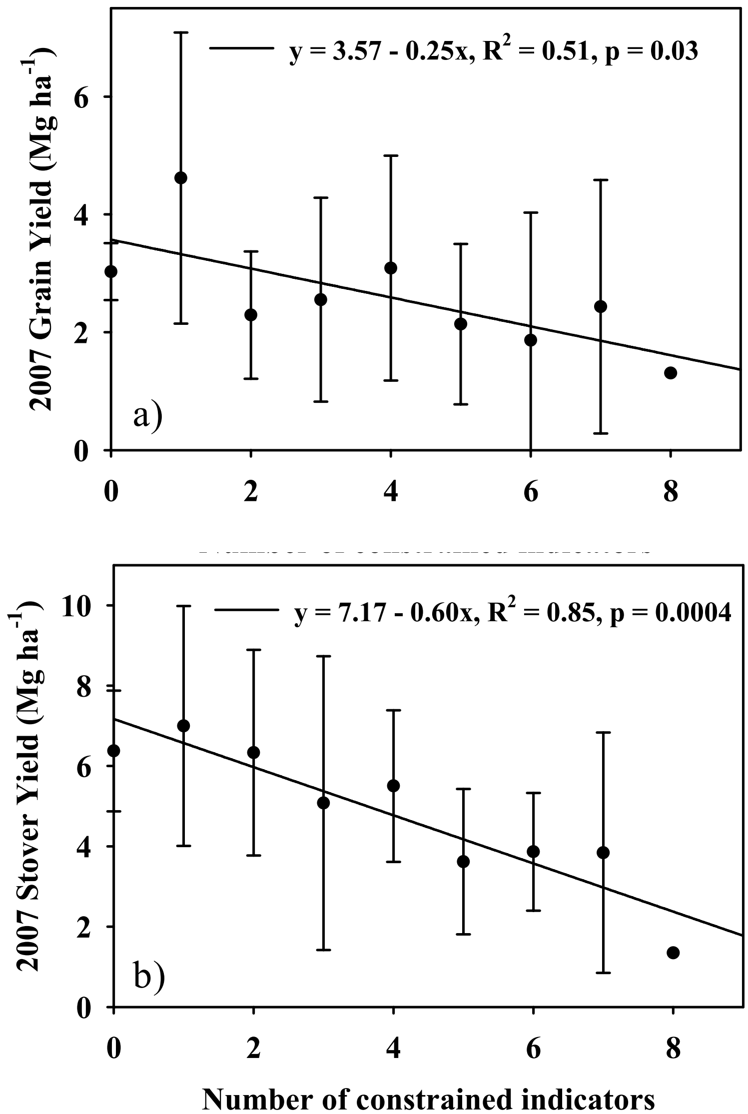

Figure 7.2 Relationship between number of indicators suggesting soil constraints and grain (n = 90) and stover (n = 89) yields.

7.5.2. Management options: effects of experimental or farmer management

There is significant debate over which kind of management is appropriate for maintaining soil quality or rebuilding degraded soils (e.g., Gowing and Palmer, 2008; Graves et al., 2004; Pretty et al., 2006). The answers to such questions are usually system- and location-specific (e.g., Chapter 5, Twomlow et al., 2008). Therefore, a tool such as the CSHT is valuable for quantitatively and relatively inexpensively assessing management systems for their ability to alleviate or prevent specific soil constraints, so that appropriate technologies can be recommended to and adapted by smallholder farmers.

In the Kakamega region (Table 7.3), we investigated 1) the contrasting effects on soil quality of two traditional, long-term management systems: continuous low-input maize (Co) vs. high-input kitchen garden (Ki) and 2) the residual effects of short-term organic matter inputs in maize cropping systems. While kitchen garden management is not a feasible alternative for an entire farm, the stark differences found between these long-term management systems can inform our understanding of management impacts on soil quality. Kitchen gardens are preferentially amended with the limited organic residues available to smallholders, such as cooking fire ashes, plant and food remains, and manure (Mtambanengwe and Mapfumo, 2008). They maintain significantly higher nutrient status, have better soil structure and biological activity, and therefore tend to remain less constrained under long-term cultivation (Chapters 4, 5 and 6).

The residual effects of experimental short-term additions of organic matter (Ma, Ch, Sa and Ti) to continuously cropped fields were small 16 months after their last application, likely because fresh organic matter degrades quickly in the tropics (Bol et al., 2000; Jenkinson and Ayanaba, 1977), and because recalcitrant charcoal remains were not detected by the loss on ignition assay (Chapter 5) as is apparent here.

Table 7.3 Mixed model LS means of indicator scores derived from scoring functions for each management scenario in the Kakamega region.

	Ki	Co	Ma	Ch	Sa	Ti	Co vs. avgOM
WSA	**57a†**	**22b**	**32b**	**31b**	**29b**	**30b**	*‡
AWC	**65a**	**56a**	**50a**	**54a**	**54a**	**51a**	ns
PR15	**94a**	**100a**	**95a**	**100a**	**92a**	**92a**	ns
PR45	**45ab**	**71a**	**39b**	**42ab**	**41b**	**47ab**	***
LoiOM	**41a**	**24b**	**25b**	**25b**	**24b**	**26b**	ns
ActC	**65a**	**24b**	**27b**	**27b**	**27b**	**29b**	ns
pH	**65a**	**50a**	**60a**	**47a**	**50a**	**59a**	ns
EC	**48a**	**0b**	**0b**	**0b**	**0b**	**0b**	ns
P	**54a**	**43a**	**82a**	**65a**	**73a**	**68a**	*
K	**96a**	**62b**	**100a**	**87a**	**90a**	**93a**	***
CSHI	**63a**	**45b**	**51b**	**48b**	**48b**	**49b**	+
	Medium			**Low**			

† Means followed by same letter are not significantly different at $\alpha = 0.05$, based on Tukey's test of fixed effects in mixed model.
‡ Significance of linear contrasts of Co vs. average organic matter amendments (avgOM) is shown by p-values of <0.001 (***), <0.01 (**), <0.05 (*), <0.10 (+), and ns = not significantly different.

It should be noted that the latter point has implications for the common use of the loss-on-ignition method in standard soil quality analysis. As biochar becomes a popular amendment due to its increasingly understood positive effects on SQ (Lehmann and Rondon, 2006), this method will not be adequate to track increases in total organic matter. However, significant residual positive effects of the amendments on soil structural, buffering and nutrient retention processes were nevertheless detected by the CSHT 16 months after they were applied. This indicates that there is potential to reverse SQ declines with such management, despite rapid mineralization of OM in tropical climates.

The lower PR45 scores in OM-amended plots and kitchen gardens suggest somewhat agronomically limiting subsurface compaction in both systems. Deep root proliferation in the Kakamega region was the only soil process that was significantly more constrained under management systems that otherwise improved SQ. This can be explained by the increased tillage and foot traffic that occurred in these systems, particularly when soils were wet (Hamza and Anderson, 2005). Organic matter was incorporated into amended plots by at least two additional intensive tillage passes at the beginning of each rainy season when the soil was wet, because this made hand-hoeing easier. Kitchen gardens are used intensively for both perennial and annual crops, and thus are tilled more frequently than the outlying maize fields, as discussed earlier.

The CSHT was used successfully to show differences between contrasting long-term management systems, as well as intentional and unintentional changes in soil constraints due to short-term experimental OM management changes. Thus, the CSHT constitutes a useful set of indicators that could be applied in similar studies to develop management recommendations for specific soil constraints. For example, approaches used in conservation agriculture, such as minimum tillage and surface cover, have been studied widely in Brazil and other regions, but less in sub-Saharan Africa (Bolliger et al., 2006; Gowing and Palmer, 2008; Hobbs, 2007). Further studies of such approaches and their effects on SQ in sub-Saharan Africa's smallholder systems would provide better information about locally appropriate management options. Such quantitatively-based decision support will facilitate scientifically informed decision-making to complement or replace the often recipe-driven management recommendations that are frequently based on broad sets of management practices without a clear understanding of actual soil constraints.

A list of short- and long-term management options that can be targeted toward alleviating specific constraints in this region (Table 7.4) was adapted from a similar list designed for use with the CSHT in Northeastern United States agriculture (Gugino et al., 2009). With access to the CSHT, more regionally- and stakeholder-specific management guidelines can be developed in collaboration with innovative farmers and consultants who are able to evaluate management systems that are compatible with their needs.

7.5.3. Targeting management at soil constraints

7.5.3.1 Addressing constraints at the field scale

The CSHT was developed primarily as a management guide. A step-by-step process (Table 7.5), adapted from Gugino et al. (2009), allows for better informed decisions about soil management changes needed. Based on identified soil constraints, one can choose management options that have been shown to alleviate the identified constraints, and that are logistically feasible. Data from two soil health reports prepared for one farm's Co and Ki fields are shown in Table 7.6. The continuous low-input maize field was severely constrained in multiple physical, biological and chemical soil processes essential for good crop production. Depending on options

Table 7.4 Suggested management strategies to target soil health constraints, modified from Gugino et al. (2009).

	Short-term or intermittent	**Long-term**
Physical Constraints		
Low aggregate stability	Fresh organic materials (shallow-rooted cover/rotation crops, manure, green clippings)	Reduced tillage, surface mulch, rotation with sod/agroforestry crops
Low available water capacity	Stable organic materials (compost, crop residues high in lignin, biochar)	Reduced tillage, rotation with sod/agroforestry crops
High surface density	Limited mechanical soil loosening/tillage; shallow-rooted cover crops, bio-drilling, fresh organic matter	Shallow-rooted cover/rotation crops, regular organic matter additions, avoid hoeing wet soils, controlled footpaths
High subsurface density	Targeted deep tillage, deep-rooted cover crops; create raised beds	Avoid hoeing and excessive foot traffic when wet, maintain permanent raised beds
Biological Constraints		
Low organic matter content	Stable organic matter (compost, crop residues high in lignin, biochar), cover and rotation crops	Reduced tillage, rotation with sod/agroforestry crops
Low active carbon	Fresh organic matter (shallow-rooted cover/rotation crops, manure, green clippings)	Reduced tillage, rotation
Chemical Constraints		
Unfavorable pH	Low: apply liming materials (such as wood/cooking ash; High: stop applying liming materials, apply acidifier (such as sulfur, acidic leaves)	Repeated applications based on soil tests as needed
Low EC, P, K	Add fertilizer or fresh, easily decomposed, nutrient-rich organic matter, such as *Tithonia*, weeds or manure	Continue regular organic matter additions, follow soil fertility recommendations

Table 7.5 Steps in determining a feasible management strategy, adapted from Gugino et al. (2009)

Steps	Explanation
1. Identify constraints	Any soil processes represented by indicators rating ≤ 30
2. Identify management strategies relevant to identified constraints	Some options are provided in Table 7.2. Further innovations can be developed at the local level
3. Determine farmer constraints and opportunities	Note any situational constraints (for example: "fertilizer not available/too expensive") and opportunities (for example: "ample *Tithonia* growth at road side" or "farmer next door successful with raised beds")
4. Plan management changes	Which of the management strategies identified in #2 are feasible, considering the farmer's constraints and opportunities identified in #3? Plan next steps and strategy in changing management.

