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Article

Restoring Soil Quality to Mitigate Soil Degradation

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Abstract: Feeding the world population, 7.3 billion in 2015 and projected to increase to 9.5 billion by 2050, necessitates an increase in agricultural production of ~70% between 2005 and 2050. Soil degradation, characterized by decline in quality and decrease in ecosystem goods and services, is a major constraint to achieving the required increase in agricultural production. Soil is a non-renewable resource on human time scales with its vulnerability to degradation depending on complex interactions between processes, factors and causes occurring at a range of spatial and temporal scales. Among the major soil degradation processes are accelerated erosion, depletion of the soil organic carbon (SOC) pool and loss in biodiversity, loss of soil fertility and elemental imbalance, acidification and salinization. Soil degradation trends can be reversed by conversion to a restorative land use and adoption of recommended management practices. The strategy is to minimize soil erosion, create positive SOC and N budgets, enhance activity and species diversity of soil biota (micro, meso, and macro), and improve structural stability and pore geometry. Improving soil quality (*i.e.*, increasing SOC pool, improving soil structure, enhancing soil fertility) can reduce risks of soil degradation (physical, chemical, biological and ecological) while improving the environment. Increasing the SOC pool to above the critical level (10 to 15 g/kg) is essential to set-in-motion the restorative trends. Site-specific techniques of restoring soil quality include conservation agriculture, integrated nutrient management, continuous vegetative cover such as residue mulch and cover cropping, and controlled grazing at appropriate stocking rates. The strategy is to produce "more from less" by reducing losses and increasing soil, water, and nutrient use efficiency.

Keywords: soil resilience; climate change; soil functions; desertification; soil carbon sequestration

1. Introduction

Of the 5.5 billion people living in developing countries in 2014 [1], a large proportion of them depend on agriculture for their livelihood. In fact, one billion of these people are small landholders who cultivate <2 ha of land [2]. With limited resources and poor access to inputs, management of soil quality is essential to strengthen and sustain ecosystem services. Soil degradation is a 21st century global problem that is especially severe in the tropics and sub-tropics. Some estimates indicate degradation decreased soil ecosystem services by 60% between 1950 and 2010 [3]. Accelerated soil degradation has reportedly affected as much as 500 million hectare (Mha) in the tropics [4], and globally 33% of earth's land surface is affected by some type of soil degradation [5]. In addition to negatively impacting agronomic production, soil degradation can also dampen economic growth, especially in countries where agriculture is the engine for economic development [6]. Over and above the environmental and economic impacts, there are also health risks of soil erosion [7] and other degradation processes [8].

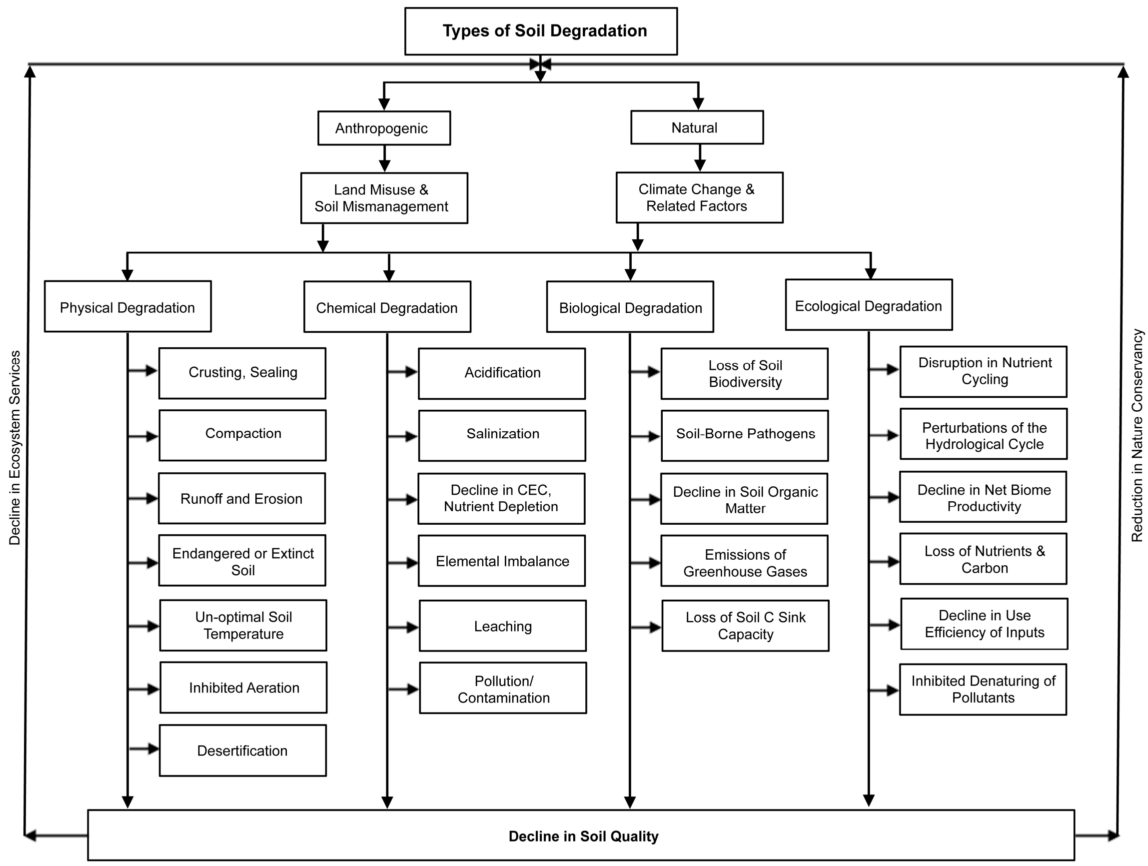

Figure 1. Types of soil degradation.

Soil degradation implies a decline in soil quality [8] with an attendant reduction in ecosystem functions and services. Conceptually, there are four types of soil degradation: (i) physical; (ii) chemical; (iii) biological; and (iv) ecological (Figure 1). Soil physical degradation generally results in a reduction in structural attributes including pore geometry and continuity, thus aggravating a soil's susceptibility to crusting, compaction, reduced water infiltration, increased surface runoff, wind and water erosion, greater soil temperature fluctuations, and an increased propensity for desertification.

Soil chemical degradation is characterized by acidification, salinization, nutrient depletion, reduced cation exchange capacity (CEC), increased Al or Mn toxicities, Ca or Mg deficiencies, leaching of NO_3-N or other essential plant nutrients, or contamination by industrial wastes or by-products. Soil biological degradation reflects depletion of the soil organic carbon (SOC) pool, loss in soil biodiversity, a reduction in soil C sink capacity, and increased greenhouse gas (GHG) emissions from soil into the atmosphere. One of the most severe consequences of soil biological degradation is that soil becomes a net source of GHG emissions (*i.e.*, CO_2 and CH_4) rather than a sink. Ecological degradation reflects a combination of other three, and leads to disruption in ecosystem functions such as elemental cycling, water infiltration and purification, perturbations of the hydrological cycle, and a decline in net biome productivity. The overall decline in soil quality, both by natural and anthropogenic factors, has strong positive feedbacks leading to a decline in ecosystem services and reduction in nature conservancy. Once the process of soil degradation is set-in-motion, often by land misuse and soil mismanagement along with the extractive farming, it feeds on itself in an ever-increasing downward spiral (Figure 2).

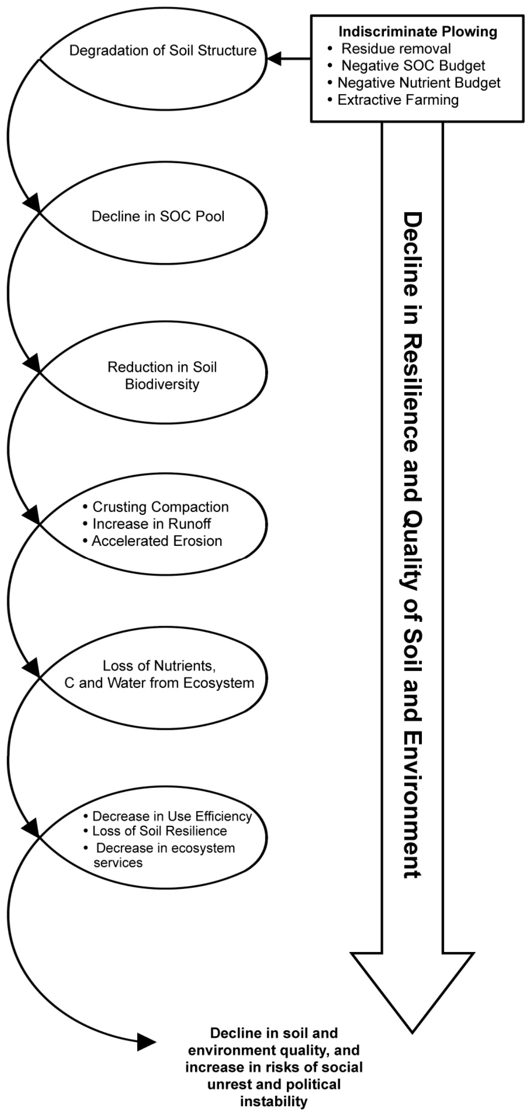

Figure 2. The downward spiral of decline in soil and environment quality exacerbated by indiscriminate plowing, residue removal and extractive farming.

