Chapter 8

Soil Quality and Productivity Improvement Under Rainfed Conditions – Indian Perspectives

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Additional information is available at the end of the chapter

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1. Introduction

India, predominantly has agrarian economy with an about 83 m ha area without irrigation and totally dependent on rainfall. This rainfed area constitutes about 58 % of net cultivated area of 142 m ha. The rainfed area supports about 44% of the total food production in the country. Most of the essential commodities such as coarse cereals (90%), pulses (87%), and oil seeds (74%) are produced from the rainfed lands. These statistics emphasise the role that rainfed regions play in ensuring food for the ever-increasing population. Owing to diversity in rainfall pattern, temperature, parent material, vegetation and relief or topography, this country is bestowed with different soil types predominantly alluvial soils, black soil, red soils, laterites, desert soils, mountainous soils etc. Taxonomically, soils in India represent Entisols (80.1 m ha), Inceptisols (95.8 m ha), Vertisols (26.3 m ha), Aridisols (14.6), Mollisols (8.0 m ha), Ultisols (0.8 m ha), Alfisols (79.7 m ha), Oxisols (0.3 m ha) and non-classified soil (23.1 m ha). Based on the rainfall pattern, 15 m ha area falls in a rainfall zone of <500mm, 15 m ha under 500 to 750 mm, 42 m ha under 750 to 1150 mm and 25 m ha under > 1150 mm rainfall. Predominant soil orders which represent semi-arid tropical region are Alfisols, Entisols, Vertisols and associated soils. Other soil orders such as Oxisols, Inceptisols and Aridisols also form a considerable part of rainfed agriculture. Most of the soils in rainfed regions are at the verge of degradation having low cropping intensity, relatively low organic matter status, poor soil physical health, low fertility, etc.

Moisture stress accompanied by other soil related constraints result in low productivity of majority of the crops (Sharma et al 1999). Besides natural causes, agricultural use of land is causing serious soil losses in many places across the world including India. It is probable that human race will not be able to feed the growing population, if this loss of fertile soils continues at the existing rate. In many developing countries, hunger is compelling the community to cultivate land that is unsuitable for agriculture and which can only be converted to agricultural use through enormous efforts and costs, such as those involved in the construction of terraces and other surface treatments. India represents wide spectrum of climate ranging from arid to semi arid, sub humid and humid with wider variation in rainfall amount and pattern. Seasonal temperature fluctuations are also enormous.

2. Constraints in improving the productivity in rainfed agriculture

The major constraints in improving the productivity and returns from rainfed farming in India are as follows: (i) erratic and uncertain rainfall, leading to moisture scarcity, droughts and failure of crops, especially annual crops, (ii) soil degradation and poor soil quality (iii) fragmented and low holding size, leading to constraints in mechanization, (iv) poverty among growers and constraints in availability and purchase of essential inputs, such as seeds and fertilizers, bullock-drawn small seed-cum-fertilizer drills, etc., (v) lack of assured credit and financial support and marketing, (vi) inadequate infrastructure for post-harvest value-addition and storage of produce, (vi) low procurement prices of agricultural commodities, in general, and (vii) inadequate earnings for livelihood from the farming profession because of low volume of business due to small holding size, low productivity and low produce prices, etc. The consequences of these constraints are likely to lead the marginal and small-farming communities towards distraction from agriculture, migration to cities to look for alternate assured wages, suicides, etc. To mitigate these constraints and transform the rainfed farming to an attractive option, there is a strong need for strategic planning and policy changes in a phased manner.

2.1. Specific causes of land degradation and soil quality deterioration

Out of the 329 m ha of total geographical area in the country, the total degraded area accounts for120.7 m ha, of which 73.3 m ha area is affected by water erosion, 12.4 m ha by wind erosion, 6.73 m ha by salinity and alkanity and 25 m ha by soil acidity. The predominant reasons which degrade land and deteriorate soil quality could be enumerated as : i) washing away of topsoil and organic matter associated with clay size fractions due to water erosion resulting in a 'big robbery in soil fertility', ii) intensive deep tillage and inversion tillage with moldboard and disc plough resulting in a) fast decomposition of remnants of crop residues which is catalyzed by high temperature, b) breaking of stable soil aggregates and aggravating the process of oxidation of entrapped organic C and, c) disturbance to the habitat of soil micro flora and fauna and loss in microbial diversity, iii) dismally low levels of fertilizer application and widening of removal-use gap in plant nutrients, iv) mining and other commercial activities such as use of top soil for other than agricultural purpose, v) mono cropping without following any suitable rotation, vi) nutrient imbalance caused due to disproportionate use of primary, secondary and micronutrients, vii) no or low use of organic manures such as FYM, compost, vermi-compost and poor recycling of farm based crop residues because of competing demand for animal fodder and domestic fuel, viii) no or low green manuring as it competes with the regular crop for date of sowing and other resources, ix) poor nutrient use efficiency attributing to nutrient losses due to leaching, volatilization and denitrification, x) indiscriminate use of other agricultural inputs such as herbicides, pesticides, fungicides, etc., resulting in poor soil and water quality, xi) water logging, salinity and alkalinity and acid soils. Among the various causes of degradation mentioned here, the first predominant cause of soil degradation in rainfed regions undoubtedly is water erosion. In fact, the process of water erosion sweeps away the topsoil along with organic matter and exposes the subsurface horizons. The second major indirect cause of degradation is loss of organic matter by virtue of temperature mediated fast decomposition owing to high temperature prevailing in these regions. Above all, the several other farming practices such as reckless tillage methods, harvest of every small component of biological produce and virtually no return of any plant residue back to the soil, burning of the existing residue in the field itself for preparation of clean seed bed, open grazing etc aggravate the process of soil degradation.

As a result of several above-mentioned reasons, soils encounter diversity of constraints broadly on account of physical, chemical and biological soil quality and ultimately end up with poor functional capacity (Sharma et al., 2007). In order to restore the quality of degraded soils and to prevent them from further degradation, it is of paramount importance to focus on restorative practices and conservation agricultural practices on long-term basis.

There is no doubt that, agricultural management practices such as crop rotations, inclusion of legumes in cropping systems, addition of animal based manures, adoption of soil water conservation practices, various permutations and combinations of deep and shallow tillage, mulching of soils with leafy materials grown in-situ grown and brought externally always remained the part and parcel of agriculture in India. Despite all these efforts, the concept of conservation farming could not be followed in an integrated manner to expect greater impact in terms of protecting the soil resource from degradative processes. In the context of likely changes in climate in the years to come , threats to agriculture in general and land and soil resources in particular, will be more and more , hence concrete strategies to protect the land resource and mange the soil effectively are must.

2.2. Climatic threat to Agriculture – Indian perspective

According to Rao et al (2010), the major weather related risks in Agriculture could be as follows: Monsoons in India exhibits substantial inter-seasonal variations, associated with a variety of phenomena such as passage of monsoon disturbances related with active phase and break monsoon periods whose periodicities vary from 3-5 and 10-15 days respectively. It is well noticed that summer monsoon rainfall in India varied from 604 to 1020 mm. The inter-seasonal variations in rainfall cause floods and droughts, which are the major climate risk factors in Indian Agriculture. The main unprecedented floods in India are mainly due to movement of cyclonic disturbances from Bay of Bengal and Arabian Sea on to the land masses during monsoon and post-monsoon seasons – and during break monsoon conditions in some parts of Uttar Pradesh and Bihar States. The thunderstorms due to local weather conditions also damages agricultural crops in the form of flash floods. Beside floods, drought is a normal, repetitive feature of climate associated with deficiency of rainfall over extended period of time to different dryness levels describing its severity. Rao et al (2010), have reported that during the period 1871 to 2009, there were 24 major drought years, defined as years with less than one standard deviation below the mean. Another important adverse effect of climate change could be unprecedented heat waves. Heat waves generally occur during summer season where the cropped land is mostly fallow, and therefore, their impact on agricultural crops is limited. However, these heat waves adversely affect orchards, livestock, poultry and rice nursery beds. The heat wave conditions during 2003 May in Andhra Pradesh and 2006 in Orissa are recent examples that have affected the economy to a greater extent. Also occurrence of heat waves in the northern parts during summer is common every year resulting in quite a good number of human deaths. Further, the water requirements of summer crops grown under irrigated conditions increase to a greater extent. Another adverse effect of climate change is cold waves which mostly occur in northern states. The Northern states of Punjab, Haryana, U.P., Bihar and Rajasthan experience cold wave and ground frost like conditions during winter months of December and January almost every year. The occurrence of these waves has significantly increased in the recent past due to reported climatic changes at local, regional and global scales. Site-specific short-term fluctuations in lower temperatures and the associated phenomena of chilling, frost, fogginess and impaired sunshine may sometimes play havoc in an otherwise fairly stable cropping/farming system of a region. All these apprehensions, however, are based on the data base generated in India. The reports of the Non-Governmental International Panel on Climate Change (NIPCC, 2009), has dispelled many fears about the global warming and its consequent adverse effects on climate change an in-turn influence on agriculture.

2.3. Likely climate change effects on soil

It is anticipated that climate change is likely to have a variety of impacts on soil quality. Soils vary depending on the climate and show a strong geographical correlation with climate.

The key components of climate in soil formation are moisture and temperature. Temperature and moisture amounts cause different patterns of weathering and leaching. Wind redistributes sand and other particles especially in arid regions. The amount, intensity, timing, and kind of precipitation influence soil formation. Seasonal and daily changes in temperature affect moisture effectiveness, biological activity, rates of chemical reactions, and kinds of vegetation. Soils and climate are intimately linked.

Climate change scenarios indicate increased rainfall intensity in winter and hotter, drier summers. Changing climate with prolonged periods of dry weather followed by intense rainfall could be a severe threat to soil resource.

Climate has a direct influence on soil formation and cool, wet conditions and acidic parent material have resulted in the accumulation of organic matter.

A changing climate could also impact the workability of mineral soils and susceptibility to poaching, erosion, compaction and water holding capacity. In areas where winter rainfall becomes heavier, some soils may become more susceptible to erosion. Other changes include the washing away of organic matter and leaching of nutrients and in some areas, particularly those facing an increase in drought conditions, saltier soils, etc. Not only does climate influence soil properties, but also regulates climate via the uptake and release of greenhouse gases such as carbon dioxide, methane and nitrous oxide. Soil can act as a source and sink for carbon, depending on land use and climatic conditions. Land use change can trigger organic matter decomposition, primarily via land drainage and cultivation. Restoration and recreation of peat lands can result in increased methane emissions initially as soils become anaerobic, whereas in the longer term they become a sink for carbon as organic mater accumulates. Climatic factors have an important role in peat formation and it is thus highly likely that a changing climate will have significant impacts on this resource.

No comprehensive study has yet been made of the impact of possible climatic changes on soils.

Higher temperatures could increase the rate of microbial decomposition of organic matter, adversely affecting soil fertility in the long run. But increases in root biomass resulting from higher rates of photosynthesis could offset these effects.

Higher temperatures could accelerate the cycling of nutrients in the soil, and more rapid root formation could promote more nitrogen fixation. But these benefits could be minor compared to the deleterious effects of changes in rainfall.

For example, increased rainfall in regions that are already moist could lead to increased leaching of minerals, especially nitrates. In the Leningrad region of the USSR a one-third increase in rainfall (which is consistent with the GISS 2 x CO2 scenario) is estimated to lead to falls in soil productivity of more than 20 per cent. Large increases in fertilizer applications would be necessary to restore productivity levels.

Decreases in rainfall, particularly during summer, could have a more dramatic effect, through the increased frequency of dry spells leading to increased proneness to wind erosion. Susceptibility to wind erosion depends in part on cohesiveness of the soil (which is affected by precipitation effectiveness) and wind velocity.

Nitrogen availability is important to soil fertility and N cycling is altered by human activity. Increasing atmospheric CO_2 concentrations, global warming and changes in precipitation patterns are likely to affect N processes and N pools in forest ecosystems. Temperature, precipitation, and inherent soil properties such as parent material may have caused differences in N pool size through interaction with biota. Keller et al., 2004 reported that climate change will directly affect carbon and nitrogen mineralization through changes in temperature and soil moisture, but it may also indirectly affect mineralization rates through changes in soil quality.

Climate change is having a major impact on biodiversity and in turn biodiversity loss (in the form of carbon sequestration trees and plants) is a major driver of climate change. Land degradation such as soil erosion, deteriorating soil quality and desertification are driven by climate variability such as changes in rainfall, drought and floods. Degraded land releases more carbon and greenhouse gases back into the atmosphere and slowly kills off forests and other biodiversity that can sequester carbon, creating a feed back loop that intensifies climate change.

