Sustainability **2015**, *7*, 6523-6552; doi:10.3390/su7066523

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Review

The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions

Katherine Tully [1,2,*], Clare Sullivan [2], Ray Weil [3] and Pedro Sanchez [2]

[1] Department of Plant Science and Landscape Architecture; University of Maryland, College Park, Maryland, MD 20742, USA

[2] Agriculture and Food Security Center, Earth Institute at Columbia University, Palisades, NY 10964, USA; E-Mails: csullivan@ei.columbia.edu (C.S.); psanchez@ei.columbia.edu (P.S.)

[3] Department of Environmental Science and Technology; University of Maryland, College Park, Maryland, MD 20742, USA; E-Mail: rweil@umd.edu

* Author to whom correspondence should be addressed; E-Mail: kltully@umd.edu; Tel.: +1-301-405-1469; Fax: +1-301-314-9306.

Academic Editor: Marc A. Rosen

Received: 4 February 2015 / Accepted: 5 May 2015 / Published: 26 May 2015

Abstract: The primary cause of soil degradation in sub-Saharan Africa (SSA) is expansion and intensification of agriculture in efforts to feed its growing population. Effective solutions will support resilient systems, and must cut across agricultural, environmental, and socioeconomic objectives. While many studies compare and contrast the effects of different management practices on soil properties, soil degradation can only be evaluated within a specific temporal and spatial context using multiple indicators. The extent and rate of soil degradation in SSA is still under debate as there are no reliable data, just gross estimates. Nevertheless, certain soils are losing their ability to provide food and essential ecosystem services, and we know that soil fertility depletion is the primary cause. We synthesize data from studies that examined degradation in SSA at broad spatial and temporal scales and quantified multiple soil degradation indicators, and we found clear indications of degradation across multiple indicators. However, different indicators have different trajectories—pH and cation exchange capacity tend to decline linearly, and soil organic carbon and yields non-linearly. Future research should focus on how soil degradation in SSA leads to changes in ecosystem services, and how to manage these soils now and in the future.

Keywords: soil degradation; sub-Saharan Africa; baselines; indicators; sustainability; resilience

1. New Perspectives for Examining Soil Degradation in Sub-Saharan Africa

Soil degradation is a major global problem, the effects of which may be felt most strongly in developing countries where large proportions of the population reap their livelihoods directly from the soil. In this review, we will focus on soil degradation in sub-Saharan Africa (SSA), where declines in crop productivity have been linked to hunger and poverty [1,2]. While the reality of hunger in SSA is undeniable, the nature and extent of soil degradation, and the role it plays in the vicious cycle of poverty, is still under debate [3]. Across SSA, 75 percent of the population depended on subsistence farming at the end of the last century [4,5]. Livelihoods are diversifying [6] and urbanization is on the rise [7], but in the near-term, soils in SSA must currently sustain a largely subsistence population. Using the Brundtland Commission's definition of "sustainability", sustainable soils meet the needs of present populations without preventing future generations from meeting their needs [8]; thus, soil degradation can be defined in contrast to this, as the processes by which soils can no longer maintain the provisioning, supporting and regulating ecosystem services required by current and future generations. In order to reverse soil degradation, it is critical to understand the factors that affect the stability and resilience of soils.

Unfortunately, there are few data on soil degradation across SSA, so rigorous assessment frameworks are lacking to guide research on the topic. In this review, we will highlight the handful of studies that have evaluated soil degradation in SSA in a comprehensive way by clearly defining the (1) temporal and (2) spatial scale of analysis and (3) examining multiple degradation indicators. We then provide a description of useful methods for measuring degradation in remote regions. Finally, we will provide a brief overview of practices that may reverse soil degradation in SSA.

1.1. Time Horizons

Long-term data are crucial for evaluating soil degradation, as a snapshot of soil properties can be misleading. Soil phosphorus (P) levels in tropical forests, for example, can fluctuate within a day [9], year [10], and across centuries [11,12]. Capturing one point in time could incorrectly suggest soil P depletion or P surplus. Humans can drive change in soils. Their activities, such as farmer management practices, play a large role in soil degradation and may vary greatly between seasons and across years [13,14]. Thus, longitudinal studies that follow specific sites for years provide the most reliable data on the changes in soil properties over long time scales. Unfortunately, longitudinal studies require continuity of access to study sites, funding, and infrastructure. While difficult to secure in any region, this is especially true in SSA, where land tenure, political systems, and local markets are frequently unstable, and there has been low and inconsistent investment in national universities and research institutions.

Chronosequences are often used in place of longitudinal studies and substitute space for time. A primary assumption of chronosequence studies, with respect to soil degradation, is that the soil properties at sites characterized by different times since conversion to agriculture were initially the same when under natural vegetation. This approach further assumes that differences among these sites represent the trajectory of change in soil properties during periods of cultivation. While this approach can be useful, it is limited by (1) the fact that farmers tend to clear the best land first; (2) ability to find sites that have similar soil textures and horizon structures; and (3) selection of an appropriate benchmark or baseline site. We will examine a number of chronosequences to evaluate and contextualize their findings.

In order to understand the extent of soil degradation in SSA, we need clear baselines from which to examine the differences in physical and chemical properties. Studying fossil plants (e.g., pollen grains and macrofossils) allows scientists to reconstruct the history of forest loss [15], and river sediments to provide insights into erosion rates over several centuries [16]. Still, there is a paucity of data on early forest cover and practically no data on historical soil fertility in SSA (even from this last century). Appropriate selection of a baseline or reference state is particularly crucial for any study on degradation. When a forest becomes a farm, a land use shift occurs, and suddenly, the controls on ecosystem structure and function change as the system settles into a different state (stability domain) [17,18]. For example, monitoring the system on any stable branch before or after the switch would lead one to conclude that little change occurred, but monitoring during the rapid state change might suggest "catastrophic" losses in SOC [17]. Thus resilience, like soil degradation, must be evaluated over a long time period in order to observe the ability or inability of the ecosystem to continue to perform its desired functions when confronted with stress or external shocks [19].

Sub-Saharan Africa itself underwent a major land use change about 3000 years ago when much of the Central African rainforest was rapidly replaced by savannas. Though often linked to climate change, recent evidence suggests that the transformation may have been related to a major population expansion of the Bantu people across Central Africa, which led to the clearance of vast swaths of land for shifting cultivation and charcoal production [20]. Such strong ecosystem shifts indicate that ecosystem resilience itself can be changed or degraded by both natural and human forcings. At the same time, the persistence of ecosystems and societies suggests that resilient systems must be adaptive systems [21,22]. The resilience conceptual framework is particularly useful for evaluating soil degradation in SSA as both degradation and resilience must be evaluated within its spatial, temporal, economic, environmental, and cultural context [23].

1.2. Spatial Scales

Sub-Saharan Africa is an enormous region of 24.6 million km^2, with a huge range of soil and land management types [24]. The predominant soils (Table 1) are Arenosols (21.5%), Cambisols (10.8%), and Ferralsols (10.4%), and Leptosols (17.5%). The type and degrees of soil constraints vary widely. Nearly 40% of soils in SSA are low in nutrient capital reserves (<10% weatherable minerals), 25% suffer from aluminum toxicity, and 18% have a high leaching potential (low buffering capacity; [25]; Table 3). A region's initial soil fertility will affect the extent of soil degradation—with regions of low soil fertility degrading more quickly than regions with higher natural soil fertility. If (plant-available) soil nutrient stocks are initially high, the process of nutrient depletion can take a long time, but the absolute amount of nutrients lost will be high. However, if nutrient stocks are low to begin with, this process can reach critical levels within a few years. Further, inherent soil properties will play a large role in resilience and sustainability of a particular land use (e.g., how long continuous agriculture remains productive). For example, anion exchange capacity in subsoils will affect the ability of soils to retain and efficiently recycle nutrients (in particular, anions like NO_3^-; [26,27]). These subsoil properties are highly spatially variable [28,29] and often ignored in soil degradation studies—only two out of 18 studies in Table 4 reported subsoil properties.

Table 1. Distribution of soil types in Africa based on the Harmonized World Soil Database. Modified from [24].

	Million ha in Africa	Percent of Land in Africa *
Acrisol	87.8	2.9
Alisols	20.3	0.7
Andosols	4.0	0.1
Arenosols	650.3	21.5
Chernozems	1.0	<0.1
Calcisols	161.0	5.3
Cambisols	325.4	10.8
Durisols	0.9	<0.1
Fluvisols	82.2	2.7
Ferralsols	312.4	10.3
Gleysols	52.5	1.7
Gypsisols	37.5	1.2
Histosols	4.4	0.1
Kastanozems	2.7	0.1
Leptosols	530.0	17.5
Luvisols	105.1	3.5
Lixisols	126.8	4.2
Nitisols	60.4	2
Phaeozems	12.1	0.4
Planosols	27.7	0.9
Plinthosols	146.1	4.8
Podzols	2.9	0.1
Regosols	93.5	3.1
Solonchaks	32.6	1.1
Solonets	36.0	1.2
Stagnosols	0.5	<0.1
Technosols	0.0	<0.1
Umbrisols	5.6	0.2
Vertisols	102.0	3.4

* Note that percentages do not add up to 100% as soil may be affected by multiple soil modifiers.

Soil degradation occurs at multiple scales: a farm field (individual), a farming community (social system), or landscape (biophysical system). There is no single scale at which it must be studied, but it is critical that the chosen spatial scale of analysis can encompass the type of soil degradation being described. For example, the presence of gullies in farms is usually indicative of a change in land use upstream (at the head of the watershed) such as heavy grazing or excessively mechanized agriculture, which leads to erosion or contamination downstream [30]. In SSA, this raises some interesting cultural concerns, because uplands and foothills will surely be managed by different households (landholdings are small in SSA). In some cases, neighboring areas are managed by different ethnic groups, with pastoralists of one ethnic group grazing cattle upslope from agriculturalists of a different ethnic group. Clearly, solving landscape-level erosion issues requires community cooperation across agroecological zones that may cross ethnic and cultural lines.

Most studies in the literature compare and contrast management practices [31–34] or examine one farming practice across different regions [5,35]. There are relatively few studies that attempt to examine soil degradation at a scale that can encompass the spatial and temporal heterogeneity of farmed landscapes in SSA. Although a great deal of soil data exists for Africa, there is little standardization in the sampling design or analytical tests conducted. The Africa Soils Information System is an example of how this situation may be remedied in the future by standardized protocols that examine change at large spatial scales through time [36].

