

Carbon Sequestration: The Great Opportunity of Challenging Task in Soil

**B. Sri Sai Siddartha Naik^{1*}, Gorantla Prathap Reddy², Sharvan Kumar Yadav³, S.K Sharma⁴,
Roshan Choudhary⁵ and Piyush Choudhary⁶**

¹Department of Agronomy, Research Scholar in Ph.D. (Ag) Agronomy, MPUAT, RCA,
Udaipur, Rajasthan, India

²Director Research, MPUAT, Udaipur

³Department of Agronomy, Research scholar in Ph.D. (Ag) Agronomy,
Institute of Agricultural Sciences, Banaras Hindu University-221005, U.P., India

⁴SRF in ICAR, RCA, MPUAT, Udaipur

⁵Assistant Professor in Agronomy, RCA, MPUAT, Udaipur

⁶Ph.D. Research Scholar, Department of Agronomy, Rajasthan College of Agriculture, MPUAT, Udaipur

*Corresponding Author E-mail: siddunaik08@gmail.com

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ABSTRACT

Recently, the contributions of the soil in various ecosystems have become more prominent with the recognition of its role as a carbon sink and the potential of that in reducing the concentration of carbon dioxide (CO₂), which is a vital greenhouse gas, from the atmosphere. Conversely, the soil capacity to increase the concentration of CO₂ in the atmosphere through mineralization of organic matter is also a source of concern. Mineralization of only 10% of the soil organic carbon pool globally is believed to be equivalent to about 30 years of anthropogenic emissions. This underscores the need to preventing carbon loss (emission) from the soil resource. Globally, the soil contains a large carbon pool estimated at approximately 1500Gt of organic carbon in the first one meter of the soil profile. This is much higher than the 560 Gt of carbon (C) found in the biotic pool and twice more than atmospheric CO₂. By holding this huge carbon stock, the soil is preventing carbon dioxide build up in the atmosphere which will confound the problem of climate change. There are a lot of strategies used in sequestering carbon in different soils, however, many challenges are being encountered in making them cost effective and widely acceptable.

Keywords: Atmosphere, Carbon, Mineralization, Emission

INTRODUCTION

The role of soil the ecosystem is increasingly being recognized with the realization that it has the capacity of reducing the concentration of carbon dioxide (CO₂) in the atmosphere (through sequestration of organic carbon in the soil) and also by releasing this CO₂ back into

the atmosphere (through mineralization of soil organic matter). It has been reported that mineralization of only 10% of the soil organic carbon pool globally can be equivalent to about 30 years of anthropogenic emissions (Kirschbaum MUF, 2000).

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This underscores the need to preventing carbon loss (emission) from the soil resource. Globally, the soil contains a large carbon pool estimated at approximately 1500 Gt of organic carbon in the first 1 m of the soil profile (Jobbagy & Jackson, 2000, & Stockmann et al., 2013). This is much higher than the 560 Gt of carbon (C) found in the biotic pool (Lal, 2008) and twice more than atmospheric CO₂ (IPCC, 2013). holding this huge carbon stock, the soil is preventing carbon dioxide build up in the atmosphere which will compound the problem of climate change. There is huge opportunity of sequestering atmospheric carbon in the soil for a long period of time because already 24% of global soils and 50% of agricultural soils are degraded globally (Batjes, 2013). Because most of agricultural soils are already degraded, they are estimated to have the potential of sequestering up to 1.2 billion tonnes of carbon per year (IPCC, 2014). Carbon sequestration in soils can be a short term solution of reducing CO₂ concentration in the atmosphere until when more effective strategies are found (Stockmann, et al., 2013). Despite the huge carbon deposit in soil ecosystem globally, research efforts in sequestration has been primarily focused on geological and vegetation carbon capture and storage while giving less attention on the role of soil as a viable carbon sink (Kane, 2015). This chapter will trace the origin of carbon sequestration idea as a potential climate mitigation measure as well as review the conceptual basis and mechanism of carbon capture and sequestration in soils. The benefits and challenges facing carbon sequestration in soils are also discussed extensively. Finally, some proven management practices and strategies used in enhancing the soil carbon stock under forest and agricultural ecosystems are outlined. The chapter concludes by emphasizing the need for the scientific community to resolve most the challenges making widespread adoption of this initiative difficult.