Soil is our most fundamental terrestrial asset and natural resource. Along with sunlight and water, it provides the basis for all terrestrial life viz., the biodiversity around us, the field crops that we harvest to meet our food and fiber demands, animal products, etc. Healthy soils provide us with a range of 'ecosystem services' - they support healthy plant growth, resist erosion, receive and store water, retain nutrients and act as an environmental buffer in the landscape. Soils supply nutrients, water and oxygen to plants, and are inhabited by soil biota which are essential for decomposition and recycling processes. According to Arshad and Martin (2002), like air and water, the soil is an integral component of our environment and constitutes the most important natural resource together with water. The intellectual and efficient use of this vital resource is essential for sustainable development and feeding the growing world population. In the recent decade, soil is perceived as an important environmental component and the need to maintain or improve its ability to perform the multitude of functions has been recognized. At the same time, it has also been recognized that the soil is not an inexhaustible resource, and if used inappropriately or mismanaged it may be deteriorated in a relatively short period of time, with very limited opportunity for regeneration or replacement.

3. Sustainability of agriculture – General concepts and scenario

Agricultural sustainability is defined as the ability of agricultural systems to remain productive, efficiently and indefinitely. Quantitatively, it implies trends in agricultural production over time. A non-negative trend in production of a system over time implies that the system is sustainable (Lal, 1998). According to Lockeretz (1988) 'sustainable agriculture' is a loosely defined term that encompasses a range of strategies for addressing many of the problems that afflict agriculture worldwide. These problems include loss of soil productivity from excessive erosion and associated plant nutrient losses, surface and groundwater pollution from pesticides fertilizers and sediment, impending shortages of nonrenewable resources and low farm income because of low market price and high production costs. Herdt and Steiner (1995) have given three dimensions of assessing the sustainability and it is essential to assess the sustainability in relation to all three dimensions. These dimensions include biophysical, economic and social. Among these, the biophysical dimension is related to the quantity of output per unit area (may be Tonnes or Mg of yield ha^{-1}), the economic dimension to the gross or net value of the output, and the social dimension to the capacity of the system to support the farming community. The biophysical output (biomass or grain yield per ha) may change due to change in soil properties over time (erosion, compaction, salinization, waterlogging, etc), introduction of new cultivars, and change in the input used. The economic output may change over time independent of the biophysical output, and the social carrying capacity may change due to change in food habits, preferences and standard of living. Lal (1994) emphasized more specific indicators for measuring sustainability. First is the productivity which indicates productivity per unit of resources used. This indicator is influenced by several factors. To cite an example, the unsustainability in rice –wheat system could be attributed to decline in organic matter owing to (i) removal of wheat straw for feeding the animals, (ii) burning or removal of rice straw for ensuring clean fields and trouble free cultivation, (iii) puddling process for transplanting the rice seedlings which breaks the soil aggregates and subjects the entrapped organic matter fractions to further loss and ultimately lead to poor soil structure. Irrespective of straw removal and burning, wheat –rice system can be compared with the analogy of 'making' the house in the morning and 'demolishing' it in the evening where wheat season during which soil gets time for aggregation can be said as 'making of the house' and rice season where puddling of soil assumes the shape of colloidal solution is just like demolishing of the house. Another important indicator emphasized is the total factor productivity which considers the total output in relation to the cost of all the inputs used to get that output. The third indicator suggested for assessing agricultural sustainability is total natural resource productivity. This indicator of sustainability takes care of the indirect cost incurred on account of quantitative depreciation or wear and tear (e.g. decrease in soil depth due to loss of top soil owing to erosion, build up of salinity, fall in groundwater table by irrigation, increase of nutrient load in water bodies etc.,) of the natural resources for achieving the specific output.

Campbell *et al.* (1995), emphasized that a sustainable agricultural system is that which is economically viable, provides safe, nutritious food, and conserves or enhances the environment. The ultimate goal or the ends of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety, and to do so over the long-term. The means of achieving this is low-input methods and skilled management, which seek to optimize the management and use of internal production inputs (i.e., on-farm resources) in ways that provide acceptable levels of sustainable crop yields and livestock production and result in economically profitable returns. This approach emphasizes such cultural and management practices as crop rotations, recycling of animal manures, and conservation tillage to control soil erosion and nutrient losses and to maintain or enhance soil productivity. Low-input farming systems seek to minimize the use of external product inputs (i.e., off-farm resources), such as purchased fertilizers and pesticides, wherever and whenever feasible and practicable; to lower production costs; to avoid pollution of surface and groundwater: to reduce pesticide residues in food; to reduce farmer's overall risk; and to increase both short- and long-term farm profitability (Parr *et al*., 1989, Parr and Hornick, 1990). According to Parr *et al*., (1990) , another reason for the focus on low-input farming systems is that most high- input systems, sooner or later, would probably fail because they are not either economically or environmentally sustainable over the long-term. How we achieve "Sustainable agriculture" depends on creative and innovative conservation and production practices that provide farmers with economically viable and environmentally sound alternatives or options in their farming systems. Stewart *et al.* (1990) emphasized that climate and soils are the two most critical factors that will determine the ultimate sustainability of agricultural systems. Jodha (1994) opined that despite significant growth and refinements in the definitions of the term "sustainability", its operationalization continued to be a major problem that reduces its practical utility. One practical way to handle this problem could be 'to approach sustainability through unsustainability' This implies identification and analysis of indicators of unsustainability and their underlying processes and focused efforts to reverse them to restore sustainability to a system. Based on the definitions of the term by ecologists, economists, environmentalists, development experts, etc, (Conway 1985, Markande and Pearce, 1988, Lynam and Herdt, 1988, Graham-Tomasi, 1991) sustainability would mean the ability of a system (say dryland agriculture) to maintain or enhance its performance, output, services, (even though linkage with other systems), without damaging own long term production potential. Hence, to halt any further deterioration of the natural resource base, that is, agricultural land, and the associated loss of soil productivity, the key to improving the sustainability of rainfed/dryland farming systems could be implementing sound soil and water management practices. In many cases, improvements can be achieved by the application of established principles of soil and water management to crop and livestock production. In other situations, new concepts and methodologies appropriate to the unique aspects of dryland areas will be required (Steiner *et al.*, 1988; Parr *et al.,* 1990).

India has been working hard since 1950 to produce adequate food to feed its increasing population and to become self dependent. Unfortunately, the growth in the food production is getting neutralized by the growth in the population. If the food production history of the country is traced back, country increased it food production from 53.87 Mt during 1950-51 and jumped to 78.61 Mt during 1960-61 which was followed by 100.64 during 1970-71, 123.7 Mt during 1980-81 and 172.39 in 1990-91, 206 Mt in 2001 and finally to 230.7 Mt in 2007-08. This made the country self sufficient in food production for the time being. But at the same time, the population growth demands more growth in food production with shrinking availability of land resource and degrading land and water resources. Lal (2008), based on a critical perusal of food production data brought out that agronomic production in India between 1960 and 2002 increased by a factor of about 2.5 for rice, 6.4 for wheat, and 2.5 for all food grains. He cautioned that country must not be satisfied with this increase in food production as the country is going to face a big mandate of feeding an expected 1.59 billion population by 2050. This rise in population from the existing 1.1 billion during 2007 to 1.59 billion by 2050 will be approximately 45%. According to some other estimates, there would be a need to increase food grain production from 206 million tonnes (Mt) in 2001 to 301 Mt with low food demand, 338 Mt with medium food demand and 423 Mt with high food demand by 2025 (Sekhon, 1997; USDA, 2004), which is a matter of growing concern for all those involved in agricultural research, planning and policy making. Country has to gear up to meet these difficult targets among all odds such as (i) stagnating yields levels even under irrigated systems, (ii) degrading land and deteriorating soil quality, (iii) increasing cost on energy, (iv) extreme climatic variations and uncertainties in rainfall pattern and (iv) frequent droughts, non-stretchable irrigation potential and major dependence on rainfed lands, (v) distraction of the farmers from agriculture because of marginal size of holdings and non remunerative nature of agriculture due to low minimum support prices etc. Lessons learnt from the success of green revolution clearly indicate that four pillars of achieving higher production were: high yielding input responsive varieties, assured irrigation, adequate amount of fertilization and appropriate plant protection measures. Under irrigated agriculture, the response to these inputs has slowed down and yield levels have stagnated in some of the crops may be due to land degradation and deterioration of soil quality. On the other hand, rainfed regions which constitute 83 m ha comprising of about 58% of net cropped area (142.2 m. ha) still do not get adequate inputs like water, fertilizer and good seed and continue to depend on 'Rain-God' even for seeding the crops. Above all, rainfed regions encounter several other productivity related constraints which may or not be common to those of irrigated agriculture, and ultimately limit the yield to a miserably low levels leading to poverty, migration of the communities to the urban areas in search of livelihoods and even suicides under most distressful condition. The situation has become so grim that out of the 110 million farm holders in the country, about 40% wish to quit the farming, if they get any alternative source of livelihood earnings (Katyal, 2008).

If we look in the world perspective, crop yields in India are not only low in comparison with developed countries viz., U.S.A., Canada, Europe, Australia, Japan, but also with those in China, South East Asia, and South America. Similar to food grains, the yields of vegetables in India are about 50% lower than those of the world average, and 60-100% lower than those of China (Pain, 2007; Lal, 2008). Besides several other factors, low yields of crops and cropping systems are also attributed to poor soil fertility and inadequate replenishment of the nutrients. The situation is grimmer in rainfed areas where the crops are poorly nourished or fertilized owing to low soil fertility, low fertilizer use due to poor economic condition of the farmers, monsoon uncertainties, etc., which has resulted in multi-nutrient deficiencies in soils. On the other hand, the changing price policies on fertilizers have made the resource poor farmers of rainfed areas to feed their crops with only certain type of fertilizer, which has resulted in low nutrient use efficiency and profitability due to deficiency/antagonistic relationships of certain essential nutrients. It has been estimated that only 9% of the districts in India use more than 200 kg of N + P_2O_5 + K_2O per hectare (Tiwari et al., 2006). On the other hand, only 32% districts used < 50 kg nutrients (N + P_2O_5 + K_2O) per hectare. Most of the rainfed regions fall in this category. The average fertilizer use in the country as a whole in the recent years is about 117 kg NPK ha^{-1} yr^{-1} (Tiwari, 2008) which is very low when compared with the neighboring countries, like China (277.7 kg ha^{-1}), Japan (290.6 kg ha^{-1}) and Korea Republic (409.7 kg ha^{-1}) as stated earlier. At the same time, the yield levels of some of the crops such as paddy, wheat, maize, etc., in India are significantly lower compared to these countries. Hence, apart from many other reasons, low fertilizer use in India is definitely one of the important causes of low yields. According to Tiwari (2008), the major challenge ahead to the country is that it needs to have about 30-35 Mt of NPK from different sources to produce 300 Mt food grains to feed its expected population of about 1.4 billion by the end of 2025. Further, he added that, if the nutrient removal by other crops like horticulture, vegetables, plantation crops, sugarcane, cotton, oilseeds and potato is considered, nutrient demand curve will touch 40-45 Mt. Further, Katyal (2008) has emphasized that, because of existence of wider gap between nutrient addition and mining by the crops, almost 50% of the Indian soils have reached below the critical limit of plant available zinc in soil. The corresponding deficiency in case of iron is about 25%. The severity of the deficiency has increased because of negligible or no application of organic sources of nutrients. Therefore, to ensure sustainability in production, all possibilities need to be explored to narrow down the nutrient removal use gap in future.

3.1. Relationship between soil quality and agricultural sustainability

Beside several other factors influencing crop production, better soil quality is definitely one of the key players influencing sustainability. At the same time, sustainable management practices are those which do not deteriorate soil quality on long term basis. Soil quality and sustainability evaluation is a fundamental concept bridging between the utilization and protection aspects of soil. In terms of agricultural production, soil quality refers to its ability to sustain productivity. There exists a strong link between soil quality and agricultural sustainability. If an agricultural system is unsustainable, it may partly due to the fact that soil quality is declining over time. Understanding soil quality means, assessing and managing soil so that it functions optimally now and is not degraded for future use. Therefore, understanding the whole concept of soil quality including methods of assessment, delineation of key indicators and their related soil functions, transformation of indicators in to a single value soil quality index etc., assumes importance.

Soil quality, in short, has been defined as the "capacity of the soil to function" (Doran and Parkin, 1994; Karlen *et al.*, 1997). But broadly, soil quality has been defined as 'the capacity of a living soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health' (Doran *et al*., 1996, 1998). A slightly modified definition of soil quality was given by Seybold *et al.* (1999), in which soil quality was defined as 'the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation'. Soil quality acts as a major linkage between the strategies of conservation management practices and achievement of the major goals of sustainable agriculture (Acton and Gregorich, 1995). The terms 'soil health' and 'soil quality' are interchangeable. 'Soil quality' is generally used more by soil scientists and 'soil health' by others, but they do have different emphasis (Doran *et al*., 1996). Some prefer the term 'soil health' as it portrays soil as a living, dynamic system whose functions are mediated by a diversity of living organisms that require management and conservation. 'Soil quality' is the capacity of soils within landscapes to sustain biological productivity, maintain environmental quality, and promote plant and animal health. 'Soil health' is the fitness (or condition) of soil to support specific uses (e.g. crop growth) in relation to its potential - as dictated by the inherent soil quality and is more sensitive to anthropogenic disturbance and is severely limited in extreme environments (Freckman and Virginia, 1997). So, soil health and soil quality are functional concepts that describe how fit the soil is to support the multitude of roles that can be defined for it. Therefore, soil quality can be regarded as soil health (Doran *et al*., 1996).