1.3. Multiple Indicators

When evaluating soil degradation, it is important to define the particular ecosystem function, management practice, and/or livelihood outcome you are trying to sustain [19], which usually cannot be captured by one soil property or indicator. Certain soil properties may be considered “degraded” for a particular crop, but not for another [37,38]. For example, higher soil residue cover may prevent N losses during the non-growing season (good for the environment), but lead to reduced available N during the following growing season (bad for yields [39,40]). While some indicators of degradation are incontrovertible (e.g., gully formation), others are evaluated subjectively (e.g., livestock walk longer to reach water; [41]). It was this subjectivity that led to the heated debates of the 1990s surrounding soil degradation in SSA. Some studies suggested that SSA agriculture was inherently unsustainable, and indicated losses of productivity due to erosion and declines in soil fertility at continental [42,43] and global scales [44]. However, estimations of the extent and rate of degradation was limited by an overall lack of biophysical data on Africa, and thus relied heavily on estimations of one indicator (namely, erosion, which was modeled not measured) and interpolation when scaling-up to regions and countries [3]. Many refuted the claim that farmers were to blame for the increased rates of soil degradation and suggested that more attention should be paid to farmer knowledge and adaptability [45–48]. It is not the goal of this review to resolve this debate, rather, we offer a critical examination of the works that have followed in its wake. We find that even decades later, there are very few studies that have comprehensively measured soil degradation in SSA.

2. Soil Degradation in Sub-Saharan Africa

2.1. Drivers of Degradation

Sociopolitical and economic drivers determine (1) where; (2) which; and (3) how many people live in a given region. In many cases, the poorest people in SSA are pushed into unproductive lands, or areas with minimal infrastructure and accessibility [49]. One of the most extreme examples of this is Tanzania’s Ujamaa “villagization” campaign of 1973–1976, where over five million rural residents were relocated from their dispersed family homesteads into concentrated settlements [50]. The social and ecological effects of this major resettlement campaign are evinced in the replacement of fallow cycles with intensified, continuous cropping systems.

The tenure system often determines how land is managed and used and thus is often implicated as a primary driver of degradation [51,52]. For example, in smallholder systems in East Africa, investments in soil fertility are more likely when there is security in tenure or ownership [53]. For those who have tenure, policies that raise the farm-gate prices of commodities are critical means for encouraging good land management strategies since they provide farmers with both resources and incentives [48]. Smallholder farmers in SSA often operate at the economic "margin" where agricultural investments are a lower household priority than school fees, medical treatment, or funeral costs [53]. Farmer wealth and ethnicity often determines whether soil degradation can be addressed on the farm. Wealthier farmers, who have more access to resources, are better equipped to cope with soil degradation [54].

Gender roles have direct input on household foods security and nutritional levels [55]. Men are often forced to seek jobs in urban areas leaving women to tend to the land, but without the primary decision-making power. Women and men also tend to invest differently in soil fertility management, with women more likely to adopt organic amendments like manure and men more likely to purchase mineral fertilizer [56]. Population density in farming communities will also have a large impact, either positive or negative, on degradation potential. High population density usually means little land available for rotation into natural vegetation fallow. However, low population density may result in labor shortages and long distance from homestead to fields. Labor shortage is a primary reason why labor-intensive conservation measures have low adoption rates in many regions of SSA [57].

2.2. Types of Degradation in Sub-Saharan Africa

Soils can be altered physically, chemically, or biologically as the result of natural processes (Table 2). For example, soil itself forms over millennia through physical and chemical weathering of rocks (morphogenesis/soil formation). Wind erosion shifts the dunes in sparsely vegetated deserts, and transports dust to other continents. Humans, however, are accelerating many of these natural processes, causing the degradation of soils.

Physical degradation can occur when excessive soil tillage breaks down soil aggregates; thus rapidly decomposing organic matter, loosening the soil in excess and making it vulnerable to wind and water erosion. Cultivation on steep slopes, clearing of vegetation (especially leaving land bare between cultivation cycles), and poorly managed grazing are the primary factors accelerating soil erosion in SSA [58]. High rates of topsoil loss contribute to downstream sedimentation and degradation of local and regional water bodies. For example, in Tigray, Ethiopia, reservoirs designed to improve water access with a 20-year lifespan, lost half of their storage capacity in only five years due to sedimentation [59]. Tillage itself—independent of wind and water—also moves a great deal of soil downslope. This is especially evident on steep, short slopes where hand or animal traction tillage moves the soil preferentially in the easier downslope direction [60]. Poorly managed grazing in pastureland can also contribute significant amounts of sediment downstream [61]. Poor management of both grazing and tillage can lead to compaction of surface or subsurface soil layers [62], and in turn to reduced infiltration [63].

Table 2. Major types of soil degradation and the conditions under which they are most commonly found. Although the table separates physical, chemical and biological degradation, in reality soils are complex systems in which these processes interact and influence one another. The first three processes listed, erosion by water, wind and tillage, together dominate soil degradation on the vast majority of land area degraded. (Modified from [64]).

Category	Specific degradation processes	State factors		Socioeconomic drivers
		Parent material and topography	Climate	
Physical	Soil erosion by water	Slope	Humid to semi-arid regions	Tillage agriculture, deforestation and improper grazing
	Soil erosion by wind	Less vegetation	Semi-arid to arid regions	Disturbance of soil, vegetation or bio-crust by agricultural tillage and poorly-managed grazing
	Soil erosion by tillage	Hilly landscapes		Continuous cultivation, especially with tillage
	Surface sealing	Low organic matter sandy or silty soils		Urbanization, compaction, tillage
	Soil compaction	Clayey soils	Humid regions	Heavy machinery, grazing
	Reduced capacity to store water	Low organic matter		Compaction, erosion, removal of mulch or residue
Chemical	Nutrient depletion	Low inherent fertility		Low input agriculture, grazing, excessive forest harvest
	Acidification	Old, weathered soils	Humid regions	Excessive N fertilization, leaching, sulfur and nitrogen oxidation
	Dispersion/alkalization	Excessive monovalent ions, exposure and incorporation of calcareous subsoil material into surface horizon		Poor quality irrigation water, loss of perennial vegetation, tillage
	Salinization	Shallow water table	Arid to semi-arid regions	Excessive irrigation
	Toxic Contamination			Urbanization, mining, industrial waste spillage or disposal
Biological	Depletion of soil organic matter	Sandy texture, steep slopes, deep water table	High temperatures, limited rainfall	Degradation of vegetation, excessive tillage, lack of sufficient organic amendments and plant residues; excessive biomass removal by harvest, grazing or fire; erosion of sloping surface soil by tillage, wind and water
	Loss of soil biological diversity	Sandy texture, steep slopes, root limiting subsoil layers (fragipans, cemented layers, aluminum toxicity, calcic horizons)	High temperatures	Mono-cropping, deforestation and poorly managed grazing
	Loss of plant, animal and microbial biomass	Side slopes, shallow bedrock, root limiting subsoil layers (fragipans, cemented layers, aluminum toxicity, calcic horizons)		Reduced plant growth and subsequent addition of litter, roots and exudates limits carbon fuel for food web; exposure to extremes of dryness and temperature by removal of plant litter; destruction of macropores, aggregates and other habitat by tillage, compaction and erosion.

Unlike physical degradation, chemical soil degradation it not easily observed by the naked eye. Nutrient depletion is the primary form of soil degradation in SSA. For decades, across SSA, nutrient outputs have exceeded inputs, exhausting soil nutrient pools. Partial nutrient balances (or budgets) are typically used to describe the stocks and fluxes (ins and outs) of a soil [65]. They have been calculated for many different regions and countries [66], and are often used in Africa to evaluate management practices that promote nutrient surpluses or deficits [42,67–69]. In many SSA farming systems, certain soils suffer from nutrient depletion even if the whole farm or farming community does not. This pattern of nutrient depletion has been documented in many studies that show how nutrients are transported from "out fields" to fields near the homestead in the form of crops harvested and animal manure deposited [68,70].

Soils in SSA also suffer from declining cation exchange capacity, cation imbalances, and declining soil pH (which can lead to Al toxicity; Table 3). Secondary soil acidification can occur due to long-term application of relatively high rates of N fertilizers (mostly in South Africa) or continuous cropping without organic inputs [71]. In certain coastal area (e.g., Senegal, Gambia), lowering of the water table for crop production has led to formation of active acid sulfate soils and extreme acidity (pH < 3.5) [72]. Alkalization can also occur when perennial vegetation is lost, or when calcareous subsoil material is incorporated into the topsoil as a result of erosion or tillage [73]. Other forms of chemical degradation such as salinization, while common in other tropical soils, is less common than alkalization in SSA [74] (Table 3).

Table 3. Prevalence of soil constraints in sub-Saharan Africa based on the fertility capability soil classification (FCC) system [25,75].

Soil Constraint	Modifier	Million ha in SSA	Percent of Land in SSA *
Low nutrient capital reserves	k	942.06	39.94
Al toxicity	a	588.27	24.94
High P fixation	i	200.35	8.49
Steep sloped (>30%)	s	55.62	2.36
Poor drainage	g	159.95	6.78
High leaching potential	e	425.05	18.02
Calcareous reaction	b	158.11	6.70
Salinity	s	19.09	0.81
Alkalinity	n	52.06	2.21
Allophane	x	2.83	0.12
Shrink-swell	v	132.65	5.62
Total area		2358.79	

* Note that percentages do not add up to 100% as soil may be affected by multiple soil modifiers.

Biological degradation is closely linked to chemical degradation. Both the balance of different nutrients and their chemical forms are also important to soil fertility [76,77]. Population pressures in some countries have reduced or eliminated natural fallow periods, reducing nutrient and organic matter inputs [3,78,79] and thus causing declines in soil biological activity and soil species diversity [80–82] Reductions in organic matter can reduce porosity [83,84] and infiltration capacity and therefore change water and nutrient cycles, plant productivity, and even the energy balance of a system [85,86]. The abundance and biodiversity of soil organisms is reduced as a result of intensive grazing, biomass burning (either of crop residue or for land clearing) [87], tillage and bed preparation [88], leaving soils bare, mono-cropping, especially in maize growing areas, and excess fertilizer application [82,89]. Such changes in the soil diversity (or functional diversity) of soil biota can affect the availability of nutrients [90,91] and alter pest and disease pressure [81] as well as the complexity of food-webs [81] with consequences for ecosystem resilience.

3. Synthesis of Knowledge

While the African subcontinent is often at the nexus of discussions on soil degradation, a relatively small number of studies rigorously assess it. We define rigorous assessments as studies having:

(1) A temporal dimension, as degradation is a dynamic process;
(2) A spatial scale of analysis that is meaningful both for assessing degradation and for providing soil management recommendation for smallholder farmers; and
(3) Multiple criteria of assessment that reflect the use of the soil because degradation results from a complex set of processes and cannot be captured in a single measure.

We identified 18 studies that meet these criteria (see Table 4). We classified these studies into three groups: longitudinal studies, chronosequences, and integrated assessments.