Table 7.6 Cornell Soil Health Test report data from two fields on one farm, converted from primary forest in 1950 to a) continuous low-input maize, Co, and b) kitchen garden, Ki.

	a) Co since 1950		b) Ki since 1950	
PHYSICAL	**Value**	**Score**	**Value**	**Score**
Aggregate Stability (WSA, %)	**31**	**8**	**68**	**69**
Available Water Capacity (AWC, m^3m^{-3})	**0.17**	**84**	**0.15**	**63**
Surface Hardness (PR15, kPa)	**76**	**100**	**331**	**100**
Subsurface Hardness (PR45, kPa)	**1034**	**97**	**2155**	**0**
BIOLOGICAL				
Total Organic Matter (LoiOM, %)	**3.8**	**23**	**4.7**	**34**
Active Carbon (ActC, mg kg^{-1})	**160**	**21**	**343**	**52**
CHEMICAL				
pH	**5.85**	**64**	**7.95**	**9**
Electrical Conductivity (EC, dS/m)	**0.001**	**0**	**0.100**	**50**
Extractable Phosphorus (P, mg kg^{-1})	**16**	**0**	**70**	**100**
Extractable Potassium (K, mg kg^{-1})	**59**	**2**	**471**	**100**
Composite Soil Health Index (CSHI, out of 100)	**Very Low:**	**40**	**Medium:**	**58**

available at the farm, adding stable or fresh organic matter and/or fertilizer, reducing tillage, or planting cover crops would be options for improving the multiple constraints identified in this field (see Table 7.4). The kitchen garden management (Table 7.6) was causing compaction and high pH levels. While overall SQ was better than in the control field (medium vs. very low, respectively), very different constraints were present in the two systems, requiring different management approaches. A number of management options could be implemented to alleviate compaction, for example. Initially tilling deeply or growing deep-rooted crops could help break up the subsoil compaction. Raised or permanent beds could be developed after this, to confine foot traffic to pathways. Organic matter could be applied to the soil surface as mulch, be incorporated with minimal hoeing, or incorporated only when the soil is not too wet. Ash is known to increase soil pH, as well as P and K, among other nutrients (Gorecka et al., 2006). Since contents of P and K were higher than necessary, this farmer should stop applying cooking ashes to this field, to not further increase the already agronomically limiting pH of 7.95.

7.5.3.2 Addressing constraints at the farm scale through resource re-allocation

Some of the management options listed in Table 7.4 are relatively easy to implement even when resource availability is constrained, including avoiding tillage when wet, building raised beds, and discontinuing application of wood ashes. However, which management system is appropriate depends not only on the biophysical system, but also on the socioeconomic situation of the respective farmer (Braimoh and Vlek, 2006). Many options are generally out of the reach of smallholder farmers. Fertilizer and lime, as well as cover crop seeds, manure and other organic amendments are often either scarcely available or too expensive (Sanchez, 2002). Crop residues are often used as livestock fodder and cooking fuel and are thus not available as soil amendments (Lal, 2006). Especially in the heavily populated areas such as western Kenya, extra land to plant to cover crops may also not be available, particularly when yields are already low (Jayne et al., 2003).

The above example strongly suggests a situational opportunity available as a partial solution at the farm scale: the re-allocation of available resources between fields. Table 7.6 shows a scenario where P, K and pH are each excessive in one field, but inputs are needed in another field on the same farm. Over time, productivity of both fields will improve on this farm, if the available cooking ashes are simply applied to the Co field, instead of to the Ki field.

Table 7.7 shows an assessment of potential for such farm-level resource re-allocation across all sampled farms. A large percentage of sampled fields exceed a high threshold (HT) score of 97.72 for an indicator, and are located on a farm where at least one other field scores less-than-optimal (<70), or is constrained (≤ 30) in that same indicator. This is often the case for chemical constraints (pH, EC, P and K). It is notable that 42% of sampled kitchen gardens had pH values > 6.27 on farms where another field had low pH values and would benefit from the amendments that are currently being applied to the kitchen garden. Over a quarter of kitchen gardens received excessive nutrients where other fields scored below optimal. Almost a quarter of such kitchen gardens were located on farms which had combinations of agronomically significant nutrient and pH constraints in other fields. These findings indicate that valuable and limited resources on a significant fraction of smallholder farms in this region could be better distributed to attain higher crop productivity, and that the CSHT would be an appropriate tool to identify such opportunities.

It should be noted that 20% of the kitchen gardens in Kakamega had a pH value above 7.5 (i.e. above the optimum range, resulting in a score < 68). For this reason pH scores in Ki vs. Co plots did not show statistically significant differences (Table 7.3), while pH values themselves did (Chapter 5). Both management systems

Table 7.7 Analysis of farm-level resource re-allocation potential by tally of fields on which high thresholds are exceeded, that are found on same farm as fields below medium and low thresholds.

	WSA	AWC	PR15	PR45	LoiOM	ActC	pH†	EC	P	K
Total fields > HT, on farms with fields < MT (%)‡	0	< 1	4	4	0	< 1	8	4	19	18
Total fields > HT, on farms with fields < LT (%)‡	0	0	1	2	0	0	3	4	12	9
Ki > HT on a farm with fields < MT by Mgmt (%)§	0	3	3	6	0	0	42	25	28	25
Ki > HT on a farm with fields < LT by Mgmt (%)§	0	0	3	0	0	0	19	25	22	17
farms with potential to improve allocation (%)¶	0	3	5	13	0	3	41	23	46	31
farms with potential to alleviate constraint (%)#	0	0	3	8	0	0	18	23	38	18

† Low threshold (LT), medium threshold (MT) and high threshold (HT) for pH were defined at 5.57, 5.90 and 6.27 where scores of 30, 70 and 97.72 are first attained with rising pH.

‡ Percent of 226 fields that 1) scored > HT (HT = 97.72; two standard deviations above mean for CND's) and 2) are located on a farm where there are fields scoring < MT or < LT.

§ Percent of Ki fields that 1) scored > HT and 2) are located on a farm where there are fields scoring < MT or < LT.

¶ Percent of 39 farms with potential to improve resource allocation between fields (or management in the case of PR15 and PR45) for given indicator to improve scores of < 70.

Percent of 39 farms with potential to improve resource allocation between fields (or management in the case of PR15 and PR45) for given indicator to alleviate a constraint with score of < 30.

were often constrained: pH was too alkaline in a large number of kitchen gardens, while it was too acidic in 84% of Co fields.

In contrast with the heterogeneity of optimal vs. below-optimal scores found within farms for chemical SQ, physical and biological soil constraints appear to be more prevalent overall, even in kitchen gardens. Organic matter amendments are a limiting factor across tropical smallholder farms, as has been much discussed in the literature (e.g., Lal, 2006; Sanchez, 2002). Our data corroborate this, in that we found almost no farms where excessive fresh or stable organic matter additions could be transferred from a high-scoring to a low scoring field for alleviating WSA, AWC, LoiOM or ActC constraints, although Ki had significantly higher biological and physical SQ.

On a small fraction of farms, surface and subsurface hardness differed agronomically between fields, but eliminating such constraints is not generally a matter of amendment-reallocation. Thus the above analysis is less useful for these particular indicators. However, these differences most likely indicate tillage and traffic differences between fields. Thus CSHT results would inform farmers to make management changes based on their experience with current management in the less limited field.

7.5.4. Feasibility of using CSHT indicators in other environments

The measurements that make up this version of the Cornell Soil Health Test require minimal infrastructure (except for P and K content analysis), an advantage that will make this tool more accessible in developing countries (Bastida et al., 2008). They are also relatively inexpensive, as they require minimal consumables (Table 7.8) and simple methods. A costly component of the test is labor, which is less expensive in developing countries. Instruments necessary to measure these indicators require

Table 7.8 Field vs. laboratory options, and labor and consumables required per indicator measurement.

Indicator	**Performed in Field and/or Laboratory?**	**Person-time/sample (min)†**	**Consumables**
WSA	Field or laboratory	10 - 20	Filter paper
AWC	Laboratory	2 - 4	None
PR15 & PR45	Field	15 - 20	None
LoiOM	Laboratory	2 - 4	None
ActC	Field or laboratory	12 - 16	$KMnO_4$, reaction tubes, disposable field-pipettes
EC & pH	Field or laboratory	4 - 7	Probe storage solution, calibration solution
Texture	Laboratory	5 - 9	$(NaPO_3)_n$

† Person-time per sample is approximated from batch laboratory analysis (e.g. batches of 42 for AWC, 16 for WSA). Field analysis would likely require substantially more time. PR time is estimated not including variable walking time for different field sizes.

Table 7.9 Equipment investment for field measurement of subset of indicators, or laboratory measurement of all indicators, not including nutrients.

	Equipment	Measurements using Equipment	Approximate Cost ($)†
Field			
	Rainfall Simulator and accessories	WSA	$1,200
	Field Scale	WSA, ActC	$300
	Hand-held 550 nm colorimeter	ActC	$350
	Hand-held pH/EC meter	pH, EC	$200
	Compaction Tester	PR15, PR45	$250
	Trowel, sample bags, consumables for 100 tests, etc		$100
Laboratory			
	Drying oven	WSA (lab), AWC	$2,000
	Reverse osmosis system and pump	WSA (lab)	$1,000
	Muffle furnace†	LoiOM	$2,000
	High pressure chamber (1500 kPa) and 3 pressure plates	AWC	$3,000
	Med pressure chamber (10 kPa) and 3 pressure plates	AWC	$2,500
	High pressure air compressor (1)	AWC	$3,000
	Laboratory Scale	WSA, AWC, LoiOM, ActC, texture	$1,500
	Pipettes, storage, drying, ashing containers, scoops, sieves, consumables for 100 tests, etc.	WSA, AWC, LoiOM, ActC, pH, EC, texture	$1,500
Total Cost for Field Test Equipment Only			**$2,400**
Total Cost for Equipment of Soil Health Test Laboratory ‡			**$18,500**

† Prices of scales, drying oven and muffle furnace vary based on size, quality, etc. Approximate prices are for new materials.
‡ Nutrient analysis not included.

relatively simple and minimal maintenance, and could be obtained to equip a laboratory for below $20,000 (Table 7.9). Such an investment is within the reach of many non-governmental and government agencies and extension teams through grants.

Six of the indicators assessed here can be measured in the field with some loss in precision (Table 7.8), which will make these tests yet more accessible in smallholder environments. The rainfall simulator used for the aggregate stability assay was originally developed for a field-infiltration test (Ogden et al., 1997b), and is thus adapted to field measurements. Penetration resistance is only measured in the field, and, with minimal training, can provide reliable information about compaction. The active carbon test, similarly, has been developed to be available as a field assay(Weil et al., 2003), using a hand-held colorimeter. A handheld probe measures pH and EC. Thus an investment of less than $3000 could equip a team with the field equipment necessary to measure six out of ten indicators in hundreds of farm fields.

While the method used to determine P and K contents in this study (ICP) is not easily accessible, more accessible options may include 1) using colorimeters similar to the one used for ActC assessment, 2) using visible-near-infrared spectroscopy which is currently being developed in Africa, and is reasonably predictive of K and P contents (Awiti et al., 2008; Bogrekci and Lee, 2007; Cohen et al., 2005), or 3) developing less precise test strips similar to those used in the USDA's Soil Quality Test Kit (Liebig et al., 1996). Future work should add and develop further indicators, to represent other essential soil processes, such as crop-microbe symbiotic potential and weed and disease pressures. Disease suppressiveness, for example, can be assessed by a low-infrastructure root health bioassay, currently available as part of the CSHT in United States (Abawi and Widmer, 2000; Gugino et al., 2009).

Establishing the capacity to measure simple indicators of SQ could provide the facilities for low-budget applied research on regionally appropriate alternative management options, and for non-governmental organizations and consultants to subsidize assessments for farmer groups collaborating in rural development projects. Farmer participation in soil quality assessment and development of management innovations is essential as it is known to increase adoption of new technologies (Barrios et al., 2006; Sarrantonio et al., 1996; Twomlow et al., 2008). Because many of these tests can be performed in the field, this creates opportunities for such farmer-participatory development of locally adapted management strategies even in rural areas.

7.6. IMPLICATIONS FOR SQ TESTING IN SMALLHOLDER SYSTEMS AND BEYOND

We demonstrated the sensitivity of the indicators of the CSHT to agricultural management and to the degradation effects of cultivation over time, as well as its usefulness in informing management decisions in western Kenya's smallholder systems. The approach allows decision makers to choose locally appropriate strategies that take land use objectives and resource availability into account. We also showed that quantified soil constraints are predictive of crop productivity, which is an essential endpoint measure for a farmer. The development of the CSHT is thus a significant step forward from conventional soil testing, which focuses exclusively on chemical indicators. These indicators are not only useful tools for assessing soil constraints, monitoring SQ, and targeting management decisions in the Northeastern United States, where the test was developed, but also in Kenya and likely other African smallholder systems. Furthermore, this test has the potential to be developed into a standardized SQ test for use by African agricultural non-governmental and government organizations, to 1) better understand agricultural problems related to soil constraints through regional and national monitoring of SQ status and degradation trends, and 2) develop management solutions through low-budget field experiments. Additionally, the test may have global implications by establishing standard protocols for widespread assessment of soil degradation and calling attention to the need to internationally coordinate soil protection measures.

