Sustainable Agriculture

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Agronomy for Sustainable Agriculture: A Review

Eric Lichtfouse, Mireille Navarrete, Philippe Debaeke, Véronique Souchère,
Caroline Alberola, and Josiane Ménassieu

Abstract *Sustainability rests on the principle that we must meet the needs of the present without compromising the ability of future generations to meet their own needs*. Starving people in poor nations, obesity in rich nations, increasing food prices, on-going climate changes, increasing fuel and transportation costs, flaws of the global market, worldwide pesticide pollution, pest adaptation and resistance, loss of soil fertility and organic carbon, soil erosion, decreasing biodiversity, desertification, and so on. Despite unprecedented advances in sciences allowing us to visit planets and disclose subatomic particles, serious terrestrial issues about food show clearly that conventional agriculture is no longer suited to feeding humans and preserving ecosystems. Sustainable agriculture is an alternative for solving fundamental and applied issues related to food production in an ecological way [Lal (2008) Agron. Sustain. Dev. 28, 57–64]. While conventional agriculture is driven almost solely by productivity and profit, sustainable agriculture integrates biological, chemical, physical, ecological, economic and social sciences in a comprehensive way to develop new farming practices that are safe and do not degrade our environment. To address current agronomical issues and to promote worldwide discussions and cooperation we implemented sharp changes at the journal Agronomy for Sustainable Development from 2003 to 2006. Here we report (1) the results of the renovation of the journal and (2) a short overview of current concepts of agronomical research for sustainable agriculture. Considered for a long time as a soft, side science, agronomy is rising fast as a central science because current issues are about food, and humans eat food. This report is the introductory article of the book Sustainable Agriculture, volume 1, published by EDP Sciences and Springer (Lichtfouse et al., 2009, this book).

Keywords Agronomy for sustainable development • Biodiversity • Climate change • Farming system • Food • Organic farming • Pest control • Pesticide • Soil • Sustainable agriculture • Water

Foreword

This article is dedicated to Ms. Josiane Ménassieu. Josiane was the Editorial Secretary of the journal Agronomy for Sustainable Development (ASD) from 2003 and retired in April 2008. The success of the renovation of the journal from 2003 to 2006 is mainly due to her intensive work. Her kindness was greatly appreciated by authors, peer-reviewers and Field Editors. Figure 1 shows a picture of the present that was offered to her by colleagues for her retirement.

1 The Journal Agronomy for Sustainable Development

Agronomy for Sustainable Development (ASD, agronomy-journal.org) is one of the seven journals of the French Institute of Agronomical Research (INRA,

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Fig. 1 *Coquelicots* painting by artist Agathe Rémy, who lives near Aix-en-Provence, France. *Coquelicots* is the French word for poppies

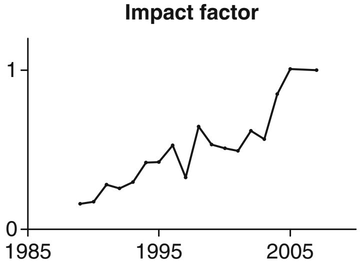

Fig. 2 Impact factor of the journal Agronomy for Sustainable Development (ASD). Note the increase in the impact factor from 0.566 in 2003 to 1.000 in 2007 (+77%). In 2006, the journal had two impact factors due to title change in 2005: 0.863 for the old title, Agronomie, and 0.306 for the new title, ASD. Those factors are not shown in the graph above because their calculation is different from that of normal impact factors. Specifically, the value for the old title is higher because it takes into account only older articles (2004) that thus have higher chances of getting cited (see scientific.thomsonreuters.com/isi for details)

international.inra.fr). The journal is managed by a collaboration of two INRA departments, the Department of Environment and Agronomy (www.inra.fr/ea) and the Department of Sciences for Action and Development (www.inra.fr/sad). Journal issues are produced by EDP Sciences (edpsciences.org). Our Editorial board collaborates with three Associate Editors and 32 Field Editors for manuscript peer-review. ASD publishes research and review articles. Submitted articles are first evaluated by a Pre-Selection Committee that declines about 50% of incoming manuscripts. Selected submissions are then sent to Field Editors for in-depth evaluation. The global rejection rate was 77% in 2006. The current impact factor (2007) is 1.000, ranking the journal 25/49 in the category Agronomy (Fig. 2).

ASD Journal was greatly reformed from 2003 to 2006. We changed topics from classical, production-oriented agronomy to sustainable and ecological agriculture (Lichtfouse et al. 2004; Alberola et al. 2008). We integrated social and economic sciences by setting up a collaboration between the INRA Department of Environment and Agronomy and the INRA Department of Sciences for Action and Development. Major journal topics currently include:

- Agriculture and global changes
- Agricultural production of renewable energies
- Ecological pest control and biopesticides
- Organic farming
- Genetically modified organisms in cropping systems
- Environmental impact on soil, water, air and biodiversity
- Risk assessment for food, ecotoxicology
- Decision support systems and companion modelling
- Social and economic issues of agricultural changes
- Innovation in farming systems
- Pollutants in agrosystem

Major journal changes implemented during the journal renovation are shown in Table 1. They include: the setting up of a pre-selection committee at the submission stage; an increase in the number of Field Editors from 14 to 32; novel topics focusing on sustainable agriculture (Lichtfouse et al. 2004); novel format instructions for more concise articles; a novel title (formerly *Agronomie)*; a switch from hardcopy to fully electronic managing; 100% of articles in English and a novel journal cover; and seven review reports produced per manuscript: three reports from Associate Editors at the pre-selection step, one report from the Field Editor, two reports from peer-reviewers and one report from the Editor-in-Chief; active commissioning of review articles by the Editor-in-Chief. As a consequence, we have observed several positive trends during the last few years (Table 1). The impact factor increased from 0.566 in 2003 to 1.000 in 2007 (+77%, Fig. 2). The rejection rate increased from 44% in 2003 to 77%

Table 1 Major changes in the journal agronomy for sustainable development (ASD) from 2003 to 2006

	Before renovation	Actual
Title	Agronomie	Agronomy for sustainable development
Field Editors	14	32
Pre-selection Committee	None	3 Associate editors
Topics	Conventional agronomy	Sustainable agronomy
Research article format	No size limit	Short articles
Language	93% English	100% English
Submissions per year	108	211
Pre-selection rejection (%)	0	50
Global rejection (%)	44	77
Research articles per year	79	44
Review articles per year	3	18
Impact factor	0.566	1,000
Acceptance delay	10.3 months	3.8 months
Article management	Hardcopy, post	100% electronic, pdfs
Article pdf downloads (/yr)	89,158	231,504
E-mail alert subscribers	417	1,307

in 2006. The number of submissions increased from 108 in 2003 to 211 in 2007 (+95%). The number of pdf article downloads at the ASD website increased from 89,158 in 2004 to 231,504 in 2007 (+160%). The number of subscribers to the free e-mail alert increased from 417 in 2004 to 1,307 in 2007 (+213%). The number of published review articles increased from 3 in 2005 to 13 in 2008 (+333%).

From 2005, review articles are published both in ASD and in the book series Sustainable Agriculture (Lichtfouse et al., 2009, this book). The first volume is issued in 2009. A call for review articles for the next volumes is posted on the ASD website (agronomy-journal.org). To conclude, the trends observed are very promising to encourage scientists to publish their best results in ASD. In the next section we discuss views on sustainable agriculture.

2 Sustainable Development and Sustainable Agriculture

The term “sustainable development” was first defined in 1987 by the Brundtland Commission, formally the World Commission on Environment and Development, solicited by the United Nations:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

This concept was then enhanced by the United Nations Conference on Environment and Development at the Earth Summit, Rio de Janeiro, in 1992. From that time, sustainable development became a key issue in political and scientific bodies, e.g. the Intergovernmental Panel on Climate Change (IPCC, ipcc.ch), the Millennium Ecosystem Assessment (millenniumassessment.org) and more recently, the *Grenelle de l’Environnement* in France (legrenelle-environnement.fr). The concept of sustainable development is well accepted by a large public because it has defined global stakes, but is very vague about the practical ways of reaching those stakes.