3.1. Methods for Data Synthesis

Information on the temporal and spatial scale, indicators measured, *etc.* from each study is reported in Table 4. We also extracted data from 15 of those studies that reported soils data. We extracted data from four studies in annual crops (e.g., maize) that reported cation exchange capacity (CEC) from soils collected from 0–10 or 0–15 cm depth. In all four studies, CEC was measured at pH 5.5–7.5, and calculated by summing the base cations. Study sites had similar clay contents (~20%) and bulk densities (66 g cm^{-3}) and did not report data from an uncultivated site, thus we report raw CEC data. Thirty-year trends in soil pH are reported for red soils near Holetta Research Center, Ethiopia. These data are previously unpublished (Appendix). Soil organic carbon (SOC) data were extracted from three published studies plus unpublished data from the Holetta red soils (R. Weil; Appendix), all of which used the Walkley-Black method for SOC determination. To normalize the data from different soil types and agroecological zones, we calculated the percent SOC remaining and plotted against time since conversion. Data on maize yields were reported in tons ha^{-1} from two regions: western Kenya and southwestern Nigeria. In some cases, the farm field age was not reported, thus we used reported sampling dates and the date of forest clearance to calculate the time since forest conversion. To avoid any site or sampling bias, we plotted maize yield data separately for the two regions. When data were reported in graphical form, they were extracted using GraphClick 3.0 (Arizona Software, 2008). Figures and statistics were performed in the R statistical package [92].

Table 4. Published studies examining soil degradation across large spatial and temporal scales using multiple indicators.

Reference	Study Type	Select Indicators of Degradation: Quantitative	Select Indicators of Degradation: Qualitative	Temporal scale	Spatial scale	Baseline (Reference)	Depth	Region	Trajectory
[93]	Chrono	Particle size, Water holding capacity, SOM, Exch. Ca, Exch. K, Exch. Mg, total N, Ext. P, pH, and CEC	NA	15 years	Landscape		0–20 cm	Nigeria	Downward
[94]	Chrono	Soil spectra, total C, Exch. Mg, Exch. Ca, Exch. K, total N, pH, ECEC, Clay, Silt, and Sand	NA	100 years	Landscape	Humid tropical forest	0–20 cm	Kenya	Downward
[95]	Chrono	Total N, pH, SOM, Sand, Silt, Clay, Bulk density, Tree density, Tree species	NA	50 years	Landscape	Tropical dry Afro-montane forest (deforested/heavy harvesting)	0–100 cm	Ethiopia	Downward
[16]	Long	Soil erosion (water-induced), Sediment flux, River discharge, and Coral Ba/Ca	NA	300 years	River basin (66,800 km^2)	None	NA	Kenya	Downward
[78]	Long; Integ	Land use and land cover. Trees in fields, CEC, Exch. Ca, Exch. K, Exch. Mg, total N, Ext. P, pH, and SOC	Farmer mgmt, perception of change, veg cover	15 years (imagery); 8 years (soils)	Multi-scale (Landscape and farm field)	1981—imagery; 1988—soils	0–20 cm	Burkina Faso	Minimal change to upward (field scale), Possibly downward (landscape scale)
[96]	Long	Exch. Ca, Exch. Mg, ECEC, SOC, pH, bulk density, maize grain yield	NA	13 years	Landscape	Tropical forest	0–15 cm	Nigeria	Mixed dependent on management strategies: Decline without fallow or addition of organic input
[97]	Chrono	Total N, Ext. P, SOM, Maize biomass, Plant tissue (N, P, K, Ca, Mg, Mn, Cu and Zn), Socioeconomic survey	Crop yield, Indicator plants, Soil softness and Soil color	57 years	Landscape	Tropical dry Afromontane forest (deforested/heavy harvesting)	0–20 cm	Ethiopia	Downward (maize biomass)

Table 4. *Cont.*

Reference	Study Type	Select Indicators of Degradation		Temporal scale	Spatial scale	Baseline (Reference)	Depth	Region	Trajectory
		Quantitative	Qualitative						
[98]	Chrono	CEC (effective and potential), pH, SOC, Grain and stover yield, Plant tissue: N, P, K, Ca, and Mg	NA	100 years	Landscape	Humid tropical forest	0–10 cm	Kenya	Downward (non-linear)
[99]	Long	Land cover classes, Precipitation, Socioeconomic survey, Soil chemical properties	Incidence of soil erosion	40 years	Landscape	Baseline (1966)	NA	Tanzania	Spatially heterogeneous (Downward in some zones)
[100]	Long	CEC, Exch. Ca, Exch. K, Exch. Mg, pH, total N, Ext. P, SOC, Bulk density, Infiltration, Penetrometer resistance, Soil moisture retention, Water stable aggregates, and Yield	NA	8 years	Farm field (Field trial)		0–20 cm	Nigeria	Downward (dependent on management)
[79,101]	Chrono	Soil depth, Base Saturation, % of CEC, C:N, Exch. Ca, Exch. K, Exch. Na, Total N, Ext. P, pH, SOC, Bulk density, Particle size analysis, Pore space, 13C and 15N, carbon fractions	Qualitative land evaluation for maize	53 years	Landscape	Tropical dry Afro-montane forest (deforested/heavy harvesting)	0–20 cm; 60–70 cm, 90–100 cm	Ethiopia	Downward (C-exponential) in topsoil, C & N increase in subsoil
[102]	Chrono	Active C, CEC, Exch. Ca, EC, Exch. K, Exch. Mg, pH, Total N, Ext. P, S, SOM, Zn, Sand, Silt, Clay, Water stable aggregation (WSA), Available water capacity (AWC), Penetrometer resistance, Crop yield	NA	77 years	Landscape	Humid tropical forest	0–15 cm, 0–45 cm	Kenya	Downward in most properties, slope of trajectory less severe with better soil management

Table 4. *Cont.*

Reference	Study Type	Select Indicators of Degradation		Temporal scale	Spatial scale	Baseline (Reference)	Depth	Region	Trajectory
		Quantitative	Qualitative						
[103]	Chrono	Mineral N, P fractions, P sorption capacity, Fertilizer recovery, Maize yield, Maize nutrient concentration	NA	100 years	Landscape	Humid tropical forest	0–10 cm	Kenya	Downward trend in soil fertility; yield increased dependent on nutrient additions
[104]	Chrono	Soil C & N concentration, Isotopic signature of soil C, Infiltrability, Bulk density, Proportion of macro and micro-aggregates in soil	Crop yield estimates	120 years	Landscape	Humid tropical forest	0–15 cm	Kenya	Downward
[105]	Long	EC, Exch. K & Exch. Mg, Ext. P, pH, SOM, and Plant tissue analysis (N, P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu and Al)	NA	7 years	Sub-national	Baseline (1991)	0–15 cm	Gambia	Minimal change
[106]	Chrono	13C, Near-edge X-ray absorption fine structure, SOC,	NA	103 years (Kenya); 90 years (South Africa)	Landscape	Humid tropical forest (Kenya); Subtropical grassland (South Africa)	0–10 cm (Kenya; 0–20 cm (South Africa)	Kenya; South Africa	Downward (exponential)
[41]	Chrono; Integ	N, P, K, SOC, Woody and herbaceous species, Land cover change	Soil properties Livestock Yield, Pests, Trees	50 years (soil); 15 years (imagery)	Landscape	Grass strips adjacent to fields	NA	Botswana and Swaziland	Downward
[107]	Chrono	CEC, Exch. Ca, Exch. K, Exch. Mg, pH, total N, Ext. P, SOC, Clay, Silt, SFI, Surface reflectance, Soil spectra	Soil quality - poor, average, good	50 years	Landscape	Rainforest	0–20 cm	Madagascar	Downward

3.2. Longitudinal Studies

We identified six studies that go beyond the traditional long-term trials to examine soil degradation in SSA. In sum, these studies indicate that rates of soil degradation vary through time (are non-linear) and that not all indicators behave the same way. The longest study is the best example of this, which uses coral barium to calcium ratios from the Malindi reef to evaluate sediment transport (erosion) from the Sabaki river basin in Kenya [16]. Sediment flux was relatively low and consistent from 1700 to 1905, but rises after 1905, corresponding to the start of British settlement and land clearing, and periodic spikes that can be traced back to historical changes in land management. This study clearly shows that picking one point (or a small portion) along the timeline does not capture the dynamics of soil degradation. While a study in Nigeria showed steady declines in pH, soil organic carbon (SOC), and available P (over eight years; [100]), a similar study in Gambia (over 1159 fields) showed no changes in any of those soil properties (over six years) [105]. Seemingly conflicting results may be due to the fact that sites are at different points along a non-linear curve. For example, a 13-year study in Nigeria showed non-linear trends in many indicators, with SOC and maize yields declining in the first seven years of the study (similar to [100]), and reaching a steady state for the remainder of the study (similar to [105]; Figure 1d). On the other hand, soil pH, exchangeable calcium and magnesium, and effective CEC all declined linearly with each year of continuous cultivation [96]; Figure 1a,c). A final study showed different conclusions about degradation could be drawn from different indicators. The comparison of land-cover maps for the Monduli District in northeast Tanzania showed a 94% increase in agricultural, but only a 16% decline in vegetation between the 1960s and the 1990s. Using only one of these indicators would easily lead one to different conclusions regarding the extent of degradation. Between the 1991 and 1999, however, was the rapid increase (by almost 1700%) in the presence of gullies and bare land, (equivalent to 1400 ha per year across 400,000 ha [99]).

3.3. Chronosequences (Space-for-Time)

Chronosequences are the most common method for studying soil degradation. Typically, forests are used as the baseline, with only the upper few cm of soil considered. Thus, cultivated soils almost always appear degraded in comparison. Most of the studies were located in the same region using Kenya's Kakamega and Nandi forests as the baseline and measured soil properties in continuous maize farms cleared between 50 and 100 years ago [94,98,102,103,106,108]. Similar to the longitudinal studies, chronosequences tended to show non-linear declines in topsoil properties with time since forest conversion to agriculture. Soil infiltrability [93], SOM [93,102,106], Soil P [103], pH [102,107], and total C and N [107,108] all showed marked declines in cultivated compared to forested baselines.

Soil type varies widely across SSA ([74]; Table 3), and thus it is possible that some results may be confounded by differences in inherent soil properties. For example, soil texture in the soil profile is a property not likely to change considerably with either management or time, and thus similarity in the texture (and color) profile is a good indication that the soils are comparable across space and time. Further, soils in chronosequence sites should belong to the same Great Group in Soil Taxonomy [109]. If one is examining erosion, the criteria should also be adjusted for topsoil loss. For an excellent example of how soil profiles are used to validate a chronosequence (in Brazil), see [110]. Almost all the studies examined only the top 10 cm, comparing the rich A horizon of a forest soil to the Ap horizon of an agricultural soil (mixture of the A and B horizons). This is a serious limitation of many of the studies presented here, as only one study presented texture data to 100 cm [95] and another to 40 cm [79].

The studies that examined multiple depths also found non-linear declines in topsoil C and N with increasing farm age, eventually reaching steady state after several decades [79,95,101] (Figure 1c). However, they also showed that a good portion of this C (70%) may be transferred to the deeper soil layers [80], and total C stocks (0–1 m) remain stable for many decades [95]. Non-linear declines in (unfertilized) maize yields, served as an indicator of soil degradation in many studies. Yields declined rapidly immediately following forest conversion to agriculture (first 14 years; [96,100]), but reached a steady state after 35 years [103], 77 years [102] and after 100 years of cultivation ([106]; Figure 1d).

