Soil quality restoration through carbon sequestration under climate change scenario in India

A.A. PATIL, B.Y. SHEWALE AND S.R. KADAM

Summary
Climate change has emerged a major challenge not only for sustainable agriculture but also for human settlement. Climate change including global warming with its adverse impact on the life on the earth is now global issue and becoming severe day by day. The increase in CO$_2$ concentration results in climate change which is directly or indirectly attributed to human activities that changes the composition of global atmosphere adversely. Scientific models and observations over the past 1000 years provide evidences that global warming is due to anthropogenic increase in green house gas (GHG’s) including that of CO$_2$. The increased atmospheric concentration of CO$_2$ may influence soil temperature, pattern of precipitation and evaporation and resultant changes in the physiochemical and biological properties of soil. Thus, there has emphasis to reduce this concentration through the process known as carbon sequestration. A considerable part of the depleted Soil Organic Carbon pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops and crop residue mulch, nutrient cycling including the use of compost and manure and other systems of sustainable management of soil and water resources.

Key words: Soil quality, Carbon sequestration, Climate change, Soil organic carbon


Introduction
Climate change is a major concern for agricultural production. The Inter-governmental panel on climate change has projected a temperature increase of 0.5-1.2°C by 2020, 0.88-3.16°C by 2050 and 1.56-5.44°C by 2080 for India. The corresponding CO$_2$ concentrations are expected to be 393, 543 and 789 ppm in year 2020, 2050 and 2080, respectively (IPCC, 2007). Climate change will reflect in extreme weather events, spatial and inter-annual variability in weather events, which will negatively affect crop yield. The restoration of soil quality through carbon sequestration is major concern for tropical soils. The accelerated decomposition of soil organic carbon due to agriculture resulting in loss of carbon to the atmosphere and its contribution to the greenhouse effect is a serious global problem.

Soil quality and carbon sequestration:
The soil quality concept evolved throughout the 1990s in response to increased global emphasis on sustainable land use and with a holistic focus emphasizing that sustainable soil management requires more than soil erosion control. Soil quality is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and human health (Doran and Parkin, 1994). Soil quality assessment and education are intended to provide a better understanding and awareness that soil resources are truly living bodies with various soil properties and processes performing essential ecosystem services (Table 1).

The favorable effects of soil organic matter on the physical, chemical and thermal properties of the soil and on biological activity and thus in sustaining soil productivity and biodiversity (Table 2) may be seen as an important added-
benefit over direct carbon mitigation techniques that would only physically store CO$_2$ in the deeper subsoil. Soil Organic Carbon is the sum of all biologically derived organic materials found in the soil or on soil surface irrespective of its source, living status or stage of decomposition but excluding the aboveground portion of living plant. The soil organic carbon in terms of its amount and quality is essential to sustain the quality and productivity soil. In the recent past the greenhouse effect has created a great concern that has led to several studies on the qualities, kinds, distribution and behaviors of SOC (Velayutham et al., 2005). The organic matter content in soils varies considerably depending on climate soil type and use system. Decomposition of SOC is largely determined by soil temperature and rainfall.

Carbon sequestration is squeezing of carbon out of the atmosphere and its absorption and storage in a terrestrial or aquatic body. Capturing and storage carbon in biomass and soils in the agriculture and forest sector has now gained widespread acceptance as one potential greenhouse gas mitigation strategies. Carbon sequestration in terrestrial ecosystems can be defined as the net removal of CO$_2$ from the atmosphere and its storage into long-lived pools of carbon. The pools can be living, above ground biomass (e.g. Trees) products with a long, useful life created from biomass (e.g. lumber), living biomass in soils (e.g. roots and microorganisms) or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments. It is important to emphasize that alone is not enough. This carbon must be fixed into long-lived pools. Otherwise, one may be simply altering the size of fluxes in the carbon cycle, not increasing carbon sequestration. There are five important global carbon pools among which oceanic pool (38,000 pg) is the largest followed by geological pool (5000 pg; 4000 pg of coal pool and 500 pg of each oil and gas) pedological pool (soil carbon pool, 2500 pg) biotic pool (560 pg) and the atmospheric pool (760 pg). The average atom of C spends about 5 yrs. in the