Sustainable agriculture does not escape this weakness, as shown by many reports (Hansen 1996; Hansen and Jones 1996; Gliessman 1998; Gold 1999; Tilman et al. 2002; Boiffin et al. 2004; Dupraz 2005). Many authors and organisations worldwide give their own definition of sustainable agriculture. Some authors consider sustainable agriculture as a set of management strategies addressing the main societal concerns about food quality or environment protection (Francis et al. 1987). Other authors focus on the ability of agricultural systems to maintain crop productivity over the long term (Ikerd 1993). Other authors focus on one main factor of sustainability; for instance, flexibility, which is the adaptive capacity of agriculture to adapt to future changes (Gafsi et al. 2006). Overall, all authors agree on the occurrence of three approaches to the concept of sustainable agriculture: environmental, economic and social approaches. In other words, agricultural systems are considered to be sustainable if they sustain themselves over a long period of time, that is, if they are economically viable, environmentally safe and socially fair. Beyond this ideological definition, the practical issue is to build operational solutions to reach global goals. This is a challenging task because the stakeholders do not agree on the criteria to measure the sustainability of a farming system, and on how to balance those criteria. Many indicators have indeed already been produced to evaluate sustainability.

The link between sustainable agriculture and sustainable development is not obvious (Legrand et al. 2002). Sustainable agriculture could involve two approaches (Boiffin et al. 2004). The first approach is that agriculture should sustain itself over a long period of time by protecting its productive resources, e.g. maintaining soil fertility, protecting groundwater, developing renewable energies and finding solutions to adapt farming systems to climate change. This first approach considers the farming system as a closed area. The second approach is to consider that agriculture also has to contribute to the sustainability of large territories and social communities. Accordingly, agriculture should help urban areas to manage wastes, e.g. by recycling urban sewage sludge, developing rural employment, and offering a rural landscape for urban people. This second approach has wider goals and does not separate rural and urban areas. To conclude, the vagueness of the concept of sustainable development and sustainable agriculture is a strength because it does not restrict the research field too much, and, in turn gives freedom to scientists to explore wide, unknown domains.

3 Future Sustainable Farming Systems

After the Second World War, the development of conventional farming, or "industrial farming," was promoted in order to increase sharply food production worldwide. This social aim led to extensive use of pesticides, fertilisers and water, and to fast crop rotations and monoculture. Positive effects on yield were rapidly counterbalanced by negative environmental impacts such as soil erosion, groundwater pollution, river eutrophication, excessive water use, and the development of weeds and diseases resistant to chemical control. Industrial farming and other industrial activities have indeed led to the presence of pesticides and persistent organic pollutants in soils, water, air and food (Lichtfouse and Eglinton 1995; Lichtfouse 1997a; Lichtfouse et al. 1997, 2005b).

Today, to reach economic profitability, environmental safety and social fairness, farming systems should use fewer inputs and resources without drastically reducing yields. As the population is forecasted to increase to 9 billion in the next 50 years, it is necessary to maintain a high level of food production. Nonetheless, farming systems should also meet food quality policies enforced by national and international policies. This issue is particularly relevant given the occurrence of pesticide residues in food products because consumers and environmental associations are concerned about a possible new sanitary crisis. Pesticide use by farmers is thus widely criticised. On the other hand, decreasing pesticide use may lead to negative effects such as toxin risk in food (Le Bail et al. 2005). To reach more sustainable practices, several strategies are described in the literature. Those strategies involve various changes, from simple adjustment of the crop management sequence to fundamental changes at the farming system level. For example, MacRae et al. (1989) proposed the following framework based on efficiency – substitution – redesign (ESR). In the following section we describe three stategies to reach sustainable agriculture: the substitution strategy, the agroecological strategy and the global strategy.

3.1 Level 1: The Substitution Strategy

This level refers to the substitution logic, meaning that existing farming systems are only slightly adapted, but not fundamentally altered (Altieri and Rosset 1996). For instance, toxic chemicals and mineral fertilisers (NPK) should be replaced by compounds that are less pollutant, less persistent in soil and less energy-consuming. Applying biopesticides and growing genetically modified plants should decrease both pest development and the use of toxic pesticides. Growing symbiotic N legumes instead of applying costly, energy-consuming N fertilisers should also improve sustainability. Here, research is usually done at the plot level, which is the most common level for agronomists. Collaborations with scientists studying elementary processes, such as geochemists, pathologists and biologists, should be fostered. The substitution logic should be effective for a short time period because it allows a substantial reduction of chemical treatments. However, it may be not be efficient in the long run due to the appearance of pest resistance following the use of biopesticides, for instance.

3.2 Level 2: The Agroecological Strategy

The principle of the agroecological strategy is to build innovative technical scenarios relying on biological regulations in an integrated crop production scheme. This strategy involves applying ecological concepts and principles to the design, development and management of sustainable agricultural systems. Promoting biodiversity in agrosystems provides ecological services such as nutrient cycling, soil structuration and disease control. Biodiversity can be enhanced by cultural practices such as intercropping, rotation, agroforestry, composting and green manuring. Recent studies also address new issues in integrated pest management by combining the use of biological, physical, cultural and genetic control measures (Gurr et al. 2004). Increasing biodiversity by crop rotations (combination in time), intercropping (combination in space) and varietal mixtures has been suggested as an alternative to chemicals (Vandermeer et al. 1998). At this level, agronomy should interact with landscape ecology, because spatial variations in the landscape may be used for pest management. The productivity of farming systems should be increased by developing ecological principles and adapting them to farming systems. The agroecological strategy thus requires the enlargement of the experimental scale. Experimental scenarios should not be designed at plot level, but at the scale of larger territories. Therefore, investigations need a much better understanding of interactions of living organisms at plot and larger levels. They also require input from other disciplines such as ecology and geography.

3.3 Level 3: The Global Strategy

The principle of the global strategy is to solve agricultural issues at the global scale, by rethinking its relation to society. Indeed, most failures of intensive agriculture are closely linked to its economic model. There are fundamental contradictions among several aims assigned to agriculture. For instance, producing more and cheaper food products without polluting soils; and producing fruits and vegetables without pesticide residues and without visual pest damage appear to be unrealistic aims. Therefore, the global strategy relies on rethinking the role of agriculture in our society, as shown by new trends in agroecology (Gliessman 2006). This approach considers that sustainability cannot be solely reached by farming systems, but should also involve the food system, the relations between farms and food consumption, and the marketing networks. For example, authors studying the relationships between production and marketing highlighted the interest in alternative food networks focused on local production (Lamine and Bellon 2008). The global strategy thus requires interdisciplinary work with scientists from various sciences such as agronomy, ecology, sociology, economics and politics.

4 Agronomical Research for Sustainable Agriculture

Agronomy was first defined as the science of crop production. It was mainly focused on the study of relationships between climate, soil, cultural practices and crop yield and quality. Agronomy therefore integrates sciences such as biology, chemistry, soil science, ecology and genetics. Agronomists then enlarged their studies to the individuals performing the cultural practices, namely farmers. This approach raised new issues on the modelling of farmers' practices, and on the consequences of farmers' choices on crop production. Agronomists further analysed environmental impacts of farmers' practices. More recently, they have also studied how agriculture could benefit from the environment and ecosystems to improve crop production, thus leading to the concept of "ecological services."

To study crop production, agronomists have to integrate highly complex sciences that rule farming systems at very different spatial and temporal scales. Agronomists also have to cope with a high environmental variability. As a consequence, results obtained in an experimental field may not be reproducible in another field due to slight – possibly unknown – variations in soil and climate factors. Therefore, a key point of agronomical investigations is to define the validity domain of each finding. Concerning the integration of agricultural practices, a key point is to enlarge the classical scales of crop production studies, "plant and plot," to scales that are meaningful for the farmers, such as combination of plots and farm territory, and even larger scales. In a way, agronomy is a science of complexity aimed at integrating knowledge at various spatial levels from the molecule to the living organism, the farming system and the global scale. Thus, agronomy appears more and more to be the science relevant for global issues because it integrates knowledge from various sciences at various spatial scales. Considered for a long time as a soft, side science, agronomy is rising fast as a central science because current issues are about food, and humans eat food.

