SUSTAINABLE AGRICULTURE IN RELATION TO PROBLEMS OF SOIL DEGRADATION AND HOW TO AMEND SUCH SOILS FOR OPTIMUM CROP PRODUCTION IN NIGERIA

M. Usman [1] F. Ibrahim [2] and S.O. Oyetola [3]

[1]Department of Agricultural Science, Federal College of Education (Technical) Potiskum-Yobe State, Nigeria

[2]Department of Soil Science, University of Agriculture, Makurdi-Benue State, Nigeria

[3]Department of Soil Science, University of Abuja, Abuja- FCT, Nigeria

Corresponding Author e-mail: usmanm2020@gmail.com

Abstract

The importance of soil degradation among global issues is being enhanced because of its impact on world food security and quality of the environment. It is a key issue that affects soil productivity and environmental sustainability. Soil degradation implies a decline in soil quality. It is a global problem that is more severe in the tropics and sub-tropics. 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. However, restoring the quality of degraded soils is a challenging task, especially in countries dominated by small, resource-poor landholders like Nigeria. The focus of this paper is on sustainable agriculture in relation to problems of soil degradation and how to amend degraded soils for optimum production. The paper examined various types of soil degradation, their causes and adopted policies in various phases for the curtailment of soil degradation with the hope that this will further enhance the development of agriculture, with the expectation that development of agriculture is the major source of livelihood for a larger percentage of the populace of developing nations including Nigeria.

Key Words: Sustainable agriculture, Soil degradation and Crop production.

Introduction

The world's population is poised to reach 9 billion by the middle of this century and over the next 40 years, 70 % more food will be needed to sustain all these people. Most of this additional food will have to be produced where it is needed, namely in developing countries. These countries will have to double their production to achieve this goal, with implications also for the natural resources that farming depends on and especially water, land for cultivation and mineral fertilizers. All of these are available in only limited amounts.

Soil, the most basic of all resources, is the essence of all terrestrial life and a cultural heritage (Bini and Zilioli, 2015). Yet, soil is finite in extent, prone to degradation by natural and anthropogenic factors, and is non-renewable over the human timescale. In many places, the soil has already suffered long-term damage, and water resources are often over used or polluted by fertilizers and pesticides. Agricultural biodiversity has decreased as farming has become industrialised. These negative effects have heightened global awareness of the fact that agriculture does more than simply produce food, animal feed and energy; it also impacts on the climate and the health of global ecosystems.

Developing sustainable agricultural management systems is complicated by the need to consider their utility to humans, their efficiency of resource use, and their ability to maintain a balance with the environment that is favourable both to humans and most other species (Harwood, 1990), "a sustainable agriculture - sustains the people and preserves the land". We are challenged to develop management systems that balance the needs and priorities for production of food and fibre with those for a safe and clean environment.

Soil Degradation

Soil degradation which implies a decline in soil quality (Lal, 2015) 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 (Leon and Osorio, 2014). Accelerated soil degradation has reportedly affected as much as 500 million hectare (Mha) 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 (Guerra *et al.*, 2005) and other degradation processes (Lal, 2009).

Most if not all countries have an experience with soil degradation, it becomes a serious and widespread process in various countries. Soil degradation causes decline in productive capacity and environmental functions of the land. This in fact is the main reason for the dramatic decrease of prime lands where only 3 % of the global surface is left prime or class I (Eswaran *et al.*, 2000). Global maps of the extent and severity of several types of soil degradation are available, and some countries have more detailed information for their territories. However, most of this information is in qualitative type. Soil degradation is the result of interactive effects of processes, factors, and causes or management practices. Mechanisms that initiate degradation include physical, chemical and biological processes (Lal, 1994), important among physical process are decline in soil structure leading to crusting, compaction, erosion, desertification, anaerobism, environmental pollution, and unsustainable use of natural resources. Significant chemical processes include acidification, leaching, salinization, decrease in cation retention capacity, and fertility depletion.