<table>
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<th>Table 1 : Example of a minimum data set of indicators for soil quality</th>
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<td><strong>Indicator</strong></td>
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<td>Soil organic matter (SOM)</td>
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<tr>
<td><strong>Physical</strong></td>
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<tr>
<td>Soil structure</td>
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<tr>
<td>Depth of soil and rooting</td>
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<td>Infiltration and bulk density</td>
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<td>Water holding capacity</td>
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<td><strong>Chemical</strong></td>
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<td>pH</td>
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<td>Electrical conductivity</td>
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<td>Extractable nitrogen (N), phosphorus (P), and potassium (K)</td>
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<td><strong>Biological</strong></td>
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<tr>
<td>Microbial biomass carbon (C) and N</td>
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<td>Potentially mineralizable N</td>
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<td>Soil respiration</td>
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(Larson and Pierce, 1994)

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<th>Table 2 : Effects of organic matter on soil productivity and biodiversity</th>
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<td><strong>Physical</strong></td>
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<td><strong>Biological</strong></td>
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(After: Wild, 1993)
atmosphere, 10 yrs. in vegetation (including trees), 35 yrs. in soil, and 100 yrs. in the sea (Lal, 2004). Increase density of C in the soil and depth of C in the profile, decrease decomposition of C and losses due to erosion are important measures to increase the soil organic carbon.

**Factors affecting soil organic carbon dynamics:**

Studies have shown that soil organic carbon dynamics is influenced by several factors such as soil texture, temperature, moisture, pH, and available C and N.

**Temperature:**

Temperature has a great influence on organic carbon depletion from soil. Prevalence of warm temperature in the tropics accelerates organic matter decomposition and loss. At low temperature (>0°C) plant growth is greater than the rate of microbial decomposition and organic matter can accumulate. Above 25°C, microbial decomposition is greater than plant growth hence, organic matter production declines. Tropical Indian soils, majority of which belongs to arid and semiarid climate, rarely exhibit organic carbon levels exceeding 0.6 per cent (Virmani et al., 1982).

**Moisture:**

Besides temperature, soil moisture content also affect organic carbon content of soil. These two factors are interdependent with the influence of soil water-content being stronger at higher temperatures. Organic matter distribution across soil is influenced strongly by mean annual rainfall. Increasing soil moisture content results in increasing carbon dioxide evolution when the soil water-content is subtropical for microbial activity. Periodic drying and wetting of the soil also increases CO₂ evolution.

**Soil texture:**

Soils pH has a profound effect on soil organic matter decomposition, although it’s precise mode of influence has yet to be fully established. It strongly influences the growth of bacteria, fungi and soil fauna. Microbial activity at very low or very high soil pH will influence the rate of organic matter decomposition. Rao and Pathak (1996) reported that at pH 8.7, CO₂ emission was found to be reduced by 18 per cent and at pH 10.0 by 83 per cent compared to that at pH 7.0.

**Salinity:**

Excessive amount of salts have adverse effect on physical and chemical properties of soil as well as on soil microbiological processes. A progressive decrease in CO₂ evolution occurs with increase in salinity. It was observed that carbon mineralization is similar in soils up to the electrical conductivity (EC) value 26 dSm⁻¹, but gets drastically reduced at higher EC (Pathak and Rao, 1998).

**Atmospheric pressure:**

The CO₂ emission is directly related to atmospheric pressure. Its decrease triggers the release of CO₂ from the soil, there by CO₂ emission.

**Organic manure:**

Soil organic carbon levels were either maintained or increased with an adequate manure treatment. Application of organic matter minimizes erosion mediated organic loss. However, climatic conditions in the dry tropics favor its disappearance as CO₂. Manures including sewage sludge increase the soil respiration. Alvarez et al. (1999) found that increase of CO₂ emission from the soil represented 21 per cent of C applied through sludge.