7.7. ACKNOWLEDGEMENTS

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CHAPTER 8. SUMMARY AND CONCLUSIONS

Soil quality management requires an integrative approach that recognizes the importance of specific physical, biological, and chemical processes that control soil functions. To allow widespread SQ monitoring and assessment, the development of a standardized, integrative SQ test that assesses soil constraints is essential. The studies presented here provide insights into the benefits of using SQ assessment methodologies in research, extension and education, both locally in New York State and internationally in Kenya.

The scientific inquiry unit that was developed, based on a selected methodology that is also used in the Cornell Soil Health Test, was successful in bringing about student learning and substantive engagement in three high school earth science classrooms. Increased use of this and similar inquiry-based units in school settings will increase student awareness about the importance of soils in their lives. Furthermore it will enhance their confidence with and excitement about doing scientific inquiry, while expanding critical thinking and collaborative team work skills, which are vital for today's citizens.

Research results from use of the Cornell Soil Health Test and its precursors provide insights on the effects of management practices on soil quality. In our assessment of the effects of stover removal and tillage, an expanded set of physical, biological and chemical indicators of SQ showed that stover harvest had greater beneficial effects on SQ under a no-till system compared to plow-till. However, overall SQ was much lower under plow-till than no-till, regardless of stover management. Our data suggest that in a temperate climate, despite its relative impact on SQ, stover harvest is relatively sustainable under no-till management.

When the CSHT framework was developed further and applied in Kenya, indicator values and interpretive scores provided insights into the dynamics of long-term SQ degradation after forest conversion to two very different traditional smallholder soil management styles, and into the residual effects of short-term organic matter interventions. High-input polyculture kitchen garden cultivation caused significantly less degradation than low-input maize monoculture, which caused dramatic degradation in almost all indicators measured. These differences became greater with long-term management. The residual benefits of short-term additions of organic matter were small, but still detectable 16 months after the last applications had been made. However, subsoils became inadvertently compacted in one of the two parent materials from imprudently timed intensive tillage during organic matter incorporation, making a strong case for basic SQ assessment. CSHT measures were also predictive of yield, which is an essential endpoint measure for smallholder farmers.

These findings suggest that agricultural SQ degradation in the tropics can be minimized by appropriate management, despite rapid organic matter turnover in the tropics. Furthermore, yields can be increased when constraints are specifically targeted. The demonstrated ability to measure degradation and management differences with a fairly basic set of SQ indicators suggests that future work on degradation dynamics and appropriate management systems could incorporate such tests to monitor and assess SQ.

Farmer and consultant access to an inexpensive, integrative SQ test is essential to allow widespread soil monitoring and assessment, and to inform targeted management decisions that can prevent or reverse degradation trends. The development of the CSHT is thus a significant step forward from conventional soil tests, which focus exclusively on chemical constraints.

In conclusion, the CSHT was shown to be useful for monitoring, assessment, and in guiding on-farm management decisions for improved crop productivity in smallholder systems in Western Kenya, and potentially elsewhere since scoring functions are easily modified for local conditions. Its low infrastructure needs make it a feasible approach to standardized SQ testing for a variety of users locally, regionally, and internationally. The test may become useful not only for applied researchers, but also for land-managers and extension, non-profit and governmental professionals. They may use the CSHT to monitor their soils and develop solution-oriented strategies, programs and policies that further the sustainable use of soil and water resources through soil enhancing management practices. The test may have global implications by establishing standard protocols for widespread assessment of SQ and calling attention to the need to internationally coordinate soil protection measures.

APPENDIX A. Pre- and Post-test Questions for Inquiry Unit on Runoff and Infiltration, Chapter 3

A.1. Non-Regents short-answer questions used for both Pre- and Post-tests

A. (3 points) Name 3 places where water will go when there is runoff.
B. (1 point) Give an example of how infiltration has a positive effect (think of something you have seen or heard about from friends, family or on the news)
C. (1 point) Give one negative effect of runoff (again, think of something you have seen or heard about from friends, family or on the news)
D. (3 points) What is the difference between an observation and an inference?

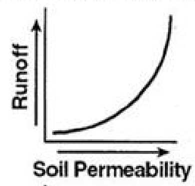
A.2. Regents multiple-choice questions

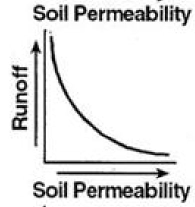
Please answer these regents-style multiple choices questions

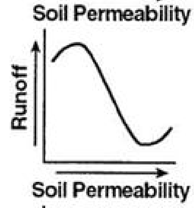
____1) Rainfall is most likely to infiltrate into soil that is

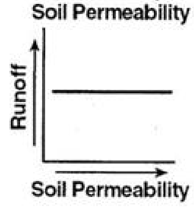
1) permeable and saturated
2) impermeable and saturated
3) impermeable and unsaturated
4) permeable and unsaturated

____2) Which graph shows the effect of soil permeability on the amount of runoff in an area?

1)


2)


3)


4)


____3) Which surface soil conditions allow the *most* infiltration of rainwater?

1) steep slope and impermeable soil
2) gentle slope and impermeable soil
3) gentle slope and permeable soil
4) steep slope and permeable soil

____4) The *greatest* amount of rainwater infiltration occurs on the side of a hill if the surface of a permeable soil has

1) large soil particles and a gentle slope
2) small soil particles and a gentle slope
3) large soil particles and a steep slope
4) small soil particles and a steep slope

____5) During a heavy rainfall, runoff will be *greatest* on a soil that has an infiltration (permeability) rate of

1) 0.3 cm/sec
2) 1.2 cm/sec
3) 0.2 cm/sec
4) 0.1 cm/sec

____6) When rainfall occurs, the rainwater will most likely become surface runoff if the land surface is

1) impermeable
2) sandy
3) covered with grass
4) nearly flat

____7) Which set of conditions would produce the *most* runoff of precipitation?

1) steep slope and permeable surface
2) gentle slope and impermeable surface
3) gentle slope and permeable surface
4) steep slope and impermeable surface

____8) During a rainfall, surface runoff will probably be *greatest* in an area that has a

1) steep slope and a clay-covered surface
2) gentle slope and a tree-covered surface
3) steep slope and a gravel-covered surface
4) gentle slope and a grass-covered surface

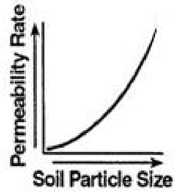
____9) Which condition would cause surface runoff to increase in a particular location?

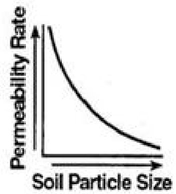
1) planting grasses and shrubs on a hillside
2) reducing the gradient of a steep hill
3) having a decrease in the annual rainfall
4) covering a dirt road with pavement

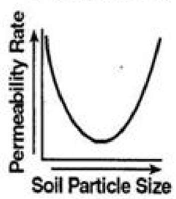
____10) In general, the probability of flooding decreases when there is an increase in the amount of

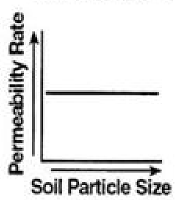
1) snow melt
2) runoff
3) precipitation
4) infiltration

____11) Which graph *best* represents the general relationship between soil particle size and the permeability rate of infiltrating rainwater?

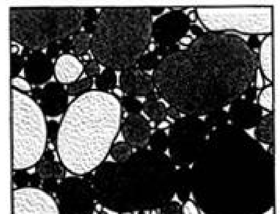
1)


2)


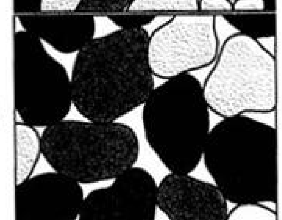
3)


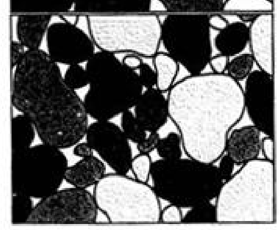
4)


____13) The diagrams below represent four permeable sediment samples. The sediments are composed of the same material, but differ in particle size and sorting. Which sediment sample will most likely have the *fastest* groundwater infiltration rate?

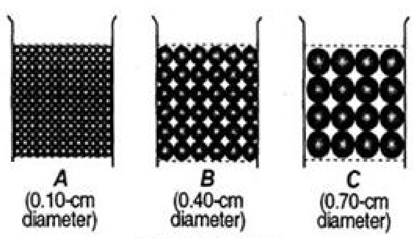
1)


2)


3)


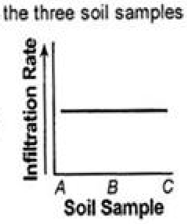
4)


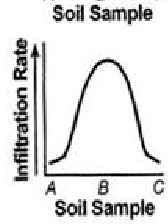
____12) The diagrams below show the relative sizes of particles from soil samples *A*, *B*, and *C*. Equal volumes of each soil sample were placed in separate containers. Each container has a screen at the bottom. Water was poured through each sample to determine the infiltration rate.

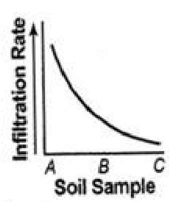


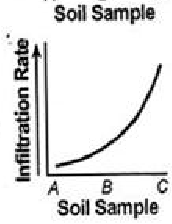
(not drawn to scale)

Which graph *best* shows how the infiltration rates of the three soil samples would compare?

1)


2)


3)


4)


APPENDIX B. Student Survey for Inquiry Unit, Chapter 3

Below are several statements about different aspects of the project. Please circle the number for your response, with 1 being "Strongly Disagree," 2 being "Disagree," 3 being "Agree" and 4 being "Strongly Agree."

	Strongly Disagree	**Disagree**	**Agree**	**Strongly Agree**
1. During this soil inquiry, I was bored more than in most classes.	**1**	**2**	**3**	**4**
2. After doing this soil inquiry, I think I could design other research experiments.	**1**	**2**	**3**	**4**
3. The runoff and infiltration unit helped me understand real world issues related to soil and water.	**1**	**2**	**3**	**4**
4. I am more excited about science than before.	**1**	**2**	**3**	**4**
5. I learned how to do the kind of teamwork that is required of research scientists.	**1**	**2**	**3**	**4**
6. I enjoyed this research experiment more than most labs.	**1**	**2**	**3**	**4**
7. This experiment was more difficult than most labs.	**1**	**2**	**3**	**4**
8. I enjoyed doing my final project.	**1**	**2**	**3**	**4**
9. I learned something from the other people in my research team	**1**	**2**	**3**	**4**
10. I learned something from seeing other people's final projects.	**1**	**2**	**3**	**4**
11. I feel good about the final project I handed in.	**1**	**2**	**3**	**4**

Please give feedback about the **Runoff and Infiltration Unit**:

I especially liked:	Suggestions for improvement:

APPENDIX C. Raw Data for Sites and Samples from Kenyan Chronosequence (Chapters 4 – 7)

C.1. List of Farm and Forest Sites

Abbreviations used for Column Headings

LabID	Identification label given to sample in soil health lab
Site Type	Type of site, either cultivated (C, Farm) or non-cultivated (N, Forest)
Site No	Number given to site; 39 farm sites and 4 forest sites were sampled
PM	Parent Material (BG = Biotite-Gneiss found in Nandi region; uBS = undifferentiated Basement System found in Kakamega regions
Elev	Elevation above sea level in meters
Year	Years since conversion from forest to agricultural production
GPS_exp	GPS coordinates of experimental plots (na = not available)
GPS_Ki	GPS coordinates of kitchen garden site (na = not available)
Date	Date sampled (all in 2007)

Site No.	Site Type	PM	Elev	Year	GPS_exp	GPS_Ki	Date
1	**C**	BG	1538	107	S 00o 00' 01.2", E 034o 44' 49.3"	S 00o 00' 03.4", E 034o 44' 51.0"	7/24
2	**C**	BG	1554	107	N 00o 00' 11.2", E 034o 44' 53.5"	N 00o 00' 10.5", E 034o 44' 54.6"	7/24
3	**C**	BG	1549	107	N 00o 00' 08.1", E 034o 44' 46.2"	N 00o 00' 08.2", E 034o 44' 43.8"	7/24
4	**C**	BG	1560	77	N 00o 00' 40.9", E 034o 48' 39.6"	N 00o 00' 41.7", E 034o 48' 40.0"	8/10
5	**C**	BG	1632	77	N 00o 01' 14.9", E 034o 49' 03.0"	na	7/25
6	**C**	BG	1654	77	N 00o 01' 28.0", E 034o 49' 15.0"	N 00o 01' 30.3", E 034o 49' 14.6"	8/10

