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Carbon sequestration opportunities in organic agriculture

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ABSTRACT

At the present time, soil carbon sequestration is of paramount importance to address the imminent threat of increased atmospheric carbon dioxide, which is looming large on the very survival and existence of the biome. The quantum of all carbon everywhere in the globe is same and fixed. It exists to the tune of 800 Pg in the atmosphere, 1700 Pg in terrestrial and 38000 Pg in aquatic ecosystem. Even though, the terrestrial carbon stock is quite meagre in comparision to aquatic carbon stock, yet it warrants attention because it is readily amenable to anthropogenic manipulations and potentially respond to modifications and management. The potential for carbon sequestration in crop-based agriculture globally is 20-30 Pg carbon, whereas, that of India is 0.039-0.049 Pg carbon y^{-1} *or about 47% of current annual fossil fuel emission. The quantity of soil organic carbon (SOC) that will be stored in an ecosystem depends on quantity and quality of organic matter returned to the soil matrix, ability of soil to retain organic carbon and abiotic influences of both temperature and precipitation. Hence, organic agriculture holds added promise to sequester and enhance the SOC pool.*

Keywords: *Organic agriculture, SOM, SOC, carbon sequestration*

Global agricultural expansion threatens to impact worldwide biodiversity on an unprecedented scale that may rival climate change in its significance for the persistence of panoply of species, during the next 50 years. Use of chemicals in agriculture has increased crop yield, yet caused many environmental problems including soil, air and water pollution and finally human health hazards and making the crop productivity unsustainable. Therefore, environment-friendly approaches to the cultivation of crops are necessary to ensure adequate crop yield. Since the beginning of 21st century, in organic farming practices has attained tremendous growth worldwide. Organic agriculture is practised in almost all countries of the world, and its share of agricultural land and farms are growing (FAO, 2002). Compared to 2000, there was 31.4% increase in worldwide organically managed cropped area that reached to about 23 million hectares during 2002. The total world retail sales of organic products reached US$25 billion in 2002,registering 42.9% increase over 2000 (Yussefi and Willer, 2003). The demand for safe food, parallelly in consonance with increased environmental awareness, has resulted in an increasing demand for organic products.

Organic agriculture has been found to enhance soil fertility and increase biodiversity (Mader *et al*., 2002). For example, one meta-analytical study, comparing conventional and organic farms, showed that the latter tend to have higher soil organic matter content and lower nutrient losses (Tuomisto *et al*., 2012). After conversion to organic farming, simulation models predict an increase in soil carbon sequestration in the form of soil organic matter during the first 50 years, which becomes stabilized after about 100 years (Foereid and Hogh-Jensen, 2004). Therefore, it is expected that organic farming systems should be able to combat climate change, allowing food supplies to be secured (Jordan *et al*., 2009). Furthermore, Schmid and Sinabell (2006) reaffirm that organic food is not only free of chemical residues, but is also free of genetically modified organisms, with consumers receiving this second attribute for free. Hence, organic agriculture might be considered a powerful tool within the framework of natural resource management, territorial development, and viable food production, which represent the three broad objectives proposed for Common Agricultural Policy (CAP) reforms after 2013 by the European Commission (2011).

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A. ORGANIC FARMING

According to the National Organic Standards Board (NOSB) of the United States Department of Agriculture (USDA), organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain, or enhance ecological harmony. The primary goal of organic agriculture is to optimize the health and productivity of interdependent communities of soil life, plants, animals, and people (NOSB, 2003). Organic Agriculture also restores ecosystems and delivers ecosystem services (ICCOA, 2013).

Organic management stresses on optimization of resource use and productivity, rather than maximization of productivity and over exploitation of resources at the cost of what is meant for future generations. Organic farming envisages a comprehensive management approach to improve soil health, the ecosystem of the region and the quality of produce. These systems take inherent soil fertility as a key to successful production, by respecting the natural capacity of plants, animals and the landscape; they aim to optimize quality in all aspects of agriculture and environment (Kar, 2013). It is often assumed that organic agriculture is synonymous with sustainable agriculture. However, sustainable agriculture scholar John Ikerd (1993) asserts that sustainable agriculture is a question rather than answer, it is a direction rather than destination, like a star that guides the ships at sea but remains forever beyond the horizon. The question of sustainability can be asked of any ongoing activity or process, including conventional agriculture and any proposed alternative. In other words, sustainable agriculture is a long-term direction not a set of specific farming practices.

B. ORGANIC AMENDMENTS FOR SUSTAINABLE FARMING

Organic manuring play a pivotal role in minimizing the ill effects of intensive agriculture that has resulted in many adverse effect on natural resources *i.e.*, decline in soil health, deficiency of major and micro nutrients and stagnation in yield (Viridi *et al*., 2006). Boosting yield, reducing production cost and improving soil health are three inter-linked components of the sustainability triangle (Singh *et al*., 2008). Organic manures supply a natural process to seasonally strengthen the nutrient pool of soil. It steps-up the power of soil to bind soil moisture and deters insects, weeds without utilizing chemicals. Organic amendments help in enhancing fertility and productivity of soil as a whole.