The systemic dimension is essential because in the next few decades most improvements of farming systems will rely on enhancing positive interactions among various parts of farming systems. To build sustainable farming systems, agronomists will not only have to assess the direct effects of techniques on a crop, but also the indirect effects on the whole ecosystem such as biodiversity changes, water pollution and soil erosion. The economic and social consequences of the new farming systems should also be evaluated with a pluridisciplinary approach with economists or social scientists. Therefore, sustainable agriculture fosters the development of multidisciplinary studies that associate agronomy with ecology, economics, sociology and geography (Lichtfouse et al. 2004). Meynard et al. (2006) identified four different ways to design innovative agricultural systems for sustainable development:

- Inventing new farming systems, breaking off with the current ones;
- Identifying and improving farming systems built by the local stakeholders;
- Giving tools and methods to stakeholders to improve their own systems or evaluate those proposed by scientists;
- Identifying the economic, social and organisation conditions that may help the actors to adopt alternative farming systems.

These approaches raise several new issues for agronomical scientists. For instance, it is not clear whether solutions will be found either by only a slight adaptation of research practices or by a sharp change in experimentation and modelling. Studying new spatial scales that show heterogeneous areas such as field margins will be a challenge. The integration of long-term changes in farming systems, such as soil organic matter turnover (Lichtfouse 1997b) and sewage sludge pollution (Lichtfouse et al. 2005a), should also be investigated and modelled because concepts of resilience and flexibility are relevant. It should also be noted that some farmers already have an accurate expertise in sustainable practices. Some are even ahead of research and are experimenting with new systems for, e.g. organic farming. Here, the issue for the agronomist is to build effective methods to gather local knowledge, to check findings and eventually to redesign experiments. Innovative agricultural systems will benefit from a close collaboration between scientists and farmers.

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Laws of Sustainable Soil Management

Rattan Lal

Abstract The challenge of doubling the world's food grain production by 2030 is even more daunting because of the decrease in per capita arable land area and renewable fresh water resources; increase in risks of soil and environmental degradation; and threat of decrease in use efficiency of inputs because of the projected climate change. Thus, the need for identifying processes, practices and policies that govern sustainable management of soil resources is more critical now than ever before. The goal is to minimize risks of soil degradation by enhancing its resilience and improving ecosystem services of the finite and fragile soil resource. Here, 10 principles are given for sustainable management of soil. This report is an introductory article of the book Sustainable Agriculture, published by Springer, EDP Sciences (Lichtfouse et al. 2009, this book).

1 Introduction

The world population of 1 million about 10,000 years ago increased to merely 1 billion by 1800. The population is projected to be 10 billion by the end of the twenty-first century. Almost the entire increase of 3.3 billion, from 6.7 billion in 2008 to 10 billion by 2100, will occur in developing countries where soil resources are finite and already under great stress. An unprecedented increase in agronomic productivity between the 1960s and 2000, brought about by the Green Revolution technology of growing input-responsive varieties in irrigated soils with high input of chemicals, created a false sense of security and an unnecessary complacency. Consequently, funding support for agricultural research and development has been dwindling (Anonymous 2008). The need for a continued increase in agronomic productivity, from the cropland area and irrigation water resources already committed through increase in use efficiency of inputs with an attendant reduction in losses by erosion and leaching or volatilization, was underscored by the drastic increase in prices of food grains, e.g., wheat, rice and corn, in early 2008. The number of food-insecure people, estimated at 854 million (FAO 2006), increased to 1002 million in 2009 because of the increase in price of the basic food commodities.

The problem of global food insecurity may be exacerbated by the threat of global warming. The projected increase in temperature and decrease in effective precipitation in semi-arid regions may adversely impact agronomic productivity of food staples, e.g., corn, wheat and rice (Lobell et al. 2008; Brown and Funk 2008). Examples of "tipping elements" in these important biomes include the Indian summer monsoon, and Sahel monsoon (Lenton et al. 2008). The adverse impacts of climate change on agronomic productivity may be due to a range of complex but interacting factors. Despite the positive impact of CO_2 fertilization, the net productivity may decrease because of an increase in respiration rate, drought stress and nutrient deficiency. The global energy crisis is also diverting cropland to biofuel plantations, often with positive feedback emissions of CO_2 and N_2O from soils

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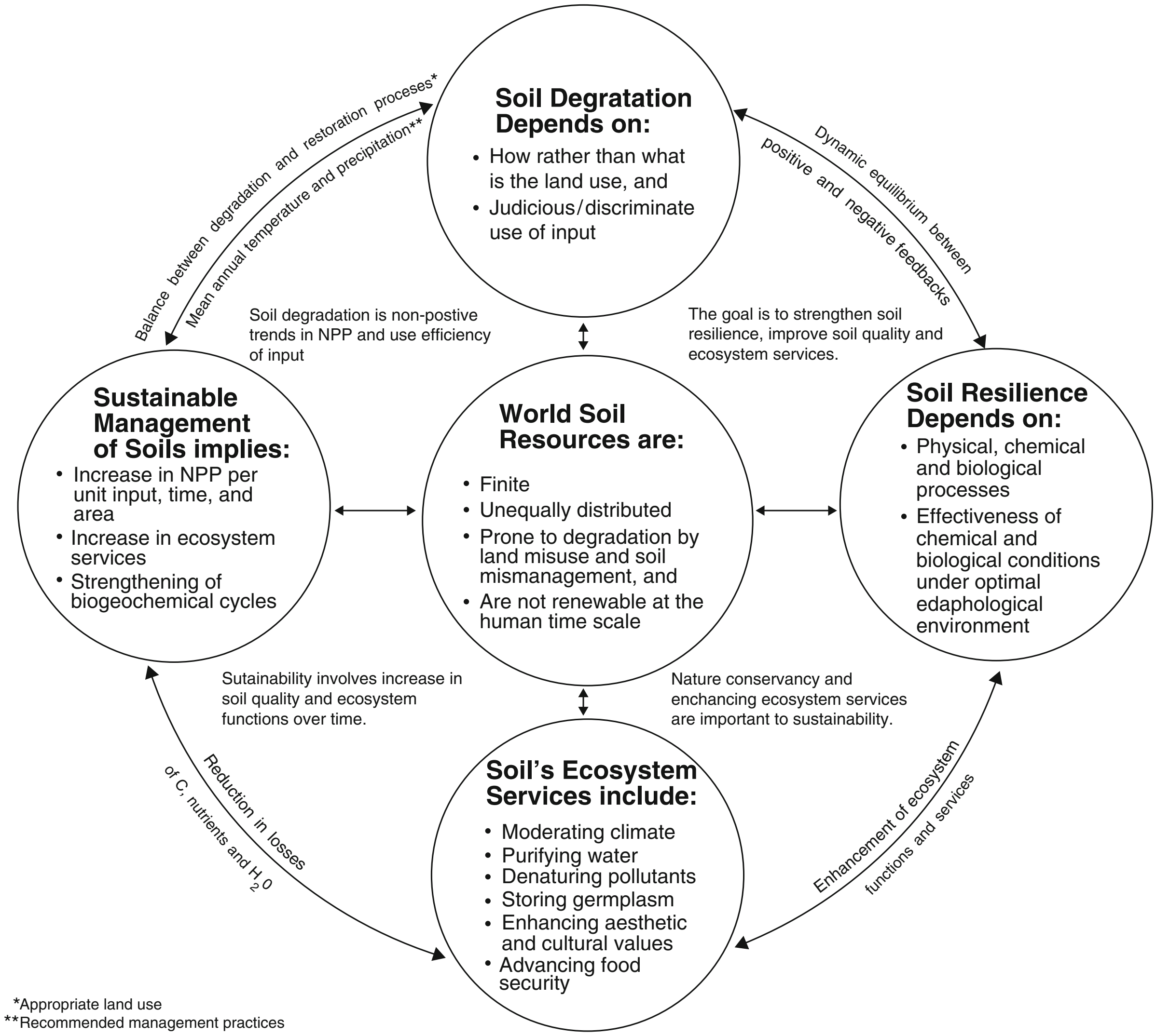

Fig. 1 Properties, processes and practices which govern soil degradation and resilience, and sustainable management

(Searchinger et al. 2008). The competition with biofuel plantations for land is leading to new land being cleared from the tropical rainforest, often with a large carbon debt (Farzione et al. 2008).