Site No.	Site Type	PM	Elev	Year	GPS_exp	GPS_Ki	Date
7	**C**	BG	1664	22	N 00o 05' 41.8", E 034o 53' 22.5"	N 00o 05' 40.5", E 034o 53' 27.0"	7/30
8	**C**	BG	1651	22	N 00o 05' 41.9", E 034o 53' 28.0"	N 00o 05' 40.5", E 034o 53' 29.0"	7/30
9	**C**	BG	1791	37	N 00o 02' 25.8", E 034o 56' 37.5"	na	7/25
10	**C**	BG	1827	37	N 00o 02' 54.1", E 034o 56' 33.1"	N 00o 02' 54.2", E 034o 56' 34.3"	7/25
11	**C**	BG	1795	37	N 00o 02' 36.7", E 034o 56' 40.2"	na	7/25
12	**C**	BG	2028	12	N 00o 03' 39.0", E 034o 58' 46.5"	na	8/10
13	**C**	BG	2013	12	N 00o 03' 37.1", E 034o 58' 49.0"	na	8/10
14	**C**	BG	2026	12	N 00o 04' 00.5", E 034o 58' 41.1"	na	8/10
15	**C**	BG	1847	22	N 00o 07' 22.9", E 034o 54' 40.3"	na	8/10
16	**C**	BG	1756	7	N 00o 09' 28.6", E 034o 57' 34.1"	N 00o 09' 26.9", E 034o 57' 33.2"	8/7
17	**C**	BG	1745	7	N 00o 09' 37.9", E 034o 57' 35.1"	N 00o 09' 37.9", E 034o 57' 35.1"	8/7
18	**C**	BG	1749	7	N 00o 09' 29.4", E 034o 57' 31.6"	N 00o 09' 31.6", E 034o 57' 31.8"	8/7
19	**N**	BG	1762	0	N 00o 09' 38.8", E 034o 57' 53.9"	na	8/7
20	**N**	BG	2027	0	N 00o 04' 58.5", E 034o 58' 28.9"		8/10
21	**C**	BG	1811	12	N 00o 09' 46.3", E 034o 59' 22.6"	N 00o 09' 46.3", E 034o 59' 22.6"	8/4
22	**C**	BG	1826	12	N 00o 09' 51.2", E 034o 59' 30.9"	N 00o 09' 46.7", E 034o 59' 32.0"	8/4
23	**C**	BG	1815	12	N 00o 10' 03.7", E 034o 59' 45.7"	N 00o 10' 03.7", E 034o 59' 45.7"	8/4
24	**C**	BG	1812	7	N 00o 09' 37.7", E 035o 00' 00.0"	na	8/3
25	**C**	BG	1808	7	N 00o 09' 39.4", E 035o 00' 02.1"	na	8/3
26	**C**	BG	1811	7	N 00o 09' 41.9", E 035o 00' 11.7"	na	8/3
27	**C**	BG	1861	57	N 00o 10' 50.8", E 035o 00' 38.2"	N 00o 10' 51.2", E 035o 00' 34.9"	8/3
28	**C**	BG	1864	57	N 00o 10' 54.0", E 035o 00' 39.7"	N 00o 10' 56.3", E 035o 00' 36.8"	8/4
29	**C**	BG	1861	57	N 00o 10' 57.4", E 035o 00' 41.9"	na	8/4

Site No.	Site Type	PM	Elev	Year	GPS_exp	GPS_Ki	Date
30	**N**	BG	1867	0	N 00o 09' 19.2", E 035o 00' 14.7"	na	8/3
31	**C**	uBS	1675	12	N 00o 08' 38.3", E 034o 52' 25.6"	N 00o 08' 38.2", E 034o 52' 23.9"	7/20
32	**C**	uBS	1692	12	N 00o 08' 36.7", E 034o 52' 22.8"	N 00o 08' 31.6", E 034o 52' 22.2"	7/20
33	**C**	uBS	1672	12	N 00o 08' 38.5", E 034o 52' 19.6"	na	7/20
34	**C**	uBS	1606	57	N 00o 09' 35.4", E 034o 51' 26.1"	N 00o 09' 34.4", E 034o 51' 24.3"	7/19
35	**C**	uBS	1612	57	N 00o 09' 37.2", E 034o 51' 25.8"	N 00o 09' 36.1", E 034o 51' 22.4"	7/19
36	**C**	uBS	1605	77	N 00o 09' 59.4", E 034o 51' 28.3"	na	7/16
37	**C**	uBS	1605	57	N 00o 09' 44.5", E 034o 51' 30.0"	N 00o 09' 46.6", E 034o 51' 26.90"	7/18
38	**C**	uBS	1603	22	N 00o 10' 03.5", E 034o 51' 34.9"	N 00o 10' 01.8", E 034o 51' 34.0"	7/17
39	**C**	uBS	1600	77	N 00o 09' 59.3", E 034o 51' 33.1"	N 00o 09' 59.5", E 034o 51' 32.1"	7/17
40	**C**	uBS	1601	22	N 00o 09' 58.4", E 034o 51' 34.9"	na	7/18
41	**C**	uBS	1604	22	N 00o 09' 57.3", E 034o 51' 35.0"	N 00o 09' 555.1", E 034o 51' 32.0"	7/18
42	**C**	uBS	1660	37	N 00o 11' 09.9", E 034o 55' 48.1"	N 00o 11' 08.4", E 034o 55' 48.6"	8/4
43	**N**	uBS	1700	0	na, close to sites 39 & 40	na	7/17

C.2. Textural and Chemical Data from Farm and Forest Fields/Samples

Abbreviations used for Column Headings

LabID	Identification label given to sample in soil health lab
Site Type	Type of site, either cultivated (C, Farm) or non-cultivated (N, Forest)
Trt	Treatment (Co = control, Ma = manure, Ti = Tithonia, Sa = sawdust, Ki = kitchen garden, F = forest)
Sand	% sand
Clay	% clay
Silt	% silt
pH	pH
EC	electrical conductivity in dS/m
P	in mg/kg
K	in mg/kg
Mg	in mg/kg
Ca	in mg/kg
CEC	in mg/kg
Zn	in mg/kg
Cu	in mg/kg
S	in mg/kg

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K1	**1**	**Ti**	9.4	41.5	49.1	6.3	0.01	9	325	241	1565	15.2	5.75	1.35	11.70
K2	**1**	**Ch**	8.6	43.5	47.9	6.2	0.01	13	250	236	1549	16.7	7.54	1.33	11.36
K3	**1**	**Co**	8.1	42.2	49.8	6.0	0.01	10	160	251	1676	16.6	6.11	1.46	13.66
K4	**1**	**Ma**	7.6	41.5	50.9	6.3	0.02	13	435	314	1727	18.7	9.93	1.40	12.49
K5	**1**	**Sa**	7.5	43.7	48.7	6.2	0.01	7	205	255	1495	15.2	8.62	1.38	12.38
K6	**1**	**Ki**	29.9	28.3	41.8	7.1	0.06	42	683	397	2419	17.2	23.77	1.73	13.18
K7	**2**	**Ti**	12.6	32.9	54.5	6.5	0.03	32	467	281	2500	22.9	12.08	1.77	11.94
K8	**2**	**Ch**	12.6	27.4	60.1	6.5	0.02	39	415	293	2442	22.6	13.38	1.71	12.30
K9	**2**	**Co**	10.0	36.6	53.4	6.0	0.02	25	333	254	1865	19.2	13.14	1.66	12.40
K10	**2**	**Ma**	12.2	29.2	58.6	6.6	0.04	63	749	322	2419	23.0	14.09	1.87	12.06
K11	**2**	**Sa**	17.2	26.7	56.1	6.6	0.02	63	555	295	2495	22.7	12.12	1.89	12.56
K12	**2**	**Ki**	14.9	28.8	56.3	7.4	0.20	62	1181	522	3029	22.4	24.52	2.20	17.03
K13	**3**	**Ti**	9.9	36.9	53.2	6.0	0.01	26	312	247	1752	19.1	10.84	1.63	13.05
K14	**3**	**Ch**	10.1	36.9	52.9	6.0	0.01	16	262	276	1868	18.0	11.94	1.67	13.52
K15	**3**	**Co**	10.0	41.5	48.5	5.9	0.01	15	220	266	1659	19.8	10.09	1.51	14.69
K16	**3**	**Ma**	11.4	40.3	48.3	6.3	0.02	21	443	319	1868	19.4	14.14	1.71	12.57
K17	**3**	**Sa**	7.9	42.8	49.4	6.0	0.01	18	225	259	1538	17.9	8.94	1.51	12.23
K18	**3**	**Ki**	10.8	32.4	56.7	6.4	0.02	9	457	393	1990	20.7	17.29	1.81	13.09
K19	**4**	**Ti**	42.9	31.7	25.4	5.4	0.02	13	185	178	972	13.1	2.70	3.38	13.83
K20	**4**	**Ch**	43.9	30.1	26.0	5.4	0.01	16	119	191	948	12.9	3.02	3.11	12.85
K21	**4**	**Ma**	41.9	32.7	25.4	5.7	0.03	17	290	224	1039	13.5	3.66	3.25	15.15
K22	**4**	**Sa**	41.1	32.8	26.1	5.5	0.02	14	105	174	977	12.3	1.93	2.73	12.07
K23	**4**	**Co**	39.0	45.3	15.8	5.4	0.02	5	173	239	1159	14.5	1.48	2.95	11.64
K24	**4**	**Ki**	50.9	19.7	29.4	7.3	0.17	78	474	315	2423	16.0	42.67	3.30	15.48
K25	**5**	**Ti**	66.1	13.8	20.1	5.7	0.01	55	241	81	660	10.3	6.81	2.56	13.57
K26	**5**	**Ch**	67.3	14.7	18.0	5.7	0.01	60	191	80	598	9.8	4.47	2.36	10.88
K27	**5**	**Ma**	68.2	12.6	19.2	6.0	0.01	68	241	125	708	10.9	6.31	2.56	12.29
K28	**5**	**Sa**	67.7	13.0	19.3	5.5	0.00	46	133	67	512	9.8	4.49	2.47	12.96
K29	**5**	**Co**	66.5	15.8	17.7	5.6	0.00	35	89	68	567	9.3	4.14	2.52	11.87