In agricultural soils, C sequestration means the increase of soil C storage. Main agronomic and related practices that can be helpful in SOC sequestration include:

- adoption of no-tillage (NT) or minimum tillage;
- adoption of environmental and soil health friendly farming systems;
- incorporation of cover crops;
- use of mulch either in the form of crop residues or synthetic materials;
- minimization of soil and water losses by surface runoff and erosion;
- adoption of integrated nutrient management practices for the increase of soil fertility;
- use of organic amendments; and
- promotion of farm forestry.

Benefits of soil carbon sequestration include the following:

- It can be helpful in the reduction of CO₂ emissions.
- It can reduce the emissions of different GHGs.
- It can be helpful in the reduction of atmospheric temperatures.
- It helps in maintaining suitable biotic habitat.
- It decreases nutrients losses.
- It can improve soil health and productivity.
- It can increase water conservation.
- It can promote and sustain root growth.
- It can reduce soil erosion.

Agriculture sector can be supportive in the lessening of emissions of GHGs, and if suitable agronomic practices are to be adopted, then agricultural soils have the potential to act as a sink for CO₂ sequestration. Healthy soils can be supportive in combating the climate change because soils having high organic matter can have higher CO₂ sequestration potential.

2. Genesis of the carbon sequestration idea in terrestrial systems

The idea that the concentration of CO₂ in the atmosphere can be minimized by sequestering it in terrestrial ecosystems, including the soil was first proposed by Dyson in 1977 (Dyson, 1977). He realized that the danger of rising CO₂ concentration in the atmosphere outweighs the benefits and that increased CO₂ into the atmosphere is inevitable in the light of continued dependence on fossil fuels. Therefore, a strategy was needed for reducing CO₂ emission without ‘drastic shutdown of

industrial civilization'. He proposed that the excess CO₂ could be absorbed by trees in a large scale plantation as a potential strategy for halting the continuous CO₂ build up in the atmosphere. This is in light of evidence that the photosynthetic turnover is 20 times larger than the annual increase in atmospheric CO₂ (Dyson, 1977). He therefore concluded that by planting of fast growing trees on a massive scale on marginal land or growing and harvesting swamp-plants and converting them into humus or peat the concentration of CO₂ in the atmosphere could be minimized. This could be a short gap measure to hold the atmospheric CO₂ level down until alternatives to fossil fuels are found. Much later in 1989, Sedjo and Solomon also wondered whether CO₂ can be offset by increasing the size of forest areas globally (Sedjo & Soloman, 1989).

3. Evidence that carbon is sequestered in the soil and terrestrial ecosystems

The soil is reputed to contain the largest terrestrial carbon pool estimated at approximately 2344 Gt (1 gigaton = 1 billion tonnes) of organic carbon in the first 3 m, 1500 Gt in the first 1 m and 615 Gt stored in the top 20 cm of the soil profile (Jobbagy & Jackson, 2000, & Stockmann et al., 2013). By holding this huge carbon stock, the soil is preventing or delaying carbon dioxide build up in the atmosphere which will compound the problem of climate change. Considering the fact that only 9 Gt of C is added to the atmosphere yearly through anthropogenic activities from fossil fuels and ecosystem degradation (Stockmann et al., 2013), the soil can be counted on as an effective carbon sink that renders vital climate regulation services. Conversely, the soil also emits CO₂ back to the atmosphere due to SOM decomposition estimated at 150 Gt which leaves a vacuum that could be filled if the lost C can be recaptured back and stored in the soil (Sanderman, 2010). The amount of carbon emitted annually into the atmosphere is estimated at 8.7 Gt C while only 3.8 Gt/year is found in the atmosphere at a given time (Stockmann et al., 2013). This leaves an unaccounted balance of 4.9 Gt C/year that is