B.1. Organic manures

Organic manuring of crops with farm yard manure (FYM) and vermicompost is practiced by Asian farmers and regarded as an important source of nutrient for crops (Singh, 1985; Watanabe, 1984). Use of green manure in agriculture was recognized as early as 500 BC in India. Vacchani and Murthy (1964) extensively surveyed about 100 leguminous green manure plants in India and recommended several suitable plants for rice ecosystem. Sunhemp and Dhanicha were more acceptable to farmers in India and widely grown in other countries of tropics. Researchers, while consolidating the research work carried out on biomass production and N accumulation of green manure and grain legumes indicated the biomass production of leguminous green manure ranging from 0.6 t to 37 t ha^{-1} fresh weight while N accumulation varied from 9 kg to 302 kg N ha^{-1}. Organic manures, particularly green manures and FYM, not only supply macronutrients but also meet the requirement of micronutrient besides improving soil health.

B.2. Cosmic formulations

Biodynamic agriculture is a unique organic farming system that utilizes, in addition to the common tools of organic agriculture, specific fermented herbal preparations as compost additives and field sprays (Boggs *et al*., 2000). The basic principle behind biodynamic farming is to conceive the farm as a self contained and self sustained entity. Biodynamic farming emphasizes on the use of nine biodynamic preparations for the purpose of enhancing soil quality and stimulating plant life (Steiner, 1974). They consist of mineral, plant or animal manure extracts usually fermented and applied in small proportions to compost, manures, the soil, or directly onto plants, after dilution and stirring procedure called “Dynamisation”. The preparations were developed to improve soil and crop quality and hasten composting (Koepf *et al*., 1976). The original biodynamic (BD) preparations are numbered from 500-508. These enhance all the bacterial, fungal and mineral processes that are found in the organic farming systems. They are intended to help, moderate and regulate biological processes as well as enhance and strengthen the ethnic forces on Earth (Rath *et al*., 2011).

Agnihotra farming method is a holistic concept of growing plants in a pure and healthy atmosphere. It is based on the ancient Vedic sciences of maintaining the balance of ecological cycles by means of performing *Yajnya*. Two pinch of uncooked, unbroken rice grains smeared with a few drops of cow's ghee are offered in the fire prepared from dried cowdung in a pyramid shaped copper vessel accompanied by chanting of two small Sanskrit mantras exactly at local sunrise and sunset timings. It purifies the atmosphere and, in turn, the purified atmosphere purifies the *prana* i.e. life energy (Das, 2011).

Two other organically produced growth promoters are Amritpani and Bokashi. Amritpani is prepared by using cow dung, cow urine, butter milk, honey and leaves of neem/basil. Bokashi technology or effective microorganisms (EM) technology was developed in

Japan, which is produced by fermentation of organic materials such as rice bran (Mohan, 2008). It contains both decomposed and undecomposed organic matter, microbial biomass, and the intermediate and ultimate substances produced by microbes during fermentation (Yamada *et al.,* 2003).

Pot manure is another fine organic preparation which enhances microbial activity and act as a soil, plant conditioner. It is prepared by adding 5 kg cow dung, 5 litre cow urine, 250 g gur, 1 kg each of *Azadirachta indica*, *Pongamia pinnata* and *Calotropis gigantia* leaves in a pot and allowing that to ferment for 15 days. Then it is diluted and sprinkled over the crop four times at 15 days interval (Bastia *et al.*, 2013; Kar *et al.*, 2013).

Panchagavya is an organic bio-dynamic formulation which, in Sanskrit, means the blend of five products obtained from cow *i.e.* milk, ghee, curd, dung and urine (Mathivann *et al.,* 2006). All these products are individually called as “Gavya” and collectively named as *Panchagavya*. *Panchagavya* has got reference in the scripts of *Vedas* (devine scripts of Indian wisdom) and *Vrikshayurveda* (Natarajan, 2002). In India, use of panchagavya in organic farming is gaining popularity in recent years especially in states like Tamilnadu and Kerala. Papen *et al.* (2002) identified the presence of macro (N, P, K and Ca) and micro (Zn, Fe, Cu, Mn) nutrients besides total reducing sugars (glucose) in *Panchagavya*. Chemolithotrops and autotrophic nitrifiers (ammonifiers and nitrifiers) present in *Panchagavya* which colonize in the leaves increased the ammonia uptake and enhance the total nitrogen supply. Perumal *et al.* (2006) reported presence of growth regulatory substances such as Indole acetic acid (IAA), Gibberrlic acid (GA_3), Cytokinin and essential plant nutrients from panchagavya. Mathivanan *et al.* (2006) revealed that *Panchagavya* at 30 days of age recorded better proposition of chemical and microbial composition favourable for utilization as a growth promoter. Swaminathan *et al.* (2007) reported presence of naturally occurring beneficial microorganisms predominantly lactic acid bacteria, yeast, actinomycetes, photosynthetic bacteria and certain fungi in *Panchagavya*.