While the debate on the magnitude and severity of global warming goes on (Florides and Christodoulides 2008), the problems of soil degradation and desertification are exacerbated by the increasing demand on finite soil resources for the food, feed, fiber and fuel needs of the world's growing population. It is thus important to identify properties, processes and practices that affect sustainable management through setting-in-motion soil restoration trends which have minimal C and water footprints (Fig. 2). Soil degradation and restoration processes are governed by a set of laws as stated below:

2 Basic Principles of Sustainable Soil Management

Law #1

Soil resources are unequally distributed among biomes and geographic regions. Highly productive soils in favorable climates are finite and often located in regions of high population density, and have already been converted to managed ecosystems, e.g., cropland, grazing land and pasture, forest and energy plantations.

Law #2

Most soils are prone to degradation by land misuse and soil mismanagement. Anthropogenic factors leading to soil degradation are driven by desperate situations and helplessness in the case of resource-poor farmers and smaller landholders; and greed, short-sightedness, poor planning and cutting corners for quick economic returns in the case of large-scale and commercial farming enterprises.

Law #3

Accelerated soil erosion and decline in soil quality by other degradation processes depend more on "how" rather than on "what" crops are grown. Productive potential of farming systems can only be realized when implemented in conjunction with restorative and recommended soil and water management practices. Sustainable use of soil depends on the judicious management of both on-site and off-site inputs. Indiscriminate and excessive use of tillage, irrigation and fertilizers can lead to as much as or even more degradation than none or minimal use of these technologies.

Law #4

The rate and susceptibility of soil to degradation increase with increase in mean annual temperature and decrease in mean annual precipitation. All other factors remaining the same, soils in hot and arid climates are more prone to degradation and desertification than those in cool and humid ecoregions. However, mismanagement can lead to desertification even in arctic climates, e.g., Iceland.

Law #5

Soil can be a source or sink of greenhouse gases, e.g., CO_2, CH_4 and N_2O, depending on land use and management. Soil is a sink of atmospheric CO_2 under those land use and management systems which create a positive C budget and gains exceed the losses (Fig. 2a, left). Soil is a source of atmospheric CO_2 when the ecosystem C budget is negative and losses exceed the gains (Fig. 2b, right). Soils are a source of radiatively-active gases with extractive farming which create a negative nutrient budget and degrade soil quality, and a sink with restorative land use and judicious management practices which create positive C and nutrient budgets and conserve soil and water while improving soil structure and tilth.

Law #6

Soils are non-renewable over a human time frame of decadal or generational scales, but are renewable on a geological scale (centennial/millennial). With the increase in the human population, projected to be 10 billion by 2100, restoring degraded and desertified soils over a centennial-millennial scale is not an option.

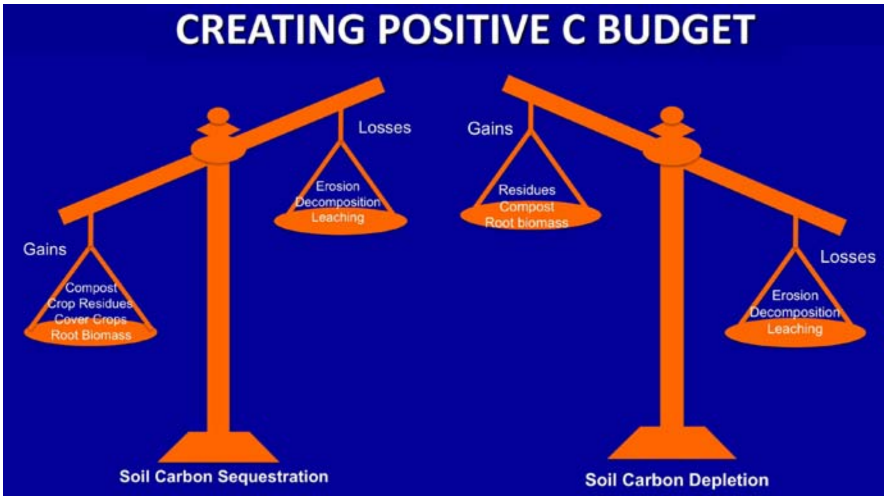

Fig. 2 A positive C (and nutrient) budget is essential to C sequestration

Because of heavy demands on finite resources, soils are essentially a non-renewable resource.

Law #7

Soil's resilience to natural and anthropogenic perturbations depends on its physical, chemical and biological processes. Favorable chemical and biological processes enhance resilience only under optimal soil physical properties, e.g., soil structure and tilth, processes, e.g., aeration, water retention and transmission, and edaphological environments, e.g., soil temperature.

Law #8

The rate of restoration of the soil organic matter pool is extremely slow, while that of its depletion is often very rapid. In general, restoration occurs on a centennial time scale and depletion on a decadal time scale. The rate of restoration and degradation processes may differ by an order of magnitude.

Law #9

Soil structure, similar to an architectural design of a functional building, depends on stability and continuity of macro-, meso- and micropores which are the sites of physical, chemical and biological processes that support soil's life support functions. Sustainable management systems, site-specific as these are, enhance stability and continuity of pores and voids over time and under diverse land uses.

Law #10

Sustainable management of agricultural ecosystems implies an increasing trend in net primary productivity per unit input of off-farm resources along with improvement in soil quality and ancillary ecosystem services such as increase in the ecosystem C pool, improvement in quality and quantity of renewable fresh water resources, and increase in biodiversity.

Soil resources can never be taken for granted. Extinct are the once thriving civilizations, e.g., Mayan, Incas, Indus, Mesopotamia, which chose to ignore their soil resources. Given its importance to human survival and dependence of all terrestrial life, soil quality must be improved, and restored. Soils must be transferred to the next generation in a better state than when received from the previous one.

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Part I
Climate Change

Soils and Sustainable Agriculture: A Review

Rattan Lal

Abstract Enhancing food production and supporting civil/engineering structures have been the principal foci of soil science research during most of the nineteenth and the first seven or eight decades of the twentieth century. Demands on soil resources during the twenty first century and beyond include: (1) increasing agronomic production to meet the food needs of additional 3.5 billion people that will reside in developing countries along with likely shift in food habits from plant-based to animal-based diet, (2) producing ligno-cellulosic biomass through establishment of energy plantations on agriculturally surplus/marginal soils or other specifically identified lands, (3) converting degraded/desertified soils to restorative land use for enhancing biodiversity and improving the environment, (4) sequestering carbon in terrestrial (soil and trees) and aquatic ecosystems to off-set industrial emissions and stabilize the atmospheric abundance of CO_2 and other greenhouse gases, (5) developing farming/cropping systems which improve water use efficiency and minimize risks of water pollution, contamination and eutrophication, and (6) creating reserves for species preservation, recreation and enhancing aesthetic value of soil resources. Realization of these multifarious soil functions necessitate establishment of inter-disciplinary approach with close linkages between soil scientists and chemists, physicists, geologists, hydrologists, climatologists, biologists, system engineers (nano technologists), computer scientists and information technologists, economists, social scientists and molecular geneticists dealing with human, animal and microbial processes. While advancing the study of basic principles and processes, soil scientists must also reach out to other disciplines to address the global issues of the twenty first century and beyond.