The objectives of this review are to: (1) deliberate the role of soil resources in provisioning essential ecosystem services; (2) illustrate the impacts of soil degradation on decline in ecosystem services; and (3) identify strategies for improving soil quality to mitigate risks of soil degradation.

2. Soil and Ecosystem Services

Soil, the most basic of all resources, is the essence of all terrestrial life and a cultural heritage [9]. Yet, soil is finite in extent, prone to degradation by natural and anthropogenic factors, and is non-renewable over the human timescale (decades). Soil quality also has strong implications to human health [8,10], thus illustrating its important role in both society and the environment. Because of numerous ecosystem services provisioned through soils (e.g., food, feed, fiber, climate moderation through C cycling, waste disposal, water filtration and purification, elemental cycling) [11,12], soil quality must be protected or restored to enhance these services. Increased public awareness and a fundamental understanding of basic pedospheric processes (*i.e.*, biology, chemistry, physics, pedology, ecology) are essential both to enhancing long-term productivity and improving the environment [13].

3. Soil Organic Carbon and Its Impact on Soil Quality

The SOC pool, including its quantity and quality, is the defining constituent of soil [14,15]. Indeed, SOC pool is the most reliable indicator of monitoring soil degradation, especially that caused by accelerated erosion [16]. Soil degradation depletes the SOC pool, along with it, plant available N and other essential nutrients such as P and S. Furthermore, as identified repeatedly in this special issue of Sustainability, depletion of SOC pool is a global issue and a principal cause of soil degradation, especially in the European semi-arid Mediterranean regions [17]. Developing strategies to ensure the SOC pool is to increase and preferably maintain above the threshold or critical level of 10 to 15 g/kg (1.0%–1.5%), which is essential for reducing soil degradation risks and reversing degradation trends. Integrated nutrient management (INM) is one strategy that embodies sustainable management of the SOC pool and its dynamics [18]. Adoption of INM or similar management practices that create a positive soil/ecosystem C budget can not only increase productivity but also sequester additional atmospheric CO_2 into the SOC pool. This has been documented for many surface soils within the U.S. Corn Belt which act as C sinks when corn (*Zea mays* L.) is grown using recommended management practices (RMPs) such as conservation agriculture (CA) [19]. There also exists a strong relationship between vegetation cover and the SOC pool, such that excessive reductions in vegetation cover exacerbates risks of soil degradation and SOC depletion. A study conducted in the sub-tropical humid grasslands in South Africa indicated that the decline in grass (vegetative) cover from 100% to 0%–5% reduced the SOC pool by 1.25 kg/m^2 and the soil organic N (SON) pool by 0.074 kg/m^2 [20], There were also attendant declines in the C:N ratio and proportion of SOC and SON in the silt + clay fraction with the decline in aerial grass cover which negatively affected ecosystem functions of the acidic sandy loam soils. Similarly, transformation of a thicket vegetation to an open savanna (dominated by grasses) due to intensive grazing decreased soil quality in the Eastern Cape region of South Africa [21]. Indeed, savanna soils have lower SOC concentration and a greater tendency to crust than thicket soils because of the decreased quantity and stability of structural aggregates.

The widespread prevalence of degraded soils in sub-Saharan Africa (SSA), a classic example of a downward spiral, is attributed to over exploitation, extractive farming, low external inputs, and poor or improper management (Figure 2). Accelerated degradation is shrinking the finite soil resource even more rapidly in these regions of harsh climate and fragile soils. In this context, enhancing the SOC pool is important to sustain soil fertility and agronomic productivity [22]. Simply adding chemical fertilizers or improved varieties, as is often erroneously recommended even by well-intended advocates, is not enough.

The SOC pool of agricultural soils of West Africa, similar to those of croplands in other developing counties (e.g., South Asia), is severely depleted by over-exploitation of natural resources [23]. These soils must therefore be managed to increase both soil C and vegetation [24,25] to restore the degraded agroecosystem services. Changes in aerial vegetative cover could thus be used as an early indicator of shifts in soil ecosystem functions within fragile environments. A shift in vegetative cover may be caused by alterations in land use or climate change. In addition to SOC and SON pools, soil moisture regime is another important indicator of climate change [26]. In conjunction with changes in soil moisture regimes, projected global warming may also influence SOC decomposition rates [27,28] including that of fine woody debris. Field experiments have shown that warming increases mass loss for all vegetative species and size classes by as much as 30%. However, larger debris and that with higher initial lignin content decomposes more slowly than smaller debris and that with lower antecedent lignin content. Indeed, degradation of lignin may not follow the same trend as that of total mass loss [29]. Along with the adverse effects of soil erosion and other degradation processes, the SOC pool is also prone to climate change and associated alterations in temperature and moisture regimes.

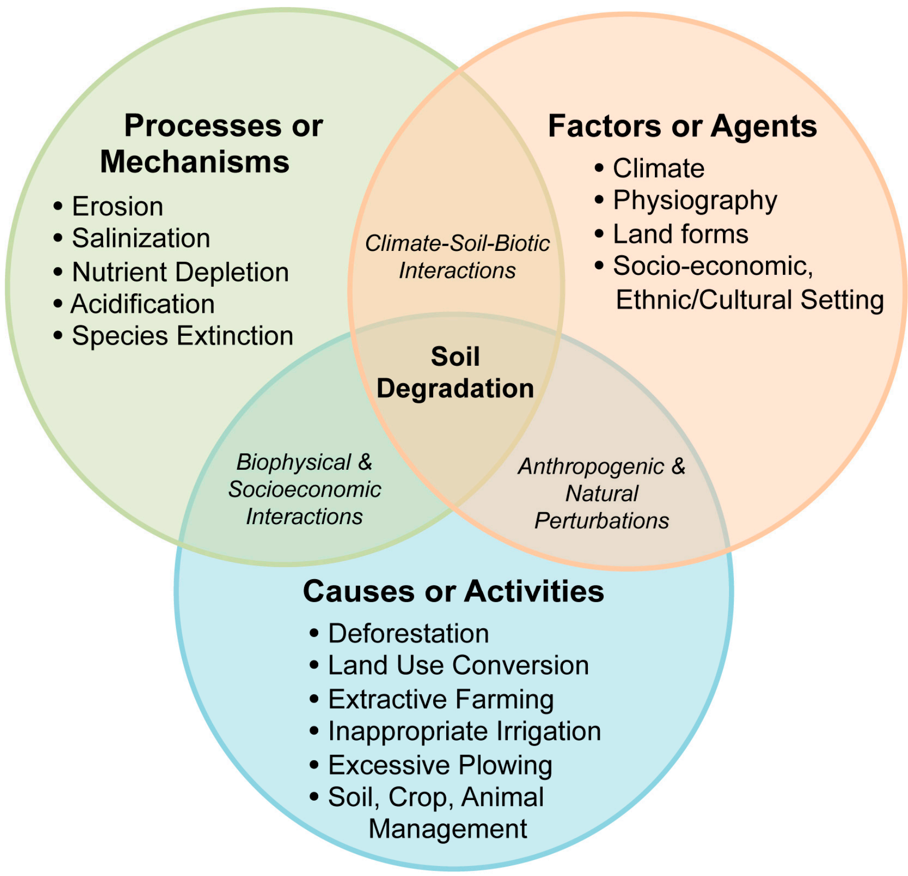

Figure 3. The process-factor-cause nexus as a driver of soil degradation.

The self-reinforcing soil degradation process (Figure 2) is strongly exacerbated by the interaction between processes, factors and causes of soil degradation (Figure 3). Processes include the mechanisms (types) of soil degradation. Factors comprise agents of degradation related to natural or anthropogenic drivers such as climate, physiography, socio-economic or ethnic/cultural parameters. Causes of soil degradation include specific activities which aggravate the adverse effects of processes and factors. Examples of specific causes include activities such as deforestation, land use conversion, extractive farming practices or over-exploitation, excessive grazing, excessive plowing *etc.* (Figure 3). The process-factor- cause nexus is strongly impacted by site-specific conditions. Thus, understanding the nexus or connectivity is critical to restoring soil quality and mitigating degradation.