B.3. Seaweed extract

Marine bioactive substances extracted from marine algae are used in agricultural and horticultural crops, and many beneficial effects could be achieved in terms of enhancement of yield and quality. Seaweed extracts contain major and micro nutrients, amino acids, vitamins, cytokinins, auxin and abscisic acid like growth promoting substances and have been reported to stimulate the growth and yield of plants, develop tolerance to environmental stress (Zang *et al.*, 2003), increase nutrient uptake from soil (Turan and Kose, 2004) and enhance antioxidant properties (Verkleij, 1992). Being a wealthy source of versatile plant nutrients especially potassium (K), phosphorous (P), calcium (Ca), iron (Fe), manganese (Mg) etc., phytohormones and stimulatory and antibiotic substances, the liquid seaweed extract enhances root volume and proliferation, bio-mass accumulation, plant growth, flowering, distribution of photosynthates from vegetative parts to the developing fruits and promotes fruit development, reduces chlorophyll degradation, disease occurrence etc., resulting in sound plant growth and vigour, ultimately reflecting higher yield and superior quality of agricultural products. Presence of microelements and plant growth regulators, especially cytokinins in *Kappaphycus* and *Gracilaria* extracts is responsible for the increased yield and improved nutrition .

Norwegian seaweed *Ascophyllum nodosum* is rich in cytokinin and auxin precursor, enzymes and hydrolyzed protein and is a storehouse of naturally occurring nutrients (Kumar *et al.*, 2000) that enables the plants to develop biomorphological and physiological behaviour in such a way that they can use the existing as well as applied input (Humphries, 1968). Foliar application of liquids extracted from the brown algae *Turbinaria decurrens* collected from Rameshwaram coast at low concentration enhanced the productivity of greengram (Gurusaravanan *et al.*, 2011). This can be attributed to the presence of some growth promoting substances, like IAA, IBA, Gibberellins (A & B), cytokinins and micronutrient elements, (Fe, Cu, Zn, Co, Mo, Mn, Ni, etc.,) vitamins and amino acids (Chellen and Hemingway, 1964).

C. SOIL ORGANIC MATTER (SOM)

Soil is a living entity: the crucible of life, a seething foundry in which matter and energy are in constant flux and life is continually created and destroyed (Hillel, 1991). The three dimensional and highly dynamic body 'soil' is composed of basically four chief components such as mineral matter, organic matter, air and water. Among these specified four, organic matter component though present in smallest quantity, have the most conspicuous impact. In defiance of its small percentage, it forms the marrow of a healthy, unimpaired and prolific soil profile. Soil organic matter is often viewed as the string that connects the biological, chemical and physical properties of soil. Sustaining soil organic matter (SOM) is of paramount importance in terms of cycling plant nutrients and improving the soil's physical, chemical and biological properties (Kundu *et al.*, 2007).

SOM includes plant and animal materials in various stages of decomposition. Decomposition is a bio-physico-chemical process which leads to physical breakdown and bio-chemical transformation of complex organic molecules of dead materials into simple organic and inorganic substances (Juma, 1998). Decomposition of organic matter is largely a biological process that occurs naturally. Its speed is determined by three major factors: soil organisms, the physical environment and the quality of the organic matter (Brussaard, 1994). Humus, a humified organic substance, comprising humic acid, fulvic acid, hymatomelanic acid and humins etc, is formed by microbial transformation of organic matter (Tan, 1994). All organic materials found in soils irrespective of origin or state of decomposition is defined as soil organic matter. Since SOM consists of C, H, O, N, P and S, it is difficult to actually measure the SOM content and most analytical methods determine the soil organic carbon (SOC) content and estimate SOM through a conversion factor (Baldock and Skjemstad, 1999).

The sources of soil organic matter (SOM) in cropland agriculture mainly come from crop residues (straws, stubble, roots, and rhizodeposition exudates) and organic manures which are applied to soil. Decomposition of SOM depends on internal properties, including the composition of SOM, soil physical, chemical and biological properties, and on external factors, such as management practices and climatic conditions (Bronick and Lal, 2005; Six *et al.*, 2004).

C.1. Functions of SOM and effect on soil properties

SOM has been associated with various soil functions like nutrient recycling, water retention and drainage, erosion control, disease suppression and pollution remediation. Soil fertility, water availability, susceptibility to erosion, soil compaction and even resistance to insects and disease all depend on soil organic matter (Leslie Cooperband, 2002).