Keywords Biofuels • Climate change • Food security • Soil functions • Sustainable agriculture • Waste management • Water resources

1 Introduction

Goals of soil management during the nineteenth century and the first half of the twentieth century, when world population was merely 38% of the 2006 level, was to maintain agronomic productivity to meet the food demands of two to three billion inhabitants. Demands on soil resources are different of a densely populated and rapidly industrializing world of the twenty first century. In addition to food supply, modern societies have insatiable demands for energy, water, wood products, and land area for urbanization, infrastructure, and disposal of urban and industrial wastes. There is also a need to alleviate rural poverty and raise the standard of living of masses dependent on subsistence farming. In addition, there are several environmental issues which need to be addressed such as the climate change, eutrophication and contamination of natural waters, land degradation and desertification, and loss of biodiversity. To a great extent, solutions to these issues lie in sustainable management of world's soil resources (Fig. 1), through adoption of agronomic techniques which are at the cutting edge of science.

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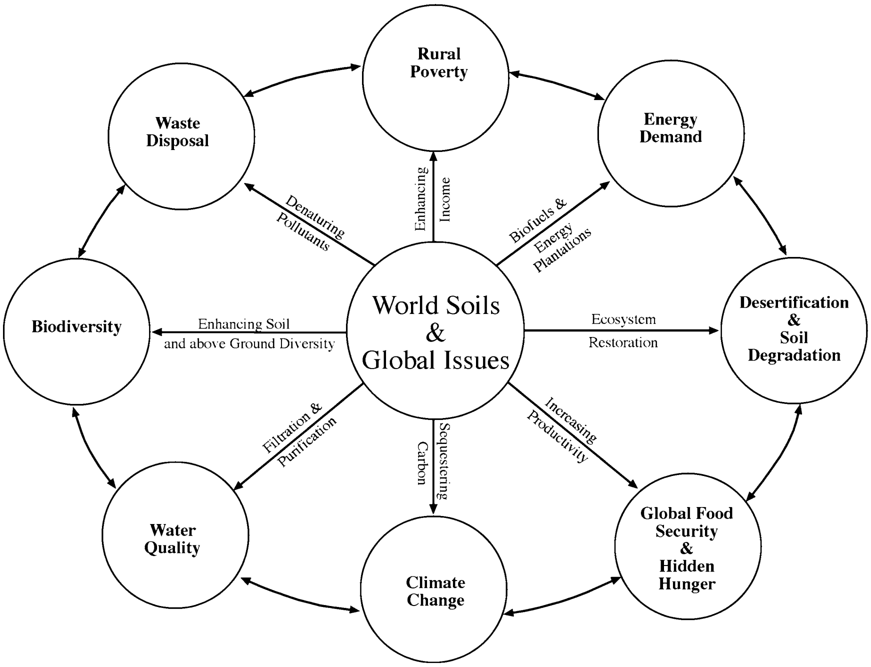

Fig. 1 World soils and global issues of twenty first century

2 Advancing Food Security

The world population of merely 0.2 billion during the biblical era increased by only 0.11 billion (to 0.31 billion) during the next 1,000 years by 1000 AD. However, the population increased 20 times to 6 billion during the next 1,000 years by 2000 AD. The world population is projected to reach 9.4 billion by 2050 and 10 billion by 2100 (Fischer and Heilig 1997; Cohen 2003). The most remarkable aspect of the future population dynamics is the fact that all of the projected increase by about 3.5 billion will occur in developing countries of Asia (mostly South Asia) and Africa (mostly sub-Saharan Africa). These are also the regions where soil resources are limited in extent (per capita), fragile to natural and anthropogenic perturbations, and prone to degradation by the projected climate change and the increase in demographic pressure. Thus, any future increase in agronomic/food production will have to occur through vertical increase in production per unit area, time and input (e.g., nutrients, water, energy) of the resources already committed to agriculture. It is in this context that developing and identification of some innovative methods of soil management are crucial to feeding the world population of 10 billion. These methods must minimize losses by delivering nutrients and water directly to the plant roots during the most critical stages of crop growth. Degraded and desertified soils must be reclaimed through enhancement of the soil organic matter (SOM) pool, creation of a positive elemental budget with balanced supply of all essential nutrients, effective control of soil erosion by water and wind, restoration of soil structure and tilth through bioturbation, and enhancement of activity and species diversity of soil fauna and flora. Soil management techniques must be chosen to ensure: (1) liberal use of crop residues, animal dung and other biosolids, (2) minimal disturbance of soil surface to provide a continuous cover of a plant canopy or residue mulch, (3) judicious use of sub-soil fertigation techniques to maintain adequate level of nutrient and water supply required for optimal growth, (4) an adequate level of microbial activity in the rhizosphere for organic matter turnover and elemental cycling, and (5) use of complex cropping/farming systems which strengthen nutrient cycling and enhance use efficiency of input. Identification, development and validation of such innovations must be based on modern technologies such as GIS, remote sensing, genetic manipulations of crops and rhizospheric organisms, soil-specific management, and slow/time release formulations of fertilizers. Increase in crop yields must occur in rainfed/dry farming systems which account for more than 80% of world's croplands. Breaking the agrarian stagnation/deceleration in sub-Saharan Africa must be given the highest priority by soil scientists and agronomists from around the world. While expanding irrigated agriculture is important, crop yields have to be improved on rainfed agriculture in Asia and Africa, by conserving or recycling every drop of rain, and by not taking soils for granted.

3 Biofuels

In comparison with the stone age or bronze age, the industrial era (1750–2050) will be referred to the carbon (C) age or carbon civilization by future generations from 2100 AD and beyond (Roston 2008). The use of fossil fuel, since the onset of industrial revolution ~1750, has drastically disturbed the global C cycle with the attendant impact on the climate change and the increase in earth's temperature along with change in rainfall amount and distribution. The present civilization is hooked on C, and is in need of a big time rehabilitation. Breaking the C-habit will require development of C-neutral or non-carbon fuel sources, and both soil science and agronomy have a major role to play in this endeavor. Not only the recommended agricultural input (fertilizers, pesticides, tillage methods, irrigation) must be efficiently used, the future energy demands will eventually be met by non-carbon fuel, most likely hydrogen. The latter can be generated from biomass produced through appropriate land uses and judicious cropping/farming systems. In the meanwhile, modern biofuels (ethanol, biodiesel) can play an important role in minimizing emissions of greenhouse gases and reducing the rate of increase of atmospheric concentration of CO_2 (Brown 1999; Cassman et al. 2006). Converting grains (e.g., corn) to ethanol is rather an inefficient method of energy production, and grains are and will remain in high demands as food staple for humans and feed for livestock and poultry.

Crop residues are also being considered as a source of energy (Somerville 2006; Service, 2007). Indeed, 1 Mg (1t) of lignocellulosic residues is equivalent to 250–300 L of ethanol, 15–18 GJ of energy, 16×10^6 kcal or 2 barrels of diesel (Lal 2005; Weisz 2004). The energy return on investment (EROI) for grain-based ethanol is low. Furthermore, crop residues (of corn, wheat, barley, millet, rice) must be used as soil amendment/mulch to control erosion, conserve water and replenish the depleted SOM pool through soil C sequestration, and restore degraded soils and ecosystems (Wilhelm et al. 2004). Crop residues must not be considered a waste, because they have multifarious but competing uses including conservation of soil and water, cycling of nutrients, enhancement of the use efficiency of fertilizers and irrigation water, and above all, as a food of soil organisms which are essential to making soil a living entity. Using crop residues for production of biofuels is "robbing Peter to pay Paul" and all that glitters is not gold, not even the green gold. The price of harvesting crop residues (such as from the US Corn Belt) will be severe soil and environmental degradation (dust bowl), because there is no such thing as a free lunch. It is, thus, important to identify dedicated crops which can be grown