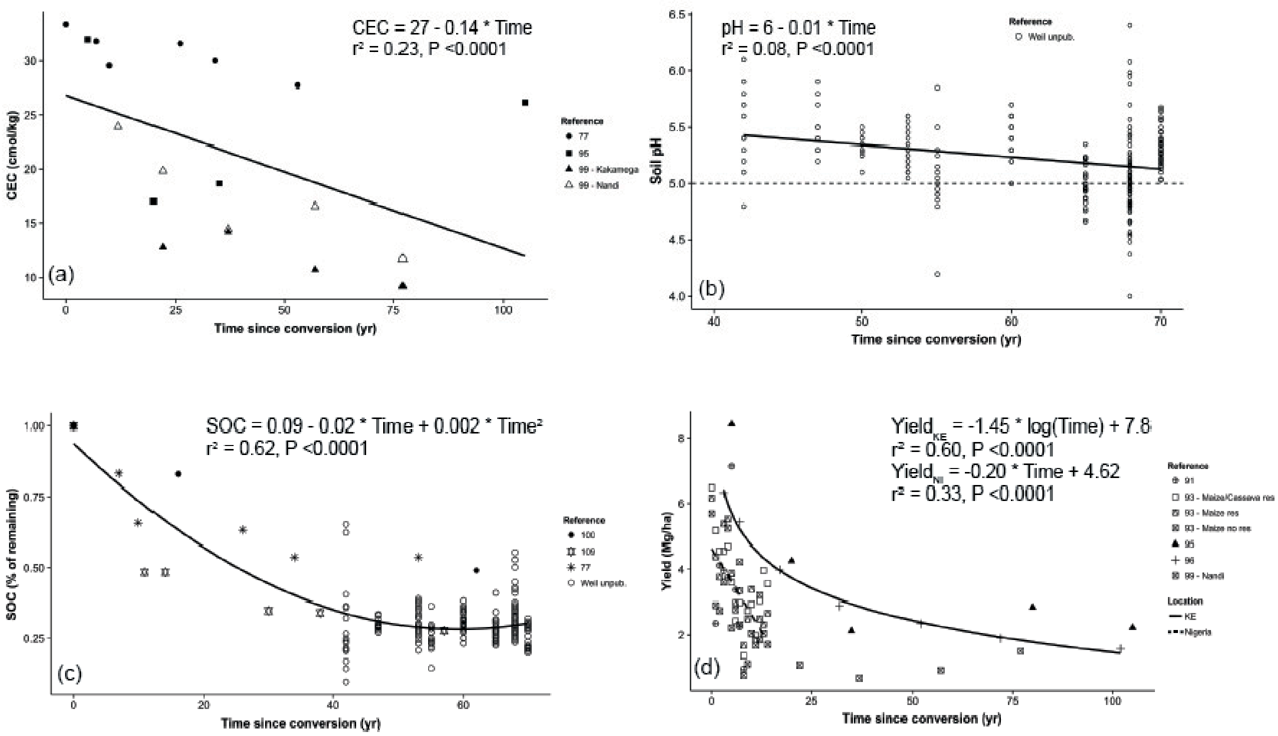

Figure 1. Selected indicators of soil degradation as a function of time since conversion. (**a**) Cation exchange capacity (CEC; 0–10 cm); (**b**) pH in water (1:1 slurry); (**c**) percent remaining soil organic carbon (SOC); and (**d**) maize yields with increasing time since forest conversion. Where data were reported in graphical form, points were extracted using GraphClick 3.0 (Arizona Software, 2008). In panel (**b**), dashed line represents the point below which aluminum toxicity can occur (pH = 5.0). In panel (**d**), two trend lines are reported for the two study regions: $Yield_{KE}$ refers to the best-fit equation for maize yields from Kenya and $Yield_{NI}$ the equation for maize yields from Nigeria. Number corresponds to the source study in References section.

3.4. Integrated Assessments

Studies that actively involve community members have the potential to improve their relevance and application, and are more likely to have broad impact on land management and system resilience.

Farmers and scientists measure soil degradation differently with the former often relying on visual assessments of crop performance and yield and the latter on chemical analyses. Still, in some cases, there is good agreement between farmers knowledge and scientific indicators of soil degradation (SOM and maize yields; [97]). There was significant overlap between scientific and local understanding of soil degradation indicators (e.g., crop yield, plant stunting and presence of weeds) in Swaziland and Botswana [41] and Ethiopia [111], however no data on soil properties other than color and texture were collected.

Where scientists manage soils to maximize fertility and improve production, farmers optimize soil use for livelihood priorities. Thus, degradation may be difficult to discern from integrated assessments, which evaluate specific priorities. For example, the replacement of forest by cropland can be used as a landscape scale indicator of degradation [78], even if at the field-scale, farmers report no declines in yield. Similarly, farmers may report improving maize yields when soil properties (C, N, and pH) remain unchanged [48].

Clearly the goal is to reverse degradation, and therefore farmer perceptions must not be overlooked, as they are a primary actor on agricultural landscapes. Farmers provide invaluable information on the location and type of degradation they observe on their lands as well as describe solutions. Still, to rigorously assess the trajectory or extent of degradation, quantitative data on soil properties must be collected.

3.5. Synthesis Summary

Overall, the longitudinal and the chronosequence studies indicate that most indicators of soil degradation decline with time since conversion. However, the rate of change differs among them, emphasizing the importance of evaluating multiple indicators when assessing degradation. We found that soil chemical properties (CEC, exchangeable bases, pH) decline linearly with farm age (Figure 1a,b). On the other hand, soil biological properties (SOC, maize yields) tend to decline rapidly at first and then reach a steady state (Figure 1c,d). Differing responses have consequences for thresholds and system resilience. For example, chemical thresholds may be easier to define and their consequences for ecosystem functioning more predictable. For example, aluminum toxicity can occur in soils with a pH (in water) below 5.5, depending on the percentage of aluminum saturation, at which point crop yields may suffer substantially [112]. On the other hand, losses of SOC will have different consequences depending on other biophysical conditions. That is, a dramatic loss of SOC in a sandy soil may lead to a regime change as the primary mechanism for water retention is removed [113–115]. Soil moisture in a clayey soil, on the other hand, which has a higher water holding capacity, may not be as sensitive to SOC loss. As agriculture in SSA is primarily rain-fed, any changes in soil moisture regimes will have serious consequences for crop yields and food security outcomes. The integrated assessments indicate that some farmers are good and others are poor quantitative estimators of soil degradation, and that soils and yield should always be monitored in tandem with farmer perceptions in order to make accurate assessments of degradation. Farmers are the primary actors and stakeholders on the SSA landscape; their perspective must not be ignored, especially when it comes to developing strategies for reversing degradation and improving food security.

4. Methods for Monitoring Soil Degradation in Sub-Saharan Africa

Clearly, long-term monitoring is needed as reporting changes in degradation indicators (especially biological indicators like SOC) on a stable branch suggest little change, while monitoring only during the rapid decline suggest dramatic losses [17]. While there have been major logistical barriers to measuring soil physical and chemical properties in SSA due to a lack of resources, recent growth in investment and technical expertise in SSA is leading to better environmental monitoring. Sample preservation, transportation, and traditional chemical analysis are limited in the region. Here, we offer practical methods for evaluating soil degradation in spite of the logistical barriers encountered in remote regions.

4.1. Visual Indicators

Visual assessment can provide much detail on the state and potential drivers of soil degradation. Root exposure in trees and shrubs are other indicators of soil erosion that can be quickly assessed. Crop productivity often declines as you move uphill (even on very gentle slopes) as soil moves downslope (Figure 2). Erosion "pins" can be deployed easily at the beginning of a cropping season to measure the amount of sheet erosion occurring within a given time period [116].

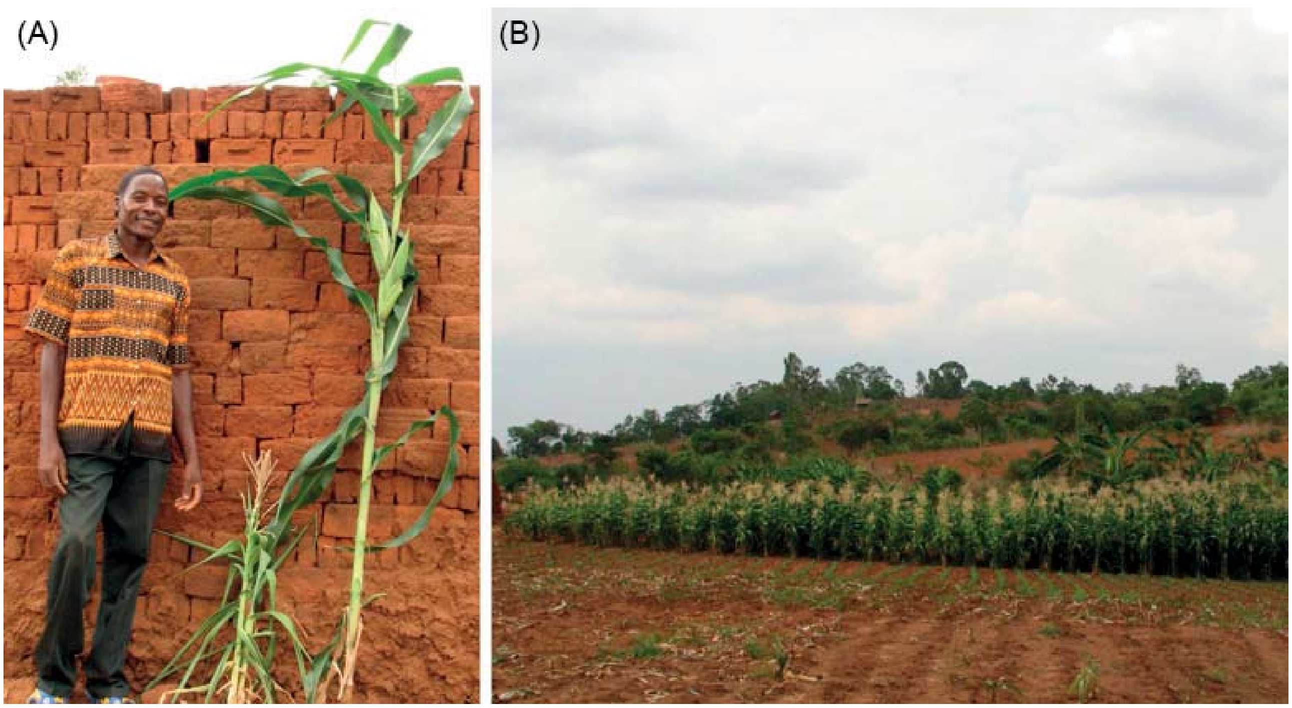

Figure 2. (**A**) Difference in size maize plants in (**B**) a field experiencing soil degradation due to erosion near Mwandama, Malawi. Reduced stature of maize (**B**) appears to be a matter of perspective however, when plants from each end of the field are compared side-by-side (**A**), it is clear that small slope can have dramatic effects on crop productivity due to the movement of water, soil, and nutrients. Photo credit, R. Weil.