Biological process includes reduction in total and biomass carbon and decline in soil biodiversity. Degradation in arid and semi-arid areas (desertification) occurs because dry land ecosystems are extremely vulnerable to over-exploitation and inappropriate land use. Dry lands usually respond quickly to climatic fluctuations; and people have learned to protect these resources with age-old strategies such as shifting agriculture and nomadic herding. However, in recent decades these strategies have become less practical; and nowadays economic and social pressure, ignorance, political instability, and drought can lead to over-cultivation, deforestation, overgrazing and bad irrigation practices that all undermine the land’s fertility. Degradation is the result when climate variations occur along with unsustainable land use practices. Degradation mostly affects arid and sub-arid zones (dry lands), i.e. where the aridity index, the ratio between the mean annual precipitation P and mean annual potential evapo-transpiration PE is less than 0.65 (UNEP,1992).

Land degradation results in the reduction of biological productivity of ecosystems caused by soil and vegetation degradations. Eswaran *et al.* (2000) stated that land degradation is a biophysical processes (land use and land management, including deforestation and tillage methods) driven by socio-economic (land tenure, marketing institutional support, income and human health) and political forces such as incentives and political stability. In terms of land quality or productivity reduction, Beinroth *et al.* (1994) stated that land degradation is a result from a mismatch between land quality and land use. However, depending on their inherent characteristics and climate, soils vary from highly resistant or stable to those that are vulnerable and extremely sensitive to degradation. Factors controlling soil degradation are ecosystems characteristics. Notable among these are climate (e.g., rainfall, temperature), terrain characteristics and vegetation. Factors are agents and catalysts, which accentuate the rate of different processes of soil degradation.

Causes of Soil Degradation

The root cause of soil degradation in agricultural land use and of decreasing productivity as seen in terms of loss of soil health is the low soil-carbon and soil-life disrupting paradigm of mechanical soil tillage, which, in order to create conditions for improved crop performance, debilitates many important soil-mediated ecosystem functions. For the most part, agricultural soils are becoming destruction, our landscape is exposed and unprotected, and soil life is starved of organic matter, reduced in biological activity, and deprived of habitat. The loss of soil biodiversity, damaged structure, and its self-recuperating capacity or resilience, increased topsoil and subsoil compaction, runoff and erosion, and greater infestation by pests, pathogens, and weeds indicate the current poor state of the health of many of our soils. In the developing regions, this is a major cause for inadequate food and nutrition security (Eswaran *et al.*, 2000).

In industrialized countries, the poor condition of soils due to excessive disturbance through mechanical tillage is being exacerbated by over reliance on application of mineral fertilizers, as the main source of plant nutrients, onto farmland that has been losing its ability to respond to nutrient inputs due to degradation in biological soil health-related to declining stocks of soil carbon-including loss/destruction of adequate soil porosity and reduced soil moisture storage and increased runoff, leading to poor root system, nutrient loss, and decrease in nutrient uptake as well as reducing or doing away with crop diversity and rotations including legumes and pastures facilitated by high levels of agrochemical inputs, standardized fixed agronomy, and commodity-based market forces that are insensitive to on-farm and landscape ecosystem functions (Lamb *et al.*, 2005).

Tillage results in accelerated oxidation of carbon-rich organic matter by soil biota, faster than it may be being replaced, leading to progressive depletion of carbon-rich SOM. The common belief is that tillage accelerates crop residue breakdown, leading to increase in soil biota and nutrient flushes when residue is mixed with soil. Any positive effect is of very short duration and with little positive effect on soil quality and function. Rapid breakdown of crop residues starves soil organisms of their future source of energy for life processes, with consequent decline in their effectiveness in maintaining/improving the health and quality of the soil as a medium for plants' rooting and functioning. Heavy and more powerful machines, combined with even more chemical fertilizers, pesticides, and herbicides, supposedly making crop rotations superfluous and promoting apparent efficiency through specialization with monocropping.

Types of Soil Degradation

Soil degradation processes whether chemical, biological or physical may occur simultaneously or sequentially and they are interrelated.

Physical

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 (Lal, 2015).

Chemical

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 (Lal, 2015).

Biological

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 (Lal, 2015). 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

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 (Lal, 2015). 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.

Effects of Soil Degradation

The adverse effect of soil degradation on productivity is accentuated by a declining progress in the per capita arable land area at national and global scales. The global per capita arable land area of 0.3 hectares in 1985 is expected to progressively decline to 0.15 hectares by 2050 and 0.14 hectares 2100. Only 5 countries have less than 0.15 hectares arable land per capita but likely will increase to 50 in 2025 (Lal, 2002). Soil degradation decreases microbial abundance and activity, leading to changes in nutrient availability, soil organic matter, and plant growth and establishment. The effects of soil degradation on productivity are hard to understand because they are often cumulative and may be observed long after degradation has occurred, and the effect may be masked by management and prevailing weather condition (Lal, 1990; Oldeman, 1998).