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K30	**5**	**Ki**	71.9	10.3	17.8	7.8	0.19	128	747	243	1420	11.0	34.59	2.98	13.37
K31	**6**	**Ki**	62.7	15.8	21.5	7.0	0.05	50	331	210	1370	12.2	22.78	2.41	11.89
K32	**6**	**Ch**	56.5	18.5	24.9	5.6	0.01	35	143	115	728	11.9	7.37	3.09	14.41
K33	**6**	**Ma**	54.3	16.5	29.2	5.6	0.01	28	152	135	719	11.4	7.40	3.10	13.26
K34	**6**	**Sa**	56.8	17.0	26.2	5.5	0.02	20	129	109	692	11.0	3.73	3.24	13.58
K35	**6**	**Co**	55.8	21.1	23.0	5.5	0.01	17	81	112	693	10.9	5.52	3.24	13.49
K36	**6**	**Ti**	59.1	15.9	25.0	5.7	0.01	22	136	125	819	12.4	4.90	3.15	12.60
K37	**7**	**Ti**	44.6	20.5	35.0	5.8	0.03	28	353	102	860	14.2	2.83	1.17	12.19
K38	**7**	**Ch**	45.6	20.8	33.6	5.8	0.02	20	254	113	940	13.8	5.25	1.37	12.93
K39	**7**	**Ma**	44.0	20.4	35.6	5.9	0.03	32	443	147	973	15.3	6.04	1.33	13.09
K40	**7**	**Sa**	42.9	22.8	34.3	5.8	0.02	33	262	111	932	13.8	3.23	1.22	12.62
K41	**7**	**Co**	36.8	36.3	27.0	5.5	0.02	6	123	71	541	12.9	2.79	1.22	13.67
K42	**7**	**Ki**	43.2	19.1	37.8	6.1	0.06	21	449	234	1257	15.1	18.43	1.67	14.58
K43	**8**	**Ti**	54.7	16.1	29.3	5.5	0.02	42	283	69	528	13.2	7.07	1.74	15.92
K44	**8**	**Ch**	54.7	17.1	28.2	5.3	0.02	42	227	66	497	10.5	8.15	1.85	15.83
K45	**8**	**Ma**	56.2	17.4	26.4	5.6	0.02	32	283	93	492	12.1	6.78	1.97	16.12
K46	**8**	**Sa**	59.7	16.8	23.5	5.4	0.02	39	185	77	485	11.6	3.76	1.84	16.18
K47	**8**	**Co**	42.2	25.8	32.0	5.2	0.01	11	148	68	513	13.4	5.48	1.97	16.26
K48	**8**	**Ki**	47.6	20.4	32.0	6.2	0.06	17	577	218	1259	14.7	14.89	1.80	14.75
K49	**9**	**Ti**	53.6	17.9	28.4	5.3	0.01	17	95	75	589	13.1	3.33	1.54	14.10
K50	**9**	**Ch**	54.1	18.0	28.0	5.3	0.01	13	165	98	726	13.6	3.35	1.70	13.82
K51	**9**	**Ma**	50.9	19.9	29.2	5.4	0.00	4	92	120	828	14.1	3.23	1.80	13.09
K52	**9**	**Sa**	51.5	20.1	28.3	5.5	0.01	10	131	115	772	13.9	3.37	1.60	12.85
K53	**9**	**Co**	47.5	19.5	33.0	5.3	0.02	8	261	112	703	15.0	6.25	2.00	14.92
K54	**9**	**Ki**	52.0	13.0	35.0	6.8	0.13	58	460	259	2174	14.2	10.21	2.18	14.80
K55	**10**	**Ti**	37.2	24.1	38.6	5.7	0.03	15	317	302	1733	20.1	20.43	2.92	11.87
K56	**10**	**Ch**	33.3	27.5	39.2	5.9	0.01	17	264	349	1788	20.0	6.06	2.81	11.66
K57	**10**	**Co**	39.0	22.3	38.6	5.8	0.01	9	186	230	1670	19.4	15.92	2.69	11.87
K58	**10**	**Ma**	46.5	19.0	34.5	5.8	0.02	22	295	245	1359	17.1	8.33	2.23	12.97

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K59	**10**	**Sa**	46.5	19.8	33.7	5.7	0.02	29	250	189	1201	16.9	8.52	2.37	13.87
K60	**10**	**Ki**	48.1	17.4	34.6	5.9	0.01	9	221	224	1370	16.8	11.31	1.85	11.77
K61	**11**	**Ti**	32.3	22.1	45.7	6.1	0.04	16	617	179	1550	18.9	9.40	1.90	10.73
K62	**11**	**Ch**	30.7	21.1	48.1	6.0	0.03	18	496	175	1492	17.7	12.83	2.00	11.85
K63	**11**	**Co**	30.0	26.2	43.8	5.8	0.02	18	358	165	1345	15.3	7.66	1.97	11.75
K64	**11**	**Ma**	29.8	22.5	47.6	6.1	0.04	30	583	209	1415	18.4	8.87	1.90	13.02
K65	**11**	**Sa**	29.2	24.4	46.4	5.8	0.02	13	446	167	1319	16.0	7.88	1.89	12.63
K66	**11**	**Ki**	28.9	26.9	44.2	5.6	0.01	5	248	184	1247	17.1	8.63	2.02	12.67
K67	**12**	**Co**	32.3	19.7	48.0	5.8	0.05	6	393	289	2066	21.2	8.05	1.65	16.07
K68	**12**	**Ki**	58.1	9.3	32.6	6.5	0.17	44	574	386	3178	24.8	69.52	2.07	18.23
K69	**13**	**Co**	38.6	18.7	42.7	5.9	0.02	8	385	251	1942	20.3	11.55	0.92	10.67
K70	**13**	**Ki**	44.0	15.2	40.8	6.4	0.04	18	495	312	2599	22.6	19.54	1.25	11.40
K71	**14**	**Ti**	48.5	13.6	38.0	5.4	0.03	27	447	144	1257	17.9	7.47	0.82	16.18
K72	**14**	**Ch**	50.3	14.3	35.4	5.4	0.03	23	263	135	1050	16.4	3.79	0.73	13.74
K73	**14**	**Ma**	55.3	11.4	33.3	5.5	0.03	29	398	145	860	20.6	8.62	0.86	18.21
K74	**14**	**Sa**	57.7	11.2	31.1	5.4	0.02	25	232	108	823	15.5	4.24	0.71	14.84
K75	**14**	**Co**	42.2	17.4	40.4	5.5	0.01	23	103	122	1306	17.1	3.48	0.87	12.59
K76	**15**	**Co**	33.3	23.1	43.6	6.1	0.03	7	198	215	2075	16.6	7.50	1.51	11.43
K77	**15**	**Ki**	34.8	26.9	38.3	6.1	0.06	7	689	325	1485	18.2	4.37	1.58	13.88
K78	**16**	**Ti**	42.2	16.9	41.0	6.2	0.05	26	551	320	2455	24.5	15.95	1.30	11.77
K79	**16**	**Ch**	54.8	12.3	32.9	6.3	0.05	34	527	392	2686	24.9	18.41	1.31	12.66
K80	**16**	**Co**	49.6	15.5	35.0	6.2	0.02	15	418	320	2234	23.0	9.07	1.09	11.40
K81	**16**	**Ma**	45.8	16.9	37.3	6.1	0.06	41	624	404	2307	24.0	10.37	1.46	13.21
K82	**16**	**Sa**	50.4	13.6	35.9	6.3	0.03	22	473	404	2537	23.0	15.42	1.16	10.72
K83	**16**	**Ki**	49.9	15.1	35.0	6.2	0.04	9	251	370	2842	25.4	9.89	1.40	14.43
K84	**17**	**Ti**	54.7	10.3	35.1	6.6	0.04	10	260	332	3217	22.3	11.26	2.16	11.55
K85	**17**	**Ch**	46.3	11.7	42.0	6.5	0.07	10	184	336	3191	24.0	12.13	2.31	12.59
K86	**17**	**Co**	51.6	8.3	40.1	6.6	0.04	8	295	346	3333	23.1	9.64	2.10	12.88
K87	**17**	**Ma**	55.7	10.4	33.9	6.3	0.05	13	302	352	3416	24.4	13.99	2.30	13.27

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K88	**17**	**Sa**	48.1	13.7	38.2	6.4	0.06	14	219	378	4127	23.2	18.88	2.39	13.93
K89	**17**	**Ki**	45.3	12.6	42.2	7.3	0.17	16	481	461	4357	20.1	32.75	2.71	15.31
K90	**18**	**Ti**	43.5	17.5	39.0	6.2	0.07	45	471	431	3266	24.9	28.44	2.01	14.06
K91	**18**	**Ch**	64.7	8.8	26.5	7.1	0.06	32	557	338	3839	19.2	18.37	1.61	11.50
K92	**18**	**Co**	50.3	12.4	37.3	6.3	0.06	13	428	440	3520	25.5	20.71	2.03	13.13
K93	**18**	**Ma**	44.7	15.9	39.4	6.1	0.06	43	514	423	3081	25.5	14.94	1.87	14.49
K94	**18**	**Sa**	44.9	26.0	29.2	6.4	0.05	26	460	370	3082	24.4	13.86	1.80	12.68
K95	**18**	**Ki**	42.4	22.2	35.4	6.6	0.07	5	237	300	2725	20.6	7.33	1.50	12.18
K96	**19**	**F**	57.8	12.6	29.6	6.8	0.10	17	380	352	3259	20.9	14.04	1.64	15.35
K97	**19**	**F**	47.3	13.8	38.9	6.6	0.16	5	213	559	3734	24.7	16.59	2.01	16.10
K98	**19**	**F**	34.3	20.7	45.0	6.1	0.10	5	159	497	3300	27.6	23.73	2.46	16.61
K99	**20**	**F**	31.3	17.2	51.5	5.8	0.13	9	242	506	2310	24.5	25.36	1.43	28.09
K100	**20**	**F**	48.4	13.4	38.2	5.2	0.08	8	202	263	1525	23.8	20.46	1.38	26.45
K101	**20**	**F**	39.8	18.5	41.8	6.7	0.17	7	457	616	3455	26.4	13.55	1.99	22.81
K102	**21**	**Ti**	58.3	7.6	34.0	6.4	0.04	42	306	254	3113	23.0	13.61	2.36	13.13
K103	**21**	**Ch**	56.4	6.5	37.1	6.6	0.05	55	302	265	3434	22.5	10.98	2.42	13.52
K104	**21**	**Ma**	53.4	7.9	38.7	6.2	0.05	39	479	290	2437	22.1	14.77	2.46	14.17
K105	**21**	**Sa**	56.8	7.8	35.4	6.3	0.05	63	268	265	2861	21.7	7.87	2.25	12.04
K106	**21**	**Co**	57.5	6.4	36.0	6.3	0.05	66	215	264	2885	23.5	10.05	1.78	12.12
K107	**21**	**Ki**	52.4	13.6	34.0	6.6	0.06	14	255	238	2163	17.4	8.37	1.55	11.94
K108	**22**	**Ti**	35.2	25.1	39.7	5.4	0.03	23	240	107	978	16.3	6.87	1.03	15.22
K109	**22**	**Ch**	30.2	25.7	44.2	5.4	0.03	35	203	94	1015	16.3	7.03	1.03	14.38
K110	**22**	**Ma**	35.9	20.3	43.8	5.8	0.05	39	375	190	1185	16.6	6.24	1.06	14.57
K111	**22**	**Sa**	35.4	21.5	43.2	5.3	0.02	41	166	81	835	15.2	5.75	1.03	14.47
K112	**22**	**Co**	39.5	19.7	40.8	5.7	0.04	18	214	135	1503	16.7	5.35	1.42	12.48
K113	**22**	**Ki**	33.7	14.3	52.0	6.5	0.10	28	684	466	3137	25.7	21.16	1.92	16.99
K114	**23**	**Ti**	48.4	10.2	41.4	5.5	0.08	62	347	266	1916	22.6	17.78	2.03	18.40
K115	**23**	**Ch**	46.8	10.3	42.9	6.2	0.09	59	580	392	2163	21.3	14.68	2.09	17.31
K116	**23**	**Ma**	43.2	10.8	46.0	5.9	0.07	75	421	370	2152	23.0	12.56	2.21	15.86