4.2. Management Indicators

Biomass removal is a common practice in smallholder systems where weeds and crop residues are uprooted from the farm field and tossed to the field edges. Relocation of this biomass translates to relocation of valuable nutrients and organic matter to the field edges and nutrient mining in the middle of the farm fields. In contrast, rice threshing often occurs in the middle of the drained paddy, which concentrates nutrients (mainly K) in the center of the field (Figure 3).

Figure 3. Aerial photograph of rice paddies after harvest in Tanzania. Difference in soil color in the middle of the fields is indicative of variation in soil nutrient availability within rice paddies, which is caused by the movement of biomass to the middle of the field during threshing. Photo credit, R. Weil.

4.3. Physical Indicators

The soil aggregate stability is a key indicator as it integrates physical, chemical, and biological information into a single measurement. It is closely related to soil organic matter composition [117], biological activity [118], infiltration capacity [119], and erosion resistance [120]. The micro-sieve method developed by [121] is a simple, field-ready assessment of aggregate stability that can provide detailed information on management-induced changes to soil structure.

4.4. Chemical Indicators

Soil organic matter content is another integrative measure of soil degradation. Active carbon (C) can be determined in the field using a dilute permanganate extraction and can serve as a good proxy for soil organic matter [122]. If laboratory facilities are available, we suggest measuring total organic matter, pH and other important plant nutrients (total N, inorganic N, available and total P, total S, exchangeable Ca, Mg, K). Further, most soil tests are performed on the top 15 cm of soil, with subsoil properties largely ignored. We suggest that studies examine both the A horizon (typically 0–15 cm) and the upper subsoil (usually a B horizon at 20–50 cm). Sampling soil increments solely by a set depth may confound changes in horizon thickness and allow a single sample to cross boundaries between contrasting horizons. In fact, the thickness of the A horizon is a valuable measure of degradation where a clear color change marks the boundary of the horizon. Likewise, if a profile is characterized by a clay accumulation or an old erosional surface or stone line, the depth from the surface or from the bottom of the A horizon to the top of the subsoil layer may also be indicative of soil truncation and degradation (but could also indicate a shallow soil). Assessing nutrient depletion solely on topsoil soil properties may be especially misleading for some elements. For example, K may be low in the topsoil, but be in sufficient quantities of the subsoil [123,124]. Other important indicators will depend on the location. For example, in regions vulnerable to salinization, such as arid or semi-arid landscapes or irrigated agriculture, electrical conductivity and pH should be more systematically measured.

4.5. Biological Indicators

Net productivity can be indicative of overall ecosystem health. In an agricultural system, it is important to consider the biomass generated in both the intentional and unintentional species present (e.g., crop and weeds). Crop yields are sensitive to minor changes in management practices, and in poorly managed farms, yields may suffer to the benefit of weed populations. In such a case, low crop productivity may suggest soil degradation when, in fact, the high weed productivity would tell a different story. The species of weeds present can serve as a proxy for certain soil properties. For example, witchweed (*Striga spp*.) is a parasitic weed that plagues cereal crops across East Africa. This weed often occurs when soil N levels are low and is often used as a visual indicator of low soil available N [41]. Further, some fern species, native to tropical forests, are indicators of extreme acidity if found in farm fields [125].

5. Positive Trajectories and Conclusions

The conversion from forest to managed land substantially alters soil physical, chemical, and biological properties, however the extent of these changes is mediated by the new land use practice. In our review thus far, we have focused on continuous (typically unfertilized) agriculture in SSA, which offers little opportunity for the rehabilitation of soils. The majority of the available literature on degradation describes longitudinal or chronosequence studies along a degradation gradient from a forest or unmanaged baseline. However, a growing body of research in SSA uses the same study design to examine land management practices that may improve soil conditions (aggrade soils) from a degraded baseline. Such practices include (but are not limited to) communal grazing [126,127], tree plantations [93,128], and fallowing [96,129].

Many studies have compared soil properties among different management treatments in SSA, with indications that some are better suited to smallholder farming systems, can be practiced across a large range of climates and soil types, and are more readily adopted by farmers. Extensive research has been conducted into the broader frameworks of integrated soil fertility management [130–137], conservation agriculture [138–143], erosion control [144–148], and improved grazing management [149–151]. There is also a wealth of information on the benefits of specific practices such as short legume rotations (improved fallows) [152–158], agroforestry systems [159–165], and no-till systems [166–170]. Most of these studies, however, are short-term and geographically limited. We know that one management cannot fit all soil types, landscapes, or cultures. Still, these evidence-based practices hold great potential for supporting sustainable soil management, and broad improvement will require a coherent policy framework to support their wider adoption and long-term investment by farmers. Fortunately, a growing global demand for good quality, low-cost soils data has been moving forward [36,85]. Such integrated research efforts are necessary to inform national and international efforts that invest in agricultural intensification across SSA [171–173]. Land management strategies will only be successful if they can adapt to future demands for food and other ecosystem services. Future research efforts should focus on how soil degradation leads to changes in soil ecosystem services, and what land management strategies make systems resilient and, thus, more sustainable.

Acknowledgments

We thank Stephen Wood and Todd Rosenstock for their comments on this paper.

Author Contributions

Katherine Tully and Clare Sullivan wrote the manuscript. Ray Weil contributed data and concepts. Pedro Sanchez edited for content and provided guidance.

Appendix: Methods Used by R. Weil for Collecting Thirty-Year Trends on Soil Properties in Red Soils near Holetta Research Center, Ethiopia

Soil archives at the Holetta Research Center, Ethiopia were searched for historical soil data from farmer fields near the station. Archived data were only present in hardcopy and were entered into a database, which excluded soil samples that were collected on the research station as they were likely from manipulated trials. Originally, soil samples that were collected between 0–30 cm were included and soils with a P_2O_5 concentration greater than 25 ppm were excluded as it was this was used as a marker of past fertilizer application. However, only 8 samples had high P concentrations, and their inclusion in statistical models did not change the patterns observed. The archived data contained 338 records that met these criteria collected between 1972 and 2000. We report data on soil organic carbon (Walkey-Black method) and pH (1:1 soil to water slurry) for this time period.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Sanchez, P.A.; Swaminathan, M.S. Hunger in Africa: The link between unhealthy people and unhealthy soils. *Lancet* **2005**, *365*, 442–444.
2. Sanchez, P.A. Soil fertility and hunger in Africa. *Science* **2002**, *295*, 2019–2020.
3. Koning, N.; Smaling, E. Environmental crisis or "lie of the land?" The debate on soil degradation in Africa. *Land Use Policy* **2005**, *22*, 3–11.
4. Sanchez, P.; Palm, C.; Sachs, J.; Denning, G.; Flor, R.; Harawa, R.; Jama, B.; Kiflemariam, T.; Konecky, B.; Kozar, R.; *et al*. The African Millennium Villages. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 16775–16780.
5. Nziguheba, G.; Palm, C.A.; Berhe, T.; Denning, G.; Dicko, A.; Diouf, O.; Diru, W.; Flor, R.; Frimpong, F.; Harawa, R.; *et al*. The African Green Revolution. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2010; Volume 109, pp. 75–115.
6. Barrett, C.B.; Reardon, T.; Webb, P. Nonfarm income diversification and household livelihood strategies in rural Africa: Concepts, dynamics, and policy implications. *Food Policy* **2001**, *26*, 315–331.
7. United Nations Human Settlements Programme (UN-Habitat). *The State of African Cities: Re-Imagining Sustainable Urban Transitions*; UN-Habitat: Nairobi, Kenya, 2014.
8. World Commission of Environment and Development. *Our Common Future: Report of the World Commission on Environment and Development*; Oxford University Press: Oxford, UK, 1987; pp. 1–300.
9. Vandecar, K.L.; Lawrence, D.; Wood, T.; Oberbauer, S.F.; Das, R.; Tully, K.; Schwendenmann, L. Biotic and abiotic controls on diurnal fluctuations in labile soil phosphorus of a wet tropical forest. *Ecology* **2009**, *90*, 2547–2555.
10. McGrath, D.A.; Comerford, N.B.; Duryea, M.L. Litter dynamics and monthly fluctuations in soil phosphorus availability in an Amazonian agroforest. *Forest Ecol. Manag.* **2000**, *131*, 167–181.
11. Crews, T.E.; Kitayama, K.; Fownes, J.H.; Riley, R.H.; Herbert, D.A.; Mueller-Dombois, D.; Vitousek, P.M. Changes in Soil Phosphorus Fractions and Ecosystem Dynamics across a Long Chronosequence in Hawaii. *Ecology* **1995**, *76*, 1407–1424.
12. Walker, T.W.; Syers, J.K. The fate of phosphorus during pedogenesis. *Geoderma* **1976**, *15*, 1–19.
13. Zingore, S.; Murwira, H.K.; Delve, R.J.; Giller, K.E. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agric. Ecosyst. Environ.* **2007**, *119*, 112–126.
14. Tully, K.L.; Wood, S.A.; Almaraz, M.; Neill, C.; Palm, C.A. The effect of mineral and organic nutrient inputs on yields and nitrogen balances in western Kenya. *Agric. Syst.* **2015**, submitted for publication.
15. Hamilton, A.C.; Taylor, D. History of climate and forests in tropical Africa during the last 8 million years. *Clim. Chang.* **1991**, *19*, 65–78.