Amending Degraded Soils

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) (Lal, 2014). 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. (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.

One common way to enhance plant establishment in degraded soils is through the use of soil amendments. Degraded soils often contain lower organic matter, nutrients (including plant available ammonium, nitrate, phosphorus, and potassium), and microbial activity than undisturbed healthy soils, which results in less successful plant establishment (Garcia *et al.*, 1994; Wong, 2003). The addition of amendments to degraded soils could improve deficiencies in nutrients and organic matter, alter soil porosity, and increase microbial biomass to improve plant establishment (Ehaliotis *et al.*, 1998; Sohi, 2010; Steinbeiss *et al.*, 2009). There are a wide variety of organic materials, including woodchips and biochar (created through the pyrolysis of plant biomass) that can be used as amendments at relatively low costs. Biochar is becoming increasingly recognized as a popular option for soil amendments. The use of biochar has two simultaneous, positive effects- mitigate anthropogenic effects of climate change by incorporating biochar into soils while improving soil fertility and plant growth (Atkinson *et al.*, 2010; Laird, 2008). Wood-based biochars have been shown to have extremely high carbon (C) to nitrogen (N) and carbon to phosphorous (P) ratios (Kookana *et al.*, 2011). Additionally, the high surface area of biochars can cause absorption of water and nutrients in the soil followed by a slow release of these resources over time (Artiola *et al.*, 2012). Woodchips reduce erosion and runoff in soils by forming mini-channels, which can trap water and sediment (Foltz and Copeland, 2009). They have also been shown to alter porosity when incorporated into soils and change nutrient dynamics by increasing N availability to plants (Miller and Seastedt, 2009). Crop rotation can have a major impact on soil health, due to emerging soil ecological interactions and processes that occur with time. These include, compared to monoculture, improved soil structural stability and nutrient use efficiency, increased crop water use efficiency and soil organic matter levels, reduced long-term yield variability, better weed control, and disruption of insect and disease life cycles, all of which may further improve soil productivity (Varvel 2000, Carter *et al.* 2002, 2003, Kelley *et al*. 2003).

Some agricultural practices are known to sequester SOC, reduce GHG emissions and reverse soil degradation, while others are well known to reduce SOC and increase degradation. In between these come a number of techniques, some widely employed, where evidence of their sequestration potential is either disputed or has recently been called into question by new research. A key point to note is that because soils vary so much between countries, regions, farms and even individual fields, no single solution fits all cases. Instead solutions need to be tailored to each situation.

A sustainable approach to soil management in rain fed and irrigated production cannot be a single technology but rather a range of mutually reinforcing practices. For both tillage and no-tillage systems, their best performances can be achieved only when the production systems are supported by effective plant nutrition, soil moisture provision, and best agronomic practices. Production systems are most sustainable and function best when all three key soil, crop, and environmental management principles are applied simultaneously. CA is a good example of progress in this regard as it is based on no-till and maintenance of soil cover and has now spread across all continents and ecologies (Hobbs 2007; Friedrich *et al.,* 2009; Kassam *et al.,* 2009 and 2010). There are other complementary ecosystem-based approaches, which together form lead to SCPI, that have also proven to be successful as a basis for sustainable intensification in all continents under a wide range of circumstances (Uphoff *et al.,* 2011; Kassam *et al.,* 2011).

Sustainable production systems also mobilize plant nutrients through biological transformations of organic matter, providing micronutrients that may not otherwise be available (Flaig *et al.*, 1977). For example, mulch-based no-till production systems can retain and mimic the soil's original desirable characteristics ("forest floor conditions") on land being first opened for agricultural use. Throughout the transformation to agricultural production, sustainable systems based on an agro ecological no-tillage approach can safeguard desirable soil characteristics, sustain the health of long-opened farmland that is already in good condition, and regenerate land that has reached poor condition due to past misuse (Doran and Zeiss, 2000).

Such types of information from soils and ecosystems in good condition under CA systems provide a range of "yardsticks" against which to compare the benefits of CA and the health of the soil and the ecosystem, as against the "classical" tillage agriculture. Tillage agriculture with monocropping and no organic cover represents the most vulnerable and detrimental production system, whereas CA represents a more sustainable option (Montgomery 2007). Sustainable soil management as practiced in CA systems has resulted in the enhancement or rehabilitation of the soil resource base and its agro ecological potentials, thus enabling the avoidance of soil degradation and repair of lands, leading to sustainable intensification and the harnessing of ecosystem services.