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K117	**23**	**Sa**	54.7	8.2	37.1	6.0	0.08	49	361	362	2193	24.8	13.47	1.97	14.45
K118	**23**	**Ki**	48.2	9.6	42.2	5.6	0.06	31	326	300	1714	21.2	9.98	1.82	16.09
K119	**24**	**Ti**	54.5	6.4	39.1	6.2	0.05	36	266	317	2832	23.2	8.67	2.01	12.08
K120	**24**	**Ch**	59.8	6.1	34.1	6.5	0.09	38	490	370	3021	23.2	10.33	2.13	12.52
K121	**24**	**Ma**	55.7	7.1	37.2	6.5	0.06	13	205	337	3124	22.2	7.57	2.15	12.31
K122	**24**	**Sa**	56.3	7.1	36.5	6.3	0.07	32	324	302	2503	19.8	6.34	1.88	13.27
K123	**24**	**Co**	57.5	5.6	36.9	6.7	0.07	32	275	355	3359	22.6	11.57	2.17	12.95
K124	**25**	**Ti**	64.7	5.2	30.0	7.1	0.09	59	428	327	4150	18.8	10.99	1.98	13.50
K125	**25**	**Ch**	58.8	7.6	33.5	6.9	0.08	78	353	329	3789	18.6	7.02	1.87	12.92
K126	**25**	**Ma**	57.3	7.8	34.9	6.8	0.10	93	391	418	3526	19.5	15.35	1.79	14.26
K127	**25**	**Sa**	61.4	6.6	32.0	7.2	0.09	97	364	343	3979	18.8	8.48	1.97	13.46
K128	**25**	**Co**	64.2	5.5	30.3	6.6	0.07	43	290	247	3554	21.1	12.52	1.67	13.19
K129	**25**	**Ki**	51.8	11.3	36.9	7.6	0.21	62	896	513	3644	21.6	13.19	2.32	18.54
K130	**26**	**Ti**	59.2	6.4	34.4	6.1	0.08	69	335	324	3515	26.7	14.31	2.00	13.09
K131	**26**	**Ch**	54.9	6.9	38.2	6.8	0.10	68	261	383	4552	18.9	11.02	2.14	14.73
K132	**26**	**Ma**	69.0	5.3	25.6	6.4	0.09	89	404	449	3410	24.3	14.27	2.28	14.92
K133	**26**	**Sa**	55.3	7.6	37.1	6.0	0.07	46	225	339	3257	27.1	10.71	2.25	13.89
K134	**26**	**Co**	60.6	6.0	33.5	6.0	0.06	33	133	299	2966	27.6	9.18	2.22	13.56
K135	**26**	**Ki**	57.5	7.3	35.2	7.7	0.31	126	1250	664	3927	23.7	17.01	2.78	27.99
K136	**27**	**Ti**	23.6	33.1	43.3	5.5	0.02	22	291	101	711	13.2	3.77	2.08	16.56
K137	**27**	**Ch**	23.1	34.6	42.3	5.5	0.02	18	304	104	723	12.8	3.73	2.15	17.17
K138	**27**	**Ma**	25.8	34.0	40.2	5.7	0.03	28	481	145	797	13.9	3.11	2.16	16.28
K139	**27**	**Sa**	23.8	34.2	42.0	5.9	0.03	18	349	145	998	14.6	1.94	2.18	14.31
K140	**27**	**Co**	20.0	41.3	38.7	5.3	0.01	21	99	81	554	13.6	1.68	2.09	17.79
K141	**27**	**Ki**	25.8	37.0	37.2	6.1	0.05	5	381	209	1342	13.3	4.82	1.53	16.92
K142	**28**	**Co**	27.3	25.6	47.1	6.3	0.03	5	292	241	2275	19.2	6.02	3.08	12.15
K143	**28**	**Ki**	50.6	13.7	35.7	7.2	0.12	80	627	326	3213	19.3	77.68	2.74	16.68
K144	**29**	**Ti**	32.4	28.5	39.1	6.0	0.02	14	289	191	2001	19.2	7.00	1.78	11.92
K145	**29**	**Ch**	34.2	19.6	46.3	6.0	0.02	47	230	162	1837	18.0	5.93	1.94	13.05

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K146	**29**	**Ma**	32.4	24.8	42.8	6.2	0.03	27	472	262	1600	19.5	8.11	2.38	12.30
K147	**29**	**Sa**	28.6	32.4	39.0	6.0	0.01	19	314	281	1298	14.7	5.08	1.96	11.23
K148	**29**	**Co**	33.3	18.7	47.9	5.9	0.02	29	197	142	1906	19.3	6.02	2.01	11.87
K149	**29**	**Ki**	39.0	14.3	46.7	6.3	0.08	24	576	286	2077	19.3	39.59	2.08	13.87
K150	**30**	**F**	40.3	10.9	48.8	7.2	0.20	10	250	409	5016	19.0	15.55	5.62	23.04
K151	**30**	**F**	36.0	11.5	52.5	6.6	0.14	5	216	607	3089	25.1	10.99	4.17	19.46
K152	**30**	**F**	69.5	4.7	25.7	7.2	0.10	11	514	377	3558	19.5	8.56	4.15	15.52
K153	**31**	**Ti**	50.9	17.5	31.7	5.1	0.03	91	231	60	420	11.3	2.25	2.62	18.24
K154	**31**	**Ch**	52.6	18.7	28.7	4.9	0.03	70	157	41	267	9.6	5.02	2.69	20.66
K155	**31**	**Ma**	51.5	19.1	29.4	5.1	0.04	72	289	74	307	11.0	5.23	2.97	20.87
K156	**31**	**Sa**	50.4	20.4	29.2	5.0	0.02	62	169	35	212	9.3	3.18	2.83	19.72
K157	**31**	**Co**	46.1	22.1	31.9	5.0	0.03	39	170	31	178	10.3	2.94	3.13	21.45
K158	**31**	**Ki**	49.3	15.6	35.1	5.5	0.04	15	218	141	560	11.4	6.09	2.92	19.56
K159	**32**	**Ti**	64.3	9.8	25.9	5.8	0.03	129	241	115	464	10.8	3.67	2.46	17.19
K160	**32**	**Ch**	59.4	19.4	21.2	5.1	0.01	74	128	32	231	9.2	2.35	2.74	18.08
K161	**32**	**Ma**	63.0	11.0	26.0	5.4	0.02	91	165	56	385	10.3	3.02	2.82	17.62
K162	**32**	**Sa**	62.3	12.6	25.1	5.3	0.02	116	155	36	239	8.2	3.81	2.54	16.64
K163	**32**	**Co**	57.2	16.7	26.2	4.9	0.02	66	85	28	150	9.9	5.15	2.75	22.48
K164	**32**	**Ki**	68.6	4.6	26.8	7.5	0.15	205	467	337	2352	15.8	68.44	4.04	18.09
K165	**33**	**Ti**	43.5	20.7	35.8	5.2	0.01	30	204	67	398	10.0	3.86	4.23	17.71
K166	**33**	**Ch**	44.2	18.4	37.4	5.1	0.02	36	194	64	335	9.6	2.92	4.25	19.76
K167	**33**	**Ma**	43.2	21.9	34.9	5.3	0.02	40	229	77	398	10.7	3.67	4.26	19.54
K168	**33**	**Sa**	44.6	18.9	36.4	5.0	0.02	33	132	44	270	10.2	4.33	3.96	19.34
K169	**33**	**Co**	42.1	21.5	36.5	5.0	0.01	20	145	44	218	10.5	8.10	4.26	21.14
K170	**33**	**Ki**	38.7	19.3	42.0	5.4	0.05	20	249	115	540	10.0	25.68	4.29	17.17
K171	**34**	**Ti**	41.9	13.3	44.8	5.8	0.03	40	98	97	781	9.5	6.97	4.81	12.89
K172	**34**	**Ch**	42.6	13.6	43.8	5.8	0.01	24	93	97	740	10.4	5.99	4.70	13.60
K173	**34**	**Ma**	39.2	13.6	47.2	6.2	0.02	48	217	129	862	8.7	9.32	5.17	11.45
K174	**34**	**Sa**	40.8	15.5	43.7	5.9	0.01	30	168	103	840	10.6	7.69	5.62	14.96

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K175	**34**	**Co**	34.0	17.6	48.4	5.9	0.00	16	59	86	714	10.7	6.67	5.10	13.74
K176	**34**	**Ki**	34.3	17.1	48.5	8.0	0.10	70	471	368	2425	16.4	61.55	5.46	12.84
K177	**35**	**Ti**	37.5	17.4	45.1	5.8	0.02	44	175	92	769	10.2	10.92	5.43	15.16
K178	**35**	**Ch**	38.3	16.5	45.2	5.8	0.01	50	132	84	732	10.4	8.16	5.43	13.68
K179	**35**	**Ma**	36.1	28.9	35.0	6.1	0.03	80	285	139	802	9.8	8.93	5.15	15.64
K180	**35**	**Sa**	38.4	17.1	44.5	5.8	0.01	41	112	85	654	9.4	6.51	5.11	11.89
K181	**35**	**Co**	34.0	18.2	47.9	5.7	0.00	38	111	79	581	8.9	5.89	4.85	13.06
K182	**35**	**Ki**	31.4	11.9	56.8	7.0	0.14	107	259	224	1977	12.4	58.59	5.15	14.00
K184	**36**	**Ti**	65.0	9.2	25.8	5.8	0.01	46	75	49	409	7.1	7.42	3.40	12.43
K185	**36**	**Ch**	64.0	7.6	28.4	5.5	0.05	47	68	54	479	8.1	9.57	3.98	12.05
K186	**36**	**Ma**	59.7	8.8	31.4	6.2	0.02	55	148	113	700	9.3	12.02	4.11	9.81
K187	**36**	**Sa**	60.2	9.2	30.6	5.8	0.01	43	89	63	571	9.3	10.10	4.47	10.99
K188	**36**	**Co**	61.7	8.6	29.7	5.6	0.00	18	42	45	403	7.6	7.55	4.08	11.00
K189	**36**	**Ki**	61.5	8.6	29.8	5.9	0.01	15	73	107	564	7.8	28.22	4.00	10.91
K190	**37**	**Ti**	22.2	23.0	54.8	5.7	0.02	18	202	129	629	9.8	5.80	7.28	14.14
K191	**37**	**Ch**	22.5	23.6	53.9	5.7	0.03	16	132	144	669	10.0	5.27	7.40	12.32
K192	**37**	**Ma**	22.2	23.9	53.9	6.2	0.03	25	216	175	716	10.7	5.84	7.42	14.48
K193	**37**	**Sa**	23.6	16.5	59.8	5.8	0.02	20	111	150	753	10.4	5.41	7.69	16.42
K194	**37**	**Co**	21.6	16.2	62.2	5.7	0.02	8	59	146	1002	12.1	11.52	7.36	16.59
K195	**37**	**Ki**	24.3	11.8	63.9	6.9	0.06	20	327	356	1746	15.3	29.73	6.73	16.12
K196	**38**	**Ti**	46.1	9.8	44.1	6.2	0.04	40	156	121	1246	11.5	5.16	4.79	14.99
K197	**38**	**Ch**	46.3	9.0	44.7	6.3	0.04	65	229	125	1409	13.2	6.41	4.82	15.21
K198	**38**	**Ma**	45.8	11.3	42.8	6.3	0.03	26	160	136	1161	10.6	5.08	5.31	13.16
K199	**38**	**Sa**	45.5	9.2	45.3	6.5	0.04	37	180	163	1281	11.5	5.90	4.61	13.68
K200	**38**	**Co**	55.6	7.9	36.6	6.1	0.02	44	93	108	1284	12.1	5.24	4.37	13.98
K201	**38**	**Ki**	57.4	7.1	35.5	7.6	0.14	128	500	401	2803	18.6	41.27	6.29	18.65
K202	**39**	**Ti**	57.4	5.7	36.9	6.1	0.03	74	214	108	985	11.5	6.33	3.30	14.97
K203	**39**	**Ch**	58.6	6.0	35.4	5.7	0.02	68	132	74	742	10.4	4.15	3.02	14.27
K204	**39**	**Ma**	57.4	5.0	37.6	5.7	0.02	85	178	101	753	10.8	5.34	4.04	15.10

LabID	Site No.	Trt	Sand	Clay	Silt	pH	EC	P	K	Mg	Ca	CEC	Zn	Cu	S
K205	**39**	**Sa**	57.7	8.9	33.4	5.6	0.01	55	127	69	568	9.4	6.92	3.31	14.59
K206	**39**	**Co**	57.6	6.9	35.5	5.8	0.01	50	79	63	602	10.6	4.31	3.05	15.87
K207	**39**	**Ki**	62.9	4.3	32.9	7.2	0.23	198	687	315	1933	14.1	78.22	3.43	20.86
K208	**40**	**Ti**	50.4	8.8	40.8	6.3	0.03	26	71	134	1591	13.8	9.70	4.81	12.23
K209	**40**	**Ch**	50.0	8.5	41.5	6.4	0.03	18	72	136	1862	13.9	12.02	5.36	13.95
K210	**40**	**Ma**	45.3	12.0	42.8	5.8	0.03	42	104	132	946	11.2	8.91	5.27	14.14
K211	**40**	**Sa**	45.9	9.9	44.2	5.9	0.03	57	112	123	1061	12.3	10.14	4.93	14.70
K212	**40**	**Co**	46.9	9.1	44.0	6.0	0.03	34	138	140	1159	12.4	8.23	5.30	15.04
K213	**41**	**Ti**	38.3	12.9	48.8	5.9	0.01	39	109	127	960	12.4	6.86	4.63	14.50
K214	**41**	**Ch**	38.8	10.2	51.0	6.0	0.01	26	105	146	936	11.3	7.16	4.98	14.27
K215	**41**	**Ma**	38.2	12.6	49.3	5.9	0.02	40	143	123	917	9.9	8.80	5.31	15.56
K216	**41**	**Sa**	39.1	12.2	48.7	6.1	0.02	54	225	177	1057	12.4	11.26	4.95	14.48
K217	**41**	**Co**	39.4	11.4	49.2	6.4	0.02	19	148	187	1304	13.0	6.77	5.42	13.07
K218	**41**	**Ki**	44.8	9.8	45.5	7.3	0.12	79	345	416	1851	13.6	22.12	5.04	16.99
K219	**42**	**Ti**	65.0	7.3	27.7	6.1	0.01	29	168	88	1354	13.6	6.51	3.93	13.66
K220	**42**	**Ch**	64.6	6.4	28.9	5.9	0.02	47	153	106	1429	14.1	7.66	3.53	13.85
K221	**42**	**Ma**	63.3	8.1	28.6	6.1	0.01	54	101	92	1724	15.9	8.63	4.55	15.01
K222	**42**	**Sa**	62.9	11.9	25.2	6.0	0.01	32	92	92	1688	16.3	9.22	4.16	14.02
K223	**42**	**Co**	61.9	11.1	27.0	6.2	0.00	16	137	101	1447	14.1	6.26	3.89	13.07
K224	**42**	**Ki**	60.6	9.6	29.8	6.1	0.04	19	216	134	1702	15.3	11.11	2.81	16.20
K225	**43**	**F**	49.1	10.7	40.2	6.5	0.05	13	111	509	2411	20.5	8.41	3.95	15.27
K226	**43**	**F**	21.5	15.5	63.0	6.1	0.07	6	60	368	2443	21.1	14.70	6.71	17.72
K227	**43**	**F**	23.3	17.3	59.4	6.6	0.07	5	77	410	2608	19.5	11.05	5.52	13.42