Quality with respect to soil can be viewed in two ways: (1) as inherent properties of a soil; and (2) as the dynamic nature of soils as influenced by climate, and human use and management. Inherent soil quality is a soil's natural ability to function and the inherent soil characteristics are those directly linked with the basic soil forming factors and these characteristics determine why any two soils will always be different. These generally focus on the entire soil profile (~ 2 m deep), and is the reason why there can be no single value describing soil quality for all soil resources and land uses. Such soils can be compared with regard to inherent differences in productivity and with regard to their capacity for a specific land use in the absence of human interventions. (Karlen *et al*, 2001). Attributes of inherent soil quality usually show little change over time. Generally, dynamic soil quality changes in response to soil use and management (Larson and Pierce, 1994). Management choices affect the amount of soil organic matter, soil structure, soil depth, water and nutrient holding capacity. Soils respond differently to management depending on the inherent properties of the soil and the surrounding landscape. According to Carter (1996), attributes of dynamic soil quality are subjected to change over a period of years to decades, while pH and labile organic matter fractions may change over a period of months to years. In comparison, microbial biomass and populations, soil respiration, nutrient mineralization rates, and macroporosity can change over a period of hours to days. Thus, maintenance and/or improvement of dynamic soil quality deal primarily with those attributes or indicators that are most subject to change, loss, depletion, and strongly influenced by agronomic practices. The distinction between inherent and dynamic soil quality can be characterized by the genetic (or static) pedological processes versus the kinetic (or dynamic) processes in soil as proposed by Richter (1987).

4. Soil quality indicators

Brejda and Moorman (2001) stated that soil quality can not be measured directly but can be measured through some sensitive indicators. Further, they emphasized that the changes in these indicators are used to determine whether soil quality is improving, stable, or declining with changes in management, land-use, or conservation practices. Indicators of soil quality can be defined loosely as those soil properties and processes that have greatest sensitivity to changes in soil functions (Andrews *et al*., 2004). Indicators are a composite set of measurable attributes which are derived from functional relationships and can be monitored via field observation, field sampling, remote sensing, survey or compilation of existing information (Walker and Reuter, 1996). Indicators signal desirable or undesirable changes in land and vegetation management that have occurred or may occur in the future. These indicators may directly monitor the soil, or monitor the outcomes that are affected by the soil, such as increases in biomass, improved water use efficiency, and aeration. Soil quality indicators can also be used to evaluate sustainability of land-use and soil management practices in agroecosystems (Shukla *et al*. 2006). The predominant soil quality indicators at micro and macro farm scale as suggested by Singer and Ewing (2000) have been listed in Table 1.

Several researchers have observed different set of key indicators for assessing soil quality depending upon the soil types and other variations. Mairura *et al.* (2007) reported the integration of scientific and farmer's evaluation of soil quality indicators and emphasized that the indicators for distinguishing productive and non-productive soils include crop yields and performance, soil colour and its texture. Parr *et al.* (1992) suggested that increased infiltration, aeration, macropores, aggregate distribution and their stability and soil organic matter and decreased rate of bulk density, soil resistance, erosion and nutrient runoff are some of the important indicators for improved soil quality. Further, Chaudhury *et al*. (2005) identified total soil N, available P, dehydrogenase activity and mean weight diameter of the aggregates as the key indicators for alluvial soils. While working in rainfed Alfisols in semiarid tropical India under sorghum - mungbean system, Sharma et al. (2008) identified easily oxidizable N ($KMnO_4$ oxidizable -N) DTPA extractable zinc (Zn) and copper (Cu), microbial biomass carbon (MBC), mean weight diameter (MWD) of soil aggregates and hydraulic conductivity (HC) as the key indicators of soil quality. In another study in Alfisols under sorghum–castor system, the key soil quality indicators identified were available N, K, S, microbial biomass carbon (MBC) and hydraulic conductivity (HC) (Sharma *et al*., 2005). Karlen *et al.* (1992) suggested biological measurements viz., microbial biomass, respiration, and ergosterol concentrations as very effective indicators for assessing long-term soil and crop management effects on soil quality. Assessment of soil-test properties from time to time has also been emphasized for evaluating the chemical aspects of soil quality (Karlen *et al*. 1992; Arshad and Coen 1992). The indicators used or selected by different researchers in different regions may not be the same because soil quality assessment is purpose and site specific (Wang and Gong 1998; Shukla *et al*. 2006). However, while selecting the indicators, it is important to ensure that the indicators should i) correlate well with natural processes in the ecosystem (this also increases their utility in process-oriented modelling, ii) integrate soil physical, chemical, and biological properties and processes, and serve as basic inputs needed for estimation of soil properties or functions which are more difficult to measure directly, iii) be relatively easy to use under field conditions, so that both specialists and producers can use them to assess soil quality, iv) be sensitive to variations in management and climate and v) be the components of existing soil databases wherever possible (Doran *et al***.** 1996; Doran and Parkin 1996; Chen 1998). Interpreting soil quality by merely monitoring changes in individual soil quality indicators may not give complete information about soil

Physical indicators	Chemical indicators	Biological indicators
Passage of air	BSP	Organic carbon
Structural stability	Cation exchange capacity	Microbial biomass carbon
Bulk density	Contaminant availability	C and N/Oxidizable carbon
Clay mineralogy	Contaminant concentration	Total biomass
Colour	Contaminant mobility	Bacterial
Consistence (dry, moist, wet)	Contaminant presence	Fungal
Depth of root limiting layer	Electrical conductivity	Potentially mineralizable N
Hydraulic conductivity	Exchangeable sodium	Soil respiration
Oxygen diffusion rate	percentage	Enzymes
Particle size distribution	Nutrient cycling rates	Dehydrogenase
Penetration resistance	pH	Phosphatase
Pore conductivity	Plant nutrient availability	Arlysulfatase
Pore size distribution	Plant nutrient content	Biomass C/total organic
Soil strength	Sodium adsorption ratio	carbon/
Soil tilth		Respiration /biomass
Structure type		Microbial community
Temperature		fingerprinting
Total porosity		Substrate utilization
Water holding capacity		Fatty acid analysis
		Nucleic acid analysis

Source: Singer and Ewing (2000)

Table 1. Predominant soil quality indicators at micro and macro farm scale

quality. Therefore, combining them in a meaningful way to a single index may assess soil quality more precisely (Jaenicke and Lengnick, 1999; Bucher, 2002) which is used to gauge the level of an improving or declining soil condition (Wienhold, 2004).

4.1. Soil quality indicators influences soil functions and sustainability

Every soil attribute or soil quality indicator has an important role to play in influencing various soil processes and functions. Hence, to understand the changes in processes and functions, quantitative measurement of attributes or indicators is inevitable. The predominant soil physical, chemical and biological attributes or indicators and corresponding processes influenced by them as suggested by Lal (1994) are given in Table 2.

Attributes / Indicators	Processes and soil functions
Physical attributes	
A. Mechanical	
Texture	Crusting, gaseous diffusion, infiltration
Bulk density	Compaction, root growth, infiltration
Aggregation	Erosion, crusting, infiltration, gaseous diffusion
Pore size distribution and continuity	Water retention, and transmission, root growth and gaseous exchange
B. Hydrological	
Available water capacity	Drought stress, biomass production, soil organic matter content
Non-limiting water range	Drought, water imbalance, soil structure
Infiltration rate	Runoff, erosion leaching
C. Rooting zone	
Effective rooting depth	Root growth, nutrient and water use efficiencies
Soil temperature	Heat flux, soil warming activity and species diversity of soil fauna
Chemical Attributes	
pH	Acidification and soil reaction, nutrient availability
Base saturation	Absorption and desorption, solublization
Cation exchange capacity	Ion exchange, leaching
Total and plant available nutrients	Soil fertility, nutrient reserves
Biological Attributes	
Soil organic matter	Structural formation, mineralization, biomass carbon, nutrient retention
Earthworm population and other soil, macro fauna and activity	Nutrient cycling, organic matter decomposition, formation of soil structure
Soil biomass carbon	Microbial transformations and respiration, formation of soil structure and organo-mineral complexes
Total soil organic carbon	Soil nutrient source and sink, bio-mass carbon, soil respiration and gaseous fluxes

Source (Lal, 1994)

Table 2. Predominant soil physical, chemical and biological indicators and associated functions

4.2. Chemical indicators and their soil functions

Of the various indicators, pH is one of the important indicator, which influence some of the soil functions. It can provide trends in change in soil health in terms of soil acidification (surface and sub surface) (Moody and Aitken, 1997), soil salinization, electrical conductivity, exchangeable sodium (soil structural stability) (Rengasamy and Olsson, 1991), limitations to root growth, increased incidence of root disease, biological activity, and nutrient availability (e.g. P availability at either high pH > 8.5 or low pH < 5; Zn availability at high pH > 8.5) (Doran and Parkin, 1996). Soil pH trends also provide changed capacity of the soil for pesticide retention and breakdown as well as the mobility of certain pesticides through soil. These processes affect soil health on-farm and have effects beyond farm gate (Karlen *et al.* 1997). Electrical conductivity is a measure of salt concentration and therefore, its measure can provide trends in salinity for both soil and water, limitations to crop growth and water infiltration, and along with pH (indicating soil sodicity), it can be a surrogate measure of soil structural decline (eg. high pH > 8.5 and low electrical conductivity, < 0.1 dSm^{-1}) (Rengasamy and Olsson, 1991).

It is a well known fact that, the organic matter is fundamental to the maintenance of soil health because it is essential to the optimal functioning of a number of processes important to sustainable ecosystems. Soil organic matter is a source and sink of carbon and nitrogen and partly of phosphorus and sulphur. It affects micronutrient availability through complexation, chelation and production of organic acids, thus altering soil pH. Conversely, it ties up metals present in toxic amounts (e.g. Cu, As, Hg) (Doran and Parkin, 1996). Organic matter is essential for good soil structure especially in low clay content soils, as it contributes towards both formation and stabilization of soil aggregates (Dalal and Mayer, 1986). Other functions include: contribution to low cation exchange capacity, especially in low clay content soil, pesticide retention (Kookana *et al.,* 1998), microbial biodiversity, water retention in sandy and sandy-loam soils, and provision of carbon sink and source for greenhouse gases. Trends in soil organic matter content provide an integrated measure of sustainable ecosystem (Karlen *et al.,* 1997). Status of plant available nutrients, for example, N, P, S and K indicate the systems sustainable land use, especially, if the nutrient concentration and availability are approaching but remain above the critical or threshold values. In the long-term, nutrient balance of the system (e.g. Input efficiency =output) is essential to sustainability. Thus, available nutrients are indicators of the capacity to support crop growth, potential crop yield, grain protein content (Dalal and Mayer, 1986), and conversely, excessive amounts may be a potential environmental hazard (e.g. algal biomass).

4.3. Physical indicators and their soil functions

The physical indicators of soil health reflect the capacity to accept, store, transmit and supply water, oxygen and nutrients within ecosystem. This includes monitoring of soil structure through pore size distribution, aggregate stability, saturated hydraulic conductivity, infiltration, bulk density, and surface crust. Rooting depth provides a good indicator of buffering against water, air and nutrient stress. Soil surface cover can be used as an indicator of soil surface protection against raindrop impact, and hence enhanced infiltration, reduced surface crust, and reduced soil erosion and runoff. Soil water infiltration measures the rate at which water enters soil surface, and transmitted through the immediate soil depth (Arshad *et al.* 1996). Rainfall is rapidly absorbed by soil with high infiltration rate, but as the soil structure deteriorates, usually with the loss of organic matter, increase in exchangeable sodium and low electrolyte concentration, infiltration rate of a soil becomes low (Rengasamy and Olsson, 1991). This increases the tendency for soil erosion and runoff in sloping soils and water logging in flat soils. Unfortunately, current procedures for measuring infiltration rates are cumbersome, and subject to large errors. A modified disc permeameter could make infiltration rate and hydraulic conductivity a routine procedure (Bridge 1997). Soil aggregate stability is a measure of structural stability and refers to the resistance of soil aggregates to breakdown by water and mechanical force. Aggregate stability is affected by health and quantity of organic matter, types of clays, wetting and drying, freezing and thawing, types and amounts of electrolyte, biological activity, cropping systems and tillage practices (Arshad *et al.* 1996). For monitoring trends in soil health, sampling procedures for aggregate stability need to be standardized. Bulk density varies with the structural condition of the soil. It is altered by cultivation, loss of organic matter (Dalal and Mayer, 1986), and compression by animals and agricultural machinery, resulting in compact plough layer. It generally increases with depth in the soil profile. In cracking clay soils such as Vertisol, it varies with water content (Bridge and Ross, 1984). In Vertisols, bulk density should be corrected for soil water content at the time of sampling, and bulk density values adjusted at field capacity moisture content assuming three dimensional matrix shrinkage.