Strategies for Sustainability

In defining sustainable agricultural management practices, Doran *et al*. (1994) stressed the importance of holistic management approaches that optimize the multiple functions of soil, conserve soil resources, and support strategies for promoting soil quality and health. They initially proposed use of a basic set of indicators to assess soil quality and health in various agricultural management systems. However, while many of these key indicators are extremely useful to specialists (i.e. researchers, consultants, extension staff, and conservationists) many of them are beyond the expertise of the producer to measure (Hamblin, 1991). Also, the measurement of soil quality and health does nothing to improve the sustainability of the system under which the soil is managed. In response to this dilemma, Doran *et al*. (1996) and Doran and Safley (1997) presented strategies for ensuring sustainable management which included generic indicators of soil quality and health which are measurable by and accessible to producers within the time constraints imposed by their normally hectic and unpredictable schedules, soil organic matter serves as a primary indicator of soil quality and health for both scientists and farmers (Romig *et al*., 1995). Strategies for sustainable management, maximize the benefits of natural cycles, reduce dependence on non-renewable resources, and help producers identify long-term goals for sustainability that also meet short-term needs for production. However, successful development and implementation of standards for assessment of soil health and sustainability can only be accomplished in partnership with agricultural producers, who are the primary stewards of the land.

Sustainable Soil Management for Crop Production

Evidence from different parts of the world suggests that it may not be possible to separate sustainable soil management from sustainable production system management. Both are inextricably linked in ways that sustainable crop production systems must first be ecologically sustainable. This means that any production system that permits the mechanical disruption of soil life and biology and soil structure and quality, and therefore ecosystem services, cannot be considered to be sustainable ecologically. The aim of "sustainable soil management" should be to reverse the trends indicated by the items listed above, via the inducing of improvements in the quality of the soil as a rooting environment for plants. Also, an agricultural soil system is of no value if the crops grown are attacked by weeds, insects, and pathogens. In other words, sustainable soil management is not enough for sustainable production as an outcome, and certainly not where sustainable production intensification is the objective in which crop, soil, nutrient, water, pest, and farm power management in space and time must be taken care of to remain ecologically and economically viable (Pretty 2008; Kassam *et al.*, 2009; Godfray *et al.*, 2010; FAO 2011b; Pretty *et al.*, 2011).

Sustainable production systems based on ecosystem approaches offer a range of productivity, socioeconomic, and environmental benefits to producers and to society at large. To achieve the increased productivity required to meet 2050 food demands and the range of ecosystem services expected by society, sustainable production systems should be based on five technical principles:

i. Simultaneous achievement of increased agricultural productivity and enhanced ecosystem services.
ii. Enhanced input-use efficiency, where key inputs include water, nutrients, pesticides, energy, land, and labour.
iii. Reduced dependency from external inputs derived from fossil fuels (such as mineral fertilizer and pesticides) and preference for alternatives (such as biological nitrogen fixation and integrated pest management).
iv. Protection of soil, water, and biodiversity through use of minimum disturbance of natural systems; interventions must not have accumulative effects but must have an impact and frequency lower than the natural recovery capacity of the ecosystem.
v. Use of managed and natural biodiversity to build and/or rebuild system resilience to abiotic, biotic, and economic stresses.

Over time, systems following these principles will show increasing production levels and decreasing levels of input use. In many degraded situations, better retention of incoming water-its capture, infiltration, and in-soil storage at plant-available tensions is an important achievement, which makes possible the optimum functioning of the entire soil/plant system.