C.3. Biological, Physical and Yield Data from Farm and Forest Fields/Samples

Abbreviations used for Column Headings

LabID	Identification label given to sample in soil health lab
Site Type	Type of site, either cultivated (C, Farm) or non-cultivated (N, Forest)
Trt	Treatment (Co = control, Ma = manure, Ti = Tithonia, Sa = sawdust, Ki = kitchen garden, F = forest)
LOI	% total organic matter by loss on ignition at 350^{o}C
ActC	Active carbon in mg/kg of soil
AWC	available water capacity in m^3/m^3
WSA	% water stable aggregates
PR15	highest penetration resistance in 0- 15cm in kPa
PR45	highest penetration resistance in 15-45cm in kPa
Y_T07	Total biomass yield (t/ha), oven dry basis 2007
Y_S07	Stover yield (t/ha), oven dry basis 2007
Y_G07	Grain yield (t/ha), oven dry basis 2007
Y_T05	Total biomass yield (t/ha), oven dry basis 2007
Y_S05	Stover yield (t/ha), oven dry basis 2007
Y_G05	Grain yield (t/ha), oven dry basis 2007

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K1	**1**	**Ti**	5.72	411	0.13	76	359	2299	6.11	1.79	4.32	12.78	8.14	3.78
K2	**1**	**Ch**	6.18	311	0.12	74	383	1999	7.26	3.06	4.21	8.17	5.03	2.37
K3	**1**	**Co**	6.06	377	0.13	71	328	2041	2.83	0.70	2.12	8.76	4.67	3.02
K4	**1**	**Ma**	6.42	385	0.15	74	427	1879				14.54	7.67	5.57
K5	**1**	**Sa**	6.34	332	0.13	78	369	2224	5.21	3.56	1.66	11.99	8.61	2.66
K6	**1**	**Ki**	6.50	529	0.12	80	207	2706						
K7	**1**	**Ti**	7.17	572	0.14	73	569	2103	8.72	5.26	3.46	25.96	16.40	8.04
K8	**1**	**Ch**	7.41	531	0.16	77	445	2137	7.82	5.76	2.06	16.62	9.74	5.74
K9	**1**	**Co**	6.36	402	0.14	69	534	1655	3.70	3.28	0.42	12.83	7.23	4.57
K10	**1**	**Ma**	6.91	512	0.15	76	552	2654				18.53	10.60	6.53
K11	**1**	**Sa**	7.34	533	0.15	78	569	2189	5.77	3.65	2.12	16.94	10.16	5.68
K12	**1**	**Ki**	8.38	593	0.11	89	810	2448						
K13	**1**	**Ti**	5.85	356	0.12	67	500	2379				17.15	10.34	5.85
K14	**1**	**Ch**	6.12	286	0.10	67	552	2361				16.57	10.19	5.31
K15	**1**	**Co**	5.71	243	0.18	61	410	2137				10.62	5.83	3.92
K16	**1**	**Ma**	5.87	517	0.14	68	365	2258				13.40	7.57	4.64
K17	**1**	**Sa**	5.60	287	0.13	69	321	1965				10.45	5.93	3.53
K18	**1**	**Ki**	6.70	473	0.14	74	300	2017						
K19	**1**	**Ti**	3.39	85	0.15	38	710	2206	8.06	3.84	4.22	12.87	6.52	5.23
K20	**1**	**Ch**	3.34	24	0.14	43	307	1999	7.79	6.32	1.47	8.06	3.33	3.95
K21	**1**	**Ma**	3.44	162	0.16	43	703	2282				7.53	3.23	3.59
K22	**1**	**Sa**	3.36	150	0.14	46	255	2372	3.50	2.68	0.82	1.75	1.23	0.41
K23	**1**	**Co**	3.80	88	0.14	37	217	2427	3.16	1.52	1.64	3.46	2.44	0.76
K24	**1**	**Ki**	5.26	431	0.14	62	159	1413						
K25	**1**	**Ti**	2.57	109	0.09	25	269	1655	9.96	4.90	5.06	18.50	7.56	9.53
K26	**1**	**Ch**	2.63	86	0.09	28	276	1741	5.42	2.74	2.68	10.00	4.09	4.89
K27	**1**	**Ma**	2.80	153	0.11	27	328	1500				13.86	6.24	6.09
K28	**1**	**Sa**	2.56	95	0.11	21	124	1379	3.95	3.26	0.69	11.30	5.33	5.11
K29	**1**	**Co**	2.49	50	0.09	22	479	1896	2.65	1.35	1.31	10.90	5.16	4.61

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K30	**1**	**Ki**	2.70	256	0.09	48	193	1965						
K31	**1**	**Ki**	3.21	277	0.11	49	341	1279						
K32	**1**	**Ch**	3.74	193	0.13	26	103	1534	13.69	8.51	5.18	12.17	5.71	5.44
K33	**1**	**Ma**	3.68	184	0.13	31	138	1613				15.30	7.40	6.67
K34	**1**	**Sa**	3.35	73	0.13	39	110	1765	17.11	10.17	6.94	14.12	7.11	5.92
K35	**1**	**Co**	3.18	52	0.14	29	224	1327	3.49	1.85	1.64	14.57	7.87	5.56
K36	**1**	**Ti**	3.44	266	0.14	43	103	1238	12.75	6.34	6.42	13.23	6.51	5.61
K37	**1**	**Ti**	7.64	386	0.12	87	221	827	10.77	8.35	2.42	22.27	13.65	7.39
K38	**1**	**Ch**	7.70	414	0.13	85	234	827	9.84	8.60	1.24	13.51	8.55	4.36
K39	**1**	**Ma**	7.64	426	0.12	84	186	879				16.97	10.43	5.78
K40	**1**	**Sa**	7.75	405	0.13	79	131	896	5.11	2.67	2.44	5.64	4.07	1.30
K41	**1**	**Co**	5.93	228	0.10	86	162	707	4.72	3.51	1.21	14.09	7.97	5.52
K42	**1**	**Ki**	7.37	528	0.13	81	76	693						
K43	**1**	**Ti**	4.52	322	0.10	67	207	827	2.35	2.32	2.53	12.53	5.42	5.97
K44	**1**	**Ch**	4.99	289	0.08	67	190	948	11.47	8.18	3.29	16.69	10.02	5.62
K45	**1**	**Ma**	4.70	304	0.10	66	103	931				17.17	9.01	6.80
K46	**1**	**Sa**	4.92	338	0.08	66	97	965	13.45	9.21	4.24	14.69	8.28	5.49
K47	**1**	**Co**	6.08	370	0.08	70	124	948	5.46	4.55	0.91	12.59	7.23	4.28
K48	**1**	**Ki**	6.36	490	0.09	81	145	776						
K49	**1**	**Ti**	4.80	263	0.09	47	331	914				11.40	7.12	3.48
K50	**1**	**Ch**	4.75	248	0.10	57	255	862				7.28	4.64	2.13
K51	**1**	**Ma**	4.33	255	0.08	52	241	1017				13.91	9.04	3.90
K52	**1**	**Sa**	4.53	238	0.09	58	369	931				7.98	4.01	3.36
K53	**1**	**Co**	5.63	353	0.12	50	200	793				11.63	7.96	3.09
K54	**1**	**Ki**	5.57	440	0.10	62	83	1103						
K55	**1**	**Ti**	7.14	413	0.13	59	90	1069	6.51	4.60	1.91	8.14	3.44	3.94
K56	**1**	**Ch**	6.76	385	0.12	58	162	1017	8.88	6.54	2.33	14.67	8.13	5.54
K57	**1**	**Co**	6.73	371	0.15	48	124	983				4.83	1.88	2.49
K58	**1**	**Ma**	6.43	350	0.12	60	193	1517				12.44	6.79	5.00

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K59	**1**	**Sa**	5.48	273	0.12	44	110	1051	2.68	1.72	0.96	6.00	3.77	1.96
K60	**1**	**Ki**	5.98	381	0.14	56	69	534						
K61	**1**	**Ti**	7.40	411	0.14	64	76	1189	9.94	7.93	2.02	5.09	2.32	2.30
K62	**1**	**Ch**	7.50	436	0.14	63	97	1224	8.16	5.72	2.44	7.36	4.66	2.22
K63	**1**	**Co**	7.17	380	0.12	64	90	1069	1.51	0.83	0.69	8.86	5.55	2.73
K64	**1**	**Ma**	7.49	425	0.14	67	69	1120				11.08	6.77	3.64
K65	**1**	**Sa**	7.15	363	0.14	58	69	965	11.57	7.88	3.68	11.06	6.84	3.61
K66	**1**	**Ki**	7.69	388	0.13	69	97	983						
K67	**1**	**Co**	12.64	607	0.15	83	283	2082						
K68	**1**	**Ki**	13.56	1020	0.18	81	431	2234						
K69	**1**	**Co**	11.56	667	0.14	81	197	1334						
K70	**1**	**Ki**	11.08	804	0.16	75	265	1562						
K71	**1**	**Ti**	10.18	712	0.14	73	145	1110				15.81	12.25	2.95
K72	**1**	**Ch**	10.56	528	0.14	80	269	1569				13.04	8.23	3.86
K73	**1**	**Ma**	9.41	570	0.13	78	145	1213				16.27	10.04	5.23
K74	**1**	**Sa**	9.89	542	0.13	82	207	1351				11.95	7.52	3.82
K75	**1**	**Co**	9.40	458	0.13	74	159	1265					5.25	
K76	**1**	**Co**	8.47	657	0.10	81	117	845						
K77	**1**	**Ki**	9.51	482	0.10	96	396	1196						
K78	**1**	**Ti**	11.74	914	0.13	77	193	1086	12.92	11.53	1.39	14.24	7.19	5.95
K79	**1**	**Ch**	12.27	830	0.13	79	97	845	12.87	8.72	4.15	22.60	13.29	7.91
K80	**1**	**Co**	11.41	717	0.12	75	69	1172	7.42	3.67	3.75	13.62	6.89	5.56
K81	**1**	**Ma**	11.23	749	0.12	80	169	1286				19.38	11.99	6.20
K82	**1**	**Sa**	11.37	840	0.13	83	152	1055	18.29	11.62	6.67	13.34	6.70	5.65
K83	**1**	**Ki**	11.90	870	0.13	78	169	1155						
K84	**1**	**Ti**	10.51	777	0.14	69	179	1148				23.00	12.65	8.67
K85	**1**	**Ch**	10.00	864	0.17	76	355	1224				19.91	11.92	6.89
K86	**1**	**Co**	9.99	938	0.20	62	145	948				20.67	9.34	9.69
K87	**1**	**Ma**	11.00	920	0.20	67	179	983				16.13	7.52	7.23

