**Strategies For Soil Health Restoration to Reduce Risks of Soil Degradation for Crop Productivity. A Review**

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**ABSTRACT**

 Feeding the world population, which is projected to increase to 9.5 billion by 2050, demands an increase in agricultural productivity by 70% . Soil degradation, characterized by the depletion of soil health, is a major constraint to achieving the required increase in agricultural productivity. 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 erosion, depletion of the soil organic carbon (SOC) pool and loss in biodiversity, loss of soil fertility and nutrient 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 health (*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 health include conservation agriculture, integrated nutrient management, continuous vegetative cover such as residue mulch and cover cropping, and controlled grazing at appropriate stocking rates. The essence of this review is to produce “more from less” by reducing losses and increasing soil, water, and nutrient use efficiency.

**Keywords:** soil quality; soil degradation; soil functions; desertification; soil carbon sequestration

**I. INTRODUCTION**

 Over the years the population of developing countries has tremendously increased, leading to a large proportion of them depend on agriculture for their livelihood (Van *et.al*, 2014). In fact, one billion of these people are small landholders who cultivate less than 2 ha of land (IFAD 2010). With limited resources and poor access to inputs, management of soil health 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 soil degradation decreased soil ecosystem services by 60% between 1950 and 2010 (Leon *et.al*, 2014). Accelerated soil degradation has reportedly affected as much as 500 million hectare (m ha) in the tropics(Lamb *et.al*, 2005), and globally 33% of earth’s land surface is affected by some type of soil degradation (Bini,2009). 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 (Scherr,2001). Over and above the environmental and economic impacts, there are also health risks of soil erosion and other degradation processes(Guerra *et.al*, 2005;Lal, 2009). According to Lal, 2009,soil degradation implies a decline in soil quality with an attendant reduction in ecosystem functions and services. Conceptually, there are four types of soil degradation which include soil physical; chemical; biological; and ecological degradation.

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 NO3-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*.,CO2 and CH4) rather than a sink. Soil 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 health, 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. The objectives of this review are to deliberate the role of soil resources in provisioning essential ecosystem services; illustrate the impacts of soil degradation on decline in ecosystem services; and identify strategies for improving soil health to mitigate risks of soil degradation for sustainable crop production.

**A. Soil and Ecosystem Services**

Soil, the most basic of all resources, is the essence of all terrestrial life and a cultural heritage(Bini et.al,2015). Yet, soil is finite in extent, prone to degradation by natural and anthropogenic factors, and is non-renewable over the human timescale (decades). Soil health or quality also has strong implications to human health(Lar, 2009), 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), soil health must be protected or restored to enhance these services (Robinson *et. al*,2012). 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.

**B. Soil Organic Carbon and Its Impact on Soil health.**

The SOC pool, including its quantity and quality, is the defining constituent of soil (Krupenikor *et.al*, 2011). Indeed, SOC pool is the most reliable indicator of monitoring soil degradation, especially that caused by accelerated erosion(Rayan *et.al*, 2010). Soil degradation depletes the SOC pool, along with it, plant available N and other essential nutrients such as P and S. Furthermore, depletion of SOC pool is a global issue and a principal cause of soil degradation. 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(Vanlauwe *et.al*,2012). 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 CO2 into the SOC pool. Accelerated degradation is shrinking the finite soil resource even more rapidly in harsh climate and fragile soils. In this context, enhancing the SOC pool is important to sustain soil fertility and agronomic productivity. 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, similar to those of croplands, is severely depleted by over-exploitation of natural resources(Lar,2004). These soils must therefore be managed to increase both soil C and vegetation to restore the degraded agro-ecosystem services(Batjes,2001). In addition to SOC and SON pools, soil moisture regime is another important indicator of climate change(Eaton *et.al*, 2012). In conjunction with changes in soil moisture regimes, projected global warming may also influence SOC decomposition rates(Melillo *et.al,* 2010) including that of fine woody debris. 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. The self-reinforcing soil degradation process is strongly exacerbated by the interaction between processes, factors and causes of soil degradation. Processes include the mechanisms (types) of soil degradation. Factors comprise agents of degradation related to natural or anthropogenic drivers such as climate, physiographic, 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.* The process-factor- cause nexus is strongly impacted by site-specific conditions. Thus, understanding the nexus or connectivity is critical to restoring soil health and mitigating degradation.

**C. Soil Health Index**

 The SOC pool is a key indicator of soil health, 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. Relevant indicators of soil physical 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; aeration and gaseous exchange; effective rooting depth; soil heat capacity and the temperature regime. Similarly, appropriate indicators of soil chemical include pH, CEC, nutrient availability; and favorable elemental balance and lack of any toxicity or deficiency. Relevant indicators of soil biological are microbial biomass C, 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 health differ among soil types, climates and land uses. A spectral soil health index based on application of reflectance spectroscopy has also been proposed as a diagnostic tool to assess soil health (Paz-kagan *et.al*, 2014). 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 (Gugino,2009).