The farming practices required to implement the above-mentioned key principles will differ according to local conditions and needs but will have the following required characteristics, based on optimizing conditions in the root zone as being essential to (1) biotic activity; (2) provision of water and crops; and (3) assurance of self-sustainability of soil structure and porosity. These include capacities for achieving the following: maximum rain infiltration/minimum runoff and optimum water storage; minimum compaction; reduced diurnal temperature ranges in upper soil layers; regular supply of C-rich organic matter to the surface; minimal loss of SOM by oxidation; N levels in soil maintained; and optimized P availability. Such are best achieved by incorporating the following three main tenets of CA as a base or a foundation for sustainable soil management.

i. Minimizing soil disturbance by mechanical tillage. Whenever possible, seeding or planting directly into untilled soil, in order to maintain SOM, soil structure, and overall soil health.

ii. Enhancing and maintaining permanent mulch cover on the soil surface. Use of crops, cover crops, or crop residues to protect the soil surface conserves water and nutrients, promotes soil biological activity, and contributes to integrated weed and pest management.

iii. Diversification of species. Utilize both annuals and perennials in associations, sequences, and rotations that can include trees, shrubs, pastures, and crops (some or all of which may be N-fixing legumes). All will contribute to enhanced crop nutrition and improved system resilience.

CA practices related to the above-described principles are now widely used in a range of farming systems in all continents on nearly 10% of the global crop land. They add to sustainability of production and soil systems and generate a range of ecosystem services. They also improve soil conditions and result in beneficial outcomes for production, ecosystem services, and socioeconomic conditions. However, to achieve the sustainable intensification necessary to meet future food requirements, these CA practices need to be complemented by additional best management practices:

i. Use of well-adapted, high-yielding varieties, and good-quality seeds
ii. Enhanced crop nutrition, based on healthy soils
iii. Integrated management of pests, diseases, and weeds
iv. Efficient water management
v. Careful management of machines and field traffic to avoid soil compaction.

Sustainable crop production intensification (SCPI) is the combination of all of these improved practices applied in a timely and efficient manner. For this, the ensuring of soil stability and the favouring of self-recuperation of appropriate soil structural conditions are essential. Thus, sustainable soil management depends on how and what crops are grown. However, for sustainable production intensification occur, the core or foundation CA practices must integrate with other complementary practices that allow the intensification of output and the optimization of the production inputs (Kassam *et al.* 2009; Godfray *et al.*, 2010; FAO 2011b; Pretty *et al.*, 2011). Maintenance or improvement of SOM content and soil structure and associated porosity are critical indicators for sustainable production and other ecosystem services (Kassam *et al.* 2009).

A key factor for maintaining soil structure and organic matter is to limit mechanical soil disturbance in the process of crop management. For this reason, no-tillage production methods as practiced, for example, in CA have in many parts of the world been shown to improve soil conditions, reduce degradation, and enhance productivity. However, as a stand-alone practice, the elimination of tillage would not necessarily lead to a functioning sustainable production system. This requires a set of complementary practices to enable a functioning soil system as well as the whole agro ecosystem to deliver a range of ecosystem services.

The contribution of practices that implement the technical principles of CA including mulch cover, no-tillage, legume crops, and crop rotations in important ecosystem services are well noted. Even where it is not possible to install all desirable practical aspects in the production system at the same time, progressive improvements toward those goals should be encouraged (Uphoff *et al*. 2006; Pretty 2008). However, for any agricultural system to be sustainable in the long term, the rate of soil erosion and degradation (loss of organic matter) must never exceed the rate of soil formation (though the steeper the slope, the greater the danger that this could happen). In the majority of agro ecosystems, this is not possible if the soil is mechanically disturbed (Montgomery 2007). For this reason, the avoidance of mechanical soil disturbance can be seen as a starting point for sustainable production. Once it has been brought into good physical condition, no further tilling of the soil is therefore a necessary condition for sustainability but not a sufficient condition. For SCPI, including ecosystem services, other complementary techniques are required as mentioned already, of which the practices related to the above three CA principles constitute the bare minimum for ecological sustainability (FAO 2011a).

Conclusion and Recommendations

The importance of soil degradation among global issues is being enhanced because of its impact on world food security and quality of the environment. It is a key issue that affects soil productivity and environmental sustainability. Many countries have adopted policies in various phases for the curtailment of soil degradation with the hope that this will further enhance the development of agriculture, with the expectation that development of agriculture is the major source of livelihood for a larger percentage of the populace of developing nations.

1. The present non-sustainability of the farming systems and soil management practices of most tropical areas has to be recognized. There is now much experimental evidence to show that long-term arable crop production in the humid and semi-arid tropics is only possible if soil organic matter levels are maintained.

2. A greatly increased effort is needed to apply existing knowledge and techniques such as conservation agriculture to better management of soil resources, and to seek new technology where existing knowledge is inadequate for sustainable agricultural production.