16. Fleitmann, D.; Dunbar, R.B.; McCulloch, M.; Mudelsee, M.; Vuille, M.; McClanahan, T.R.; Cole, J.E.; Eggins, S. East African soil erosion recorded in a 300 year old coral colony from Kenya. *Geophys. Res. Lett.* **2007**, *34*, L04401.
17. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591–596.
18. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23.
19. Folke, C. Resilience: The emergence of a perspective for social—Ecological systems analyses. *Global Environ. Chang.* **2006**, *16*, 253–267.
20. Bayon, G.; Dennielou, B.; Etoubleau, J.; Ponzevera, E.; Toucanne, S.; Bermell, S. Intensifying Weathering and Land Use in Iron Age Central Africa. *Science* **2012**, *335*, 1219–1222.
21. Carpenter, S.; Walker, B.; Anderies, J.M.; Abel, N. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* **2001**, *4*, 765–781.
22. Levin, S.A. *Fragile Dominion: Complexity and the Commons*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999.
23. Warren, A. Land degradation is contextual. *Land Degrad. Dev.* **2002**, *13*, 449–459.
24. Dewitte, O.; Jones, A.; Spaargaren, O.; Breuning-Madsen, H.; Brossard, M.; Dampha, A.; Deckers, J.; Gallali, T.; Hallett, S.; Jones, R.; *et al*. Harmonisation of the soil map of Africa at the continental scale. *Geoderma* **2013**, *211–212*, 138–153.
25. Sanchez, P.A.; Palm, C.A.; Buol, S.W. Fertility capability soil classification: A tool to help assess soil quality in the tropics. *Geoderma* **2003**, *114*, 157–185.
26. Lohse, K.A.; Matson, P. Consequences of nitrogen additions for soil losses from wet tropical forests. *Ecol. Appl.* **2005**, *15*, 1629–1648.
27. Kinjo, T.; Pratt, P.F. In some acid soils of Mexico and South America. II. In competition with chloride, sulfate and phosphate. III. Desorption, movement and distribution in Andepts. *Soil Sci. Soc. Am. J.* **1971**, *35*, 722–732.
28. Tittonell, P.; Muriuki, A.; Klapwijk, C.J.; Shepherd, K.D.; Coe, R.; Vanlauwe, B. Soil Heterogeneity and Soil Fertility Gradients in Smallholder Farms of the East African Highlands. *Soil Sci. Soc. Am. J.* **2013**, doi:10.2136/sssaj2012.0250.
29. Almaraz, M.; Tully, K.L.; Neill, C.; Palm, C.A.; Porder, S. Nitrogen dynamics in soil profiles from intensifying agricultural fields in sub-Saharan Africa: The role of soil type. **2015**, unpublished work.
30. Scoones, I. Wetlands in drylands: Key resources for agricultural and pastoral production in Africa. *Ambio* **1991**, *20*, 366–371.
31. Mekonnen, K.; Buresh, R.J.; Jama, B. Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize fields. *Plant Soil* **1997**, *188*, 319–327.
32. Chintu, R.; Mafongoya, P.L.; Chirwa, T.S.; Mwale, M.; Matibini, J. Subsoil nitrogen dynamics as affected by planted coppicing tree legume fallows in eastern Zambia. *Ex. Agric.* **2004**, *40*, 327–340.
33. Vanlauwe, B.; Kihara, J.; Chivenge, P.; Pypers, P.; Coe, R.; Six, J. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* **2010**, *339*, 35–50.

34. Tittonell, P.; Vanlauwe, B.; Leffelaar, P.A.; Rowe, E.C.; Giller, K.E. Exploring diversity in soil fertility management of smallholder farms in western Kenya. *Agric. Ecosyst. Environ*. **2005**, *110*, 149–165.
35. Palm, C.A.; Smukler, S.M.; Sullivan, C.C.; Mutuo, P.K.; Nyadzi, G.I.; Walsh, M.G. Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19661–19666.
36. Shepherd, K.D.; Shepherd, G.; Walsh, M.G. Land health surveillance and response: A framework for evidence-informed land management. *Agric. Syst.* **2015**, *132*, 93–106.
37. Letey, J.; Sojka, R.E.; Upchurch, D.R. Deficiencies in the soil quality concept and its application. *J. Soil Water Conserv.* **2003**, *58*, 180–187.
38. Karlen, D.L.; Mausbach, M.J.; Doran, J.W. Soil quality: A concept, definition, and framework for evaluation. *Soil Sci. Soc. Am. J.* **1997**, *61*, 4–10.
39. Wyland, L.J.; Jackson, L.E.; Schulbach, K.F. Soil-plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. *J. Agric. Sci.* **1995**, *124*, 17–25.
40. Dean, J.E.; Weil, R.R. Brassica Cover Crops for Nitrogen Retention in the Mid-Atlantic Coastal Plain. *J. Environ. Qual.* **2009**, *38*, 520–528.
41. Stringer, L.C.; Reed, M.S. Land degradation assessment in Southern Africa: Integrating local and scientific knowledge bases. *Land Degrad. Dev.* **2007**, *18*, 99–116.
42. Stoorvogel, J.J.; Smaling, E.M. A. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa, 1983–2000*; Winand Staarting Center-DLO: Wageningen, The Netherlands, 1990.
43. Lal, R. Erosion-Crop Productivity Relationships for Soils of Africa. *Soil Sci. Soc. Am. J.* **1995**, *59*, 661–667.
44. Oldeman, L.R.; Hakkeling, R.T.A.; Sombroek, W.G. *World Map of the Status of Human-Induced Soil Degradation*; ISRIC: Wageningen, The Netherlands; FAO: Nairobi, Kenya, 1991. pp. 1–35
45. Mazzucato, V.; Niemeijer, D. Rethinking Soil and Water Conservation in a Changing Society: A Case Study from Burkina Faso. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 20 June 2000; pp. 1–421.
46. Scherr, S.J. Economic factors in farmer adoption of agroforestry: Patterns observed in Western Kenya. *World Dev.* **1995**, *23*, 787–804.
47. Forsyth, T. Science, myth and knowledge: Testing himalayan environmental degradation in Thailand. *Geoforum* **1996**, *27*, 375–392.
48. Tiffen, M.; Mortimer, M.; Gichuki, F. *More People, Less Erosion*; John Wiley & Sons, Ltd.: Chichester, UK, 1994; pp. 1–326.
49. Barbier, E.B. The economic linkages between rural poverty and land degradation: Some evidence from Africa. *Agr. Ecosyst. Environ.* **2000**, *82*, 355–370.
50. McCall, M. Environmental and agricultural impacts of Tanzania's villagization programme. In *Population and Development Projects in Africa*; Clark, J.I., Khogali, M., Kosinski, L.A., Eds.; Cambridge University Press: Cambridge, UK, 1985; pp. 123–140.
51. Thomas, D.S.G.; Sporton, D.; Perkins, J. The environmental impact of livestock ranches in the Kalahari, Botswana: Natural resource use, ecological change and human response in a dynamic dryland system. *Land Degrad. Dev.* **2000**, *11*, 327–341.

52. Rohde, R.F.; Moleele, N.M.; Mphale, M.; Allsopp, N.; Chanda, R.; Hoffman, M.T.; Magole, L.; Young, E. Dynamics of grazing policy and practice: Environmental and social impacts in three communal areas of southern Africa. *Environ. Sci. Policy* **2006**, *9*, 302–316.
53. Mafongoya, P.L.; Bationo, A.; Kihara, J.; Waswa, B.S. Appropriate technologies to replenish soil fertility in southern Africa. *Nutr. Cycl. Agroecosyst.* **2006**, *76*, 137–151.
54. Boserup, E. *The Conditions of Agricultural Growth*; Adine Publishing Company: Chicago, IL, USA, 1965.
55. Hoddinott, J.; Haddad, L. Does female income share influence household expenditures? Evidence from Côte d'Ivoire. *Oxford Bull. Econ. Stat.* **1995**, *57*, 77–96.
56. Nkonya, E.; Moore, K. *Smallholder Adoption of Integrated Soil Fertility Management*; USAID&Agrilinks: Washington, DC, USA, 2015; p. 51.
57. Nkonya, E. *Soil Conservation Practices and Non-Agricultural Land Use in the South-Western Highlands of Uganda*; The International Food Policy Research Institute (IFPRI): Washington, DC, USA, 2002; pp. 1–31.
58. Tamene, L.; Vlek, P.L.G. Soil Erosion Studies in Northern Ethiopia. In *Land Use and Soil Resources*; Braimoh, A.K., Vlek, P.L.G., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2008; pp. 73–100.
59. Tamene, L.; Park, S.J.; Dikau, R.; Vlek, P.L.G. Reservoir siltation in the semi-arid highlands of northern Ethiopia: Sediment yield–catchment area relationship and a semi-quantitative approach for predicting sediment yield. *Earth Surf. Process. Landforms* **2006**, *31*, 1364–1383.
60. Kimaro, D.N.; Deckers, J.A.; Poesen, J.; Kilasara, M.; Msanya, B.M. Short and medium term assessment of tillage erosion in the Uluguru Mountains, Tanzania. *Soil Tillage Res.* **2005**, *81*, 97–108.
61. Collins, A.L.; Walling, D.E.; Sichingabula, H.M.; Leeks, G.J.L.G. Suspended sediment source fingerprinting in a small tropical catchment and some management implications. *Appl. Geogr.* **2001**, *21*, 387–412.
62. Taddese, G.; Saleem, M.A.M.; Abyie, A.; Wagnew, A. Impact of grazing on plant species richness, plant biomass, plant attribute, and soil physical and hydrological properties of vertisol in East African highlands. *Environ. Manag.* **2002**, *29*, 279–289.
63. Van N du Toit, G.; Snyman, H.A.; Malan, P.J. Physical impact of grazing by sheep on soil parameters in the Nama Karoo subshrub/grass rangeland of South Africa. *J. Arid Environ.* **2009**, *73*, 804–810.
64. Weil, R.R.; Brady, N. *Nature and Properties of Soils*, 15 ed.; unpublished work, 2015.
65. Nye, P.H.; Greenland, D.J. *The Soil under Shifting Cultivation*, 51st ed.; Commonwealth Agricultural Bureau, Farnham Royal, Berks, Great Britain, 1960; p. 156.
66. Vitousek, P.M.; Naylor, R.; Crews, T.; David, M.B.; Drinkwater, L.E.; Holland, E.; Johnes, P.J.; Katzenberger, J.; Martinelli, L.A.; Matson, P.A.; *et al*. Nutrient Imbalances in Agricultural Development. *Science* **2009**, *324*, 1519–1520.
67. Oenema, O.; de Vries, W. Approaches and uncertainties in nutrient budgets: Implications for nutrient management and environmental policies. *Eur. J. Agron.* **2003**, *20*, 3–16.
68. Henao, J.; Baanante, C.A. *Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa*; Intl Fertilizer Development Center: Muscle Shoals, AL, USA, 1999.