4. Soil Quality Index

The SOC pool is a key indicator of soil quality, and an important driver of agricultural sustainability. In addition to its amount, other parameters of SOC include its depth distribution, quality or attributes (physical, chemical, biological), and the turnover rate or the mean residence time (MRT). Relevant indicators of soil physical quality include amount and stability of aggregates; susceptibility to crusting and compaction; porosity comprising of pore geometry and continuity; water transmission (infiltration rate and amount) and retention as plant-available water capacity (PAWC); aeration and gaseous exchange; effective rooting depth; soil heat capacity and the temperature regime. Similarly, appropriate indicators of soil chemical quality include pH, CEC, nutrient availability; and favorable elemental balance and lack of any toxicity or deficiency. Relevant indicators of soil biological quality are microbial biomass C (MBC), activity and diversity of soil fauna and flora, absence of pathogens and pests as indicated by a soil's disease-suppressive attributes. An optimal combination of these properties affects agronomic productivity; use efficiency of water, nutrients and other inputs; and sustainability of management systems. Indicators of soil quality differ among soil types, climates and land uses. For example, there are specific soil quality indicators for the intensively managed soils of the Indo-Gangetic Plains [30] that will differ from those for tropical Alfisols in semi-arid regions [31–34]. A spectral soil quality index based on application of reflectance spectroscopy has also been proposed as a diagnostic tool to assess soil quality [35]. This technique can provide a characterization of physical, chemical and biological attributes that can be merged together to indicate how well a soil is functioning for a specific use [36–39].

5. Conservation Agriculture and Soil Quality

Four basic principles of CA are [40]: (i) retention of crop residue mulch; (ii) incorporation of a cover crop in the rotation cycle; (iii) use of INM involving combination of chemical and bio fertilizers; and (iv) elimination of soil mechanical disturbances. Properly implemented on suitable soil types, CA has numerous co-benefits including reduced fuel consumption and increased soil C sequestration. Mechanical tillage is an energy-intensive process [41] and its reduction or elimination can decrease consumption of fossil fuels. For example, conversion from plow tillage (PT) to CA can reduce diesel consumption by as much as 41 L/ha [42].

In addition, an increase in SOC pool under CA can occur in soils not prone to accelerated erosion, and those which have optimal management strategies. A modeling study in Western Kenya showed that site-specific optimal management strategies can lead to SOC pool of 20 to 40 Mg/ha in 0.1 m depth and corn grain yield of 3.5 to 4.2 Mg/ha [43]. The most desirable tillage systems are those which restore soil quality, minimize risks of soil erosion, improve use efficiency of rain water and fertilizers [44] and minimize risks of SOC and nutrient depletion. Impacts of CA on soil quality restoration, an example of an upward spiral, is outlined in Figure 4.

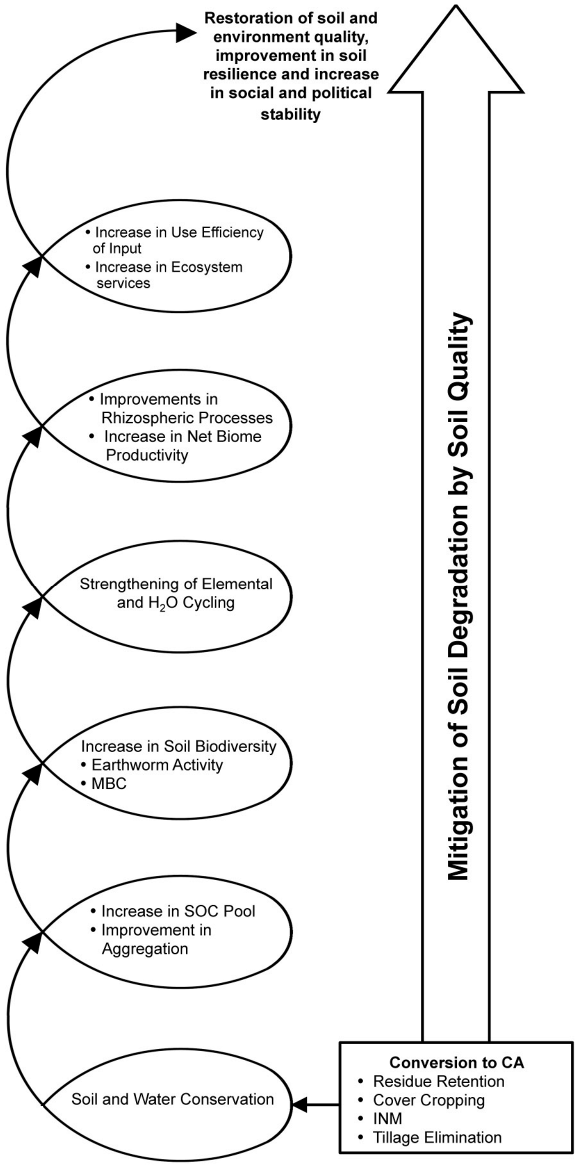

Figure 4. Increase in soil resilience and mitigation of soil degradation by conservation agriculture (CA). Meta-analyses and any other comparisons among unrelated soil management practices can lead to misinterpretation of SOC sink capacity by CA [45] and erroneous inferences on agronomic productivity [46]. The mission is to identify site-specific packages of CA practices to make it functional (INM = integrated nutrient management).

Indiscriminate use of plowing, coupled with excessive removal of crop residues and unbalanced use of chemical fertilizers, can degrade soil quality, deplete SOC pool, and aggravate risks of soil erosion (Figure 2). In contrast, conversion of plow/traditional tillage to CA, especially on sloping lands and those vulnerable to accelerated erosion by water and wind under conventional management, can be conservation-effective, reverse degradation trends, and set-in-motion soil restoration processes with an upward spiral (Figure 4). Retention of crop residue mulch, and incorporation of a cover crop (forages) in the rotation cycle while eliminating bare fallows, can conserve soil and water and improve SOC pool in the surface layer (Figure 4). Increases in soil biodiversity, MBC and activity of earthworms and termites can all improve aggregation and encapsulate C within stable micro-aggregates as outlined in the hierarchy concept [47]. Strengthening elemental cycling, in conjunction with coupled cycling of C and H_2O, can increase the solum's C sink capacity and soil profile depth through increased bioturbation by earthworms or termites, and use of deep-rooted plants such as pigeon pea (*Cajanus cajan*), townsville stylo (*Stylosanthes humilis* (Kunth) Hester), or alfalfa (*Medicago sativa*). Long-term (>10 years) soil quality improvement will increase net biome productivity, improve water and nutrient use efficiencies, and increase above and below-ground biomass-C within the ecosystem. Progressive improvements in rhizospheric processes, driven by biotic mechanisms, would restore soil quality and mitigate degradation (Figure 4). It is important to note, however, that CA is a holistic and system-based approach. Mere elimination of plowing, while removing an excessive amount of crop residues and biomass for other uses (e.g., biofuels, industrial purposes) is not CA, and is rather an extractive farming system with negative impacts on soil and the environment. Thus, comparative analyses of un-related datasets can lead to erroneous assessments of SOC sink capacity associated with a properly implemented CA system [45] and misinterpretation of agronomic yields [46]. Furthermore, improvements in soil quality require more than the input of new varieties and chemical fertilizers [48]. The real issue is improving physical, biological and ecological components of soil quality, and set-in-motion an upward spiral eventually leading to social and political stability and international security (Figure 4).

6. Soil Fertility Management to Restore Soil Quality

Sustainable intensification (SI), producing more from less by reducing losses and increasing the use efficiency, is attainable only through improvement of soil quality including chemical quality or soil fertility. Although not the only way to increase soil fertility, the use of INM is a very effective approach for achieving SI. Nutrient depletion and loss of soil fertility are major causes of low productivity [49] in many developing countries. Use of organic amendments, by recycling organic by-products including urban waste, is a useful strategy to enhance soil fertility [50], and improve structural stability or aggregates [51]. While, nitrogen (N) input is important to improving soil fertility, its improper and/or excessive use can also lead to environmental pollution. China consumes about 30% of the world's N fertilizer [52], and is able to feed ~22% of the world population on just 6.8% of the global cropland area. However, the country has severe environmental problems because of low N use efficiency, leaching of reactive N into surface and groundwater resources, and emission of N (as N_2O) into the atmosphere.