References

Artiola, J. F., Rasmussen, C. and Freitas, R. (2012). Effects of a Biochar-Amended Alkaline Soil on the Growth of Romaine Lettuce and Bermudagrass. *Soil Science* 177, 561–570.

Atkinson, C.J., Fitzgerald, J. D. and Hipps, N.A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant Soil* 337, 1–18.

Beinroth, F.H., Eswaran, H., Reich, P.F. and Van den berg, E. (1994). Land related stresses in agroecosystems. In: *Stressed Ecosystems and Sustainable Agriculture,* eds. S.M. Virmani, J.C. Katyal, H. Eswaran, and I.P. Abrol. New Delhi: Oxford and IBH.

Bini, C. (2009). Soil: A precious natural resource. In *Conservation of Natural Resources*; Kudrow, N.J. (Ed.), Nova Science Publishers: Hauppauge, NY, USA, pp. 1–48.

Bini, C. and Zilioli, D. (2015). Is Soil a Cultural Heritage? Proc. III Conv. Int. Architettura del Passaggio, 20 supplied DVD. Available online: http://arca.unive.it/handle/10278/22330 (accessed on 12 May 2015).

Carter, M.R., Kunelius H.T., Sanderson J.B., Kimpinski J., Platt H.W. and Bolinder, M.A. (2003). Productivity parameters and soil health dynamics under long-term 2-year potato rotation in Atlantic Canada. *Soil and Tillage Research*, 72: 153–168.

Carter, M.R., Sanderson J.B., Ivany J.A. and White, R.P. (2002): Influence of rotation and tillage on forage maize productivity, weed species, and soil quality of a fine sandy loam in the cool-humid climate of Atlantic Canada. *Soil and Tillage Research,* 67: 85–98.

Doran, J.W. and Zeiss, M.R. (2000). Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology*, 15: 3–11.

Doran, J.W., Sarrantonio, M. and Janke, R. (1994). Strategies to promote soil quality and soil health. In: Pankhurst, et al. (Eds.), *Soil Biota: Management in Sustainable Farming Systems*. CSIRO, Vic., Australia, pp. 230–237.

Doran, J.W., Sarrantonio, M. and Liebig, M. (1996). Soil health and sustainability. In: Sparks, D.L. (Ed.), *Advances in Agronomy,* Vol. 56, Academic Press, San Diego, CA, USA, pp. 1–54.

Ehaliotis, C., Cadisch, G. and Giller, K.E. (1998). Substrate amendments can alter microbial dynamics and N availability from maize residues to subsequent crops. *Soil Biology & Biochemistry*. 30, 1281–1292.

Eswaran, H., Arnold, R.W., Beinroth, F.H. and Reich, P.F. (2000). A global assessment of land quality. *Journal of Environmental Management*, 90, 100-160

FAO, (2011a). *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW): Managing Systems at Risks*. Summary Report. Rome: FAO.

FAO, (2011b). *Save and Grow. A Policymakers' Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome: FAO. 98. Available at www.fao.org/ag/save-and-grow/.

Flaig, W., Nagar, B., Sóchtig, H. and Tietjen, C. (1977). *Organic Materials and Soil Productivity*. FAO Soils Bulletin no. 35. Rome: FAO.

Foltz, R.B. and Copeland, N.S. (2009). Evaluating the efficacy of wood shreds for mitigating erosion. *Journal of Environmental Management*, 90, 779–785.

Friedrich, T., Kassam, A.H. and Shaxson, T.F. (2009). Conservation Agriculture. In *Agriculture for Developing Countries.* Science and Technology Options Assessment (STOA) Project. Karlsruhe, Germany: European Technology Assessment Group.

Garcia, C., Hernandez, T. and Costa, F. (1994). Microbial activity in soils under Mediterranean environmental conditions. *Soil Biology & Biochemistry* 26.

Godfray, C., Beddington, J.R. and Crute, I.R. (2010). Food security: the challenge of feeding 9 billion people. *Sciences* 327: 812–818.

Guerra, A., Marcal, M., Polivanov, H., Lima, N., Souza, U., Feitosa, A., Davies, K., Fullen, M.A. and Booth, C.A. (2005). 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, Pp. 459–467.

Hamblin, A. (1991). Environmental indicators for sustainable agriculture. Report of a National Workshop Publication. LWRRDC and GRDC, Pp. 96-101.