Effective soil depth is a good indicator of plant available water capacity, subsoil salinity and other root growth constraints in the soil profile. It is not known whether trends can be discerned over relatively long periods (Walker and Reuter, 1996; Doran and Parkin, 1996). Surface crust retards seed germination and reduces aeration and water entry. It provides an indication of soil structure decline (Aggarwal *et al.* 1994, Bridge, 1997). However, it needs to be quantitatively measured or alternatively photographed over time and the extent of area quantified. Surface cover by either crop residues or vegetation protects soil surface from raindrop impact, enhances infiltration, reduces soil erosion and may decrease runoff (Freebairn and Wockner, 1986). The extent of surface cover therefore provides an integrated indicator of soil physical management, organic matter input and the effects beyond farm gate. It can be measured by satellite imagery (currently expensive), and by combining with the terrain and digital elevation mapping, may provide an indicator of erosion hazard. However, correct timing of monitoring in relation to cropping and vegetation cycle and erosive rainfall periods is essential.

4.4. Biological indicators and their soil functions

In the set of biological soil quality indicators, soil microbial biomass and/or respiration, potentially mineralizable N, enzyme activity, fatty acid profile or microbial biodiversity, nematode communities and earthworm populations are quite predominant. Soil microbial biomass is a labile source and sink of nutrients. It affects nutrient availability as well as nutrient cycling and is a good indicator of potential microbial activity (Dalal and Mayer, 1987) and capacity to degrade pesticides (Perucci and Scarponi, 1994). Although useful as a research tool, its cumbersome measurement and variability with short-term environmental conditions makes it difficult as a routine soil quality indicator (Sparling, 1997; Dalal, 1998). Respiration measurements are also similarly affected. However, respiration rates can be measured in the field using portable CO_2 analysers. Easily oxidizable N and potentially mineralizable N are measured by alkaline-$KMnO_4$ method and aerobic or anaerobic incubation respectively. Anaerobic method is considered to be more effective and is recommended as routine procedure. Potentially mineralizable N measures soil N supplying capacity and is also a surrogate measure of microbial biomass and a labile fraction of soil organic matter (Rice *et al.* 1996). Soil enzyme activity is often closely related to soil organic matter, microbial activity and microbial biomass. It is sensitive to change in management practice and can readily be measured. Of numerous soil enzymes, dehydrogenase is a potential indicator of active soil microbial biomass. However, it is very sensitive to seasonal variability. Potentially useful indicators of soil quality could be beta-glucosidase, urease, amidase, phosphatase, and aryl-sulphatase and fluorescein diacetate hydrolyzing enzymes. Since enzyme activity is operationally defined, it requires strict protocol (Dick *et al.* 1996). Soil fauna (soil meso and macro fauna), including nematode communities, affect soil structure, alter patterns of microbial activity and influence soil organic matter dynamics and nutrient cycling (Heal *et al.*, 1996), and are sensitive to soil disturbance and contamination. Of the soil invertebrates, earthworms and nematodes are the potential indicators of soil quality (Pankhurst, 1994; Blair *et al.* 1996). It has been understood that some of the soil indicators do not change immediately and take some time for getting influenced through management practices. Hence, for to be more objective in the approach, these indicators need to be monitored after a specific intervals only.

5. Assessment of soil quality- Recent approaches

Assessment of soil quality is a sensitive and dynamic way to document soils condition, its response to management, or its resistance to stress imposed by natural forces or human uses (Larson and Pierce, 1991). It is needed to identify problem production areas, make realistic estimates of food production, monitor changes in sustainability and environmental quality as related to agricultural management, and to assist government agencies in formulating and evaluating sustainable agricultural and land-use policies (Granatstein and Bezdicek, 1992). As stated earlier, soil quality can be assessed by measuring soil attributes or properties that serve as soil quality indicators. The changes in these indicators signal the changes in soil quality (Brejda and Moorman, 2001). The first step is selecting the appropriate soil quality indicators to efficiently and effectively monitor critical soil functions as determined by the specific management goals for which an evaluation is being made. These indicators together form a minimum data set (MDS) that can be used to determine the performance of the critical soil functions associated with each management goal. In order to combine the various chemical, physical and biological measurements with totally different units, each indicator is then scored using ranges established by the soil's inherent capability to set the boundaries and shape of the scoring function. Indicator scoring can be accomplished in a variety of ways (e.g. linear or nonlinear, optimum, more is better, more is worse) depending upon the function. These unitless values are combined into an overall index of soil quality and can be used to compare effects of different practices on similar soils or temporal trends on the same soil. Andrews and Carroll (2001) suggested that dynamic soil quality assessment could be viewed as one of the components needed to quantify agro ecosystem sustainability.

In order to quantify the effects of the three tillage systems on soil quality and to test the sensitivity of various indexing procedures, Hussain *et al*. (1999) has adopted the soil quality framework developed by Harris *et al*. (1996). The overall soil quality index was computed using the equation, index = f (y nutrient + y water + y rooting) where y = weighting factor for each function. To complete the evaluation, they regressed the six overall soil quality indices and the individual function ratings against the dependent variable (erosion, yield, and plant populations). While, Andrews and Caroll (2001) and Andrews *et al.* (2002a and b) have described comprehensively another approach of soil quality assessment 'a comparative assessment technique' The three predominant steps adopted under this technique were i) selection of a minimum data set (MDS) of indicators that best represent soil function, ii) scoring of the MDS indicators based on their performance of soil functions, and iii) corroboration of the MDS indicators with functional goals set by the land manager or grower and iv) integration of the indicator score into a comparative index of soil quality. This method is being used widely in recent soil quality assessment studies (Hazra *et al*., 2004; Mandal, 2005; Sharma *et al*., 2005, 2008, Chaudhury *et al*., 2005, Masto *et al*., 2007). Sharma *et al.* (2004) has reviewed and given a brief account of various methods of assessment of soil quality such as: i) simple assessment of soil properties using quick soil test kits and to observe the changes occurred as a result of management practices, ii) issuing of soil health cards to the farmers and to advise them to observe the changes in the visible soil and crop indicators and go on recording them periodically, iii) deviation from the normal: computation of percent deviations in soil attributes with reference to control situation and to assign the score using score functions, iv) key indicator approach: identification of key indicators using functional goals and computation of soil quality index, and v) use of critical levels of indicators: identification of critical levels of indicators and assigning the rank and computation of Cumulative Rating Index (CRI).

According to Masto *et al*. (2007), the success and usefulness of a soil quality index mainly depends on setting the appropriate critical limits for individual soil properties. They stated that the optimum values of soil quality could be obtained from the soils of undisturbed ecosystems (Warkentin, 1996; Arshad and Martin, 2002), where soil functioning is at its maximum potential to provide critical values. They fixed the thresholds for each soil quality indicator based on the range of values measured in natural ecosystems or in best–managed systems and on critical values available in the literature. After finalizing the thresholds, they transformed the soil property values recorded into unitless scores (between 0 and 1), using the equation:

$$\text{Non-linear score (Y)} = 1/1+e^{-b(x-A)}$$

Where x is the soil property value, A the baseline or value of the soil property where the score equals 0.5 and b is the slope. Using the equation, they generated three types of standardized scoring functions as i) 'More is better', ii) 'Less is better' and iii) 'Optimum' as defined in earlier studies (Karlen and Stott, 1994; Hussian *et al*., 1999; Glover *et al*., 2000). For positive slopes, the equation defined a 'More is better' scoring curve; for negative slopes, a 'Less is better' curve; and for the combination of both, an 'Optimum' curve has been defined. They converted the numerical values for each soil quality indicator into unitless scores ranging from 0 to 1. The score for each indicator was calculated after establishing lower threshold limits, baseline values and upper threshold limits. Threshold values are soil property values where the score equals one (upper threshold) when the measured soil property is at most favorable level; or equals zero (lower threshold) when the soil property is at an unacceptable level. Baseline values are soil property values where the scoring function equals 0.5 and equal the midpoints between threshold soil property values. Baselines are generally regarded as minimum target values. In their study, to determine soil quality, they used the model primarily described by Karlen *et al.* (1994) with some modification, which is given as follows:

$$\text{Soil quality index (SQI)} = q_{we}(wt) + q_{wms}(wt) + q_{rsd}(wt) + q_{rbd}(wt) + q_{pns}(wt) + q_{scp}(wt)$$

Where q_{we} is the rating for the soil's ability to accommodate water entry, q_{wms} to facilitate water movement and storage, q_{rsd} to resist surface degradation, q_{rbd} to resist biochemical degradation, q_{pns} to supply plant nutrients, q_{scp} to sustain crop productivity and wt is a numerical weighting for each soil function. These were set according to the function's importance in fulfilling the overall goal of maintaining soil quality.

With the progressive development in the methodology of soil quality assessment, many new tools of soil quality assessment viz., Soil Conditioning Index (SCI), Soil Management Assessment Framework (SMAF), the Agroecosystem Performance Assessment Tool (AEPAT) and the New Cornell "Soil Health Assessment" have been recently reported. Out of these, SMAF and AEPAT were developed as malleable tools for assessing soil response to management. Weinhold et al. (2008) brought out that some of these tools can be highly useful for assessing soil quality at watershed scale. Hence, these approaches could be of importance for assessing soil quality under watershed development programme in India.

6. Effects of management practices on soil quality, productivity and sustainability – Recent reports

During the past, most of the research studies pertaining to soil quality and sustainability in India was centering around soil testing for only essential plant nutrients, crop response to fertilizer, manures, conjunctive use of fertilizers and organic sources of nutrient on medium and long term basis , computation of optimum levels of fertilizers and manures for recommendation, use of soil amendments to correct acidity, alkalinity, water logging and drainage, protection of top soil through effective soil and water conservation measures etc . Progressively, the research focus shifted with All India Coordinated Projects, where researchers started observing the long term influence of soil and nutrient management treatments on soil parameters through systematic analysis. Many useful results emerged from these studies. Somehow, the prime research focus remained on soil fertility or chemical soil quality indicators except in case of program such as soil structure improvement programs, organic waste recycling, biological nitrogen fixation and few others. In the process of soil quality monitoring, all the three pillars of soil quality (Physical, Chemical and Biological) did not get holistic deal. With advancement in the concept of research on soil quality and sustainability across the world, a paradigm shift in the thinking processes and research programs has come in India also. There are several reports describing the influence of soil and nutrient management treatments such as tillage, residue recycling, application of organic manures, green manuring and integrated use of organic and inorganic sources of nutrients on soil quality. The salient findings of some of the recently conducted studies on soil quality in India and abroad are presented in this section.

Manna et al. (2005) studied the potential impact of continuous cultivation of crops in rotation, and fertilizer and manure application on yield trends and predominant soil quality parameters in rice–wheat–jute, soybean–wheat and sorghum–wheat system at Barrackpore (Typic Eutrochrept), Ranchi (Typic Haplustalf) and Akola (Typic Haplustert), respectively In this study, the negative yield trend was observed in unbalanced use of inorganic N and NP application at all the three sites. The positive yield trend was observed in the NPK and NPK + FYM treatments at Ranchi and Akola. Results showed that the SOC in the unfertilized plot (control) decreased by 41.5, 24.5, and 15.5% compared to initial values at Barrackpore, Ranchi and Akola, respectively, wherein the treatment receiving NPK and NPK + FYM either maintained or improved it over initial SOC content in these sites reported. In a critical study, Mandal *et al.* (2007) observed that crop species and cropping systems that are cultivated may also play an important role in maintaining SOC stock because both quantity and quality of their residues that are returned to the soils vary greatly affecting their turnover or residence time in soil and thus its quality. Further, they reported that conjunctive use of organic and inorganic source of nutrients make significant contribution of carbon inputs to soil.

The impact of land configuration in combination with nutrient management treatments was studied by Selvaraju *et al.* (1999) in rainfed Alfisols. From this study, it was observed that tied ridging and application of FYM in combination with inorganic N and P fertilizer can increase the soil water storage and yield of crops compared to traditional flat bed cultivation. Mohanty *et al.* (2007) recorded that soil quality in rice-wheat cropping system is governed primarily by the tillage practices used to fulfill the contrasting soil physical and hydrological requirements of the two crops. and observed that Soil Quality Index (SQI) values of 0.84 to 0.92, 0.88 to 0.93 and 0.86 to 0.92 were found optimum for rice, wheat and the combined system (rice + wheat), respectively. Kusuma (2008) has established the quantitative relationship between Relative Soil Quality Indices (RSQI) and functional goal such as long term average yields and Sustainability Yield Indices (SYI) of sorghum and mungbean system (Fig 1). The simultaneous contribution of the key indicators towards functional goals has also been studied under sorghum - castor system in rainfed Alfisol using multiple regression functions (Table 3). These relationships help in predicting the crop yield from a given value of RSQI and quantitative contribution of indicators towards long-term crop yields and SYI. While working with biological soil health, Ghoshal (2004) proved that different biological indicators contributed differently towards explaining biological soil health for different cropping systems.