7. Soil Quality and Water Resources

High soil quality or a healthy soil provides the foundation for a healthy economy, environment, and terrestrial biosphere. Thus, there exists a close link between soil quality and water resources in close proximity, such as the health of coastal ecosystems [53]. Changes in land use often affect water quality and pollutant loading [54,55]. Off-site movement of agricultural chemicals is often a significant source of non-point pollution. Many of the major rivers in countries with emerging economies have severe water pollution, contamination and eutrophication problems [56]. Downstream areas are often adversely affected because of adhoc agricultural development activities upstream. Among the most important adverse impacts are river desiccation, ground water depletion, surface and ground water pollution, accelerated erosion, sedimentation, salinization, and nutrient depletion [57]. These problems are especially severe in densely populated regions (e.g., East Asia, South Asia). Rapid urbanization, industrialization and increases in water demand have created severe water quality problems and degradation of the Ganges [58]. Land use changes induced by urbanization have had strong impacts both on soil and water quality in northern Iran [54]. Release of P from agricultural sources to streams and rivers has become a major factor affecting surface water quality not only in China [59], but also in the Great Lakes of North America (e.g., algal bloom of 2014). In Thailand, agriculture [especially rice (*Oryza sativa*) farming] is the key nutrient source within the Thachin River Basin [56]. Recent industrialization and community development have exacerbated water pollution and habitat degradation in the Gulf of Thailand [60]. The problem has been exacerbated by a rapid decrease in mangrove forest, coral reefs, and fishery resources due to misuse and mismanagement.

Irrigated agriculture, an important management strategy for high agronomic productivity in arid and semi-arid regions, is a mixed blessing. Mismanagement of irrigation waters has exacerbated problems with saline-sodic soils which now occupy more than 20% of the irrigated lands [61]. Furthermore, arid wetlands are also prone to contamination by sub-surface agriculture irrigation and drainage as in the Western USA [62]. These areas often experience toxicity problems in fish and wildlife due to drainage of water contaminants. In response, provisions must be made to reduce the amount of contaminants entering wetlands, and to provide for better allocation of freshwater between agriculture and wildlife [62]. Salinity problems are also often confounded by the reuse of untreated waste water (gray/black water) in agriculture [63], especially in urban areas prone to water shortages or those having water resources of marginal quality.

Restoring soil quality within managed ecosystems is critical to improving and sustaining water quality. To accomplish this goal, it is essential to develop strategies for integrated management of soil and water resources because of their strong inter-connectivity or the soil-water-waste nexus. While integrated water management alone is useful [64], the importance of the soil-water nexus cannot be over-emphasized [24]. Management of sediments, especially contaminated ones [65], is another important component of the soil-water nexus that must be critically examined.

8. Strategies for Soil Quality Restoration

Restoring the quality of degraded soils is a challenging task, especially in regions dominated by small, resource-poor landholders. Re-carbonization of the depleted SOC pool, which is essential to numerous functions, requires regular input of biomass-C and essential elements (*i.e.*, N, P, and S) [66]. Thus, restoration of soil quality is a societal, national and international task that necessitates a coordinated approach.

There are three basic strategies of restoring soil quality (Figure 5): (i) minimizing losses from the pedosphere or soil solum; (ii) creating a positive soil C budget, while enhancing biodiversity; and (iii) strengthening water and elemental cycling. There is no silver bullet or panacea to accomplish these basic tasks, and site-specific factors (biophysical, social, economic, cultural) play a significant role. Some examples of site-specific, RMPs are outlined in Table 1. However, each of these technologies has their own tradeoffs, which must be duly considered and minimized.

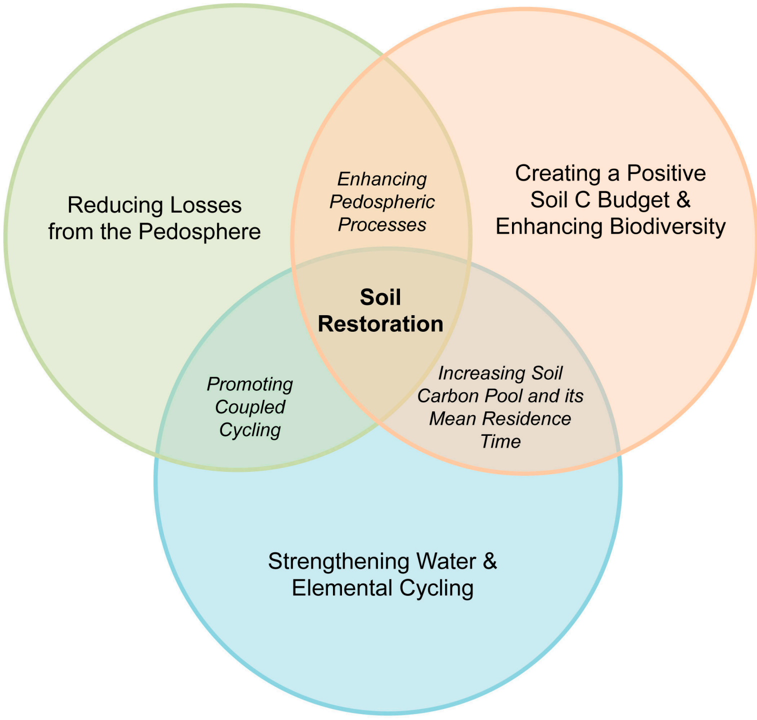

Figure 5. Three strategies of restoring and managing soil quality for mitigating risks of soil degradation.

Table 1. Strategies to improve soil quality.

Strategy	Region	Process	Reference
Litter turnover	Tropics	The rate of organic matter and C supply and nutrient cycling reactivation	[3]
Forestry Plantations	Tropics	Silvo-pastoral system for nutrient cycling	[67]
Woodlot Islets	Degraded drylands	Silvo-pastoral systems in drylands	[68]
Soil Carbon Sequestration	Agroecosystems	Optimal management strategies	[69]
Integrated Nutrient Management	Sub-Saharan Africa	Soil quality management	[17]
Nutrient Management for SOC Sequestration	Sub-Tropical Red Soils (China)	Soil carbon buildup	[70]
Manuring	Indus Plains	Application of farm manure	[71]
Residue Retention as Mulch	Mexican Highlands	Improvement of soil structure	[72]
Regular Organic Inputs	Western Kenya	Nutrient retention and soil structure improvement	[43,73]
Urban Waste	Mediterranean Europe	Enhancing soil fertility	[16,74]
Soil Biological Management	Global soils	Enhance ecosystem services provisioned by SOC pool	[15]
Environmental Awareness	U.S.	Promoting technology adoption	[75]

8.1. Soil Erosion Management

Soil erosion must be curtailed to within the tolerable limits, which is often much less than the presumed value of 12.5 Mg/ha per year. Accelerated erosion also depletes the SOC pool and nutrient reserves. In general, the enrichment ratio of SOC, clay and essential plant nutrients (N, P, S) is >1 (and most often as much as 5 or more) because of the preferential removal of these constituents. Conversion from PT to CA can reduce risks associated with soil erosion and nutrient loss while also providing numerous on- and off-site benefits (Figure 4) [12]. An important strategy is to establish cause-effect relationships, alleviate the causative factors and minimize the risks. Accelerated erosion is a symptom of land misuse and soil mismanagement. Reductions in plant cover caused by over-grazing and the trampling effect can degrade soil structure, reduce water infiltration, increase runoff, aggravate soil erosion, and cause severe economic losses [76]. As an example, experiments conducted in South Africa indicated that plant cover reduction by overgrazing significantly decreased the SOC pool with strong impact on the C cycle [77]. In arid regions, fire-induced depletions of the vegetation cover can also exacerbate the problem, especially after a torrential rainfall because ash left on the soil surface can aggravate hydrophobicity by creating an obtuse contact angle between the solid and liquid phases. When the protective litter cover is burned, the very first rainfall generally results in high surface runoff and aggravates erosion as was the classic situation of wild fire in May–June 2000 in hills which threatened the Los Alamos National Laboratory by runoff and sedimentation. Experiments conducted in Spain indicated high post-fire soil degradation risks and the need for identification of a short-term strategy to conserve soil and water on steep slopes with erodible soils [78]. In addition to the adverse effects on soil quality and productivity, there are also health risks associated with soil erosion [79]. This is especially true for regions prone to wind erosion and dust storms, such as the Harmattan in the Sahel [80].

8.2. Improving Soil/Agro-Biodiversity

Soil biota are important to soil quality and reduce risks of degradation and desertification. Indeed, soil biota comprise a major component of global terrestrial biodiversity and perform critical roles in key ecosystem functions (e.g., biomass decomposition, nutrient cycling, moderating CO_2 in the atmosphere, creating disease suppressive soils, *etc.*). Improving activity and species diversity of soil fauna and flora (micro, meso and macro) is therefore essential to restoring and improving soil quality and reducing risks of soil degradation. Adverse effects of agricultural management on soil microbiological quality is another global concern. As a management tool, either a microbiological quality index [81] or a microbiological degradation index [82] can be useful for decision-making processes [82] Relevant parameters include MBC, respiration, water soluble carbohydrates, enzymatic activities, dehydrogenase activity and activities of other important hydrolases (e.g., urease, protease, phosphatas and β-glucosidase) [82]. There are also marked seasonal changes in biotic and abiotic factors that affect the biological component of soil resources. Vegetative cover, influenced by seasonal changes, has a strong impact on soil microbiological processes. In degraded soils of arid and semi-arid regions, changes in soil moisture regimes can also affect MBC and activity [83].