SOM stores and supplies plant nutrients, stabilizes and holds soil particles together as aggregates, moderates major changes in the soil pH, improves water holding capacity, reduces bulk density, enhances porosity, helps in better seedbed preparation and root penetration and helps in earlier warming in spring season (Carter and Stewart, 1996 ; Lal, 2002). From long-term agronomic practices it has been observed that SOM, by dint of its greater impact on various biological, physical and chemical properties of soil, can be regarded as an important indicator of soil and agronomic sustainability (Reeves, 1997).

The appropriateness of soil to sustain flora mostly dependant on its physical (porosity, water holding capacity, structure and tilth) and chemical properties (nutrient supply capability, soil content, pH) which are directly linked with SOM (Doran and Safley,1997). Particulate organic matter (POM) can be taken as an indicator of soil health because of its short turn over time (Elliot, 1997). POM is the "organic fertliser property" of SOM (Swift and Woomer, 1993).

If we take the statement of Janzen *et al.* (1992) then it is clear that the relationship between soil quality indicators (e.g. SOC) and soil functions does not always comply to a simple relationship increasing linearly with magnitude of the indicator and that therefore “bigger is not necessarily better". There exists a threshold level of soil organic carbon beyond which soil productivity will not increase and beneficial effect of SOC is diminished. SOM is, however, a key attribute of soil quality (Gregorich *et al.*, 1994). SOM is crucial to soil fertility (Rhoton *et al.*, 1993; Riffaldi *et al.*, 1994) and physical soil quality (Reeves, 1997), and it serves as a nutrient and energy source for a diverse population of bacteria, fungi (Bunemann *et al.*, 2004; Birkhofer *et al.*, 2008) and invertebrates such as earthworms (Hendrix *et al.*, 1992; Leroy 2008).

C.2. Availability of soil organic matter

Soil organic matter tends to increase as the clay content increases. This increase depends on two mechanisms. First, bonds between the surface of clay particles and organic matter retard the decomposition process. Second, soils with higher clay content increase the potential for aggregate formation. Macroaggregates physically protect organic matter molecules from further mineralization caused by microbial attack (Rice, 2002).

Soil organic matter level commonly increase as mean annual precipitation increases. Conditions of elevated level of soil moisture result in greater biomass production, which provides more residues, and thus more potential food for soil biota. Soil biological activity requires air and moisture. Optimal microbial activity occurs at near "field capacity", which is equivalent to 60-percent water-filled pore space (Linn and Doran, 1984). A larger portion of SOM that persists for decades to centuries is critical for long-term ecosystem stability and global carbon cycle (Trumbore, 1997). Physical and chemical protection offered by soil mineral is thought to enhance the longevity of SOM by separating substrates from decomposer organisms and their enzymes and by binding active sites on organic compounds (Baldock and Skjemstad, 2000; Kaiser and Guggenburger, 2007; Mayer, 1994). Anthropological activities can frivol away the soil productivity and lessen dexterity of soil to produce food (McNeill and Winiwater, 2004). According to Ontl and Schulete (2012) depletion of SOM may lead to severe impacts on whole ecosystems as well as the entire earth. The rapidity of SOM decline in tropical soils is worrisome since it is a principal factor in soil quality of the biome (Ramesh, 2010). In Western Europe, the transition towards modern agriculture with adoption of short crop rotations or monoculture, deep tillage operations, and declining use of manure or other organic fertilizers, has resulted in drastic reductions of soil organic matter (SOM) level (Gardi and Sconosciuto, 2007). Restoration of organic matter levels in soil requires a clear know-how about the ecological process important for SOM storage. Proper restoration techniques can help restore terrestrial ecosystem functions.

D. SOIL ORGANIC CARBON

SOM is made of organic compounds that are highly enriched in carbon. Soil organic carbon (SOC) levels are directly related to the amount of organic matter contained in soil and SOC is often used to measure the SOM content. SOC levels result from the interactions of several ecosystem processes, of which photosynthesis, respiration, and decomposition are the keys. SOC input rates are primarily determined by the root biomass of a plant, but also include litter deposited from plant shoots. Soil carbon results both directly from growth and death of plant roots, as well as indirectly from the transfer of carbon-enriched compounds from roots to soil microbes (Ontl and Schulete, 2012). Maintenance of soil organic carbon is essential for long-term sustainable agriculture, since declining levels generally lead to decreased crop productivity (Allison, 1973). SOC is an important index of soil quality because of its relationship to crop productivity (Campbell *et al.*, 1996; Lal *et al.*, 1997).