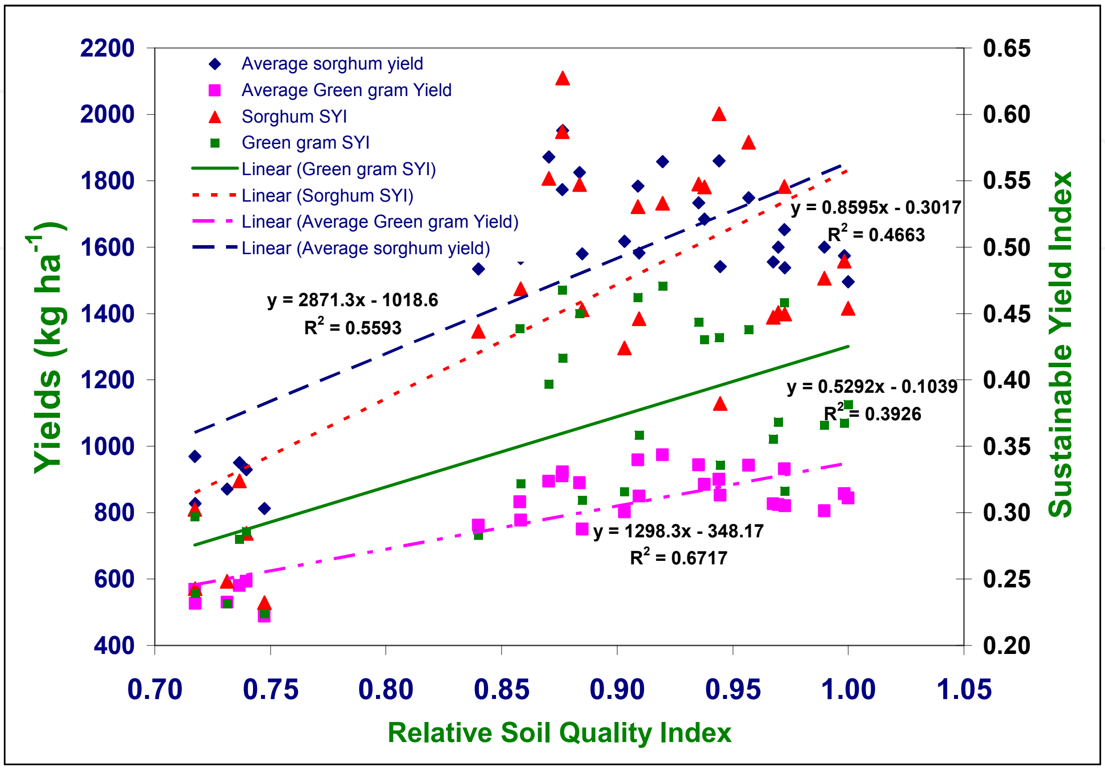

Figure 1. Relationships between functional goals and relative soil quality indices

SNo	Parameter	Equation	R	R^2	Level of significance
1	Castor average yield	-1527.7 + 5.69 (N)** + 16.25 (S) + 1.83 (K)** -2.26 (MBC)** + 252.0 (HC)**	0.712	0.507	P= 0.01
2	Sorghum average yield	-1466.62 + 6.69 (N)** +1.20 (K) +22.96 (S) + - 0.330 (MBC) + 209.1 (HC)**	0.648	0.420	P= 0.01
3	Sustainability Yield Index	-0.598 +0.003 (N)** + 0.0006 (K) + 0.0137 (S)** - 0.0006 (MBC) + 0.096 (HC)**	0.641	0.411	P= 0.01
4	Organic matter	- 0.324 -0.0002 (N) + 0.001(K)** + 0.0052 (S) +0.00596 (MBC)** + 0.0077 (HC)	0.812	0.659	P= 0.01

Source: Kusuma (2008)

Table 3. Relationship of key soil quality indicators with functional goal in sorghum –castor system in rainfed Alfisol

Through a collaborative study with a number of centres and involving a large number of long-term experiments under various agro-climatic zones, Mandal (2005) identified a few master variables and their relative contributions towards soil quality index calculated for different cropping systems and soil types (Table 4). Sharma *et al.*, (2008), in a long term study conducted in rainfed Alfisol, on integrated nutrient management under reduced and conventional tillage in sorghum – mungbean system reported that irrespective of conventional and reduced tillage, the sole organic treatments out-performed in aggrading the soil quality to the extent of 31.8 % over control whereas, the conjunctive nutrient use treatments aggraded the soil quality by 24.2 to 27.2 %, and the sole inorganic treatment could aggrade only to the extent of 18.2 % over unamended control. The extent of percent contribution of the key indicators towards soil quality index (SQI) as presented in Fig 2 was: microbial biomass carbon (MBC) (28.5%), available nitrogen (28.6%), DTPA- Zn (25.3%), DTPA- Cu (8.6%), HC (6.1%) and MWD (2.9%). Conjunctive use of organic and inorganic sources of nutrients also proved effective in realizing significantly higher grain yields and sustainability of both sorghum and mungbean crops (Sharma *et al.,* 2009). The predominant soil quality indicators identified for Vertisols under cotton + green gram system were: pH, electrical conductivity (EC), organic carbon (OC), available K, exchangeable magnesium (Mg), dehydrogenase assay (DHA), and microbial biomass carbon (MBC). The soil quality indices as influenced by different long-term soil and nutrient-management treatments in this study varied from 1.46 to 2.10. Among the treatments, the conjunctive use of 25 kg P2O5 ha^{-1} + 50 kg N ha^{-1} through leuceana green biomass maintained significantly higher soil quality index with a value of 2.10 followed by use of 25 kg N +25 kg P2O5 + 25 kg N ha^{-1} through FYM (T5) (2.01) (Sharma et al 2011). In a review on effects of tillage, Ishaq *et al*. (2002) reported that tillage affects soils physical, chemical and biological properties. Tillage-induced changes in these properties depend on antecedent soil properties, type of tillage, and climate. A proper tillage can alleviate soil related constraints while improper tillage leads to a range of degradative processes, e.g., decline in soil structure, accelerated erosion, depletion of soil organic matter (SOM) and fertility and disruption in cycles of water, organic carbon and plant nutrients (Lal, 1993).

Location	Soil classification /textural type	Cropping system	Indicators identified	Indicator's contributions towards SQI		
				> 25%	15-25%	< 15%
Varanasi	Typic Haplustept/ Sandy loam	Rice – Lentil	Available P and organic C	-	Available P	Organic C
Barrack-pore	Eutrochrept/ Sandy loam	Jute – Rice – Wheat	Mean weight diameter Available P, Microbial biomass C, and organic C	Mean weight diameter, Available P	Microbial biomass C	Organic C
Mohanpur	Aeric Haplaquept/ Sandy loam	Rice – Wheat	Alkaline phosphatase, organic C, mineralizable N	Alkaline phosphatase	Organic C	Minerali-zable N

Source: Mandal, 2005

Table 4. Soil quality indicators identified for different soil types and cropping systems and their contributions towards soil quality index (SQI)

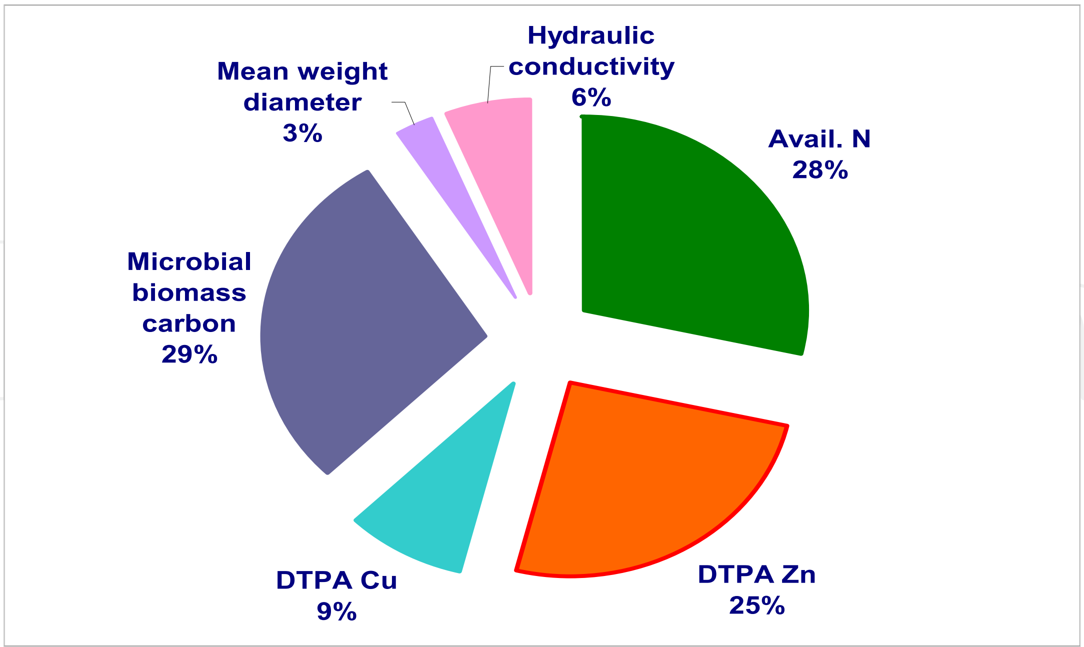

Figure 2. Per cent contribution of different soil quality indicators towards relative soil quality index (RSQI) in Alfisol

According to Ghuman and Sur (2001), reduced tillage in conjunction with crop residue improves soil properties and subsequent wheat yield on sandy-loam soils in the subtropical climate of northwestern Punjab. Roldan *et al*. (2005) observed that conservation tillage systems, in particular no-tillage, increased crop residue accumulation on the soil surface. Soil electrical conductivity and pH were not affected by the tillage practices. The no-tilled soil had higher values of water soluble C, dehydrogenase, urease, protease, phosphatase and β-glucosidase activities and aggregate stability than tilled soils, but had lower values than the soil under native vegetation. The enzyme activity and aggregate stability showed higher sensitivity to soil management practices than did physical–chemical properties. They finally concluded that no tillage system was the most effective for improving soil physical and biochemical qualities.

Beside conservation tillage, positive effect of other soil and nutrient management practices such as green manuring, integrated nutrient management practices, manure application, crop residue recycling, legume based crop rotations, balanced fertilization etc have been observed on predominant soil quality indicator, overall soil quality indices and Sustainability Yield Indices of crops. Sharma *et al.*, (2005) reported that organic carbon in the soil was significantly influenced by long term application of crop residues such as sorghum stover and gliricidia @ 2 tons ha^{-1} under minimum and conventional tillages in sorghum-castor rotation in rainfed Alfisols. Further, they reported that increase in nitrogen levels from 0 to 90 kg N ha^{-1} also helped in significantly improving the organic carbon status in these soils over a period of 8 years. From these studies, they concluded that continuous application of organic residues is inevitable to see the significant effect on organic carbon status in soils. Green manuring, which is considered as one of the important practice for improving soil fertility and soil health, is the process of turning a crop into the soil, whether originally intended or not, irrespective of its state of maturity, for the purpose of affecting some agronomic improvement (Mac Rae and Mehuys, 1985). This practice has been found to increase soil N and P availability for the following crop and at the same time, contribute to the conservation of soil organic matter and soil biological, physical and chemical properties (Astier *et al*., 2006). While studying the management of residues in cropping systems, Smith and Elliot (1990) and Rasmussen and Collins (1991) emphasized the importance of residue application in conserving soil and water and thus ensuring sustainable production, especially in the semi-arid regions where soil and water conservation are of utmost importance. Prasad and Power (1991) emphasized that no one-residue management practice is superior under all conditions. It is important, therefore, to establish under local conditions the beneficial and detrimental consequences associated with a residue management practice before it is propagated among farmers for implementation. It was reported that the application of manure as amendment proved quite effective in improving the soil nutrient status and increasing soil organic C (SOC) levels (Rochette and Gregorich, 1998). The conjunctive use of urea and organics such as loppings of leuceana and gliricidia (1:1 ratios on N equivalent basis) had considerable effects on raising the sorghum grain yield to the levels of 16.9 and 17.2 q ha^{-1} respectively and thus revealed that a minimum of 50 % N requirement of sorghum can be easily met from farm based organic sources of nutrients (Sharma *et al.,* (2002). Based on a long term study conducted in rainfed Alfisol soils prone to hardsetting and crusting, it was observed that integrated nutrient management treatments. viz. , 2t gliricidia loppings + 20 kg N and 4 t compost + 20 kg N were found to be most effective in increasing the sorghum grain yield by 84.62 and 77.7 percent over control. However, the highest amount of organic carbon content (0.74%) was recorded in 100 % organic treatment (4 t compost + 2 t gliricidia loppings). Some of these options of managing nutrients by using farm based organics can save expenditure on fertilizer and help in improving organic C in soil (Sharma *et al*., 2004).