**Fertilizer application:**

Fertilizers generally increase soil organic carbon content because the increased crop growth returns lager amounts of residues to the soil. Aerts and Toet (1997) suggested that increase in the supply of NH₄⁺N leads to reduction in the decay of organic matter and loss of C. In tropical soils, application of fertilizers at suboptimal rates causes reduction in the SOC pool.

**Vegetation:**

Another important factor influencing organic carbon levels in soil is the nature and amount of vegetation. The presence of crops also influences carbon dynamics in soil. The production of carbon dioxide is approximately 2 to 3 fold more in cropped soils compared to bare soils (Russell, 1973). Within different crops also, there is variability in carbon dioxide production. In an alluvial, sandy loam soil, having pH 7.5 and organic matter 0.66 per cent, planted to wheat and maize crops, CO₂ emissions have been found as 36.7 and 61.7 kg CO₂ ha⁻¹ d⁻¹, respectively.

**Tillage:**

Ploughing causes rapid, larger changes in decomposition, exposing SOM previously protected inside soil aggregates. During a tillage event, soil aggregates are broken, increasing oxygen supply and surface area exposure of organic material. This promotes the decomposition of organic matter. In contrast, conservation tillage favours organic carbon enrichment of soil (Lal, 1999).

**Impact of climate change on soil properties:**

The increased atmospheric concentration of CO₂ may influence soil temperature, pattern of precipitation and evaporation and resultant changes in soil moisture regimes. These changes may influence:

- Soil processes
- Soil quality deterioration through reduction in SOC pool
– Increased risk of soil erosion and salinization
– Alterations in elemental cycling
– Changes in activities and species diversity of soil fauna
– Biomass production.

The detailed information pertaining to the effect of climate change on soil properties is presented as follows.

The soil physical properties provide information related to water and air movement through soil, as well as conditions affecting germination, root growth erosion processes. Many soil physical properties thus form the foundation of other chemical and biological processes which may be further governed by climate, landscape position and land use. The key soil physical indicators in relation to climate change include bulk density, structure, rooting depth, hydraulic conductivity and water infiltration (Allen et al., 2011).

Among the physical parameters, aggregate stability, the resistance of soil aggregates to external energy such as high intensity rainfall and cultivation is determined by soil structure, as well as a range of chemical and biological properties (Dalal and Moloney, 2000). It is considered a useful soil health indicator since it is involved in maintaining important ecosystem functions in soil including organic carbon (C) accumulation, infiltration capacity, movement of water and root and microbial community activity, it can also be used to measure soil resistance to erosion and management changes (Lal,1999 and Rimal and Lal, 2009).

Porosity a measure of the void spaces in a material as a fraction and pore size distribution provide a direct, quantitative estimate of the ability of a soil to store root-zone water and air necessary for plant growth (Reynolds et al., 2002). Pore characteristics are strongly linked to soil physical quality; bulk density and macro porosity are functions of pore volume, while soil porosity and water release characteristic directly influence a range of soil physical indices including soil aeration capacity plant available water capacity and relative field capacity (Reynolds et al., 2009).

Soil available water and distribution may respond to climate change, especially to variable and high intensity rainfall or drought events, and thus, management strategies such as the planting of cover crops, conservation tillage and incorporation of organic matter, not maintain or even enhance water infiltration and available water in soil may help in mitigating the impacts of severe rainfall and drought events or severe erosion events (Salvador Sanchis et al., 2008). Intense rainfall events can be a major cause of erosion in slopped lands systems and where soil instability results from farming practices that have degraded soil structure and intensity.

Soil fertility in simple terms is the ability of the soil to provide nutrient in appropriate form and in right quality to the plants. The various soil physical, chemical and biological properties and some of the processes like weathering, mineralization, immobilization, nitrification, de-nitrification, biological nitrogen fixation, root microbes interactions and nutrient movement influence soil fertility. Soil properties and processes that influence the availability of nutrients to plant growth depends on rainfall, temperature, soil carbon dioxide content, amount of moisture in soil and drought.