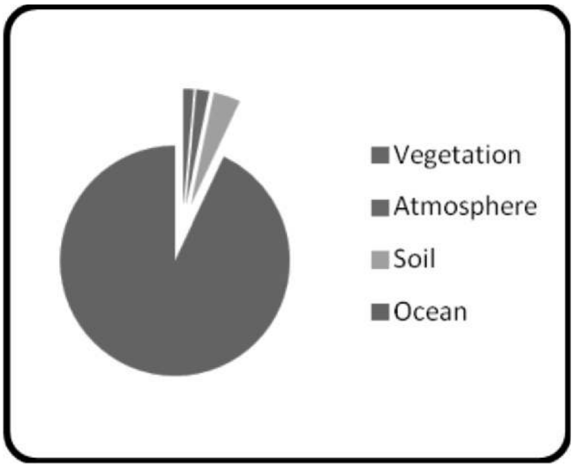

Fig. 1: Carbon pool size of different components ($Pg.year^{-1}$)

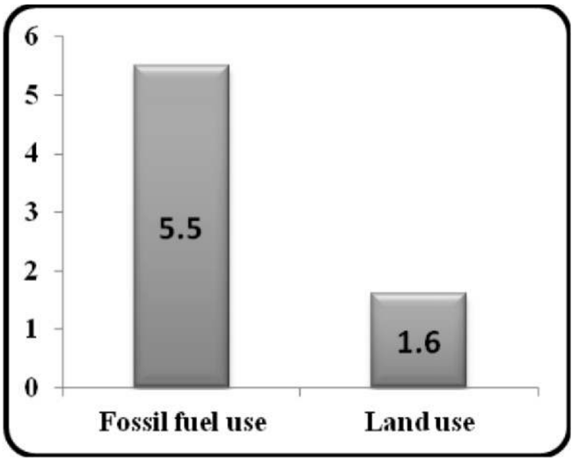

Fig. 2: Carbon changes due to human activities (Castings, 1998)

D.1. Soil carbon pool and its significance

Carbon stored in soils represents the largest terrestrial carbon pool and factors affecting this will be vital in the understanding of future atmospheric CO_2 concentrations in the climate change arena. SOC pool facilitates numerous on-site and off-site functions which accelerate ecosystem services of value to ecological association and community. Depletion of SOC pool is observed to create major adverse economic and ecological consequences. It was rightly observed by Albrecht (1938) that, SOM is one of our most important national resources; it's unwise exploitation has been devastating; and it must be given its proper rank in any conservation policy. The various onsite functions of the SOC pool are development of a congenial soil physical condition, improved water holding capacity, moderation of soil temperature and enhancement of nutrient and water use efficiency etc. The off-site functions of SOC pool bearing economic and ecological significance include: auto-remediation against agricultural chemical pollution, controlling GHG emission, recharging ground water, increasing fresh water storage and reducing sediment load in streams and rivers. SOC is simultaneously a source and sink for nutrients and plays a vital role in soil fertility maintenance. Optimum management of the soil resource for provision of goods and services requires good management of organic resources, mineral inputs and the SOC pool (Vanlauwe, 2004).

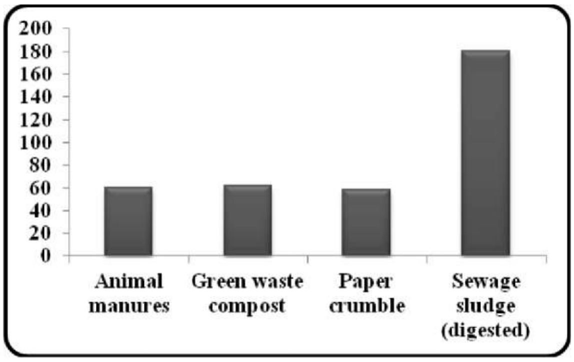

Fig. 3: Estimates of SOC accumulation (kg C ha^{-1} yr^{-1} t^{-1} dry solids applied) from a range of sources of organic carbon (Bhogal et al., 2008)

D.2. Factors interacting with SOC

The actual amount of SOC that can be stored is dependent on the farming system (management practices), soil type and climatic conditions, as well as the initial soil carbon level of the site. Feng and Li (2001), observed that during fallow, the rate of soil organic carbon decomposition was approximately 2 to 2.5 times faster than in a cropped year. In distinction to findings of Post *et al.* (1982) it is established that SOC is positively correlated with precipitation, and negatively with temperature at any particular amount of precipitation. So it seems likely that SOC will decrease with increasing temperature.

The net change in SOC depends not only on the current management practices but also on the management history of the soil. Long-term experiments are the primary source of information to determine the effect of cropping systems, continuous cropping, and retention of residues in soils and fertilizer/manure addition on changes in SOC (Leigh and Johnston, 1994). Some experiment reported declining rice and wheat yields due to gradual decline in the supply of soil nutrients and SOC (Cassman *et al.*, 1995; Yadav et al., 1998, 2000; Duxbury et al., 2000), while others have reported increase in SOC due to addition of organic sources of nutrients along with high inputs of NPK fertilizers (Gami *et al.*, 2001; Bhandari *et al.*, 2002).