Chaudhury *et al*. (2005) in a study of identifying several biological, chemical, and physical indicators of soil quality concluded that the highest SQI was found in 100% NPK+FYM treatment followed by 100% NPK, 100% NP, 100% N, and control treatment, respectively. A collaborative study coordinated by Mandal (2005) indicated that cultivation without any fertilization (control) or only with N caused a net degradation of soil quality. Cultivation even with application of balanced NPK could hardly maintain such quality at the level where no cultivation was practiced. Only integrated use of organic and inorganic sources of nutrients could aggrade the system (Table 5). Manna *et al*. (2007) compared the fertilizer treatments in a long-term study for 30 Years in Alfisol (Typic Haplustalf) Ranchi, India. They reported that yield increased with time for NPK +FYM and NPK + lime treatments in wheat. Biological soil health indicators such as Soil Microbial Biomass Carbon (SMBC), nitrogen (SMBN) and acid hydrolysable carbohydrates (HCH) were greater in NPK + FYM and NPK + lime as compared to other treatments. Findings of this study suggested that continuous use of NPK + FYM or NPK + lime would sustain yield in a soybean – wheat system without deteriorating soil quality. Soil degradation occurs due to nutrient depletion, soil structure degradation, acidification and sub–optimal addition of organic and inorganic fertilizer to soil. Masto *et al*. (2007) quantified the effects of 10 fertilizer and farm yard manure (FYM) treatments applied for 31 years to a rotation that included maize, pearl millet, wheat and cowpea on an Inceptisol in India. A soil quality index (SQI) based on six soil functions was derived for each treatment using bulk density, water retention, pH, electrical conductivity (EC), plant-available nutrients, soil organic matter (SOM), microbial biomass, soil enzymes and crop yield. SQI ratings ranged from 0.552 (unfertilized control) to 0.838 for the combined NPK fertilizer plus manure treatment.

Treatment / Cropping system	Rice - wheat	Rice - Lentil	Jute-Rice-Wheat
Control	- 56.0	- 8.0	- 49.0
N only	-	- 11.7	- 35.0
NPK only	-10.8	-9.7	19.0
NPK+FYM	18.7	8.6	45.1

Source: Mandal, 2005

Table 5. Soil quality change (as % over fallow) under different nutrient management practices and cropping systems

Soil quality indices have been used to compare tillage practices, organic and conventional vegetable production systems, litter management practices, and spatially large regions Plains, Hills, and several other practices (Andrews *et al*., 2003). These varied uses suggest that SQ indices may be applicable not only to different soil types but also to multiple regions and management systems. The impact of long term soil and nutrient management treatments on soil quality using 19 soil chemical , physical and biological indicators has been assessed by Sharma (2009 a, b) at All India Coordinated Research Project Centers spread across the country and reported that conjunctive nutrient use as well as sole organic nutrient treatments found superior to 100 % inorganic nutrient application. Further, he has also suggested the set of key soil quality indicators for each location depending upon the soil type and cropping system. Mandal *et al.* (2001) worked out a crop specific land quality index (LQI) for sorghum [Sorghum bicolor (L.) Moench] under semiarid tropics of India. The method developed as LQI is a function of climatic quality index (CQI) and soil quality index (SQI). The LQI was correlated with the actual sorghum yield obtained from benchmarks soils and it was found that LQI bears good agreement with the yield. Doran and Parkin (1994) described a performance based index of soil quality that could be used to provide an evaluation of soil function with regard to the major issues of (i) sustainable production, (ii) environmental quality, and (iii) human and animal health. They proposed a soil quality index consisting of six elements: SQ = f (SQE1, SQE2, SQE3, SQE4, SQE5, SQE6); Where SQET is the food and fibre production, SQE2 the erosivity, SQE3 the ground water quality, SQE4 the surface water quality, SQE5 the air quality, and SQE6 is the food quality. Awasthi *et al*. (2005) computed integrated soil quality indices in four dominant land uses [forest, upland maize and millet (Bari), irrigated rice (Khet), and grazed systems). Integrated soil quality index (SQI) values varied from 0.17 to 0.69 for different land uses, being highest for undisturbed forest and lowest for irrigated rice. The SQI demonstrated the degradation status of land uses in the following ascending order: irrigated rice > grazed system > forest with free grazing > upland maize and millet > managed forest > grass land > undisturbed forest. The irrigated rice, grazed system, upland maize and millet, and freely grazed forestlands need immediate attention to minimize further deterioration of soil quality in these land uses. From the information presented in this section, it is evident that (i) effective soil and nutrient management practices can help in a long to improve soil quality indicators and overall indices of soil quality and crop yield sustainability. Hence soil management practices assume great importance in improving soil quality and sustainability.

7. Effective steps for improving soil quality, productivity and sustainability with emphasizes in rainfed areas

The following steps are suggested for effective land care and soil quality improvement for higher productivity and sustainability in rainfed areas.

7.1. Controlling soil erosion through effective soil and water conservation (SWC) measures

It is well accepted connotation that 'Prevention is better than cure'. In order to protect the top soil, organic mater content contained in it and associated essential nutrients, it is of prime importance that there should be no migration of soil and water out of a given field. If this is controlled, the biggest robbery of clay-organic matter -nutrients is checked. This can be easily achieved, if the existing technology on soil and water conservation is appropriately applied on an extensive scale. The cost for in-situ and ex-situ practices of SWC has been the biggest concern in the past. There is a need to launch 'Land and Soil Resource Awareness Program' (LSRAP) at national level to educate the farming community using all possible communication techniques. It is desirable to introduce the importance of soil resource and its care in the text books at school and college levels. The subject at present is dealt apparently along with geography. Farming communities too need to be made aware about soil, its erosion, degradation, benefits and losses occurred due to poor soil quality. This can be done through various action learning tools which explain the processes of soil degradation in a simple and understandable manner

7.2. Rejuvenation and reorientation of soil testing program in the country

About more than 600 Soil testing labs situated in the country need to be reoriented, restructured and need to be given fresh mandate of assessing the soil quality in its totality including chemical, physical, biological soil quality indicators and water quality. The testing needs to be on intensive scale and recommendations are required to be made on individual farm history basis. Special focus is required on site specific nutrient management (SSNM). Soil Health Card (SHC) system needs to be introduced. Soil fertility maps of intensive scale need to be prepared. District soil testing labs need to be renamed as 'District Soil Care Labs' and required to be well equipped with good equipments and qualified manpower for assessing important soil quality indicators including micronutrients. Fertilizer application needs to be based on soil tests and nutrient removal pattern of the cropping system in a site specific manner. This will help in correcting the deficiency of limiting nutrients. Keeping in mind the sluggish and inefficient activities of regional soil testing labs of the states, private sector can also be encouraged to take up Soil Care Programs with a reasonable costs using a analogy of 'Soil Clinics for Diagnosis and Recommendation' (SCDR).

7.3. Promotion of agricultural management practices which enhance soil organic matter

Enhancing organic matter in soils in semi-arid tropics and tropics is indomitable task. However regular additions of organics without hastening their decomposition process can provide some relief. Management practices such as application of organic manures (composts, FYM, vermi-composts), legume crop based green manuring, tree-leaf based green manuring, crop residue recycling, sheep-goat penning, organic farming, conservation tillage, inclusion of legumes in crop rotation need to be encouraged (Sharma et al., 2002, 2004). Similar to inorganic fertilizer, provision for incentives for organic manures including green manuring can also be made so that growers should be motivated to take up these practices as inbuilt components of integrated nutrient management (INM) system.

7.4. Development and promotion of other bio-resources for enhancing microbial diversity and ensuring their availability

In addition to organic manures, there is a huge potential to develop and promote bio-fertilizers and bio-pesticides in large scale. These can play an important role in enhancement of soil fertility and soil biological health. Use of toxic plant protection chemical can also be reduced. In addition to this, there is a need to focus on advance research for enhancing microbial diversity by identifying suitable gene pools.

7.5. Ensuring availability of balanced multi-nutrient fertilizers

Fertilizer companies need to produce multi-nutrient fertilizers containing nutrients in a balanced proportion so that illiterate farmers can use these fertilizers without much hassle.

7.6. Enhancing the input use efficiency through precision farming

The present level of use efficiency of fertilizer nutrients, chemicals, water and other inputs is not very satisfactory. Hence, costly inputs go waste to a greater extent and result in monetary loss and environmental (soil and water) pollution. More focus is required to improve input use efficiency. The components required to be focused could be suitable machinery and other precision tools for placement of fertilizers, seeds and other chemicals in appropriate soil moisture zone so that losses could be minimized and efficiency could be increased. This aspect has a great scope in rainfed agriculture. This will also help in increasing water use efficiency (WUE) too.

7.7. Amelioration of problematic soils using suitable amendments and improving their quality to a desired level

History has a record that poor soil quality or degraded soils have taken toll of even great civilizations. No country can afford to let its soils be remaining degraded by virtue of water logging, salinization, alkalinity, erosion etc. Lots of efforts have already gone into the research process in relation to soil amendments. There is a need to ameliorate the soils at extensive scale on regular basis. No matter, how much it costs. Soil amelioration programs should be national programs linked with 'state agricultural departments'

7.8. Land cover management

The concept of land cover management is still ridiculed at some quarters in India may be because of lack of understanding. The lessons of United States Department of Agriculture (USDA) regarding soil erosion due to wind and water during dusty storms and torrential rains are adequate to understand the concept of land cover management. Covering the land with cover crops such as legumes , natural and pasture grasses, mulches with separable crop residues will help in protecting the land from the direct hits of high energy raindrops, ill effects of extreme temperatures during summer and winter, reduction in evaporation, enhanced biological activity due to congenial soil habitat conditions, higher C sequestration etc. Hence, this concept needs to be propagated extensively among the farming community.

7.9. Need for organized functional statutory bodies at Centre and in the States on Land Care and Soil Resource Health

State Soil and Water Conservation departments restrict their activities only up to construction of small check dams, plugging of gullies etc in common lands. State Soil testing labs are almost sluggish in action, poorly equipped and are with under-qualified manpower. Mostly, no tests are done except for Organic C, P and K. State agricultural universities (SAU) only adopt few villages, and consequently, no extensive testing of soil health is done. ICAR institutions also take up few watersheds covering few villages. Then, there will be no one to work for Land Care and Soil Health program at large scale. Hence, **organized functional statutory bodies at Centre and in the States on Land Care and Soil Resource Health** are necessary to effectively coordinate the Land Care and Soil Health Restoration and maintenance programs . It is beyond the capacity of research organizations to take up such giant and extensive task in addition to their regular research mandates. Some of the activities of land care can be linked with National Rural Employment Guarantee Program.

7.10. More intensive research on soil quality

There is a need for developing critical levels of some of the soil quality indicators for which this information is not available for Indian condition. Research experiments should be planned keeping in view three aspects viz. soil quality restoration, improvement and maintenance. The subject of soil resilience is still not explored much world over. Systematic research is needed to study soil resilience for diversity of edaphic, climatic and management conditions. Conservation agricultural practices such as conservation tillage, residue recycling, land cover management, appropriate crop rotations have shown the proven benefit to improve soil quality across the world. The quantum of impact may vary depending upon the variations in soil, climate, duration of the practice and level of overall management of the farms. It would be relevant to study soil quality, resilience and sustainability quantitatively under long term restorative management practices in different crop growing environments. There is a need to develop Soil health Cards covering important visible and easily understandable indicators so that even illiterate farmers should be able to use them periodically

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8. References

Acton, D.F. and Gregorich, L.J. (eds) (1995) The health of our soils. Towards sustainable agriculture in Canada. Agriculture and Agri-Food Canada, Ottawa, Canada. Soil Science Society of America. Statement on soil quality. *Agronomy News*, p 7.

Aggarwal, R. P., Phogat, V.K., Chand, T. and Grewal, M.S. (1994) *Improvements of Soil Physical Conditions in Haryana. Dept. of Soil Sci.,* CCS Haryana Agric. Univ., Hisar, India.

Andrews, S.S., and Carroll, C.R. (2001) Designing a soil quality assessment tool for sustainable agro-ecosystem management. *Ecological Applications* 11, 1573-1585.

Andrews, S.S., Flora, C.B., Mitchell, J.P., and Karlen, D. L. (2003) Grower's perceptions and acceptance of soil quality indices. *Geoderma* 114, 187-213.

Andrews, S.S., Karlen, D.L., and Cambardella, C.A. (2004) The soil management assessment framework: A quantitative evaluation using case studies. *Soil Science Society of America Journal* 68, 1945–1962.

Andrews, S.S., Karlen, D.L., and Mitchell, J.P., (2002a) A comparison of soil quality indexing methods for vegetable production systems in northern California. *Agriculture, Ecosystems and Environment* 90, 25–45.

Andrews, S.S., Mitchell, J.P., Mancineelli, R., Karlen, D.L., Hartz, T.K., Horwath, W.R., Pettygrove, G.S., Scow, K.M. and Munk, D.S. (2002 b) On-farm assessment of soil quality in California's central valley. *Agronomy Journal* 94, 12-23.

Arshad, M.A., and Coen, G.M. (1992) Characterization of soil quality: physical and chemical criteria. *American Journal of Alternative Agriculture* 7, 25-31.

Arshad, M.A., and Martin, S. (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. *Agriculture, Ecosystems and Environment* 88, 153-160.

Arshad, M.A., Lowery, B., and Grossman, B. (1996) Physical tests for monitoring soil quality. In: *Methods for Assessing Soil Quality* (J.W. Doran and A.J. Jones, Eds.) Special Publ. 49. *SSSA, Madison*, WI. p. 123–141.

Astier, M. Maass, J.M., Etchevers-Barra, J.D., Pena, J.J., and de Leon Gonzalez. F. (2006) Short-term green manure and tillage management effects on maize yield and soil quality in an Andisol. *Soil and Tillage Research* 88, 153-159.