69. Cobo, J.G.; Dercon, G.; Cadisch, G. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agric. Ecosyst. Environ.* **2010**, *136*, 1–15.
70. Amede, T.; Belachew, T.; Geta, E. *Reversing the Degradation of Arable Land in the Ethiopian Highlands*; IIED: London, UK, 2001; p. 23.
71. Juo, A.S.R.; Dabiri, A.; Franzluebbers, K. Acidification of a kaolinitic Alfisol under continuous cropping with nitrogen fertilization in West Africa. *Plant Soil* **1995**, *171*, 245–253.
72. Barbiéro, L.; Mohamedou, A.O.; Roger, L.; Furian, S.; Aventurier, A.; Rémy, J.C.; Marlet, S. The origin of Vertisols and their relationship to Acid Sulfate Soils in the Senegal valley. *CATENA* **2005**, *59*, 93–116.
73. Van Asten, P.J.A.; Barbiéro, L.; Wopereis, M.C.S.; Maeght, J.L.; van der Zee, S.E.A.T.M. Actual and potential salt-related soil degradation in an irrigated rice scheme in the Sahelian zone of Mauritania. *Agric. Water Manag.* **2003**, *60*, 13–32.
74. *Soil Atlas of Africa*; Jones, A., Ed.; Publications Office of the European Union: Luxembourg, 2013.
75. HarvestChoice Updating Soil Functional Capacity Classification System. Available online: http://harvestchoice.org/node/1435 (accessed on 24 January 2015).
76. Vlek, P.L.G. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. *Fert. Res.* **1990**, *26*, 327–339.
77. Bationo, A.; Lompo, F.; Koala, S. Research on nutrient flows and balances in West Africa: State-of-the-art. *Agr. Ecosyst. Environ.* **1998**, *71*, 19–35.
78. Gray, L.C. Is land being degraded? A multi-scale investigation of landscape change in southwestern Burkina Faso. *Land Degrad. Dev.* **1999**, *10*, 329–343.
79. Lemenih, M.; Karltun, E.; Olsson, M. Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. *Agric. Ecosyst. Environ.* **2005**, *105*, 373–386.
80. Bossio, D.A.; Girvan, M.S.; Verchot, L.; Bullimore, J.; Borelli, T.; Albrecht, A.; Scow, K.M.; Ball, A.S.; Pretty, J.N.; Osborn, A.M. Soil Microbial Community Response to Land Use Change in an Agricultural Landscape of Western Kenya. *Microb. Ecol.* **2005**, *49*, 50–62.
81. Brussaard, L.; de Ruiter, P.C.; Brown, G.G. Soil biodiversity for agricultural sustainability. *Agr. Ecosyst. Environ.* **2007**, *121*, 233–244.
82. Wood, S.A.; Almaraz, M.; Bradford, M.A.; McGuire, K.L.; Naeem, S.; Palm, C.A.; Tully, K.L.; Zhou, J. Farm management, not soil microbial diversity, controls nutrient loss from smallholder tropical agriculture. *Front. Micr*. **2015**, *6*, 1–10.
83. Swift, M.J.; Anderson, J.M. Biodiversity and ecosystem function in agricultural systems. In *Biodiversity and Ecosystem Function*; Schulze, E.D., Mooney, H.A., Eds.; Springer: Berlin, Germany, 1994; pp. 15–41.
84. Beare, M.H.; Reddy, M.V.; Tian, G.; Srivastava, S.C. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: The role of decomposer biota. *Appl. Soil Ecol.* **1997**, *6*, 87–108.
85. Palm, C.; Sanchez, P.; Ahamed, S.; Awiti, A. Soils: A Contemporary Perspective. *Annu. Rev. Environ. Resourc.* **2007**, *32*, 99–129.

86. Manlay, R.J.; Feller, C.; Swift, M.J. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. *Agric. Ecosyst. Environ.* **2007**, *119*, 217–233.
87. Mathieu, J.; Rossi, J.P.; Mora, P.; Lavelle, P.; Martins, P.F.D.S.; Rouland, C.; Grimaldi, M. Recovery of soil macrofauna communities after forest clearance in eastern Amazonia, Brazil. *Conserv. Biol.* **2005**, *19*, 1598–1605.
88. Mutema, M.; Mafongoya, P.L.; Nyagumbo, I.; Chikukura, L. Effects of crop residues and reduced tillage on macrofauna abundance. *J. Org. Syst.* **2013**, *8*, 5–16.
89. Wood, S.A.; Bradford, M.A.; Gilbert, J.A.; McGuire, K.L.; Palm, C.A.; Tully, K.; Zhou, J.; Naeem, S. Agricultural intensification and the functional capacity of soil microbes on smallholder African farms. *J. Appl. Ecol*. **2015**, doi:10.1111/1365-2664.12416.
90. Bradford, M.A.; Wood, S.A.; Bardgett, R.D.; Black, H.I.J.; Bonkowski, M.; Eggers, T.; Grayston, S.J.; Kandeler, E.; Manning, P.; Setala, H.; *et al*. Discontinuity in the responses of ecosystem processes and multifunctionality to altered soil community composition. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 14478–14483.
91. De Vries, F.T.; Bardgett, R.D. Plant–microbial linkages and ecosystem nitrogen retention: lessons for sustainable agriculture. *Front. Ecol. Environ.* **2012**, *10*, 425–432.
92. R Development Core Team 2008. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2008.
93. Adejuwon, J.O.; Ekanade, O. A comparison of soil properties under different landuse types in a part of the Nigerian Cocoa Belt. *CATENA* **1988**, *15*, 319–331.
94. Awiti, A.O.; Walsh, M.G.; Shepherd, K.D.; Kinyamario, J. Soil condition classification using infrared spectroscopy: A proposition for assessment of soil condition along a tropical forest-cropland chronosequence. *Geoderma* **2008**, *143*, 73–84.
95. Demessie, A.; Singh, B.R.; Lal, R. Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District, Southern Ethiopia. *Nutr. Cycl. Agroecosyst.* **2013**, *95*, 365–375.
96. Juo, A.S.R.; Franzluebbers, K.; Dabiri, A.; Ikhile, B. Changes in soil properties during long-term fallow and continuous cultivation after forest clearing in Nigeria. *Agr. Ecosyst. Environ.* **1995**, *56*, 9–18.
97. Karltun, E.; Lemenih, M.; Tolera, M. Comparing farmers' perception of soil fertility change with soil properties and crop performance in Beseku, Ethiopia. *Land Degrad. Dev.* **2011**, *24*, 228–235.
98. Kimetu, J.M.; Lehmann, J.; Ngoze, S.O.; Mugendi, D.N.; Kinyangi, J.M.; Riha, S.; Verchot, L.; Recha, J.W.; Pell, A.N. Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality Along a Degradation Gradient. *Ecosystems* **2008**, *11*, 726–739.
99. Kiunsi, R.B.; Meadows, M.E. Assessing land degradation in the Monduli District, northern Tanzania. *Land Degrad. Dev.* **2006**, *17*, 509–525.
100. Lal, R. Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. II. Soil chemical properties. *Land Degrad. Dev.* **1998**, *7*, 87–98.
101. Lemenih, M.; Karltun, E.; Olsson, M. Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia. *Agric. Ecosyst. Environ.* **2005**, *109*, 9–19.

102. Moebius-Clune, B.N.; van Es, H.M.; Idowu, O.J.; Schindelbeck, R.R.; Kimetu, J.M.; Ngoze, S.; Lehmann, J.; Kinyangi, J.M. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. *Agr. Ecosyst. Environ.* **2011**, *141*, 86–99.
103. Ngoze, S.; Riha, S.; Lehmann, J.; Verchot, L.; Kinyagi, J.; Mbuga, D.; Pell, A. Nutrient constraints to tropical agroecosystem productivity in long-term degrading soils. *Global Change Biol.* **2008**, *14*, 2810–2822.
104. Nyberg, G.; Bargués Tobella, A.; Kinyangi, J.; Ilstedt, U. Soil property changes over a 120-yr chronosequence from forest to agriculture in western Kenya. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 2085–2094.
105. Peters, J.B. Gambian soil fertility trends, 1991–1998. *Commun. Soil Sci. Plan.* **2000**, *31*, 2201–2210.
106. Solomon, D.; Lehmann, J.; Kinyagi, J.; Amelung, W.; Lobe, I.; Pell, A.; Riha, S.; Ngoze, S.; Verchot, L.; Mbuga, D.; *et al*. Long-term impacts of anthropogenic perturbations on dynamics and speciation of organic carbon in tropical forest and subtropical grassland ecosystems. *Global Change Biol.* **2007**, *13*, 511–530.
107. Vågen, T.-G.; Shepherd, K.D.; Walsh, M.G. Sensing landscape level change in soil fertility following deforestation and conversion in the highlands of Madagascar using Vis-NIR spectroscopy. *Geoderma* **2006**, *133*, 281–294.
108. Awiti, A.O.; Walsh, M.G.; Kinyamario, J. Dynamics of topsoil carbon and nitrogen along a tropical forest–cropland chronosequence: Evidence from stable isotope analysis and spectroscopy. *Agr. Ecosyst. Environ.* **2008**, *127*, 265–272.
109. Sanchez, P.A.; Palm, C.A.; Davey, C.B.; Szott, L.T.; Russell, C.E. Tree Crops as Soil Improvers in the Humid Tropics? In *Attributes of Trees as Crop Plants*; Cannell, M.G.R., Jackson, J.E., Eds.; Institute of Terrestrial Ecology: Huntingdon, UK, 1985; pp. 327–358.
110. Russell, C.E. *Nutrient Cycling and Productivity of Native and Plantation Forests at Jari Florestal, Pará, Brazil*; Institute of Ecology, University of Georgia: Athens, GA, USA, 1983.
111. Tesfahunegn, G.B.; Tamene, L.; Vlek, P.L.G. A participatory soil quality assessment in Northern Ethiopia's Mai-Negus catchment. *CATENA* **2011**, *86*, 1–13.
112. Sanchez, P.A. *Properties and Management of Soils in the Tropics*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1976.
113. Hudson, B. Soil organic matter and available water capacity. *J. Soli Water Conserv*. **1994**, *49*, 189–194.
114. Weil, R.R.; Magdoff, F. Significance of soil organic matter to soil quality and health. In *Soil Organic Matter in Sustainable Agriculture*; Magdoff, F., Weil, R.R., Eds.; CRC Press: Boca Raton, FL, USA, 2004; pp. 1–42.
115. Lotter, D.W.; Seidel, R.; Liebhardt, W. The performance of organic and conventional cropping systems in an extreme climate year. *Am. J. Alt. Agric.* **2003**, *18*, 146–154.
116. Vigiak, O.; Okoba, B.O.; Sterk, G.; Groenenberg, S. Modelling catchment-scale erosion patterns in the East African Highlands. *Earth Surf. Process. Landforms* **2005**, *30*, 183–196.
117. Tisdall, J.M. Formation of soil aggregates and accumulation of soil organic matter. In *Structure and Organic Matter Storage in Agricultural Soils*; Carter, M.R., Stewart, B.A., Eds.; CRC Press: Boca Raton, FL, USA, 1996; pp. 57–96.