Soil moisture deficit increases vulnerability to nutrient losses from the rooting zone through erosion. Because nutrients are carried to the roots by water. Soil moisture deficit decreases nutrient diffusion over short distances and the mass flow of water soluble nutrients such as nitrate, sulphate, calcium, magnesium and silicon over longer distance (Barber, 1995). Reduction in both carbon and oxygen fluxes and nitrogen accumulation in root nodules under drought condition inhibits nitrogen fixation in legume crops (Athar and Ashraf, 2009). Soil moisture stress alters the composition and activity of soil microbial communities which determine the C and N transformations that underlie soil fertility and nutrient cycling (Schimel et al., 2007).

Surface erosion during intense precipitation events is a significant source of soil nutrient loss in developing countries (Zougmore et al., 2009). High mobility in soil nitrate leaching following intense rainfall events can also a significant source of N loss in agriculture. Areas with poorly drained soils or that experience frequent intense rainfall events can become waterlogged and hypoxic. The change in soil redox status under low oxygen can lead to elemental toxicities of Mn, Fe, Al and B that reduce crop yields. The significant nitrogen losses can be also occur under hypoxic conditions through denitrification as nitrate is used as an alternative electron acceptor by microorganisms in the absence of oxygen (Marschner, 1995).

The soil warming can increase nutrient uptake by 100-300 per cent by enlarging the root surface area and increasing rates of nutrient diffusion and water influx (Mackay and Barber, 1984). Emerging evidence suggests that warmer temperatures have the potential to significantly affect nutrient status by altering plant phenology (Nord and Lynch, 2009). High temperature results in increased soil salinization and volatilization losses of added nitrogen have recorded increased loss of ammonia with the increase in the temperature from 15 to 45°C which attributed to increased rate of urea hydrolysis and solubility of added fertilizers to soils.

Moscatelli et al. (2005) reported the positive effect of microbial and various enzymatic activities which would lead to greater decomposition activity and therefore to a decrease in organic carbon content of the soil. The effects, however appear to be short term, in very few years, normal activity values are regained. This result should be considered with care, because it is practically impossible to separate the direct effect on microbial activities from the indirect effects of inputs of root exudates and other labile forms of carbon from the
roots, which also undergo an increase due to the \( \text{CO}_2 \) increase. Higher temperature could increase the rate of microbial decomposition of organic matter adversely affecting soil fertility in the long run. But increase in root biomass resulting from higher rates of photosynthesis could offset these effects. Higher temperature could accelerate the cycling of nutrients in the soil and more rapid root formation could promote more nitrogen fixation. Nitrogen availability is important to soil fertility and N cycling is altered by human activity. Increased atmospheric \( \text{CO}_2 \) concentrations global warming and changes in precipitation pattern 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 difference 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.

**Strategies for carbon sequestration**

Improved management techniques have shown that scientific agriculture can be a solution to environmental issues in general and specifically for mitigating the greenhouse effect by increasing soil carbon storage and effectively removing \( \text{CO}_2 \) from the atmosphere. Soil management practices like increasing soil organic carbon content, reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro-aggregation, and mulching can play important roles in sequestration carbon in soil.

**Conservation tillage**

Conservation tillage involves reducing the intensity and frequency of ploughing and leaving crop residues on the soil surface as mulch. This is an important strategy for enhancing SOC content. Higher SOC in the surface layer under conservation tillage have been reported for soils of West Africa, South Africa, Australia, Argentina, Tropical America and North America. According to Campbell et al. (1995) continuous wheat cultivation under no tillage condition gained about 1.5 t ha\(^{-1}\) more C than under conventional tillage condition. Soil microbial biomass carbon was often found to be higher, but never lower, under zero tillage than under conventional tillage. However, \( \text{CO}_2 \) evolution (basal respiration) was usually higher under conventional tillage than under zero tillage, resulting in higher specific respiration (q \( \text{CO}_2 \)) under conventional tillage than under zero tillage. The higher additions but lower losses of labile C under zero tillage mean that more C is sequestered in the soil in the zero-tillage system. Thus, this system contributes less to atmospheric C than conventional tillage, and soil organic matter accumulates more under zero tillage.