Table 1 Species for establishing biofuel plantations

English name	Botanical name
1. Warm season grasses	
• Switch grass	*Panicum virgutum* L.
• Big blue stem	*Andropogan gerardi*, Vitnam
• Indian grass	*Sorghastrum nuttans* L. Nas
• Blue giant grass	*Calanagrostis canadensis* Michx Bean L.
• Guines grass	*Panicum maximum* L.
• Elephant grass	*Pennisetum perpereum* schm.
• Kallar/Karnal grass	*Leptochloa frscha* L.
• Molasses grass	*Melinis minutiflona*
• Reed canary grass	*Phalaris arundinacae* L.
• Cord grass	*Spartina pectinata* Link.
2. Short rotation woody crops	
• Popalar spp	*Populus* spp.
• Willow spp	*Salix* ssp.
• Mesquite (Velayti Babul)	*Prosopis juliflora*
• Miscanthus	*Miscanthus* spp.
• Black locust	*Robinia pseudoacacia* L.
• Birch	*Onopordum nervosum*
3. Halophytes	
• Pickle weed	*Salicornia bigelovii*
• Salt grass	*Distichlis palmeri*
• Salt brushes	*Atriplex* spp.
• Algae	*Spirulina geitleri*
• Cyanobacteria	*Cyanobacteria* spp.
4. Drought tolerant trees	
• Gum tree	*Eucalyptus* spp.
• Leucaena (Subabul)	*Leucaena leucocephala*
• Casurinas	*Casurina equisetifolia*
• Acacia	*Acacia* spp.
• Teak	*Tectona grandis*
• Cassia	*Casia siamea*

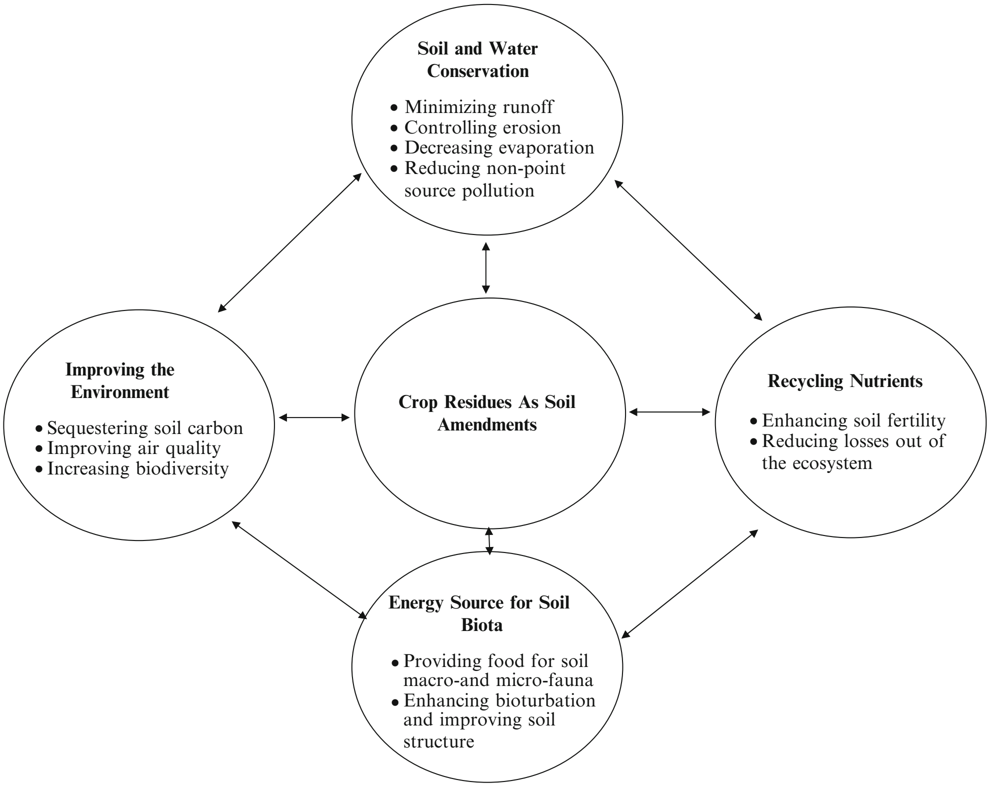

Fig. 2 Site and eco-system specific effects of crop residue management on soil and environment quality must be assessed in relation to improvement in soil quality and sustainable use of natural resources

to establish biofuel plantations (Table 1). Furthermore, new lands (agriculturally marginal/surplus soils; and degraded, disturbed and polluted soils) must be identified to establish appropriate biofuel plantations. In addition to providing the lignocellulosic biomass for conversion to ethanol, establishment of biofuel plantations on degraded soils would also lead to soil C sequestration and enhance soil quality and the ecosystem services that it would provide. The EORI of biofuel production system must be carefully assessed through a comprehensive life cycle analysis. In addition to establishing managed biofuel plantations, lignocellulosic biomass can also be harvested from natural vegetation growth on abandoned/set aside or fallowed land (Tilman et al. 2006). The issue of using crop residues for cellulosic ethanol production must not be resolved on the basis of short-term economic gains. The rational decision must be based on the long-term sustainable use of natural resources (Figs. 2 and 3). Indeed, the immediate needs for fuel must not override the urgency to achieve global food security, especially for almost 1 billion food-insecure people in Africa and Asia. If the crop residues harvested for celunol production are not returned as compost (with enhanced plant nutrients such as N, P, K), the long-term adverse impacts on soil quality (such as has been the case in severely degraded soils of sub-Saharan Africa and South Asia due to perpetual removal of crop residues) will jeopardize global food security and set-in-motion the soil degradation spiral with the attendant impact on social unrest and political instability (Fig. 4).

4 Waste Disposal

The importance of soil for the safe disposal of ever-increasing industrial and urban wastes cannot be over-emphasized. The municipal solid wastes generated in the US doubled between 1970 and 2003 (USEPA 2006), as is also the case in western Europe and developing economies, in addition, there are wastes of animal and poultry industry, and food

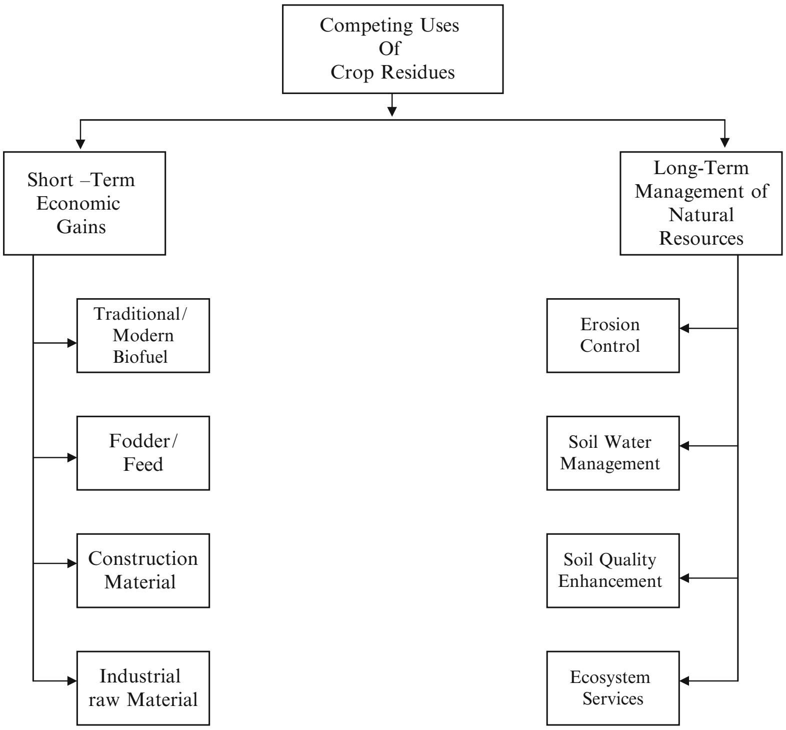

Fig. 3 An objective assessment of short-term economic gains vs. long-term and sustainable use of natural resources important to the decision-making process for competing uses of crop residues

processing plants and restaurants. These wastes containing biosolids which can be used as energy source (either for direct combustion or conversion to methane or ethanol), and as soil amendment, or both. The by products of biosolids used for production of methane gas or ethanol must be composted and used as soil amendment.