The importance of macro-organisms (e.g., earthworms, termites) for restoring soil quality has been widely recognized for centuries [84]. Conversion of PT to CA, with crop residue mulch and cover cropping (Figure 4), can increase earthworm activity and also improve structural properties [85,86], but the conversion can also have implications regarding transport of agricultural pollutants into the drainage water [85]. Experiments conducted in central Mexico indicated that conversion of PT to CA improved soil surface aggregation and aggregate stability, increased water infiltration, and enhanced most parameters related to soil quality [87]. Therefore, risks of soil degradation can be mitigated through adoption of land use and management systems which improve soil biological processes, and introduction of beneficial organisms into soils by selective inoculation. For these and other reasons, the presence of earthworms, termites and other soil biota are often identified as important indicators of quality in tropical soils [86,88].

8.3. Soil Restorative Farming/Cropping Systems

Farming/cropping systems (rotations, soil fertility management, erosion control, grazing/stocking rate, water management) affect the type, rate and severity of soil degradation by altering the SOC pool, structural morphology, and other properties. Specifically, crop rotations and grazing can significantly impact SOC pool and the attendant soil properties [89]. Similar to arable lands, managing quality of rangeland soils is also essential for reducing risks of degradation. Sustainable management of rangeland soils is especially challenging because of high variability, harsh environments, and the temptation for over-grazing. A reduction in the proportion of palatable perennials, increases in densification (compaction), and declines in SOC are some of the constraints that need to be alleviated [90–92]. An important strategy to reduce the risks of degrading rangeland soils is to conserve and efficiently manage soil water through an improved understanding of the hydrological attributes [93,94]. Under West African conditions, construction of stone bunds and establishment of contour vegetative hedgerows can be effective for water conservation [95]. Establishment and management of forage trees (*i.e.*, *Acacia fadherbia*) [96] and grass-legume mixtures [97] can also improve the quality of rangeland soils.

9. Soil Resilience

The term soil resilience refers to the ability of the soil to recover its quality in response to any natural or anthropogenic perturbations. Soil resilience is not the same as soil resistance, because resilience refers to “elastic” attributes that enable a soil to regain its quality upon alleviation of any perturbation or destabilizing influence [98,99]. Sound rhizospheric processes are essential for soil resilience against anthropogenic/natural perturbations. Being a dominant site of microbial metabolism, it is pertinent to identify management systems that stimulate soil microbiotic activity and related microbial processes. In this context, an “eco-physiological index” has been proposed to assess the impact of soil resilience [100] on soil processes. Managing the quantity and quality of SOC pool is once again a crucial guiding principle in identifying appropriate management practices that will strengthen resilience and reduce risks for soil degradation [101]. The SOC pool size is strongly related to the quantity of both above and below-ground biomass-C inputs. It is the assured, continuous input of the biomass-C that moderates MBC, provides a reservoir of plant nutrients (e.g., N, P, S), influences nutrient cycling, and improves/stabilizes soil structural morphology and geometry [98,99]. The so-called "sustainable land management (SLM)" concept is based on similar strategies of preserving productivity of the resource base for future generations [101]. There are also some organic management options for reducing soil degradation risk and improving human health [102], that may have site-specific niches. Biochar, a C-rich soil amendment derived from biomass by pyrolysis, can be produced from human sewage [103] and used to improve soil resilience [98] while also mitigating climate change.

In addition to biotic techniques, ancient farmers also developed mechanical/engineering techniques to sustain and improve their soils. Terraced agriculture evolved independently at several locations around the world (e.g., East Asia, the Himalayan region, Yemen, the Andean region). A study of pre-Columbian terraces from the Paca Valley, Peru, indicated that soil depletion from cultivation has compromised soil quality through loss of fine material and SOC. Overall, however, Paca Valley terraces have improved topsoil retention and supported deep profile with a good soil resilience [104].

There are no universally applicable techniques of managing soil resilience, but there are several approaches for ensuring sustainable soil management. Each of these approaches has tradeoffs that must be objectively and critically assessed (Table 1, Figure 6). In view of the heavy demands for agricultural produce to meet the needs of the growing and increasingly affluent population and emerging economies (e.g., India, China, Brazil, Mexico), the role of agricultural practices and their impact on soil, climate, gaseous emission, water resources, biodiversity, along with economic, political, social and ecologic dimensions [105] must be considered more now than in the past. The ideal strategy is to meet increasing global food demands while simultaneously restoring soil quality, improving the environment, and minimizing the tradeoffs.

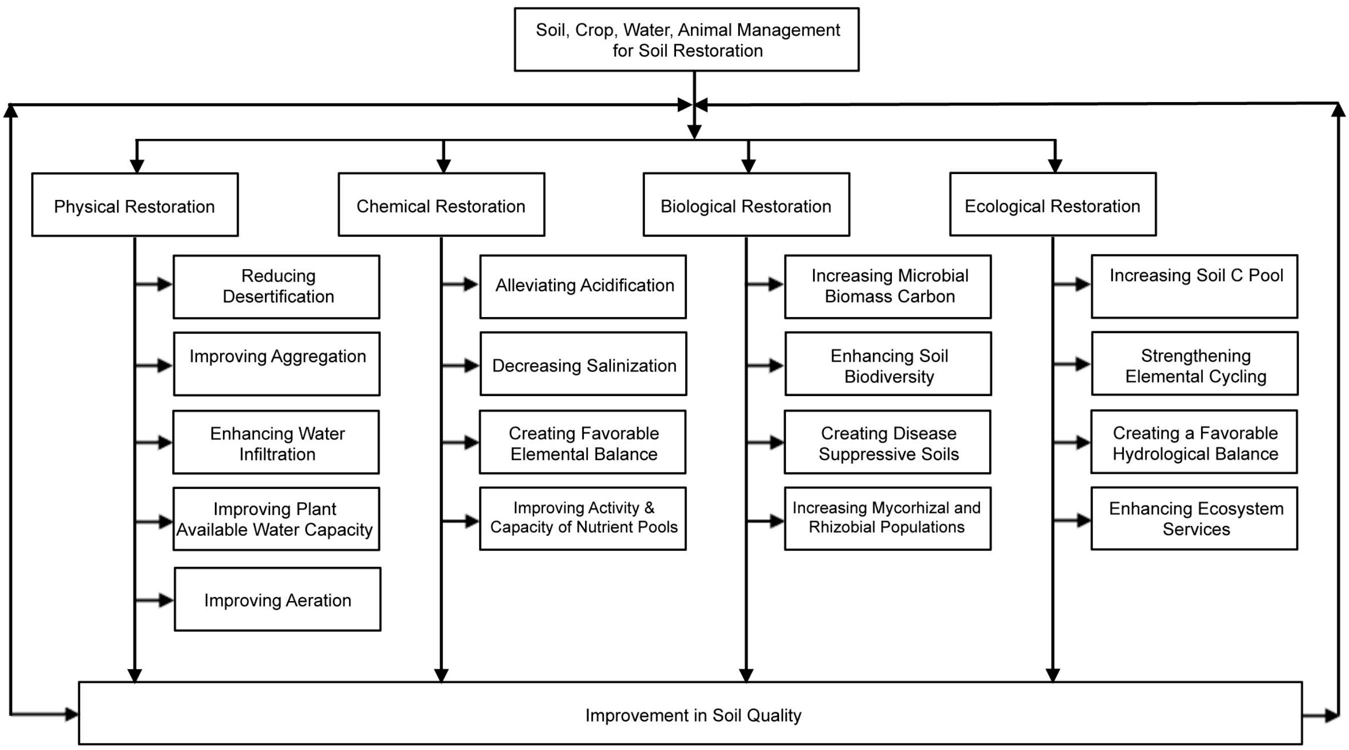

Figure 6. Strategies of restoring soil quality.

In the context of social, economic and cultural issues, it would be a serious omission to ignore poverty, human drudgery and social/gender equity. There is a strong link between poverty and soil quality. When people are poor, desperate and hungry, they pass on their sufferings to the land. Yet, some sociologists have questioned poverty as a major cause of soil/environmental degradation [106]. Stewardship and desperateness are mutually exclusive. Yield gaps, due to lack of adoption of RMPs in SSA and SA, are poverty traps that require a paradigm shift [107]. Since the 1980s, China has bridged the yield gap, alleviated poverty and improved soil quality [108]. Nonetheless, environmental issues remain to be addressed, effectively and immediately, to make China's agricultural revolution a successful venture [109].