118. Wander, M.M.; Traina, S.J.; Stinner, B.R.; Peters, S.E. Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools. *Soil Sci. Soc. Am. J.* **1994**, *58*, 1130–1139.
119. Pierson, F.B.; Blackburn, W.H.; Vactor, S.S.; Wood, J.C. Partitioning small scale spatial variability of runoff and erosion on sagebrush rangeland. *J. Am. Water Resour. As.* **1994**, *30*, 1081–1089.
120. Blackburn, W.H.; Pierson, F.B. Sources of Variation in Interrill Erosion on Rangelands. In *Variability in Rangeland Water Erosion Processes*; Blackburn, W.H., Pierson, F.B., Schulman, G.E., Zartman, R., Eds.; SSSA Special Publication; Soil Science Society of America: Madison, WI, USA, 1994; pp. 1–9.
121. Herrick, J.E.; Whitford, W.G.; de Soyza, A.G.; van Zee, J.W. Field soil aggregate stability kit for soil quality and rangeland health evaluations. *CATENA* **2001**, *44*, 27–35.
122. Lucas, S.T.; Weil, R.R. Can a Labile Carbon Test be Used to Predict Crop Responses to Improve Soil Organic Matter Management? *Agron. J.* **2012**, *104*, 1160–1170.
123. Khan, S.A.; Mulvaney, R.L.; Ellsworth, T.R. The potassium paradox: Implications for soil fertility, crop production and human health. *Renew. Agric. Food Syst.* **2013**, *29*, 3–27.
124. Marín-Spiotta, E.; Silver, W.L.; Ostertag, R. Long-term patterns in tropical reforestation: Plant community composition and aboveground biomass accumulation. *Ecol. Appl.* **2007**, *17*, 828–839.
125. Murage, E.W.; Karanja, N.K.; Smithson, P.C.; Woomer, P.L. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. *Agr Ecosyst. Environ.* **2000**, *79*, 1–8.
126. Verdoodt, A.; Mureithi, S.M.; Ye, L.; van Ranst, E. Chronosequence analysis of two enclosure management strategies in degraded rangeland of semi-arid Kenya. *Agric. Ecosyst. Environ.* **2009**, *129*, 332–339.
127. Fterich, A.; Mahdhi, M.; Mars, M. Impact of grazing on soil microbial communities along a chronosequence of Acacia tortilis subsp. raddiana in arid soils in Tunisia. *Eur. J. Soil Biol.* **2012**, *50*, 56–63.
128. Dawoe, E.K.; Quashie-Sam, J.S.; Oppong, S.K. Effect of land-use conversion from forest to cocoa agroforest on soil characteristics and quality of a Ferric Lixisol in lowland humid Ghana. *Agroforest. Syst.* **2013**, *88*, 87–99.
129. Mando, A.; Ouattara, B.; Somado, A.E.; Wopereis, M.C.S.; Stroosnijder, L.; Breman, H. Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. *Soil Use Manag.* **2005**, *21*, 25–31.
130. Vanlauwe, B.; Diels, J.; Sanginga, N.; Merckx, R. Long-term integrated soil fertility management in South-western Nigeria: Crop performance and impact on the soil fertility status. *Plant Soil* **2005**, *273*, 337–354.
131. Zingore, S.; Murwira, H.K.; Delve, R.J.; Giller, K.E. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Res.* **2007**, *101*, 296–305.

132. Vanlauwe, B.; Bationo, A.; Chianu, J.; Giller, K.E.; Merckx, R.; Mokwunye, U.; Ohiokpehai, O.; Pypers, P.; Tabo, R.; Shepherd, K.D.; *et al*. Integrated soil fertility management. *Outlook Agric.* **2010**, *39*, 17–24.
133. Vanlauwe, B.; Giller, K. Popular myths around soil fertility management in sub-Saharan Africa. *Agric. Ecosyst. Environ.* **2006**, *116*, 34–46.
134. Defoer, T. Learning about methodology development for integrated soil fertility management. *Agric. Syst.* **2002**, *73*, 57–81.
135. Zingore, S.; Tittonell, P.; Corbeels, M.; van Wijk, M.T.; Giller, K.E. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutr. Cycl. Agroecosyst.* **2011**, *90*, 87–103.
136. Chivenge, P.; Vanlauwe, B.; Six, J. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant Soil* **2011**, *342*, 1–30.
137. Bationo, A.; Waswa, B.; Kihara, J.; Six, J. Advances in integrated soil fertility management in sub Saharan Africa: Challenges and opportunities. *Nutr. Cycl. Agroecosyst.* **2006**, doi:10.1007/978-1-4020-5760-1.
138. Bot, A.; Benites, J. *Conservation agriculture: Case studies in Latin American and Africa*; Food & Agriculture Organization: Rome, Italy, 2001.
139. Erenstein, O.; Sayre, K.; Wall, P.; Dixon, J.; Hellin, J. Adapting No-Tillage Agriculture to the Conditions of Smallholder Maize and Wheat Farmers in the Tropics and Sub-Tropics; Goddard, T., Zoebisch, M., Gan, Y., Ellis, W., Watson, A., Sombatpanit, S., Eds.; *No-till Farming Systems*. Special Publication 3 World Association of Soil and Water Conservation (WASWC): Bangkok, Thailand, 2007; pp. 253–274.
140. Chivenge, P.; Murwira, H.; Giller, K.; Mapfumo, P.; Six, J. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil Till. Res.* **2007**, *94*, 328–337.
141. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture andecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105.
142. Verhulst, N.; Govaerts, B.; Verachtert, E.; Castellanos-Navarrete, A.; Mezzalama, M.; Wall, P.; Deckers, J.; Sayre, K. Conservation agriculture, improving soil quality for sustainable production systems? In *Food Security and Soil Quality*; Lal, R., Stewart, B.A., Eds.; CRC Press: Boca Raton, FL, USA, 2010; pp. 137–208.
143. Thierfelder, C.; Cheesman, S.; Rusinamhodzi, L. Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. *Int. J. Agric. Sustain.* **2013**, *11*, 108–124.
144. Nyssen, J.; Poesen, J.; Haile, M.; Moeyersons, J.; Deckers, J. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. *Soil Till. Res.* **2000**, *57*, 115–127.
145. Valentin, C.; Poesen, J.; Li, Y. Gully erosion: Impacts, factors and control. *CATENA* **2005**, *63*, 132–153.
146. Gebrernichael, D.; Nyssen, J.; Poesen, J.; Deckers, J.; Haile, M.; Govers, G.; Moeyersons, J. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. *Soil Use Manag.* **2005**, *21*, 287–297.

147. Astatke, A.; Jabbar, M.; Tanner, D. Participatory conservation tillage research: an experience with minimum tillage on an Ethiopian highland Vertisol. *Agric. Ecosyst. Environ.* **2003**, *95*, 401–415.
148. Bryan, R.B. *Soil Erosion, Land Degradation and Social Transition: Geoecological Analysis of A Semi-Arid Tropical Region, Kenya*; Catena-Verlag: Cremlingen Destedt, Germay, 1994.
149. Beukes, P.C.; Cowling, R.M. Non-Selective Grazing Impacts on Soil-Properties of the Nama Karoo. *J. Range Manag.* **2003**, *56*, 547-552.
150. Gebremeskel, K.; Pieterse, P.J. Impact of grazing around a watering point on soil status of a semi-arid rangeland in Ethiopia. *Afr. J. Ecol.* **2007**, *45*, 72–79.
151. Mekuria, W.; Veldkamp, E.; Tilahun, M.; Olschewski, R. Economic valuation of land restoration: The case of exclosures established on communal grazing lands in Tigray, Ethiopia. *Land Degrad. Dev.* **2011**, *22*, 334–344.
152. Bünemann, E.K.; Smithson, P.C.; Jama, B.; Frossard, E.; Oberson, A.; Oberson, A. Maize productivity and nutrient dynamics in maize-fallow rotations in western Kenya. *Plant Soil* **2004**, *264*, 195–208.
153. Ojiem, J.O.; Vanlauwe, B.; de Ridder, N.; Giller, K.E. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. *Plant Soil* **2007**, *292*, 119–135.
154. Oikeh, S.O.; Carsky, R.J.; Kling, J.G.; Chude, V.O.; Horst, W.J. Differential N uptake by maize cultivars and soil nitrate dynamics under N fertilization in West Africa. *Agric. Ecosyst. Environ.* **2003**, *100*, 181–191.
155. Adiku, S.G.K.; Jones, J.W.; Kumaga, F.K.; Tonyigah, A. Effects of crop rotation and fallow residue management on maize growth, yield and soil carbon in a savannah-forest transition zone of Ghana. *J. Agric. Sci.* **2009**, *147*, 313–322.
156. Chikowo, R.; Mapfumo, P.; Nyamugafata, P.; Giller, K.E. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. *Plant Soil* **2004**, *259*, 315–330.
157. Ndufa, J.K.; Gathumbi, S.M.; Kamiri, H.W.; Giller, K.E.; Cadisch, G. Do mixed-species Legume fallows provide long-term maize yield benefit compared with monoculture legume fallows? *Agron. J.* **2009**, *101*, 1352–1362.
158. Bado, B.V.; Bationo, A.; Cescas, M.P. Assessment of cowpea and groundnut contributions tosoil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). *Biol. Fert. Soils* **2006**, *43*, 171–176.
159. Shepherd, K.D.; Ohlsson, E.; Okalebo, J.R.; Ndufa, J.K. Potential impact of agroforestry on soil nutrient balances at the farm scale in the East African Highlands. *Fert. Res.* **1996**, *44*, 87–99.
160. Buresh, R.J. Soil improvement by trees in sub-Saharan Africa. *Agroforest. Syst.* **1998**, *38*, 51–76.
161. Odhiambo, H.O.; Ong, C.K.; Deans, J.D.; Wilson, J.; Khan, A.; Sprent, J.I. Roots, soil water and crop yield: Tree crop interactions in a semi-arid agroforestry system in Kenya. *Plant Soil* **2001**, *235*, 221–233.
162. Akinnifesi, F.K.; Makumba, W.; Sileshi, G.; Ajayi, O.C.; Mweta, D. Synergistic effect ofinorganic N and P fertilizers and organic inputs from Gliricidia sepium on productivity of intercropped maize in Southern Malawi. *Plant Soil* **2007**, *294*, 203–217.

163. Van Noordwijk, M.; Lusiana, B. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. In *Agroforestry for Sustainable Land-Use Fundamental Research and Modelling with Emphasis on Temperate and Mediterranean Applications*; Springer Netherlands: Dordrecht, The Netherlands, 1999; Volume 60, pp. 217–242.
164. Sileshi, G.; Akinnifesi, F.K.; Ajayi, O.C.; Place, F. Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant Soil* **2008**, *307*, 1–19.
165. Nyamadzawo, G.; Nyamugafata, P.; Wuta, M.; Nyamangara, J.; Chikowo, R. Infiltration and runoff losses under fallowing and conservation agriculture practices on contrasting soils, Zimbabwe. *Water South Africa* **2012**, *38*, 233–240.
166. Munodawafa, A. Assessing nutrient losses with soil erosion under different tillage systems and their implications on water quality. *Phys. Chem. Earth Pt. A/B/C* **2007**, *32*, 1135–1140.
167. Agbede, T. Nutrient availability and cocoyam yield under different tillage practices. *Soil Till. Res.* **2008**, *99*, 49–57.
168. Enfors, E.; Barron, J.; Makurira, H.; Rockström, J.; Tumbo, S. Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanzania. *Agric. Water Manag.* **2011**, *98*, 1687–1695.
169. Mchunu, C.N.; Lorentz, S.; Jewitt, G.; Manson, A.; Chaplot, V. No-Till Impact on Soil and SoilOrganic Carbon Erosion under Crop Residue Scarcity in Africa. *Soil Sci. Soc. Am. J.* **2011**, *75*, 1503–1512.
170. Ouédraogo, E.; Mando, A.; Stroosnijder, L. Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa. *Soil Till. Res.* **2006**, *91*, 57–67.
171. Sanchez, P.A.; Denning, G.L.; Nziguheba, G. The African Green Revolution moves forward. *Food Sec.* **2009**, *1*, 37–44.
172. Sanchez, P.A. En route to plentiful food production in Africa. *Nature Plants* **2015**, *1*, 1–2
173. Alliance for a Green Revolution in Africa (AGRA). *Building on the New Momentum in African Agriculture: AGRA in 2008*; Alliance for a Green Revolution in Africa: Nairobi, Kenya, 2009.