Soils of appropriate characteristics (e.g., good drainage, absence of impermeable layer in the vadoze zone, high activity and species diversity of macro and micro-organisms in the surface layer, highly aggregated and stable structure) is also a natural biomembrane which must be used to filter and denature/biodegrade industrial pollutants. Carefully chosen soils and the underlying parent material/geologic strata are being used as a repository for nuclear wastes (e.g., Yucatan mountain range in the southwestern US). Although questionable in terms of effectiveness and economic cost, geologic strata are also being used/considered for storage of industrial CO_2 emitted from point sources (Schrag 2007). The importance of soil as a medium for waste disposal is bound to increase with increase in population and industrialization, and soil scientists must be pro-active in this emerging field of great significance. Similarly, agronomists must be very actively involved in phytoremediation of polluted soils by using plants to denature industrial pollutants.

5 Farming Carbon

Carbon sequestration in terrestrial ecosystems (e.g., soils, trees, wetlands), and improving soil quality so that soils can be a net sink for CH_4 and release less N_2O, is an important issue which must be addressed by soil scientists, crop scientists, agronomists, foresters, and wetland ecologists. While understanding the processes which impact the ecosystem carbon pool and fluxes is important, soil scientists and agronomists must liaise with economists and policy experts to develop a methodology for trading of carbon credits so that it can be traded like any farm commodity (e.g.,

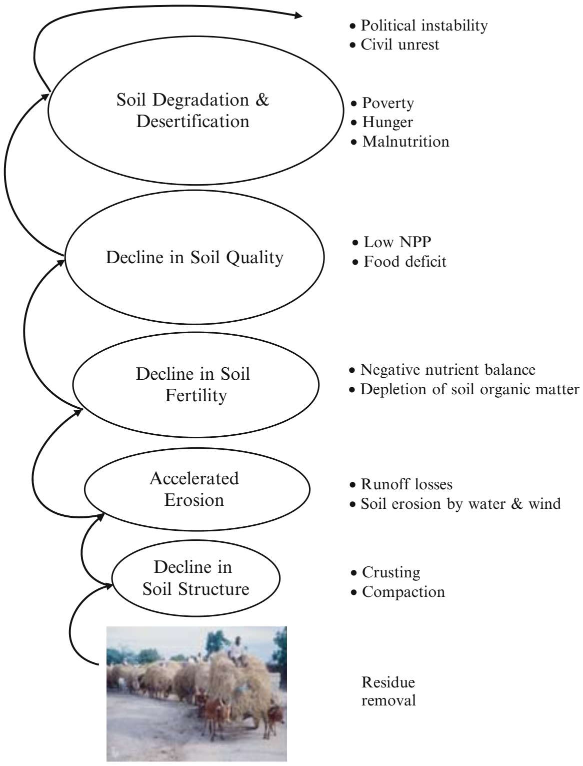

Fig. 4 The classic collapse

corn, millet, poultry). Similar to C sequestered in trees, methodology must be developed to trade C in soils (Breslau 2006; Brahic, 2006). In addition, emissions of CH_4 and N_2O can be converted to CO_2 equivalent, and also traded. Trading C credits can provide another income stream for farmers, and provide the much needed incentives to invest in soil improvements (e.g., erosion control, fertility management, irrigation).

Restoration of degraded soils and ecosystems is an important facet intimately linked to soil C sequestration. Soil degradation and desertification, biophysical processes driven by socio-economic and political factors, are severe problems in developing countries of South Asia and sub-Saharan Africa (Oldeman 1994). Restoration of eroded/degraded soils, through land use conversion via afforestation and conversion of degraded croplands to improved and well managed pastures, will lead to terrestrial C sequestration (in soils and trees) as an ancillary benefit. Soil degradation through land misuse, soil mismanagement, and excessive consumption of water through flood irrigation that leads to salinization and inundation are luxuries that the land-starved and the water-scarce world cannot afford, not anymore.

There is a strong link between soil restoration, carbon sequestration, food security (Lal 2006) and biodiversity (Fig. 5). Improvement of soil quality, gradual and a slow process as it may be, is caused by an increase in the terrestrial C pool. The latter is also linked with biodiversity, water quality and micro and mesoclimate, and emission of greenhouse gases into the atmosphere. Understanding interactive mechanisms, especially those which link processes in soil with those in atmosphere and hydrosphere through biosphere, are of a high priority for soil scientists and agronomists. In addition to quantifying these processes, soil scientists and agronomists must also communicate their findings to policy makers such as the US Congress, European Parliament, and the UN organizations. Through their interactive research outlined above, soil scientists must provide the basic information which is needed to bring together three UN Conventions (i.e., UNFCCC, UNFCBD, and UNFCDC). While providing crucial information on biodiversity, desertification control and climate change to strengthen cross linkages among three UN Conventions, soil scientists can also build bridges to link these organizations with the noble UN Millenium Development Goals of cutting poverty and hunger in half. In agricultural economy, which involves two-thirds to three-fourths of the rural population, increasing agronomic productivity and providing another income stream for farmers through trading of C credits are important strategies to advance food security while alleviating poverty and improving the environment. Generating income through trading of soil/terrestrial carbon credits may be the entry point or the handle to break the vicious cycle of soil degradation-low yields-poverty – hunger-severe soil degradation. It is a truly win-win-win strategy that deserves a serious attention of the world community.

6 Water Resources

In addition to fertility and nutrient supply, agricultural productivity will be constrained by lack of water resources, whose severity will be exacerbated by frequent and severe drought stress due to the projected climate change. Whereas agriculture is the largest consumer of water, the competition from industrial and

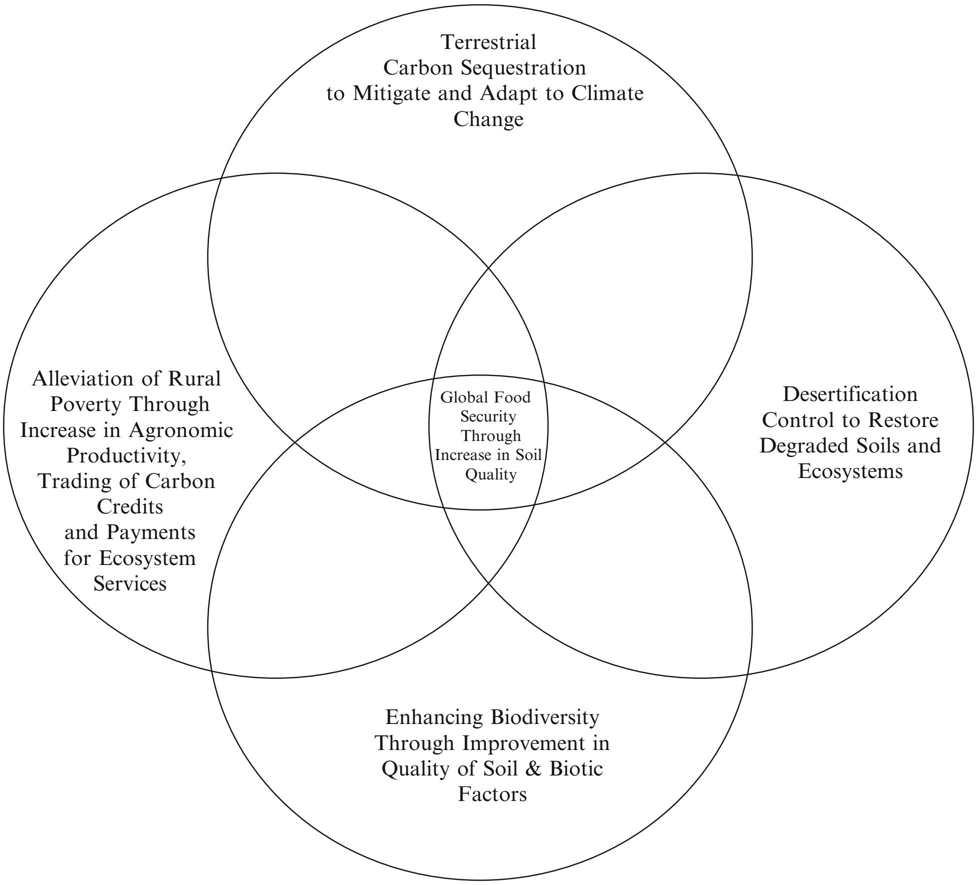

Fig. 5 A positive and synergistic interaction between desertification control, biodiversity improvement, climate change mitigation, and food security. The latter is improved through improvement in soil quality, increase in availability of water resources, strengthening of elemental cycling, and enhancement of bioturbation in the rhizosphere. Soil scientists and agronomists must be actively pursuing quantification of these synergistic effects