believed to have been sequestered on terrestrial systems (oceans, forests, soils, etc.). The realization that the terrestrial systems (including soil) have the capacity to sequester this difference (4.9 Gt C/year) has generated interest in the potential of these systems to sequester and store carbon in long-lived pools thereby preventing its accumulation in the atmosphere (Guo, & Gifford, 2002, Stockmann et al., 2013, Lal, 2004, Post & Kwon, 2000, & Smith, 2008). Just like the way the soil sequesters and stores, organic carbon, thereby reducing the amount in the atmosphere, it can equally release carbon (through CO₂) into the atmosphere and raise the concentration of carbon dioxide (Sanderman, 2010). Over the last few decades, the soil has lost considerable quantity of carbon as a result of anthropogenic activities such as deforestation and agricultural activities. Managed ecosystems such as agriculture are believed to have already lost 30–55% of their original soil organic carbon stock since conversion (Batjes, 2013). The lost productivity of agricultural and degraded lands together offers an opportunity for recovering 50–60% of the original carbon content through adoption of carbon sequestration strategies (Lal, 2004). This situation creates an opportunity for the replenishment of the lost carbon stock through adoption of deliberate strategies and policies of carbon sequestration. This may likely reduce the amount of CO₂ in the atmosphere.

Mechanisms of carbon capture and sequestration

Soil carbon is originally derived from the CO₂ assimilated by plants through photosynthesis and converted to simple sugars and eventually returned to the soil as soil organic matter. Photosynthesis is the process where plants produces organic compounds such as carbohydrate by using solar energy to convert CO₂ and water into organic compounds such as carbohydrates. These organic compounds are then used in making the plants structural components (also known as biomass) and generating the energy needed for metabolic activities. The maximum amount of carbon

that can be produced, otherwise known as gross primary productivity (GPP), depends on the plant's ability to produce these compounds through photosynthesis. The biomass produced through photosynthesis is utilized by the plants themselves in generating the energy needed for metabolic activities in a process called respiration. The difference between the GPP and respiration is called the net primary productivity (NPP). NPP is generally believed to be 45% of the GPP (Gifford, 2003). NPP is determined by the portion of solar radiation captured by the plants and used for the photosynthesis (also known as photosynthetically active radiation (PAR), the leaf area index, the light use efficiency (the ratio of primary productivity to absorbed PAR) of the vegetation and autotrophic respiration (Sanderman et al., 2010). The higher the NPP the more carbon is transferred to stable pools in the soils (Sitch et al., 2008).

4. Carbon sequestration

Carbon sequestration is the process of transferring carbon dioxide (CO₂) from the atmosphere into stable terrestrial carbon (C) pools. The process can be driven naturally or anthropogenically. The anthropogenically driven sequestration ensures that there is no net gain in the atmospheric C pool because the CO₂ sequestered comes from the atmosphere. There are basically two types of sequestration: abiotic and biotic. The abiotic techniques involve injection of CO₂ into deep oceans, geological strata, old coal mines and oil wells. The biotic component on the other hand, involves managing higher plants and micro-organisms to remove more CO₂ from the atmosphere and fixing this C in stable soil pools. Biotic sequestration is further subdivided into oceanic and terrestrial sequestration. Oceanic sequestration involves C capture by photosynthetic activities of organisms such as phytoplankton, which converts the C into particulate organic material and deposits such on the ocean floor. This type of sequestration is reported to fix about 45 Pg C/year (Falkowski et al., 2000). Terrestrial sequestration involves the transfer of CO₂ from the atmosphere into the biotic and

pedologic C pools. This is accomplished by the transfer or sequestration of CO₂ through photosynthesis and storage in live and dead organic matter. The major terrestrial C sinks include: forests, soils and wetlands.