Awasthi, K.D., Singh, B.R., and Sitaula, B. K. (2005) Profile carbon and nutrient levels and management effect on soil quality indicators in the Mardi watershed of Nepal.: Acta-Agriculturae-Scandinavica-Section-B, *Soil and Plant Science* 55(3), 192-204.

Blair, J.M., Bohlen, P.J., and Freckman, D.W. (1996) Soil invertebratesas indicators of soil quality. In: *Methods for Assessing Soil Quality* (J.W. Doran and A.J. Jones, Eds.) Soil Science Society of America, Special Publication 49, Madison, WI, pp 273–291.

Brejda, J. J., and Moorman, T.B. (2001) Identification and interpretation of regional soil quality factors for the Central High Plains of the Midwestern USA. In: *Sustaining the global farm—Selected papers from the 10th International Soil Conservation Organization Meeting (ISCO99)* (D. E. Stott, R. H. Mohtar, and G. C. Steinhardt, Eds), West Lafayette, In: International Soil Conservation Organization in cooperation with the USDA and Purdue University. Pp. 535-540.

Bridge, B.J. (1997) Soil physical deterioration. In: *Sustainable Crop Production in Subtropics: An Australian Perspective* (A.L. Clarke, and P. Wylie, Eds.), Queensland Department of Primary Industries: Brisbane. pp 64-78.

Bridge, B.J. and Ross, P.J. (1984) Relations among physical properties of cracking clay soils. In: *Properties and Utilization of Cracking Clay Soils* (J.W. McGarity, E.Hoult and H.B. So, Eds.), Reviews in Rural Science, University of New England, Armidale. Pp 97-104.

Bucher, E. (2002) Soil quality characterization and remediation in relation to soil management. PhD Thesis, Department of Crop and Soil Sciences, Pennsylvania State University, USA.

Campbell, C.A., and Zentner, R.P. (1995) Soil organic matter as influenced by crop rotations and fertilization. *Soil Science Society of America Journal* 57, 1034- 1040.

Carter, M.R. (1996) Concepts of soil quality. In: *Soil Quality is in the Hands of the Land Manager* (R.J. MacEwan, M.R. Carter, Eds), Symposium Proceedings, University of Ballarat, Ballarat.

Chaudhury, J., Mandal, U.K., Sharma, K.L., Ghosh, H., and Biswapati Mandal (2005) Assessing soil quality under long-term rice based cropping system. *Communications in Soil Science and Plant Analysis* 36(9/10), 1141-1161.

Chen, Z. S. (1998) Selecting indicators to evaluate the soil quality of Taiwan soils and approaching the national level of sustainable soil management pp. 131-171. In FFTC ASPAC (Editor). Proceedings of International Seminar on soil management fro sustainable agriculture in the tropics. Dec. 14-19, 1998. Taichung, Taiwan, ROC. (Invited Speaker).

Conway, G. (1985) Agro ecosystem analysis. *Agricultural Administration* 20 (1), 31-55.

Dalal, R. C. (1998) Soil microbial biomass-what do the numbers really mean? *Australian Journal of Experimental Agriculture* 38, 649-665.

Dalal, R.C. (1989) Long term effects of no-tillage, crop residues and nitrogen application on properties of a Vertisol, *Soil Science Society of America Journal* 53, 1511–1515.

Dalal, R.C., and Mayer, R.J. (1986) Long term trends in fertility of soils under continuous cultivation in southern Queensland. 11. Total organic carbon and its rate of loss from the soil profile. *Australian Journal Soil Research* 37, 265–279.

Dalal, R.C., and Mayer, R.J. (1987) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. VI. Loss of total nitrogen from different particle-size and density fractions. *Australian Journal Soil Research* 25, 83–93.

Dick, R.P., Breakwell, D.P., and Parkin, T.B. (1996) Soil enzyme activities and biodiversity measurements as integrative microbiological indicators, In: *Methods for Assessing Soil Quality* (J.W. Doran et al., (eds.), SSSA Spec. Pub. 49. Madison, WI. pp. 247-271.

Doran, J. W., and Parkin. T. B. (1996) Quantitative indicators of soil quality: A minimum data set. In: *Methods for Assessing Soil Quality*, (J. W. Doran and A. J. Jones, Eds.). Soil Sci. Am. Special Publication No. 49, Madison, Wisconsin, USA, pp. 25-37.

Doran, J. W., Sarrantonio, M., and Liebig, M. A. (1996) Soil health and sustainability. *Advances in Agronomy* 56, 1-54.

Doran, J.W., Liebig, M.A., and Santana, D.P. (1998) Soil health and global sustainability. In: *Proceedings of the 16th World Congress of Soil Science*. Montepellier, France, 20-26 August 1998.

Doran. J.W., and Parkin, T. B. (1994) Defining and assessing soil quality. In: *Defining Soil Quality for a Sustainable Environment,* (J. W. Doran, D. C. Coleman, D. F. Bezdicek, and B. A. Stewart, Eds.), Soil Sci. Soc.Am. Special Publication No.35, Madison, Wisconsin, USA, pp. 3-21.

Freckman, D.W., and Virginia, R.A. (1997) Low-diversity Antarctic soil nematode communities: distribution and response to disturbance. *Ecology* 78, 363-369.

Freebairn, D.M., and Wockner, G.H. (1986) A study on soil erosion on Vertisols of the eastern Darling Downs, Queensland. I. Effect of surface conditions on soil movement within contour bay catchment. *Australian Journal of Soil Research* 24, 135-158.

Ghoshal, S.K. (2004) Studies on biological attributes of soil quality for a few long-term fertility experiments with rice base cropping systems. PhD Thesis, Bidhan Chandra Krishi Viswavidyalaya, pp.146.

Ghuman B.S., and Sur, H.S. (2001) Tillage and residue management effects on soil properties and yields of rainfed maize and wheat in a subhumid subtropical climate, *Soil and Tillage Research* 58, 1–10.

Glanz, J.T. (1995) *Saving Our Soil: Solutions for Sustaining Earth's Vital Resource*, Johnson Books, Boulder, CO, USA.

Glover, J.D., Reganold, J.P., and Andrews, P.K. (2000) Systematic method for rating soil quality of conventional, organic, and integrated apple orchard in Washington State, *Agriculture Ecosystem and Environment* 80, 29–45.

Graham – Tomasi, T. (1991) Sustainability: concept and implications for agricultural research policy. In: *Agricultural Research Policy: International Quantitative Perspectives* (P.C., Pardey, J. Roseboom, and J.R. Anderson, Eds.). Cambridge University Press. Pp 81-102.

Granatstein , D., and Bezdicek, D. F. (1992) The need for a soil quality index: Local and regional perspectives. *American Journal of Alternative Agriculture.* 17, 12-16.

Harris, R.F., Karlen, D. L., and Mulla, D.J. (1996) A conceptual framework for assessment and management of soil quality and health. In: *Methods for Assessing Soil Quality* (J. W. Doran, and A.J. Jones, Eds.), Soil Sci. Soc. Am. Spec. Publ. # 49. SSSA, Madison, WI, USA, pp. 61-82.

Hazra, G.C., Ghoshal, S.K. and Mandal, Biswapati (2004) Soil quality evaluation for a long-term fertility experiment with organic and inorganic inputs under rice-wheat cropping system. *Proc. Intl. Symp. on Agro environ.* pp 311-321 held during October 20-24, 2004 at Udine, Italy.

Heal, O.W., S. Struwe, and Kjoller, A. (1996) Diversity of soil biota and ecosystem function. Annual Conference, Australian Agricultural and Resource Economics Society, Amidale, New South Wales. pp 1-10.

Herdt, R.W. and Steiner, R.A. (1995) Agricultural Sustainability: Concepts and Conundrums. In: *Agricultural Sustainability: Economic, Environmental and Statistical Considerations*, (V. Barnett, R. Payne, and R.Steiner, Eds.), J. Wiley & Sons, Chichester, U.K., pp.1-13.

Hussain, I., Olson, K. R., Wander, M. M., and Karlen, D.L. (1999) Adaptation of soil quality indices and application to three tillage systems in southern Illinois. *Soil and Tillage Research* 50, 237-249.

Ishaq, M., Ibrahim, M., and Lal, R. (2002) Tillage effects on soil properties at different levels of fertilizer application in Punjab, Pakistan. *Soil and Tillage Research* 68 (2), 93-99.

Jaenicke, E.C., and Lengnick, L.L. (1999) A soil –quality index and its relationship to efficiency and productivity growth measures two decompositions. *American Journal of Agricultural Economics* 81, 881-893.

Jodha, N.S. (1994) Indicators of Unsustainability. In: *Stressed Ecosystems and Sustainable Agriculture.* (S.M. Virmani, J.C. Katyal, H. Eswaran and I.P. Abrol, Eds.), Oxford & IBH Publishing Co.PVT.LTD. Pap. No 65-77.

Karlen, D.L., and Stott, D.E. (1994) A framework for evaluating physical and chemical indicators of soil quality. In: *Defining Soil Quality for a Sustainable Environment* (J. W. Doran, D. C. Coleman, D. F. Bezdicek, and B. A. Stewart, Eds.), Madison, WI. *Soil Science Society of America Journal* 35, 53-72 (special publication).

Karlen, D.L., Andrews, S.S., Doran, J.W. (2001) Soil quality: current concepts and application. *Advances in Agronomy* 74, 1-40.

Karlen, D.L., Eash, N.S., Unger, P.W. (1992) Soil and crop management effects on soil quality indicators. *American Journal of Alternative Agriculture* 7, 48–55.

Karlen, D.L., Mausbach, M.J., Doran, J. W., Cline, R. G., Harres, R. F., and Schuman. G. E. (1997) Soil quality: A concept definition, and framework for evaluation. *Soil Science Society of America Journal* 61, 4-10.

Katyal, J.C. (2008) Presidential Address. *Journal of the Indian Society of Soil Science* 56 (4), 322-324.

Keller, K., B.M. Bolker, D.F. Bradford (2004). Uncertain climate thresholds and optimal economic growth, Journal of Environmental Economics and Management, 48, pp. 723- 741.

Kookana, R.S., Baskaran, S., and Naidu, R. (1998) Pesticide fate and behaviour in Australian soils in relation to contamination and management of soil and water - a review. *Australian Journal of Soil Research* 36:715-764.

Kusuma Grace, J. (2008) Assessment of soil quality under different land use treatments in rainfed Alfisol. Ph.d Thesis, Jawaharlal Nehru Technological University, Hyderabad, Andhra Pradesh, India. p. 250.

Lal R. (1993) Tillage effects on soil degradation, soil resiliency, soil quality and sustainability. *Soil and Tillage Research* 27(1-4), 1-8.

Lal, R. (1994) Date analysis and interpretation. In: *Methods and Guidelines for Assessing Sustainable Use of Soil and Water Resources in the Tropics*, (R. Lal, Ed.). Soil Management Support Services Technical. Monograph. No. 21. SMAA/SCS/USDA, Washington D. C, pp. 59-64.

Lal, R. (2008) Soils and India's Food Security. *Journal of the Indian Society of Soil Science*, 56 (2), 129-138.

Lal, R. (Ed.). (1998) Soil quality and agricultural sustainability. In: *Soil Quality and Agricultural Sustainability*. Ann Arbor Press, Chelsea, MI, pp. 3-12

Lal, R., Hall, G.F., Miller, P. (1989) Soil degradation: I. Basic processes. *Land Degradation and Rehabilitation* 1, 51-69.

Larson, W. E., and Pierce. F. J. (1994) The dynamics of soil quality as a measure of sustainable management. In: *Defining Soil Quality for a Sustainable Environment*. (J. W. Doran, D. C. Coleman, D. F. Bezdicek, and B. A. Stewart, Eds.), Soil Science Society of America Special Publication No. 35. Madison, Wisconsin, USA, pp. 37-51.

Larson, W.E., and Pierce. F.J. (1991) Conservation and enhancement of soil quality. In: *Evaluation for Sustainable Land Management in the Developing World* (J. Dumanski, Ed.). Proceedings of the International Workshop, Chiang Rai, Thailand, 15-21 Sept. 1991. Technical papers, vol. 2 Int. Board for Soil Res.and Management, Bangkok, Thailand, pp. 175-203.

Lockeretz, W. (1988) Open questions in sustainable agriculture. *American Journal of Alternative Agriculture.* 3, 174—181.

Lynam, J.K., and Herdt, R.W. (1988) Sense and sustainability: sustainability as an objective in international agriculture research. Presented at the CIP-Rockefeller Foundation Conference on Farmer and Food Systems, 26-30 September 1988, Lima, Peru .(Limited distribution.)

Mac Rae, R.Y., and Mehuys, G.R. (1985) The effect of green manuring on the physical properties of temperate area soils. *Advances in Soil Science*. Vol. 3, Springer-Verlag, Inc., New York. pp. 71–94.

Mairura, F.S., Mugendi, D.N., Mwanje, J.I., Ramisch, J.J., Mbugua, P.K., and Chianu, J.N. (2007) Integrating scientific and farmer's evaluation of soil quality indicators in central Kenya. *Geoderma* 139, 134 -143.