Carbon change due to use of fossil fuel and land use, have been estimated at 5.5 and 1.6 Pg/year, respectively, while the rate of carbon change in the atmosphere at 3.3 Pg /year (Castings,1998). Howards and Howards (1990) reported 2% level of SOC (3.4% SOM) as the threshold level for most soils and below this level they observed destabilization of soil structure and aggregation and decreased crop yield. Kay and Angers (1999) and Greenland *et al.* (1975) also found out similar type of pertinence amidst SOC and soil aggregation. Greenland *et al.* (1975) & Kemper and Koch (1966) reported that soil aggregates were less stable at SOC < 2%, moderately stable at 2-2.5% and highly stable at > 2.5%. While Dick and Gregorich (2004), Rasmussen *et al.* (1980) and Bhogal *et al.* (2006 and 2007) reported linear relationship between SOC and amount of SOC applied to soil, Johnston *et al.* (1989) observed dependence of SOC accumulation on source of organic carbon. They observed slower rate of SOC accumulation with application of farm yard manure (FYM).

E. SOIL CARBON SEQUESTRATION

Soil carbon sequestration is a process in which CO$_2$ is removed from the atmosphere and stored in the soil carbon pool. Lal (2004) defines soil carbon sequestration as the process of removal of atmospheric CO$_2$ by plants and storage of fixed carbon as soil organic matter. The strategy is to increase SOC density in the soil, improve depth distribution of SOC and stabilize SOC by encapsulating it within stable micro-aggregates so that carbon is protected from microbial processes or as recalcitrant carbon with long turnover time. According to Hutchinson *et al.*, 2007 carbon sequestration can be defined as persistent increase in carbon storage (in soil or plant material or in the sea). Some carbon date is modern while other components date is greater than 1000 years (Campbell, 1967).

E.1. Rate of carbon sequestration and storage

Schlensinger (1990) documented long-term rates of soil organic carbon storage from 0.2 g C m^{-2} y^{-1} in some polar deserts to greater than 10 g C m^{-2} y^{-1} in some forest ecosystems, with an average rate of 2.4 C m^{-2} y^{-1} over all ecosystems. The amount of organic carbon stored in soil results from the net balance between the rate of soil organic carbon inputs and rate of mineralization in each of the organic carbon pools (Post and Kwon, 2006). Since the industrial revolution, conversion of natural ecosystems to agricultural use has resulted in the depletion of SOC levels, releasing 50 to 100 Pg of carbon from soil into the atmosphere (Lal, 2008). This is the combined result of reductions in the amount of plant roots and residues returned to the soil, increased decomposition from soil tillage, and increased soil erosion (Lemus and Lal, 2005). Depletion of SOC stocks has created a soil carbon deficit that represents an opportunity to store carbon in soil through a variety of land management approaches.

The world's estimated soil carbon content (1500 Pg) though roughly double the amount of carbon in the atmosphere (Schlesinger, 2000), is quite meager in comparison to the carbon content of the oceans (38,000 Pg) but it draws attention because of its' potential response to natural and anthropological modifications. Emphasizing the contribution of soils in increasing atmospheric CO_2, Kucharik *et al.* (2001) reported from United States that many soils have lost 30-50 % of the carbon that they contained prior to cultivation. Paustian *et al.* (2000) estimated that crop-based agriculture occupying 1.7 billion hectares, globally, have soil carbon stock of approximately 170 Pg. While oxidation of soil organic matter in cultivated soils has contributed approximately 50 Pg carbon to the atmosphere, the capacity of carbon sequestration in agricultural soils globally can be in the order of 20-30 Pg carbon over the next 50-100 years (Paustian, 1997). Generally agricultural emissions are produced from machinery used for cultivating the land, production and application of fertilizers, pesticides and the oxidation of SOC following soil disturbance (West and Marland, 2002). Returning the lost soil carbon via increasing carbon storage in soils is a clear sequestration possibility. The potential for carbon sequestration in cropland of India has been estimated to be the order of 0.039-0.049 Pg carbon y^{-1} or about 47% of current annual fossil fuel emission (Lal *et al.*, 1998).

The atmospheric CO_2 concentration is increasing, primarily due to fossil-fuel combustion and deforestation. Sequestering atmospheric carbon in agricultural soils is being advocated as a possibility to partially offset fossil-fuel emissions. Sequestering carbon in agriculture requires a change in management practices, i.e. efficient use of pesticides, irrigation, and farm machinery. Although emphasis is focused on decreasing the rate of CO_2 emissions from fossil-fuel use, there is increasing recognition that the rate of emissions can be mitigated by transferring CO_2 from the atmosphere to the terrestrial biosphere.