10. Peak Soil *vs.* Endangered Soil

Endangered soil [110] and peak soil (losing soil more quickly than it is replaced [111] are concepts that need to be considered philosophically and scientifically because soil resources are finite and non-renewable over the human time frame. They are also geographically disturbed in a non-uniform manner. Excessive plowing, accelerated erosion, and over fertilization are all depleting soil resources, threatening food security, and jeopardizing the environment. Food insecurity is made even more acute by scarcity of soil resources of good quality (prime land) and risks of soil degradation [112]. Soil degradation is affecting 33% of all soils. Indeed, soil is an essentially forgotten resource [113]. In response, a holistic management approach is needed to improve soil quality. Site-specific and appropriate land husbandry practices must be identified to restore physical, chemical, biological, and ecological components of soil quality [114]. The goal should be to increase productivity per unit area, time, and energy input; while restoring soil quality and reducing environmental degradation risks. In terms of soil quality, ecosystem services provisioned by the SOC pool cannot be by-passed by applying commercial chemicals or other technologies [15]. Only by increasing SOC pool can the need for additional inorganic fertilizer N be reduced, especially in degraded soils. Conversion to CA, combined with residue retention and other components, is a sustainable option for several soil-specific conditions (Figure 4). Environmental awareness and stewardship are also important for improving adoption of RMPs and promoting soil restoration.

11. Conclusions

Soil resources are finite in extent, unequally distributed geographically, prone to degradation by land misuse and mismanagement, but essential to all terrestrial life and human wellbeing. Soil degradation can be physical (e.g., decline in structure, crusting, compaction, erosion, anaerobiosis, water imbalance), chemical (e.g., acidification, salinization, elemental imbalance comprising of toxicity or deficiency, nutrient deficiency), biological (depletion of SOC pool, reduction in soil biodiversity, decline in microbial biomass-C), or ecological (e.g., disruption in elemental cycling, decline in C sink capacity). Soil degradation leads to reduction in ecosystem functions and services of interest to human and conservation of nature. The SOC pool, its amount and depth-distribution along with turnover and mean residence time, is a critical component of soil quality and source of numerous ecosystem services. Soil degradation depletes SOC pool, and its restoration to threshold levels of at least 11 to 15 g kg^{-1} (1.1%–1.5% by weight) within the root zone is critical to reducing soil and environmental degradation risks. Important strategies for soil quality restoration and reducing environmental degradation risks are: (i) reducing soil erosion; (ii) creating a positive soil/ecosystem C budget; (iii) improving availability of macro (N, P, S) and micro-nutrients (Zn, Fe, Cu, Mo, Se); (iv) increasing soil biodiversity especially the microbial process; and (v) enhancing rhizospheric processes. The ultimate goal should be to adopt a holistic and integrated approach to soil resource management. The finite nature of soil resources must never be taken for granted—they must be used, improved, and restored.

Conflicts of Interest

There is no conflict of interest in publishing this article by the author.

References

1. Van Pham, L.; Smith, C. Drivers of agricultural sustainability in developing countries: A review. *Environ. Syst. Decis.* **2014**, *34*, 326–341.
2. IFAD. *The Rural Poverty Report 2011*; International Fund for Agricultural Development: Rome, Italy, 2010.
3. Leon, J.; Osorio, N. Role of Litter Turnover in Soil Quality in Tropical Degraded Lands of Colombia. *Sci. World J.* **2014**, *13*, doi:10.1155/2014/693981.
4. Lamb, D.; Erskine, P.; Parrotta, J. Restoration of degraded tropical forest landscapes. *Science* **2005**, *310*, 1628–1632.
5. Bini, C. Soil: A precious natural resource. In *Conservation of Natural Resources*; Kudrow, N.J., Ed.; Nova Science Publishers: Hauppauge, NY, USA, 2009; pp. 1–48.
6. Scherr, S.J. The future food security and economic consequences of soil degradation in the developing world. In *Response to Land Degradation*; Oxford Press: New Delhi, India, 2001; pp. 155–170.
7. Guerra, A.; Marcal, M.; Polivanov, H.; Lima, N.; Souza, U.; Feitosa, A.; Davies, K.; Fullen, M.A.; Booth, C.A. Environment management and health risks of soil erosion gullies in São Luíz (Brazil) and their potential remediation using palm-leaf geotextiles. In *Environmental Health Risk II*; WIT Press: Southampton, UK, 2005; pp. 459–467.
8. Lal, R. Soil degradation as a reason for inadequate human nutrition. *Food Sec*. **2009**, *1*, 45–57.
9. Bini, C.; Zilioli, D. Is Soil a Cultural Heritage? Proc. III Conv. Int. Architettura del Passaggio, 20 suppl. DVD. Available online: http://arca.unive.it/handle/10278/22330 (accessed on 12 May 2015).
10. Abrahams, P. Soils: Their implications to human health. *Sci. Total Environ.* **2002**, *291*, 1–32.
11. Robinson, D.; Emmett, B.; Reynolds, B.; Rowe, E.; Spurgeon, D.; Keith, A.; Lebron, I.; Hockley, N.; Hester, R.; Harrison, R. Soil Natural Capital and Ecosystem Service Delivery in a World of Global Soil Change. *Soils Food Secur.* **2012**, *35*, 41–68.
12. Graber, D.R.; Jones, W.A.; Johnson, J.A. Human and ecosystem health. *J. Agromedicine* **1995**, *2*, 47–64.
13. Singer, M.J.; Warkentin, B.P. Soil in an environmental context: An American perspective. *Catena* **1996**, *27*, 179–189.

14. Krupenikov, I.; Boincean, B.; Dent, D.; Krupenikov, I.; Boincean, B.; Dent, D. Humus-Guardian of Fertility and Global Carbon Sink. In *The Black Earth: Ecological Principles for Sustainable Agriculture on Chernozem Soils*; International Year of Planet Earth 2011; Springer: Dordrecht, The Netherlands, 2011; pp. 39–50.
15. Manlay, R.; Feller, C.; Swift, M. 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.
16. Rajan, K.; Natarajan, A.; Kumar, K.; Badrinath, M.; Gowda, R. Soil organic carbon—the most reliable indicator for monitoring land degradation by soil erosion. *Curr. Sci.* **2010**, *99*, 823–827.
17. Diacono, M.; Montemurro, F. Long-term effects of organic amendments on soil fertility: A review. *Agron. Sustain. Dev.* **2010**, *30*, 401–422.
18. Vanlauwe, B.; Hester, R.; Harrison, R. Organic Matter Availability and Management in the Context of Integrated Soil Fertility Management in sub-Saharan Africa. *Soils Food Secur.* **2012**, *35*, 135–157.
19. Clay, D.; Chang, J.; Clay, S.; Stone, J.; Gelderman, R.; Carlson, G.; Reitsma, K.; Jones, M.; Janssen, L.; Schumacher, T. Corn Yields and No-Tillage Affects Carbon Sequestration and Carbon Footprints. *Agron. J.* **2012**, *104*, 763–770.
20. Dlamini, P.; Chivenge, P.; Manson, A.; Chaplot, V. Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. *Geoderma* **2014**, *235*, 372–381.
21. Mills, A.; Fey, M. Transformation of thicket to savanna reduces soil quality in the Eastern Cape, South Africa. *Plant Soil* **2004**, *265*, 153–163.
22. Tiessen, H.; Cuevas, E.; Chacon, P. The role of soil organic-matter in sustaining soil fertility. *Nature* **1994**, *371*, 783–785.
23. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*, 1623–1627.
24. Lal, R. Soil carbon sequestration in natural and managed tropical forest ecosystems. *J. Sust. For.* **2005**, *21*, 1–30.
25. Batjes, N. Options for increasing carbon sequestration in West African soils: An exploratory study with special focus on Senegal. *Land Degrad. Dev.* **2001**, *12*, 131–142.
26. Eaton, W.; Roed, M.; Chassot, O.; Barry, D. Differences in soil moisture, nutrients and the microbial community between forests on the upper Pacific and Caribbean slopes at Monteverde, Cordillera de Tilaran: Implications for responses to climate change. *Trop. Ecol.* **2012**, *53*, 235–240.
27. Melillo, J.M.; Steudler, P.A.; Tian, H.; Butler, S. Fertilizing change: Carbon-nitrogen interactions and carbon storage in land ecosystems. In *Handbook of Climate Change and Agroecosystems: Impact, Adaptation and Mitigation*; Hillel, D., Rosenzweig, C., Eds.; Imperial College Press: London, UK, 2010; pp. 21–36.
28. Melillo, J.; Steudler, P.; Aber, J.; Newkirk, K.; Lux, H.; Bowles, F.; Catricala, C.; Magill, A.; Ahrens, T.; Morrisseau, S. Soil warming and carbon-cycle feedbacks to the climate system. *Science* **2002**, *298*, 2173–2176.
29. Berbeco, M.; Melillo, J.; Orians, C. Soil warming accelerates decomposition of fine woody debris. *Plant Soil* **2012**, *356*, 405–417.