**D. Conservation Agriculture and Soil Health**

 According to Lar, 2015, there are four basic principles of conservation agriculture which include: (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, conversation agriculture has numerous co-benefits including reduced fuel consumption and increased soil C sequestration. Mechanical tillage is an energy-intensive process and its reduction or elimination can decrease consumption of fossil fuels. In addition, an increase in SOC pool under conservation agriculture can occur in soils not prone to accelerated erosion, and those which have optimal management strategies. The most desirable tillage systems are those which restore soil quality/health, minimize risks of soil erosion, improve use efficiency of rain water and fertilizers (So,2001) and minimize risks of SOC and nutrient depletion.

 Indiscriminate use of plowing, coupled with excessive removal of crop residues and unbalanced use of chemical fertilizers, can degrade soil health, deplete SOC pool, and aggravate risks of soil erosion. In contrast, conversion of plow/traditional tillage to conservation agriculture, 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. 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. 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 (Pittelkow *et.al*,2015). Strengthening elemental cycling, in conjunction with coupled cycling of C and H2O, can increase the solum’s C sink capacity and soil profile depth through increased bio-turbation 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 health 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. It is important to note, however, that conservation agriculture 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., bio-fuels, industrial purposes) is not conservation agriculture, 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 conservation agriculture system and misinterpretation of agronomic yields. Furthermore, improvements in soil health require more than the input of new varieties and chemical fertilizers(Sanhez, 2015).

**E. Soil Fertility Management to Restore Soil Health**

 Sustainable intensification (SI), producing more from less by reducing losses and increasing the use efficiency, is attainable only through improvement of soil quality/health 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 in many developing countries. Use of organic amendments, by recycling organic by-products including urban waste, is a useful strategy to enhance soil fertility, and improve structural stability or aggregates (Abiven *et.al*,2008). While, nitrogen (N) input is important to improving soil fertility, its improper and/or excessive use can also lead to environmental pollution.

**F. Soil Health 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 health and water resources in close proximity, such as the health of coastal ecosystems. Changes in land use often affect water quality and pollutant loading (Tsatsaros *et.al*,2013). 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 (Shaffner *et.al*,2009). Downstream areas are often adversely affected because of ad-hoc 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 (Atapattus *et.al*, 2009). 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 (Qadir *et.al*,2004). Furthermore, arid wetlands are also prone to contamination by sub-surface agriculture irrigation and drainage. 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. Salinity problems are also often confounded by the reuse of untreated waste water (gray/black water) in agriculture (Dakoure *et.al*, 2013), especially in urban areas prone to water shortages or those having water resources of marginal quality. Restoring soil health 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, the importance of the soil-water nexus cannot be over-emphasized. Management of sediments, especially contaminated ones (Apitz *et.al*,2002), is another important component of the soil-water nexus that must be critically examined.

**G. Strategies for Soil Health Restoration**

 Restoring the quality/health 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), (Lar, 2015). Thus, restoration of soil health is a societal, national and international task that necessitates a coordinated approach. There are three basic strategies of restoring soil health which include: (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.

**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 conservation agriculture can reduce risks associated with soil erosion and nutrient loss while also providing numerous on- and off-site benefits (Helman *et.al*, 2014). 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 (Pimentel *et.al,*1995). 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.

**2. Improving Soil/Agro-Biodiversity**

 Soil biota are important to soil health 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 CO2 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 or a microbiological degradation index can be useful for decision-making processes (Bastida *et.al*,2006). 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). 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 (Fterich *et.al*,2014). The importance of macro-organisms (e.g., earthworms, termites) for restoring soil health has been widely recognized for centuries. Conversion of PT to conservation agriculture, with crop residue mulch and cover cropping, can increase earthworm activity and also improve structural properties, but the conversion can also have implications regarding transport of agricultural pollutants into the drainage water. 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 (Ayuke *et.al*, 2012; Ryan *et.al*, 2008).

**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 (Ryan *et.al*,2008). 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 b alleviated (Snyman *et.al*,2005). 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 (Wiegand *et.al*,2004).

**H. 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 (Greenland *et.al*,1994). 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 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 (Lynch 2002). 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 (Greenland *et.al*,1994). The so-called “sustainable land management (SLM)” concept is based on similar strategies of preserving productivity of the resource base for future generations. There are also some organic management options for reducing soil degradation risk and improving human health (Horrigan *et.al*,2002), that may have site-specific niches. Biochar, a C-rich soil amendment derived from biomass by pyrolysis, can be produced from human sewage and used to improve soil resilience while also mitigating climate change (Brevlman *et.al*,2015).

 In addition to biotic techniques, ancient farmers also developed mechanical/engineering techniques to sustain and improve their soils. There are no universally applicable techniques of managing soil resilience, but there are several approaches for ensuring sustainable soil management. In view of the heavy demands for agricultural produce to meet the needs of the growing and increasingly affluent population and emerging economies, the role of agricultural practices and their impact on soil, climate, gaseous emission, water resources, biodiversity, along with economic, political, social and ecologic dimensions (Ogaji, 2005) must be considered more now than in the past. The ideal strategy is to meet increasing global food demands while simultaneously restoring soil health, improving the environment, and minimizing the tradeoffs.

**II. 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.

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