F. CARBON SEQUESTRATION IN AGRICULTURE

Agriculture is defined as an anthropogenic manipulation of carbon through uptake, fixation, emission and transfer of Carbon among different pools. Thus land use change, along with adoption of recommended management practices can be important instrument of SOC sequestration (Post and Kwon, 2006). In arid and semi-arid climates, soil carbon sequestration can also occur from the conversion of CO_2 from air into inorganic forms such as secondary carbonates; although, the rate of inorganic carbon formation is comparatively low (Lal, 2008).

Converting agricultural land to a more natural or restorative land use essentially reverses some of the effects responsible for SOC losses that occurred upon conversion of natural to managed ecosystems. Applying ecological concepts to the management of natural resources (e.g., nutrient cycling, energy budget, soil engineering by microorganisms and enhance soil biodiversity) may be an important factor for improving soil quality and SOC sequestration (Lavelle, 2000). Recommended management practices build up SOC by increasing carbon input to soil through crop residues and biosolids.(Paustian *et al.*,1997).

Sequestered SOC with a relatively long turn-over time (Swift, 2001), is attributed to the recalcitrant soil pool, thus decreasing the rate of accumulation of atmospheric CO_2 concentration. Generally SOC concentration in the surface layer is directly proportional with increase inputs of biosolids (Graham *et al.*, 2002) although the specific empirical relation depends on soil moisture and temperature regimes, nutrient availability, texture and climate. A healthy soil is rich with life and comprises diverse soil biota including representatives of all groups of micro-organisms like fungi, green algae and cyanobacteria along with a few exclusively marine phyla of animals (Lee, 1991). As regards SOC pool and its dynamics, important members of soil biota include earthworms, termites, ants, some insect larvae and few others of the large soil animals that comprise “bio-turbation” (Lavelle, 1997).

Compared to the use of same amount of nutrients through inorganic fertilizers, application of organic manures and compost result in higher SOC pool (Gregorich *et al*., 2001). Sommerfeldt *et al*. (1988); Gilley and Risse (2000) concluded that long-term organic manuring adds to SOC pool and may also enhance soil aggregation. Compton and Boone (2000) emphasized that the above beneficial effect may persist for a long time span. Hao *et al*. (2002) observed that in soil amended with sufficient organic manure the potential of conservation tillage to sequester SOC is high. Judicious application of irrigation water in a drought prone soil can enhance biomass production, increase the amount of above-ground and the root biomass returned to the soil and improve SOC concentration. In addition, enhancing irrigation efficiency can also decrease the hidden carbon costs (Sauerbeck, 2001). Restoring degraded soils and ecosystems has a high potential for sequestrating soil C (Lal, 2004).

Rice soil reports more sequestration and more accumulation of SOC than others as soils being under an unique aquic moisture regime for 3-4 months and high biomass production in rice (Jenkinson, 1998). Due to lack of oxygen in submerged condition rate of decomposition is slower. There is a preferential accumulation of organic matter in submerged rice soils as compared to aerobic soils due to incomplete decomposition of organic materials and decreased humification (Witt *et al*., 2000). The quantity of SOC that will be stored in an ecosystem depends on quantity and quality of organic matter returned to the soil matrix, ability of soil to retain organic carbon and abiotic influences of both temperature and precipitation (Grace *et al*., 2006). Generally, a high carbon input leads to high carbon sequestration in soil. However, the relationship between the carbon sequestration and the Carbon input was reported to be linear (Ghosh *et al*., 2012; Kong *et al*., 2005; Li *et al*., 2010; Majumder *et al*., 2008), whereas other researchers found a logarithmic correlation (Cai and Qin, 2006; Fan *et al*., 2005; Pan *et al*., 2006; West and Six, 2007) based on long-term agro-ecosystem experiments. The different relations demonstrate the differences in carbon sequestration efficiency and carbon saturation limit. The linear relation indicates that the soil has constant carbon sequestration efficiency and no carbon saturation level. In contrast, the logarithmic relation emphasizes a decrease of carbon sequestration efficiency when the SOC approaches the saturation level (Six *et al*., 2002).

F.1. Agricultural practices influencing SOC sequestration

Conventional tillage and erosion deplete SOC pools in agricultural soils. Thus, soils can store carbon upon conversion from plough till to no till or conservation tillage, by reducing soil disturbance, decreasing the fallow period and incorporation of crops in the rotation cycle (Lal, 2004). Smith *et al*. (1998) estimated that adoption of conservation tillage has the potential to sequester about 0.023 Pg carbon /year in the European Union. Smith *et al*. (1998) calculated that 100% conversion to no till agriculture could mitigate all fossil fuel carbon emission from agriculture in Europe. We can enhance biodiversity, the quality of residue input and SOC pool by growing leguminous cover crops (Singh *et al*., 1998; Fullen and Auerswald, 1998; Uhlen and Tveitnes, 1995). The beneficial effect of growing cover crops on enhancing SOC pool has been reported from Hungary by Berzseny and Gyrffy (1997), U.K. by Fullen and Auerswald (1998) and Johnston (1973), Sweden by Nilsson (1986), Netherlands by Van Dijk (1982) and Europe by Smith *et al*. (1997). These reports demonstrated that ecosystems with teeming biodiversity absorb and sequester more carbon than those with low or reduced biodiversity.