30. Ray, S.; Bhattacharyya, T.; Reddy, K.; Pal, D.; Chandran, P.; Tiwary, P.; Mandal, D.; Mandal, C.; Prasad, J.; Sarkar, D.; *et al.* Soil and land quality indicators of the Indo-Gangetic Plains of India. *Curr. Sci.* **2014**, *107*, 1470–1486.
31. Sharma, K.; Grace, J.; Mandal, U.; Gajbhiye, P.; Srinivas, K.; Korwar, G.; Bindu, V.; Ramesh, V.; Ramachandran, K.; Yadav, S. Evaluation of long-term soil management practices using key indicators and soil quality indices in a semi-arid tropical Alfisol. *Aust. J. Soil Res.* **2008**, *46*, 368–377.
32. Karlen, D.; Mausbach, M.; Doran, J.; Cline, R.; Harris, R.; Schuman, G. Soil quality: A concept, definition, and framework for evaluation. *Soil Sci. Soc. Am. J.* **1997**, *61*, 4–10.
33. Karlen, D.; Stott, D.; Doran, J.; Coleman, D.; Bezdicek, D.; Stewart, B. A framework for evaluating physical and chemical indicators of soil quality. *Defin. Soil Q. Sustain. Environ.* **1994**, *35*, 53–72.
34. Andrews, S.S.; Carroll, C.R. Designing a soil quality assessment tool for sustainable agroecosystems management. *Ecol. Appl.* **2001**, *11*, 1573–1585.
35. Paz-Kagan, T.; Shachak, M.; Zaady, E.; Karnieli, A. A spectral soil quality index (SSQI) for characterizing soil function in areas of changed land use. *Geoderma* **2014**, *230*, 171–184.
36. Lal, R. *Methods and Guidelines for Assessing Sustainable Use of Soil and Water Resources in the Tropics*; USDA/SMSS Bull: 21; US Department of Agriculture: Washington, DC, USA, 1994.
37. Andrews, S.; Karlen, D.; Cambardella, C. The soil management assessment framework: A quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.* **2004**, *68*, 1945–1962.
38. Andrews, S.; Karlen, D.; Mitchell, J. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agric. Ecosyst. Environ.* **2002**, *90*, 25–45.
39. Gugino, B.K. *Cornell Soil Health Assessment Training Manual*; New York State Agricultural Experiment Station Cornell University: New York, NY, USA, 2009.
40. Lal, R. On Sequestering Carbon and Increasing Productivity by Conservation Agriculture. *J. Soil Water Conserv.* **2015**, in press.
41. Rodríguez, Y.E.O.; Hernández, D.C. Energetic balance of two farming tools in a Fluvisol for the cultivation of sweet potato (Ipomoea batatas Lam). *Rev. Cienceis Tecinas Agropecu.* **2013**, *22*, 21–25.
42. Labreuche, J.; Lellahi, A.; Malaval, C.; Germon, J. Impact of no-tillage agricultural methods on the energy balance and the greenhouse gas balance of cropping systems. *Cah. Agric.* **2011**, *20*, 204–215.
43. Kimetu, J.; Lehmann, J.; Ngoze, S.; Mugendi, D.; Kinyangi, J.; Riha, S.; Verchot, L.; Recha, J.; Pell, A. Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems* **2008**, *11*, 726–739.
44. So, H.; Kirchhof, G.; Bakker, R.; Smith, G. Low input tillage/cropping systems for limited resource areas. *Soil Tillage Res.* **2001**, *61*, 109–123.
45. Powlson, D.; Stirling, C.; Jat, M.; Gerard, B.; Palm, C.; Sanchez, P.; Cassman, K. Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Chang.* **2014**, *4*, 678–683.
46. Pittelkow, C.; Liang, X.; Linquist, B.; van Groenigen, K.; Lee, J.; Lundy, M.; van Gestel, N.; Six, J.; Venterea, R.; van Kessel, C. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **2015**, *517*, U365–U482.

47. Tisdall, J.; Oades, J. Organic-matter and water-stable aggregates in soils. *J. Soil Sci.* **1982**, *33*, 141–163.
48. Sanchez, P.A. En route to plentiful food production in Africa. *Nat. Plants* **2015**, *1*, 1–2.
49. Hüttl, R.; Frielinghaus, M. Soil fertility problems—An agriculture and forestry perspective. *Sci. Total Environ.* **1994**, *143*, 63–74.
50. Abbott, L.K.; Murphy, D.V. What is soil biological fertility? In *Soil Biological Fertility—A Key to Sustainable Land Use in Agriculture*; Springer: Berlin/Heidelberg, Germany, 2007
51. Abiven, S.; Menasseri, S.; Chenu, C. The effects of organic inputs over time on soil aggregate stability. *Soil Biol. Biochem.* **2008**, *41*, 1–12.
52. Li, S.; Wang, Z.; Hu, T.; Gao, Y.; Stewart, B.; Sparks, D. Nitrogen in dryland soils of China and its management. *Adv. Agron.* **2009**, *101*, 123–181.
53. Sherman, K. Sustainability, biomass yields, and health of coastal ecosystems: An ecological perspective. *Marine Ecol. Progr. Series* **1994**, *112*, 277–301.
54. Khaledian, Y.; Kiani, F.; Sohaila, E. The effect of land use change on soil and water quality in northern Iran. *J. Mt. Sci.* **2012**, *9*, 798–816.
55. Tsatsaros, J.; Brodie, J.; Bohnet, I.; Valentine, P. Water Quality Degradation of Coastal Waterways in the Wet Tropics, Australia. *Water Air Soil Pollut.* **2013**, *224*, doi:10.1007/s11270-013-1443-2.
56. Schaffner, M.; Bader, H.; Scheidegger, R. Modeling the contribution of point sources and non-point sources to Thachin River water pollution. *Sci. Total Environ.* **2009**, *407*, 4902–4915.
57. Atapattu, S.; Kodituwakku, D. Agriculture in South Asia and its implications on downstream health and sustainability: A review. *Agric. Water Manag.* **2009**, *96*, 361–373.
58. Trivedi, R. Water quality of the Ganga River—An overview. *Aquat. Ecosyst. Health Manag.* **2010**, *13*, 347–351.
59. Chen, M.; Chen, J. Phosphorus release from agriculture to surface waters: Past, present and future in China. *Water Sci. Technol.* **2008**, *57*, 1355–1361.
60. Cheevaporn, V.; Menasveta, P. Water pollution and habitat degradation in the Gulf of Thailand. *Marine Pollut. Bull.* **2003**, *47*, 43–51.
61. Qadir, M.; Oster, J. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Sci. Total Environ.* **2004**, *323*, 1–19.
62. Lemly, A.; Finger, S.; Nelson, M. Sources and impacts of irrigation drainwater contaminants in arid wetlands. *Environ. Toxicol. Chem.* **1993**, *12*, 2265–2279.
63. Dakoure, M.; Mermoud, A.; Yacouba, H.; Boivin, P. Impacts of irrigation with industrial treated wastewater on soil properties. *Geoderma* **2013**, *200*, 31–39.
64. Bouwer, H. Integrated water management for the 21st century: Problems and solutions. *J. Irrig. Drain. Eng.-Asce* **2002**, *128*, 193–202.
65. Apitz, S.E.; Brils, J.; Marcomini, A.; Critto, A.; Agostini, P.; Micheletti, C.; Pippa, R.; Scanferla, P.; Zuin, S.; Lanczos, T.; *et al.* Approaches and frameworks for managing contaminated sediments—A European perspective. In *Assessment and Remediation of Contaminated Sediments*; Springer: Berlin/Heidelberg, Germany, 2006.
66. Lal, R. Societal value of soil carbon. *J. Soil Water Conserv.* **2014**, *69*, 186A–192A.