urban uses is increasing with increase in demographic pressure and rapid industrialization (Moldan 2007; Gleick 2003; Kondratyev 2003; Johnson et al. 2001). The scarcity of fresh water is exacerbated by non-point and point source pollutions (Tilman et al. 2006), and will be further aggravated by likely shift in diet in developing economies (e.g., China, India) from plant-based to animal-based products (Clay 2004). In this regard, improved understanding of soils and agronomic processes which enhance water use efficiencies is highly relevant and extremely critical. Soil scientists and agronomists need to work closely with plant breeders to develop genetically engineered plants which have high productivity per unit consumption of water, with irrigation engineers to reduce losses of water during conveyance and delivery, with micrometeorologists to reduce losses from soil evaporation, with hydrologists to economically and effectively recycle water drained into the sub-soil or ground water, and with municipalities of large urban centers to develop techniques of recycling waste water for irrigation and aquifer recharge. Replacing flood irrigation with subirrigation or drip irrigation techniques is a high priority.

7 Reaching Out

The traditional functions of soil have been: (1) the medium for plant growth, (2) foundation for civil structures, and (3) source of raw materials for industry. During the twenty first century and beyond, functions of soil must be expanded to include the following: (1) mitigation of climate change through C sequestration in terrestrial and aquatic ecosystems, (2) purification of water through filtration and denaturing of pollutants, (3) disposal of urban and industrial wastes in a way that these do not contaminate water or pollute air, (4) store germ plasm including that of microbes which can be used to combat diseases, (5) archive human and planetary history, (6) support being a reactor of chemical and physical processes, and (7) provide a strategic entity in national and international affairs to give peace a chance.

The concept of "sustainable agriculture" needs to be revisited in the context of the need for increasing productivity in developing countries which will entirely inherit the future increase in population of 3.5 billion by the end of the twenty first century. With reference to the densely populated countries of Asia and Africa, sustainable agricultural practices are those which: (1) maximize productivity per unit area, time and input of fertilizers, water and energy, (2) optimize the use of off-farm input, (3) increase household income through increase in production, trading of carbon credits, off-farm employment, and value addition of farm produce, (4) improve quality and quantity of fresh water resources at the farm level, (5) provide education opportunities especially for women, (6) create clean household cooking fuel for the rural population to improve health of women and children and spare animal dung and crop residues for use as soil amendments, and (7) address concerns of the farm family especially food security until the next harvest. It is a fact that indiscriminate use of chemicals, excessive tillage and luxury irrigation have degraded soils, polluted waters and contaminated air. The problem is not with the technology. It has been the over-fertilization, overuse of pesticides, excessive application of irrigation because of free water, unnecessary plowing, complete removal of crop residues along with uncontrolled grazing, and the use of animal dung for household fuel rather than soil amendment that have caused the problems.

Access to adequate and balanced food and clean drinking water are the most basic human rights which must be respected. Political stability and ethnic conflicts are caused by hunger and the desperateness created by it. Thus, the concept of sustainable agriculture must be based on the simple fact that agricultural ecosystems are only sustainable in the long-term if the outputs of all components produced balance the inputs into the system. Whether the required amount of input (nutrients) to obtain the desired yield is supplied in organic rather than inorganic form is a matter of availability and logistics. Plants cannot differentiate the nutrients supplied through the organic or synthetic sources. The important question is of supplying nutrients in adequate quantity and when needed to produce enough food to meet the needs of 6.5 billion people now and 10 billion by the end of the century. In some cases, in vicinity of large livestock or poultry farms, organic manures may be available. In other cases, massive intervention through fertilizer use has no practical alternatives in a world of growing population. In some cases traditional breeding is acceptable, in others the natural process of gene manipulation may have to be accelerated through techniques of genetic engineering. The strategy is to use the technology prudently and with utmost objectivity and rationality. Transgenic plants can be grown on degraded and salt-affected soils to produce biomass for biofuels, and to alleviate biotic and abiotic stresses on dryland agriculture. If effective, why not?

While those holding the neo-Malthusian views will again be proven wrong through adoption of already proven and emerging technologies for sustainable management of soil resources, soil scientists and agronomists cannot undertake these serious issues all by themselves. These are far reaching and complex functions that soil scientists may take lead in but must develop close cooperation with other disciplines. While advancing and improving the knowledge of basic processes, soil scientists must also work with geologists, hydrologists, climatologists, biologists, chemists, physicists, computer scientists, nano technologists, system engineers, economists and political scientists to address these emerging issues of the twenty first century. The key strategy is to reach out to other disciplines while strengthening and advancing the science of soil and its dynamics in an ever changing physical, social, economic and political climate. Agriculture, implemented properly, is an important solution to the issue of achieving global food security but also of improving the environment. The agricultural history of 10–13 millenia has taught us that the motto of modern civilization must be "In Soil We Trust".

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Soils and Food Sufficiency: A Review

Rattan Lal

Abstract Soil degradation, caused by land misuse and soil mismanagement, has plagued humanity since the dawn of settled agriculture. Many once thriving civilizations collapsed due to erosion, salinization, nutrient depletion and other soil degradation processes. The Green Revolution of the 1960s and 1970s, that saved hundreds of millions from starvation in Asia and elsewhere, by-passed Sub-Saharan Africa. This remains the only region in the world where the number of hungry and food-insecure populations will still be on the increase even by 2020. The serious technological and political challenges are being exacerbated by the rising energy costs. Resource-poor and small-size land-holders can neither afford the expensive input nor are they sure of their effectiveness because of degraded soils and the harsh, changing climate. Consequently, crop yields are adversely impacted by accelerated erosion, and depletion of soil organic matter (SOM) and nutrients because of the extractive farming practices. Low crop yields, despite growing improved varieties, are due to the severe soil degradation, especially the low SOM reserves and poor soil structure that aggravate drought stress. Components of recommended technology include: no-till; residue mulch and cover crops; integrated nutrient management; and biochar used in conjunction with improved crops (genetically modified, biotechnology) and cropping systems, and energy plantation for biofuel production. However, its low acceptance, e.g., for no-till farming, is due to a range of biophysical, social and economic factors. Competing uses of crop residues for other needs is among numerous factors limiting the adoption of no-till farming. Creating another income stream for resource-poor farmers, through payments for ecosystem services, e.g., C sequestration in terrestrial ecosystems, is an important strategy for promoting the adoption of recommended technologies. Adoption of improved soil management practices is essential to adapt to the changing climate, and meeting the needs of growing populations for food, fodder, fuel and fabrics. Soil restoration and sustainable management are essential to achieving food security, and global peace and stability.

Keywords Biochar • Conservation agriculture • Food security • Integrated nutrient management • No-till farming • Soil degradation • Soil restoration • Sustainable development

1 Introduction

Global estimates of food-insecure populations of 825 million (Lobell et al. 2008) to 850 million (Borlaug 2007) have increased to >1 billion in 2009. Regional estimates of the food insecure population include 263 million in South Asia (SA), 268 million in China and Southeast Asia, 212 million in sub-Saharan Africa (SSA), 60 million in South and Central America and the Caribbean, and 50 million in other regions of the world. Contrary to the United Nations' (UN) Millennium Development Goals of cutting hunger by half by 2015, the number of food-insecure populations in the world will increase. The stock of food grains in

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