Mandal B (2005) Assessment and Improvement of Soil Quality and Resilience for Rainfed Production System. Completion Report. National Agricultural Technology Project, Indian Council of Agricultural Research, New Delhi, 30 pp.

Mandal, B., Majumder, B., Bandopadhyay, P.K. (2007) The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology* 13, 357-369.

Mandal, D.K., Mandal, C., and Velayutham, M. (2001) Development of a land quality index for sorghum in Indian semi-arid tropics (SAT). *Agric-syst.* Oxford : Elsevier Science Ltd. Oct 2001. 70 (1), 335-350.

Manna, M.C., Swarup, A., Wanjari, R.H., Mishra, B., and Shahi D.K. (2007) Long-term fertilization, manure and liming effects on soil organic matter and crop yields. *Soil and Tillage Research*, 94 (2): 397-409.

Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V., Sahi, D.K., and Sarap, P.A. (2005) Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research* 93, 264–280.

Markanday, A., and Pearce, D.W. (1988) Environment considerations and the choice of the discount rate in developing countries. *Environment Department Working Paper* no.3. Washington, DC, USA: World Bank.

Masto, R.E., Chhonkar, P.K., Dhyan Singh, and Patra, A.K. (2007) Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. *Agriculture, Ecosystems and Environment* 118, 130 –142.

Mohanty, M., Painuli, D.K., Misra, A.K., and Ghosh, P.K. (2007) Soil quality effects of tillage and residue under rice–wheat cropping on a Vertisol in India. *Soil and Tillage Research,* 92 (1-2), 243-250.

Moody, P.W., and Aitken, R.L. (1997) Soil acidification under some tropical agricultural systems. I. Rates of acidification and contributing factors. *Australian Journal of Soil Research* 35, 163-173.

Pain, A.K. (2007) Indian agriculture: The present scenario. *Agrarian Crisis in India: An Overview* (A.K. Pain, Ed.), pp. 1-11. The ICFAI Press, Hyderabad, India.

Pankhurst, C.E. (1994) Biological indicators of soil health and sustainable productivity. In: *Soil Resilience and Sustainable Land Use* (D.J. Greenland, and I. Szabolcs, Eds.), CAB International, Wallingford, UK. pp 331-351.

Parr, J.F. and Hornick, S.B. (1990) Recent developments in alternative agriculture in the United States. In: *Proc. of Intl. Conf. on Kyusei Nature Farming*, October 17—21, 1989, Khon Kaen University, Khon Kaen. Thailand.

Parr, J.F., Papendick R.L., Hornick, S.B., and Meyer, R.E. (1990) Strategies for developing low-input sustainable farming systems for rainfed agriculture. In: *Proc. Intl. Symposium for Managing Sandy Soils,* February 6 -11, 1989, Jodhpur, India. Indian Council of Agricultural Research. New Delhi.

Parr, J.F., Papendick, R.I., Hornick, S.B., and Meyer, R. E. (1992) Soil quality: attributes and relationship to alternative and sustainable agriculture. *American Journal of Alternative Agriculture* 7, 5-11.

Parr, J.F., Papendick, R.I., Youngberg, 1G. and Meyer, R.E. (1989) Sustainable agriculture in the United States. Chap. 4, In: *Proc. Intl. Symposium on Sustainable Agricultural Systems*. Soil and Water Conservation Society, Ankeny, Iowa. pp. 50 - 67.

Perucci, P. and Scarponi, L. (1994) Effects of the herbicide imazethapyr on soil microbial biomass and various soil enzymes. *Biology and Fertility of Soils* 17, 237-240.

Prasad, R. and Power, J.F. (1991) Crop residue management. *Advances in Soil Science* 15, 205–251.

Rao, G.G.S.N., Rao, V.U.M., Vijaya Kumar, P., Rao, A.V.M.S., and Ravindra Chary, G. (2010) Climate risk management and contingency crop planning. Lead papers. In: National Symposium on Climate Change and Rainfed Agriculture, 18-20 February, 2010, CRIDA, Hyderabad, India. Organized by Indian Society of Dryland Agriculture and Central Research Institute for Dryland Agriculture. Pp. 37.

Rasmussen, P.E. and Collins. H.P. (1991) Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. *Advances in Agronomy* 45, 93-134.

Rengasamy, P. and Olsson, K.A. (1991) Sodicity and soil structure. *Australian Journal of Soil Research* 29, 935-952.

Rice, C.W., Moorman, T.B. and Margules C.R. (1996) Role of microbial biomass carbon and nitrogen in soil quality. In: *Methods for Assessing Soil Quality*. (J.W. Doran, and A.J. Jones, Eds.), Special Publication number 49, SSSA, Madison. pp 203-215.

Richter, J. (1987) *The Soil as a Reactor*. Catena Verlag. Cremilingen, Germany.

Rochette P. and Gregorich E.G. (1998) Dynamics of soil microbial biomass C, soluble organic C and CO_2 evolution after three years of manure application. *Canadian Journal of Soil Science.* 78, 283-290.

Roldán, A., Salinas-García, J.R., Alguacil, M.M., Díaz, E. and Caravaca, F. (2005) Soil enzyme activities suggest advantages of conservation tillage practices in sorghum cultivation under subtropical conditions. *Geoderma,* 129 (3-4), 178-185.

Sekhon, G.S. (1997) Nutrient needs of irrigated food cropsin India and related issues. In: *Plant Nutrient Needs, Supply, Efficiency and Policy Issues 2000-2025* (J.S. Kanwar and J.C. Katyal, Eds), National Academy of Agricultural Sciences, New Delhi, India.

Selvaraju, R., Subbian, P., Balasubramanian, A. and R. Lal. (1999) Land configuration and soil nutrient management options for sustainable crop production on Alfisols and Vertisols of southern peninsular India. *Soil and Tillage Research* 52, 203-216.

Seybold, C.A., Herrick, J.E., Brejda, J.J. (1999) Soil Resilience a fundamental component of soil quality. *Soil Science* 164 (4), 224-234.

Sharma , K.L. (2009b) Restoration of soil quality through conservation agricultural management practices and it's monitoring using Integrated Soil Quality Index (ISQI) approach in rainfed production system (s). Consolidated Report (2005-09) of National Fellow Project. Submitted to ICAR, New Delhi. Central Research Institute for Dryland Agriculture pp.1-419.

Sharma, K. L. , Grace, J. Kusuma , Mishra, P. K. , Venkateswarlu, B. , Nagdeve, M. B. , Gabhane, V. V. , Sankar, G. Maruthi , Korwar, G. R. , Chary, G. Ravindra , Rao, C. Srinivasa , Gajbhiye, Pravin N. , Madhavi, M. , Mandal, U. K. , Srinivas, K. and Ramachandran, Kausalya(2011) 'Effect of Soil and Nutrient-Management Treatments on Soil Quality Indices under Cotton-Based Production System in Rainfed Semi-arid Tropical Vertisol', Communications in Soil Science and Plant Analysis, 42: 11, 1298 — 1315

Sharma, K. L., Grace, J. Kusuma, Srinivas, K., Venkateswarlu, B., Korwar, G. R., Sankar, G. Maruthi, Mandal, Uttam Kumar, Ramesh, V., Bindu, V. Hima, Madhavi, M. and Gajbhiye, Pravin N. (2009) Influence of Tillage and Nutrient Sources on Yield Sustainability and Soil Quality under Sorghum-Mung Bean System in Rainfed Semi-arid Tropics', Communications in Soil Science and Plant Analysis,40:15,2579 — 2602

Sharma, K. L., Kusuma Grace, J., Srinivas, K., Venkateswarlu, B., Korwar, G. R. Maruthi Sankar, G. Uttam Kumar Mandal ; Ramesh, V., Hima Bindu, V., Madhavi M., Pravin N. Gajbhiye. (2009a) Influence of Tillage and Nutrient Sources on Yield Sustainability and Soil Quality under Sorghum-Mung Bean System in Rainfed Semi-arid Tropics. *Communications in Soil Science and Plant Analysis,* 40 (15), 2579-2602.

Sharma, K. L., Vittal, K. P. R., Ramakrishna, Y. S., Srinivas, K., Venkateswarlu, B., and Kusuma Grace, J. (2007) Fertilizer use constraints and management in rainfed areas with special emphasis on nitrogen use efficiency. In: (Y. P. Abrol, N. Raghuram and M. S. Sachdev (Eds)), Agricultural Nitrogen Use and Its Environmental Implications. I. K. International Publishing House, Pvt., Ltd. New Delhi. Pp 121-138.

Sharma, K.L., Kusuma Grace, J., Uttam Kumar Mandal, Pravin N. Gajbhiye, Srinivas, K., Korwar, G. R., Himabindu, V., Ramesh, V., Kausalya Ramachandran, and Yadav, S.K. (2008) Evaluation of long-term soil management practices through key indicators and soil quality indices using principal component analysis and linear scoring technique in rainfed Alfisols. *Australian Journal of Soil Research* 46: 368-377.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Biswapati Mandal, Grace, J.K., and Ramesh, V. (2005) Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil and Tillage Research* 83(2), 246-259.

Sharma, K.L., Srinivas, K., Das, S.K., Vittal, K.P.R. and Kusuma Grace, J. (2002) Conjunctive Use of Inorganic and Organic Sources of Nitrogen for Higher Yield of Sorghum in Dryland Alfisol. *Indian Journal of Dryland Agricultural Research and Development* 17 (2), 79-88.

Sharma, K.L., Srinivas, K., Mandal, U.K., Vittal, K.P.R., Kusuma Grace, J., and Maruthi Sankar, G. (2004) Integrated Nutrient Management Strategies for Sorghum and Green gram in Semi arid Tropical Alfisols. *Indian Journal of Dryland Agricultural Research and Development* 19 (1), 13-23.

Sharma, K.L., Vittal, K.P.R., Srinivas, K., Venkateswarlu, B. and Neelaveni, K. (1999) Prospects of organic farming in dryland agriculture. *In* Fifty Years of Dryland Agricultural Research in India (Eds. H.P. Singh, Y.S. Ramakrishna, K.L. Sharma and B. Venkateswarlu) Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad, pp 369-378.

Shukla, M.K., Lal, R. and Ebinger, M. (2006) Determining soil quality indicators by factor analysis. *Soil and Tillage Research* 87, 194-204.

Singer, M.J. and Ewing, S. (2000) Soil quality. In: *Handbook of Soil Science* (Sumner, Ed.), CRC Press, Boca Raton, FL, pp. G-271-G-298.

Smith, L.J. and Elliott, F.L. (1990) Tillage and residue management effects on soil organic matter dynamics in semiarid regions. *Advance in Soil Science* 13, 69–88.

Sparling, G.P. (1997) Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In: *Biological Indicators of Soil Health.* (C. E. Pankhurst, B. M. Doube, and V. V. S. R. Gupta, Eds.), CAB International, Wallingford, pp. 97–119.

Steiner. J.L.. Day, J.C., Papendick. R.I., Meyer, R.E. and Bertrand, A.R. (1988) Improving and sustaining productivity in dryland regions of developing countries. *Soil Science* 8: 79 - 122.

Stewart, B.A., Lal, R. and El-Swaify, S.A. (1990) Sustaining the resource base of an expanding world agriculture. In: *Proc. Workshop on Mechanisms for a Productive and Sustainable Resource Base*. July 29-30. 1989. Edmonton, Canada. Soil and Water Conservation Society, Ankeny, Iowa.

Szabolcs, I. (1994) The Concept of Soil Resilience. In: *Soil Resilience and Sustainable Land Use* (D. J.Greenland and I.Szabolcs, Eds). CAB International Pap.No:33-39.

Tiwari, K. N. (2008) Future of plant nutrition research in India. *Journal of the Indian Society of Soil Science* 56, 327-336.

Tiwari, K.N., Sharma, S.K. Singh, V.K., Dwivedi, B.S. and Shukla, A.K. (2006) Site Specific Nutrient Management for Increasing Crop Productivity In India. PDCSR (ICAR) – PPIC, India Programme, pp 92.

USDA (2004) Food Security Assessment. Agriculture and Trade Reports. USDA-ERS. GFA-15, Washington, D.C. 88 pp.

Walker, J. and Reuter, D.J. (1996) *Indicators of Catchments Health: A Technical Perspective*, CSIRO, Collingwood, Australia, 174 pp.

Wang, X. and Gong, Z. (1998) Assessment and analysis of soil quality changes after eleven years of reclamation in subtropical China. *Geoderma* 81, 339-355.

Warkentin, B.P. (1996) Overview of soil quality indicators. In: *Proceedings of the Soil Quality Assessment on the Prairies Workshop*, Edmonton, 22-24 January, 1996. pp. 1-13.

Wienhold, B.J., Andrews, S.S. and Karlen, D.L. (2004) Soil quality: a review of the science and experiences in the USA. *Environmental Geochemistry and Health* 26, 89–95.

Wienhold, B.J., Andrews, S.S., Kuykendall, H. and Karlen, D.L. (2008) Recent Advances in Soil Quality Assessment in the United States. *Journal of the Indian Society of Soil Science,* 56 (3), 237-246.