67. Kohli, R.V.; Singh, H.P.; Batish, D.R.; Jose, S. Ecological interactions in agroforestry: An overview. In *Ecological Basis of Agroforestry*; Kohli, R.V.S., Batish, D.R., Jose, S., Eds.; CRC Press: Boca Raton, FL, USA, 2008; pp. 3–14.
68. Helman, D.; Lensky, I.; Mussery, A.; Leu, S. Rehabilitating degraded drylands by creating woodland islets: Assessing long-term effects on aboveground productivity and soil fertility. *Agric. For. Meteorol.* **2014**, *195*, 52–60.
69. Berazneva, J.; Conrad, J.; Guerena, D.; Lehmann, J. Agricultural productivity and soil carbon dynamics: A bio-economic model. In Proceedings of the Agricultural and Applied Economics Association 2014 Annual Meeting, Minneapolis, MN, USA, 27–29 July 2014.
70. Gong, X.; Liu, Y.; Li, Q.; Wei, X.; Guo, X.; Niu, D.; Zhang, W.; Zhang, J.; Zhang, L. Sub-tropic degraded red soil restoration: Is soil organic carbon build-up limited by nutrients supply. *For. Ecol. Manag.* **2013**, *300*, 77–87.
71. Iqbal, M.; van Es, H.; Anwar-ul-Hassan, R.R.; Schindelbeck, R.; Moebius-Clune, B. Soil Health Indicators as Affected by Long-term Application of Farm Manure and Cropping Patterns under Semi-arid Climates. *Int. J. Agric. Biol.* **2014**, *16*, 242–250.
72. Govaerts, B.; Sayre, K.; Deckers, J. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. *Soil Tillage Res.* **2006**, *87*, 163–174.
73. Moebius-Clune, B.; van Es, H.; Idowu, O.; Schindelbeck, R.; Kimetu, J.; Ngoze, S.; Lehmann, J.; Kinyangi, J. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. *Agric. Ecosyst. Environ.* **2011**, *141*, 86–99.
74. Sortino, O.; Montoneri, E.; Patane, C.; Rosato, R.; Tabasso, S.; Ginepro, M. Benefits for agriculture and the environment from urban waste. *Sci. Total Environ.* **2014**, *487*, 443–451.
75. Baumgart-Getz, A.; Prokopy, L.; Floress, K. Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. *J. Environ. Manag.* **2012**, *96*, 17–25.
76. Pimentel, D.; Harvey, C.; Resosudormo, P.; Sinclair, K.; Kurz, D.; McNair, M.; Crist, S.; Shpritz, L.; Fitton, L.; Saffouri, R.; *et al.* Environmental and economic costs of soil erosion and conservation benefits. *Science* **1995**, *267*, 1117–1123.
77. Mchunu, C.; Chaplot, V. Land degradation impact on soil carbon losses through water erosion and CO_2 emissions. *Geoderma* **2012**, *177*, 72–79.
78. Badia, D.; Marti, C. Fire and rainfall energy effects on soil erosion and runoff generation in semi-arid forested lands. *Arid Land Res. Manag.* **2008**, *22*, 93–108.
79. Du Preez, C.C.; van Huyssteen, C.W.; Mnkeni, P.N.S. Land use and soil organic matter in South Africa 2: A review on the influence of arable crop production. *South African J. Sci.* **2011**, *107*, 35–42.
80. Longeuville, D.; Henry, S.; Ozer, P. Saharan dust pollution: Implications for the Sahel. *Epidemiology* **2009**, *20*, doi:10.1097/EDE.0b013e3181afef49.
81. Moreno, J.; Bastida, F.; Hernandez, T.; Garcia, C. Relationship between the agricultural management of a semi-arid soil and microbiological quality. *Commun. Soil Sci. Plant Anal.* **2008**, *39*, 421–439.
82. Bastida, F.; Moreno, J.; Hernandez, T.; Garcia, C. Microbiological degradation index of soils in a semiarid climate. *Soil Biol. Biochem.* **2006**, *38*, 3463–3473.

83. Fterich, A.; Mahdhi, M.; Mars, M. Seasonal Changes of Microbiological Properties in Steppe Soils from Degraded Arid Area in Tunisia. *Arid Land Res. Manag.* **2014**, *28*, 49–58.
84. Darwin, C.R. *The Formation of Vegetable Mould, through the Action of Worms, with Observations on their Habitats*; John Murray: London, UK, 1881.
85. Edwards, W.M.; Shipitalo, M.J.; Norton, L.D. Contribution of macropososity to infiltration into a continuous corn no-tilled watershed: Implications for contaminant movement. *J. Contam. Hydrol.* **1988**, *3*, 193–205.
86. Lal, R. *Tropical Ecology and Physical Edaphology*; John Wiley Sons: Chichester, UK, 1987.
87. Castellanos-Navarrete, A.; Rodriguez-Aragones, C.; de Goede, R.; Kooistra, M.; Sayre, K.; Brussaard, L.; Pulleman, M. Earthworm activity and soil structural changes under conservation agriculture in central Mexico. *Soil Tillage Res.* **2012**, *123*, 61–70.
88. Ayuke, F.; Karanja, N.; Okello, J.; Wachira, P.; Mutua, G.; Lelei, D.; Gachene, C.; Hester, R.; Harrison, R. Agrobiodiversity and Potential Use for Enhancing Soil Health in Tropical Soils of Africa. *Soils Food Secur.* **2012**, *35*, 94–134.
89. Ryan, J.; Masri, S.; Ibrikci, H.; Singh, M.; Pala, M.; Harris, H. Implications of cereal-based crop rotations, nitrogen fertilization, and stubble grazing on soil organic matter in a Mediterranean-type environment. *Turkish J. Agric. For.* **2008**, *32*, 289–297.
90. Teague, W.; Foy, J.; Cross, B.; Dowhower, S. Soil carbon and nitrogen changes following root-plowing of rangeland. *J. Range Manag.* **1999**, *52*, 666–670.
91. Emmerich, W.; Heitschmidt, R. Drought and grazing: II. Effects on runoff and water quality. *J. Range Manag.* **2002**, *55*, 229–234.
92. Snyman, H.; du Preez, C. Rangeland degradation in a semi-arid South Africa—II: Influence on soil quality. *J. Arid Environ.* **2005**, *60*, 483–507.
93. Oesterheld, M.; Loreti, J.; Semmartin, M.; Sala, O. Inter-annual variation in primary production of a semi-arid grassland related to previous-year production. *J. Veg. Sci.* **2001**, *12*, 137–142.
94. Wiegand, T.; Snyman, H.; Kellner, K.; Paruelo, J. Do grasslands have a memory: Modeling phytomass production of a semiarid South African grassland. *Ecosystems* **2004**, *7*, 243–258.
95. Thapa, G.; Yila, O. Farmers land management practices and status of agricultural land in the Jos Plateau, Nigeria. *Land Degrad. Dev.* **2012**, *23*, 263–277.
96. Garrity, D.; Akinnifesi, F.; Ajayi, O.; Weldesemayat, S.; Mowo, J.; Kalinganire, A.; Larwanou, M.; Bayala, J. Evergreen Agriculture: A robust approach to sustainable food security in Africa. *Food Secur.* **2010**, *2*, 197–214.
97. Muir, J.; Pitman, W.; Foster, J. Sustainable, low-input, warm-season, grass-legume grassland mixtures: Mission (nearly) impossible? *Grass Forage Sci.* **2011**, *66*, 301–315.
98. Lal, R. Degradation and resilience of soils. *Phil. Trans. R. Soc. Lond. B*. **1997**, *352*, 997–1010.
99. Greenland, D.J., Szabolcs, I., Eds. *Soil Resilience and Sustainable Land Use*; CAB International: Wallingford, UK, 1994.
100. Lynch, J. Resilience of the rhizosphere to anthropogenic disturbance. *Biodegradation* **2002**, *13*, 21–27.
101. Syers, J.K. Manging soils for long-term productivity. *Philos. Trans. R. Lond. B* **1997**, *352*, 1011–1021.

102. Horrigan, L.; Lawrence, R.; Walker, P. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environ. Health Perspect.* **2002**, *110*, 445–456.
103. Breulmann, M.; van Afferden, M.; Fühner, C. Biochar: Bring on the sewage. *Nature* **2015**, *518*, 483.
104. Goodman-Elgar, M. Evaluating soil resilience in long-term cultivation: A study of pre-Columbian terraces from the Paca Valley, Peru. *J. Archaeol. Sci.* **2008**, *35*, 3072–3086.
105. Ogaji, J. Sustainable agriculture in the UK. *Environ. Dev. Sustain.* **2005**, *7*, 253–270.
106. Ravnborg, H. Poverty and soil management—Relationships from three Honduran watersheds. *Soc. Nat. Resour.* **2002**, *15*, 523–539.
107. Tittonell, P.; Giller, K. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res.* **2013**, *143*, 76–90.
108. Rozelle, S.; Huang, J.; Zhang, L. Poverty, population and environmental degradation in China. *Food Policy* **1997**, *22*, 229–251.
109. Fan, M.; Shen, J.; Yuan, L.; Jiang, R.; Chen, X.; Davies, W.; Zhang, F. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *J. Exp. Bot.* **2012**, *63*, 13–24.
110. Tennesen, M. Rare Earth. *Science* **2014**, *346*, 692–695.
111. Reuters. Peak soil threatens global food security. *Reuters*, 17 July 2014.
112. Flora, C. Food security in the context of energy and resource depletion: Sustainable agriculture in developing countries. *Renew. Agric. Food Syst.* **2010**, *25*, 118–128.
113. Wall, D.; Six, J. Give soils their due. *Science* **2015**, *347*, 695.
114. Gregory, P.; Hester, R.; Harrison, R. Soils and Food Security: Challenges and Opportunities. *Soils Food Secur.* **2012**, *35*, 1–30.