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K88	**1**	**Sa**	11.96	1225	0.24	64	231	931				14.62	8.31	5.34
K89	**1**	**Ki**	10.64	955	0.22	71	97	1189						
K90	**1**	**Ti**	11.55	879	0.20	75	172	1172	16.26	8.21	8.05	26.11	16.94	7.49
K91	**1**	**Ch**	9.58	925	0.21	68	345	1241	19.68	11.77	7.90	16.31	9.35	5.70
K92	**1**	**Co**	13.08	947	0.23	74	83	1034	9.44	5.61	3.83	17.32	8.50	7.52
K93	**1**	**Ma**	12.14	803	0.19	72	190	1103				19.80	12.04	6.47
K94	**1**	**Sa**	10.98	887	0.23	78	238	1207	11.57	10.56	1.01	19.05	12.11	5.42
K95	**1**	**Ki**	8.44	530	0.17	86	276	1000						
K96	**19**	**F**	9.79	869	0.18	86	241	793						
K97	**19**	**F**	16.59	876	0.20	97	328	1155						
K98	**19**	**F**	15.66	933	0.19	99	214	1176						
K99	**20**	**F**	20.87	872	0.20	95	276	1544						
K100	**20**	**F**	16.37	820	0.20	97	379	1507						
K101	**20**	**F**	19.76	1306	0.22	95	159	1372						
K102	**21**	**Ti**	8.89	796	0.19	59	83	758	11.80	7.23	4.57			
K103	**21**	**Ch**	9.77	685	0.18	56	69	845	16.52	7.79	8.73			
K104	**21**	**Ma**	8.25	695	0.20	62	69	724						
K105	**21**	**Sa**	8.09	732	0.21	63	69	727	16.56	9.72	6.84			
K106	**21**	**Co**	10.05	876	0.22	57	76	879	8.65	6.32	2.32			
K107	**21**	**Ki**	6.61	504	0.18	58	76	879						
K108	**21**	**Ti**	11.23	621	0.15	81	97	1251	11.23	7.98	3.25			
K109	**21**	**Ch**	11.51	535	0.16	78	69	1120	9.16	5.43	3.72			
K110	**21**	**Ma**	11.69	580	0.16	89	110	1279						
K111	**21**	**Sa**	11.61	589	0.16	83	110	1176	7.19	5.30	1.89			
K112	**21**	**Co**	11.84	624	0.15	79	97	965	4.62	3.33	1.29			
K113	**21**	**Ki**	16.35	1048	0.22	89	303	1234						
K114	**21**	**Ti**	12.91	871	0.18	74	90	1189	10.11	8.46	1.65			
K115	**21**	**Ch**	10.47	697	0.18	68	145	1172	14.14	10.12	4.02			
K116	**21**	**Ma**	12.57	968	0.18	79	83	1017						

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K117	**21**	**Sa**	12.99	989	0.19	79	69	1051	13.98	9.31	4.67			
K118	**21**	**Ki**	13.92	817	0.19	84	76	638						
K119	**21**	**Ti**	10.01	850	0.20	74	76	931						
K120	**21**	**Ch**	10.48	948	0.19	65	83	983						
K121	**21**	**Ma**	9.62	824	0.18	72	76	603						
K122	**21**	**Sa**	10.19	787	0.20	72	103	638						
K123	**21**	**Co**	11.39	942	0.22	68	76	621						
K124	**21**	**Ti**	9.49	904	0.16	75	97	810	9.96	7.40	2.56			
K125	**21**	**Ch**	9.97	863	0.19	67	131	534	9.02	5.43	3.59			
K126	**21**	**Ma**	9.76	845	0.19	77	110	621						
K127	**21**	**Sa**	10.30	931	0.23	73	110	810	7.64	4.65	2.99			
K128	**21**	**Co**	10.84	991	0.22	72	83	517	6.40	4.15	2.24			
K129	**21**	**Ki**	6.90	579	0.21	43	124	1155						
K130	**21**	**Ti**	13.10	1006	0.21	75	69	603	10.87	7.63	3.24			
K131	**21**	**Ch**	14.36	1141	0.23	76	69	724	10.61	7.08	3.53			
K132	**21**	**Ma**	10.78	848	0.19	77	83	769						
K133	**21**	**Sa**	12.27	977	0.21	66	69	724	13.70	8.43	5.26			
K134	**21**	**Co**	12.42	935	0.21	67	83	631	11.36	4.49	6.86			
K135	**21**	**Ki**	14.46	1003	0.19	86	548	1431						
K136	**21**	**Ti**	7.94	445	0.15	72	90	1172	8.53	6.68	1.85			
K137	**21**	**Ch**	7.83	426	0.15	76	90	1182	10.65	8.04	2.61			
K138	**21**	**Ma**	8.00	445	0.15	78	69	1045						
K139	**21**	**Sa**	8.29	477	0.15	79	69	1086	12.04	8.91	3.13			
K140	**21**	**Co**	7.65	306	0.14	75	69	896	1.27	0.76	0.52			
K141	**21**	**Ki**	6.31	360	0.11	83	110	965						
K142	**21**	**Co**	7.82	564	0.13	67	69	1086						
K143	**21**	**Ki**	10.52	744	0.12	83	276	1655						
K144	**21**	**Ti**	7.33	494	0.14	64	97	1000	10.45	7.42	3.03			
K145	**21**	**Ch**	7.76	588	0.13	53	69	776	11.36	8.42	2.94			

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K146	**21**	**Ma**	6.37	469	0.16	67	97	1062						
K147	**21**	**Sa**	5.83	355	0.12	68	214	1069	3.62	3.12	0.51			
K148	**21**	**Co**	7.68	501	0.15	58	83	1196	6.07	4.78	1.29			
K149	**21**	**Ki**	9.79	701	0.17	75	83	965						
K150	**30**	**F**	21.18	1100	0.17	96	83	1207						
K151	**30**	**F**	17.51	958	0.18	98	165	1327						
K152	**30**	**F**	13.51	926	0.17	87	152	765						
K153	**31**	**Ti**	4.68	323	0.11	53	186	2586						
K154	**31**	**Ch**	4.45	202	0.14	62	338	2792						
K155	**31**	**Ma**	4.33	269	0.10	58	165	2448						
K156	**31**	**Sa**	4.24	275	0.10	57	165	2827						
K157	**31**	**Co**	4.02	158	0.11	48	214	2965						
K158	**31**	**Ki**	5.23	432	0.10	60	1210	2930						
K159	**31**	**Ti**	4.67	338	0.07	74	2172	3103	5.23	3.68	1.55			
K160	**31**	**Ch**	3.99	148	0.07	68	524	2999	4.47	3.09	1.38			
K161	**31**	**Ma**	4.48	297	0.07	70	1172	3103						
K162	**31**	**Sa**	4.04	230	0.07	74	1427	3103	2.57	2.15	0.41			
K163	**31**	**Co**	3.89	202	0.08	57	221	2896	4.51	2.18	2.33			
K164	**31**	**Ki**	4.30	589	0.11	52	138	2310						
K165	**31**	**Ti**	3.97	189	0.09	56	69	1189	11.10	6.06	5.05			
K166	**31**	**Ch**	4.11	274	0.09	56	69	1569	7.90	5.21	2.68			
K167	**31**	**Ma**	4.01	235	0.08	58	83	1189						
K168	**31**	**Sa**	3.93	216	0.10	53	97	1120	6.83	4.71	2.12			
K169	**31**	**Co**	3.82	211	0.13	50	69	931	3.38	2.18	1.20			
K170	**31**	**Ki**	4.62	301	0.17	47	69	510						
K171	**31**	**Ti**	3.38	208	0.16	35	159	3068						
K172	**31**	**Ch**	3.39	170	0.16	31	165	2896						
K173	**31**	**Ma**	3.40	236	0.14	49	97	2672						
K174	**31**	**Sa**	3.20	131	0.15	50	90	2568						

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K175	**31**	**Co**	3.76	160	0.17	31	76	1034						
K176	**31**	**Ki**	4.75	343	0.15	68	331	2155						
K177	**31**	**Ti**	3.27	140	0.15	29	186	1069						
K178	**31**	**Ch**	3.41	150	0.16	36	197	1148						
K179	**31**	**Ma**	3.55	221	0.16	30	76	1062						
K180	**31**	**Sa**	3.20	119	0.16	27	103	1151						
K181	**31**	**Co**	3.01	128	0.17	39	69	845						
K182	**31**	**Ki**	5.38	588	0.25	39	117	845						
K184	**31**	**Ti**	2.14	50	0.11	31	103	1520						
K185	**31**	**Ch**	2.40	53	0.12	32	217	1982						
K186	**31**	**Ma**	2.75	184	0.13	42	117	1565						
K187	**31**	**Sa**	2.47	111	0.13	31	124	1503						
K188	**31**	**Co**	2.27	72	0.11	38	110	896						
K189	**31**	**Ki**	2.66	153	0.13	54	97	1172						
K190	**31**	**Ti**	4.20	216	0.21	32	69	1051						
K191	**31**	**Ch**	4.70	257	0.21	36	386	1017						
K192	**31**	**Ma**	4.23	328	0.20	31	124	1062						
K193	**31**	**Sa**	4.37	277	0.22	31	138	1200						
K194	**31**	**Co**	5.13	320	0.22	25	69	445						
K195	**31**	**Ki**	6.28	576	0.22	57	138	603						
K196	**31**	**Ti**	3.96	413	0.20	33	69	2086						
K197	**31**	**Ch**	3.95	421	0.21	36	83	896						
K198	**31**	**Ma**	3.42	348	0.20	26	110	1920						
K199	**31**	**Sa**	3.94	381	0.20	34	110	1758						
K200	**31**	**Co**	3.27	328	0.16	24	69	879						
K201	**31**	**Ki**	5.47	649	0.18	52	469	2827						
K202	**31**	**Ti**	3.79	245	0.17	44	179	1800	11.06	7.30	3.76			
K203	**31**	**Ch**	3.70	230	0.17	34	541	2258	6.83	4.71	2.12			
K204	**31**	**Ma**	3.28	179	0.18	36	138	2413						

LabID	Site No.	Trt	LOI	ActC	AWC	WSA	PR15	PR45	Y_T07	Y_S07	Y_G07	Y_T05	Y_S05	Y_G05
K205	**31**	**Sa**	3.23	199	0.17	32	124	1879	3.38	3.05	0.34			
K206	**31**	**Co**	3.31	170	0.17	28	165	1737	5.26	3.33	1.93			
K207	**31**	**Ki**	5.56	600	0.20	67	131	3103						
K208	**31**	**Ti**	4.40	506	0.20	35	138	1276	8.80	8.53	0.27			
K209	**31**	**Ch**	4.17	520	0.20	36	110	1448	11.22	7.08	4.15			
K210	**31**	**Ma**	3.71	243	0.19	33	76	1982						
K211	**31**	**Sa**	3.89	297	0.21	28	176	2344	9.91	6.83	3.08			
K212	**31**	**Co**	4.09	303	0.22	33	128	1810	4.38	3.48	0.91			
K213	**31**	**Ti**	4.32	304	0.24	30	152	2810						
K214	**31**	**Ch**	4.09	228	0.22	38	83	2275						
K215	**31**	**Ma**	4.11	241	0.22	25	69	2293						
K216	**31**	**Sa**	4.38	341	0.21	31	131	2413						
K217	**31**	**Co**	4.23	355	0.23	33	69	1000						
K218	**31**	**Ki**	6.30	662	0.22	74	138	1913						
K219	**31**	**Ti**	3.80	232	0.13	40	69	762	3.11	1.71	1.39			
K220	**31**	**Ch**	3.96	255	0.15	48	69	793	2.97	1.03	1.93			
K221	**31**	**Ma**	4.44	346	0.14	42	69	672						
K222	**31**	**Sa**	4.33	386	0.15	46	69	555	0.39	0.22	0.17			
K223	**31**	**Co**	3.78	214	0.14	41	69	603	1.98	1.30	0.68			
K224	**31**	**Ki**	5.06	404	0.18	54	69	776						
K225	**43**	**F**	7.81	671	0.24	75	131	741						
K226	**43**	**F**	9.46	724	0.26	78	193	1072						
K227	**43**	**F**	8.79	590	0.22	87	272	1034						

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