Converting degraded soils under agriculture and other land uses into forests and perennial land use can enhance the SOC pool. The magnitude and rate of SOC sequestration with afforestation depends on climate, soil type, species and nutrient management (Lal, 2001). An increase in chemically recalcitrant humic compounds enhances the relative proportion of passive fraction of SOC. A high clay content and relatively higher proportion of high activity clays (HACs) enhance the retention of recalcitrant SOC fraction (Lal, 2004). While assessing the net SOC sequestration by land use change and adoption of soil/crop management practices, it is important to consider the hidden carbon costs of input (e.g., fertilizer, herbicides, tillage, irrigation) (West and Marland, 2002). However, because the farmlands are intensively managed, there exists possibility to make the farmlands absorb more gases than they emit. In this case, the land acts as a sink or storehouse of carbon. But, it is observed that soil carbon varies in its degree of permanence or in its residence time. That is why some workers argue that only very recalcitrant carbon should be regarded as sequestered carbon. Thus, in case of agricultural interventions, it is to be assumed that if a management promoting sequestration is adopted, sequestration will continue until some steady-state asymptote is achieved, as long as the management is not changed and weather conditions remain comparative year after year.

The objective of increasing SOC density, distribution of SOC in the subsoil can be achieved through integrated nutrient management, mulch farming, conservation tillage and diverse crop rotations based on legumes and cover crops in the rotation cycle (Lal, 1997). Intensification of agriculture and recycling of crop residues can also enhance SOC density by rapid sequestration (Lal, 2004). Higher crop productivity under intensive agriculture increases plant residue input into the soils and thus has the potential of increasing SOC level (Franzluebbers, 2005). Land-based soil carbon sequestration has been widely suggested as a potentially cost-competitive means for reducing net greenhouse gas (GHG) emissions as well as a way to increase opportunities for farmers and foresters (Dixon *et al*., 1993; Sampson and Sedjo, 1997; Marland and Schlamadinger, 1999).

F.2. Rhizosphere management in soil carbon sequestration

Rhiozosphere is the soil surrounding the roots with a different physical, chemical and biological environment from the bulk soil. The root-soil interface is called the rhizosplane. The study of rhizosphere essentially encompasses the soil, the root and their intimate interaction, mostly as regards to the inhabiting microorganisms. Soil texture, structure, pore space, water holding capacity, nutrient status and above all, soil organic carbon are highly instrumental in the activity around rhizosphere. Similarly, root hair, root architecture and rhizo-deposition govern the microbial activity and hence mineralization and uptake of nutrient by plants. Rhizospheric microorganisms play a pivotal role in future augmentation of production and productivity. This is highly just to employ concerted effort to exploit the benefit of microbes for sustainable agriculture for the time to come, and this is rightly termed as 'the century of microbes'. Soil organic matter plays a key role to achieve the desired goal of soil-plant-microbe consortium. Hence, management of rhizosphere with organic options remains the most cogent avenue for future scientific approach in crop production.

As much as 30-50% of the carbon fixed in photosynthesis is initially translocated below-ground (Buyanovsky and Wagner, 1997). Same is used for structural growth of the root system and for autotrophic respiration, and same is lost to the surrounding soil in organic form and rhizodeposition, either being sloughed during root expansion or excreted in a variety of compounds. Swinnen *et al.* (1995) found that rhizodeposition by wheat and barley accounted for up to 15% of net carbon assimilation during the growing season. These organic carbon exudates may play an important nutritional role, stimulating microbial activity (Sanchez *et al*., 2002). Evidence also indicates that below-ground part carbon is the major source for subsequent conversion into more stable forms of SOC. Using stable isotope fractionation, Wilts *et al*. (2004) estimated that the ratio of SOC derived from below-ground part carbon to that derived from above-ground stover was nearly 2:1 in long-term maize plots, further emphasizing the importance of root system and root zone in carbon sequestration.

Human civilization has progressed parallelly and perpetually in consonance with the hustling and mutating time. In the process, mankind has rocketed CO_2 emission and has galvanized global climate change. However, concerns and cognizance about this conflagrant topic is now leading to concerted efforts to find ways and means to reduce it. Permanently sequestering or storing carbon in the soil is the best doable and candid choice that shows assurance and affirmation. Soil carbon sequestration can limit CO_2 emanation to a large extent and for sequestering soil carbon, organic agriculture is the most cogent and assured option, which has promise and potential to remove vast amount of atmospheric CO_2 and to store it in the soil carbon pool.

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