**Cover crops**

The effectiveness of conservation tillage in SOC sequestration is enhanced by use of cover crops, such as clover and grains. Frequent use of pod type legumes and grasses in rotation with food crops is an important strategy to enhance SOC and soil quality (Entry et al., 1996). Gains in SOC by growing cover crops in rotation with food crops have been reported throughout the world including Haryana, India, Southwestern Nigeria, Syria, Argentina and Norway.

**Crop rotation**

The effects of crop rotation on SOC content have been widely reflected in numerous long term experiments. Cropping systems provide an opportunity to produce more biomass C than in a monoculture system and to thus increase SOC sequestration. Chander et al. (1997) studied soil organic matter under different crop rotations for 6 years and found that inclusion of green manure crop of Sesbania aculeate in the rotation improved the soil organic matter status and microbial C increased from 192 mg kg\(^{-1}\) soil in pearl millet-wheat fallow rotation to 256 mg kg\(^{-1}\) soil in pearl millet-wheat green manure rotation. Legume-based cropping systems could help to increase crop productivity and soil organic matter levels, thereby enhancing soil quality, as well as having the additional benefit of sequestering atmospheric C. The soil organic matter below the plough layer in soil under the legume-based rotation appeared to be in more biologically resistant form (i.e., higher aromatic C content) compared with that under monoculture.

**Incorporation of crop residue in soil**

Management of crop residues is of primary importance. Incorporation of crop residues in soil leads to increased soil organic matter levels. Incorporation of rice and wheat residues helps in sequestering C in agricultural soils. Incorporation of crop residues significantly increased soil organic C content in a long term field experiment conducted in rice-wheat cropping system (Singh et al., 2000). Cereal crop residues with high C:N ratio leaves more C in soil for conversion to soil organic matter. Lal et al. (1998) estimated that the amount of residue C produced each year on US cropland is about 447.3 million metric tonnes, including above-ground residues and below-ground biomass plus weeds. By assuming that 50 per cent of the residue C can be efficiently managed and then with C sequestration efficiency of 5 to 10 per cent, the amount of SOC sequestered is estimated as 11.2-22.4 million metric tonnes per year.

**Nutrient management**

On a long-term basis, increased crop yield and organic matter returned to the soil with judicious fertilizer application result in higher SOC content and biological activity than under controlled conditions (absence of fertilizers.) Lal et
al. (1998) summarized the results of a number of studies and concluded that fertility management practices can enhance the SOC content at the rate of 50-150 kg ha\(^{-1}\) yr\(^{-1}\). Increase in N doses increases amount of organic matter in soil. Phosphorus fertilizer also has a beneficial impact on soil organic C. Integrated addition of inorganics with organics through farmyard manure, green manure and crop residues is beneficial in increasing organic carbon content of soil.

**Conclusion:**

The dynamic processes that influence soil quality are complex, and they operate through time at different locations and situations. Soil organic matter is both a source of carbon release and a sink for carbon sequestration. Cultivation and tillage can reduce and change the distribution of SOC while an appropriate crop rotation can increase or maintain the quantity and quality of soil organic matter, and improve soil chemical and physical properties. The return of crop residues and the application of manure and fertilizers can all contribute to an increase in soil nutrients and SOC content, but would need to be combined into a management system for more improvement. The negative prominent impacts of monoculture are influenced by crop type with fauna impoverishment, an increased number of crop pests, a decline in activities of dehydrogenase and phosphatase, and increased levels of phenolic acids in the soil. SOC can only be preserved by using crop rotations with reduced tillage frequency and additions of chemical fertilizers, crop residues and/or manure. Continuous monitoring of long-term changes in the SOC and soil quality under conservation tillage in different agro-ecological zones is essential. There is also a need to obtain more data on long term effects of different tillage systems on carbon and nitrogen mineralization and immobilization in various field situations. The issue involved in understanding soil quality and the design of crop and soil systems for agricultural sustainability should be more holistic, and it needs further investigation.

**Literature Cited**