Harwood, R.R., (1990). A history of sustainable agriculture. In: Edwards, C.A. (Ed.), Sustainable Agricultural Systems. *Soil and Water Conserv. Society*., Ankeny, IA, USA, pp. 3–19.

Hobbs, P.R. (2007). Conservation agriculture: what is it and why is it important for future sustainable food production? *Journal of Agric Science* 145: 127–137.

Kassam, A.H., Friedrich, T. and Derpsch, R. (2010). Conservation Agriculture in the 21st Century: A Paradigm of Sustainable Agriculture. European Congress on Conservation Agriculture, October 4–6, 2010, Madrid, Spain.

Kassam, A.H., Friedrich, T. Shaxson, T.F. and Pretty, J.N. (2009). The spread of conservation agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability* 7 (4): 292–320.

Kassam, A., Friedrich, T., Shaxson, T.F., Reeves, T., Pretty, J. and de Moraes Sà, J. C. (2011). Production systems for sustainable intensification: integrated productivity with ecosystem services. *Technikfolgenabschatzung Theorie Praxis* 2: 39−45.

Kelley K.W., Long J.H. and Todd T.C. (2003): Long-term crop rotations affect soybean yield, seed weight, and soil chemical properties. *Field Crops Research, 83*: 41–50.

Kookana, R.S., Sarmah, A.K., Zwieten, L. and Krull, E. (2011). Biochar Application to Soil : Agronomic and Environmental Benefits and Un intended Consequences, 1st Ed, *Advances in Agronomy*. Elsevier

Lal, R. (1994). Tillage effects on soil degradation, soil resilience, soil quality, and sustainability. *Soil Tillage Research*, 27, 1–8.

Lal, R. (2002). Soil carbon dynamic in cropland and rangeland. *Environmental Pollution* 116: 353–362.

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. *Food Sciences*. 1, 45–57.

Lal, R. (2014). Societal value of soil carbon. *Journal of Soil Water Conservation* 69, 186A–192A

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability* 7, 5875-5895.

Lamb, D., Erskine, P. and Parrotta, J. (2005). Restoration of degraded tropical forest landscapes. *Science*, 310, 1628–1632.

Leon, J. and Osorio, N. (2014). Role of Litter Turnover in Soil Quality in Tropical Degraded Lands of Colombia. *Sci. World Journal* 13, doi:10.1155/2014/693981.

Miller, E.M., Seastedt, T.R., (2009). Impacts of woodchip amendments and soil nutrient availability on understory vegetation establishment following thinning of a ponderosa pine forest. *Forestry Ecology Management*. 258, 263–272.

Montgomery, D.R. (2007). *Dirt: The Erosion of Civilizations.* Berkeley and Los Angeles: University of California Press.

Oldeman, L.R. (1998). *Guidelines for General Assessment of the Status of Human-Induced Soil Degradation.* International Soil Reference and Information Centre (ISRIC), Wageningen, the Netherlands.

Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philos Transact R Soc Land B* 363 (1491): 447–466.

Pretty, J.N., Toulmin, C. and S. Williams. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability* 9 (1): 5–24.

Scherr, S. J. (2001). The future food security and economic consequences of soil degradation in the developing world. In *Response to Land Degradation*; Oxford Press: New Delhi, India, pp. 155–170.

Sohi, S.P. (2010). A Review of Biochar and Its Use and Function in Soil, 1st Ed, *Advances in Agronomy*. Elsevier Inc.10.1016/S0065-2113(10)05002-9

Steinbeiss, S., Gleixner, G. and Antonietti, M., (2009). Effect of biochar amendment on soil carbon balance and soil microbial activity. *Soil Biol. Biochem*. 41, 1301–1310.

UNEP, (1992). *World Atlas of Desertification.* London: Edward Arnold.

Uphoff, N. (2006). Issues for more sustainable soil system management. *Biological Approaches to Sustainable Soil Systems*, 715–716. CRC Press, Boca Raton, FL.

Uphoff, N., A. Kassam, and Harwood, R. (2011). SRI as a methodology for raising crop and water productive adaptations in rice agronomy and irrigation water management. *Paddy Water Environ Special Issue* 9 (1): 3−11.

Varvel, G.E. (2000). Crop rotation and nitrogen effects on normalized grain yields in a long-term study. *Agronomy Journa*l, *92*: 938–941.

Wong, M. (2003). Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere* 50, 775–780.