Benefits of carbon sequestration in soils:

Soils are the largest carbon reservoir of the terrestrial carbon cycle. It stores large amount of soil organic carbon (SOC), which is originated from plants and animal tissue that exist at different stages of decomposition. According to Batjes and Sombroek (1997), soils contained 1550 Pg of organic C upto 1 m depth, 2500 Pg of organic C upto 2 m and 750 Pg of inorganic carbon at 1 m depth. This total soil C pool of 2300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg. Carbon storage in soils is the balance between the input of dead plant material (leaf and root litter) and losses from decomposition and mineralization processes (heterotrophic respiration). Carbon is sequestered in soils in direct and indirect ways (Soil Science Society of America, 2001). Direct soil C sequestration occurs by inorganic chemical reactions that convert CO₂ into soil inorganic C compounds such as calcium and magnesium carbonates. Indirect plant C sequestration occurs as plants photosynthesize atmospheric CO₂ into plant biomass. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. Removing CO₂ from the atmosphere is only one significant benefit of enhanced carbon storage in soils.

The benefits of atmospheric carbon sequestration into SOM are as follows:

- i. Improved soil quality through enhanced fertility, soil structure and aggregate stability
- ii. Increased water holding capacity
- iii. Decreased nutrient loss
- iv. Reduced soil erosion
- v. Increased capacity to reduce the toxic elements from the soil
- vi. Increased crop production

The researchers explored the impact of raised atmospheric CO₂ levels on carbon sequestration by soil microbes. When soils were rich in nitrogen, microbes processed

more carbon, leading to a greater release of CO₂ into the atmosphere. This release of CO₂ was also affected by the species and season. In unfertilized soil where nitrogen was limited, microbes living beneath trees in a raised CO₂ atmosphere sequestered more carbon. The application of nitrogen based fertilizers, sometimes used to stimulate growth of young trees, will lead to greater CO₂ loss from soils (Lagomarsino, 2007).

4.1. Carbon stock in agricultural soils

According to the IPCC agricultural soils have the potential of sequestering up to 1.2 billion tonnes of carbon per year. However, it has been estimated that already about 50% of agricultural soils have been degraded globally, a situation that creates an opportunity for sequestering atmospheric carbon in the soil for a long period of time (IPCC, 2014). The potential of sequestering carbon in agricultural land is huge as over one third of the world's arable land is in agriculture (World Bank, 2015). Agricultural land could sequester at least 10% of the current annual emissions of 8–10 Gt/year (Hansen et al., 2013).

4.2. Carbon sequestration in soil ecosystem

Soil carbon sequestration is defined by Olson et al. (Olsen, 2014) as: the process of transferring carbon dioxide from the atmosphere into the soil of a land unit through plants, plant residues, and other organic solids, which are stored or retained in the unit as part of the soil organic matter (humus) (Olsen, 2014).

According to the Soil Science Society of America, it is the storage of carbon in a stable solid form in the soil as a result of direct and indirect fixation of atmospheric CO₂ (Burras et al., 2001). The direct fixation involves natural conversion of CO₂ into soil inorganic compounds such as calcium and magnesium carbonates while the indirect sequestration takes place when plants produce biomass through the process of photosynthesis. This biomass is eventually transferred into the soil and indirectly sequestered as soil organic carbon after decomposition. Subsequently, some of this plant biomass is indirectly sequestered as soil organic carbon (SOC)

during decomposition processes. The amount of carbon sequestered in the soil reflects the long term balance between carbon uptake and release mechanisms. Many agronomic, forestry and conservation practices, including best management practices lead to a beneficial net gain in carbon fixation in soil. The carbon sequestered under direct fixation is also referred to as soil inorganic carbon (SIC) while C fixed indirectly is called soil organic carbon (SOC) (Lal, 2008). Carbon can also be sequestered in soil through the accumulation of humus onto the surface layers (usually 0.5–1 m depth) of soil or anthropogenically through land use change or adoption of right management practices (RMPs) in agricultural, pastoral or forest ecosystems (Lal, 2008). Soils in managed ecosystems tend to have a lower SOC pool than those in natural ecosystems due to oxidation or mineralization, leaching and erosion (Lal, 2008). Globally, soils are reported to have the capacity of sequestering 0.4–0.8 Pg (IPCC, 2001). The sequestration of carbon in soils depends on a number of factors depending on whether it is abiotic or biotic. Abiotic soil C sequestration depends on clay content, mineralogy, structural stability, landscape position, soil moisture and temperature regimes (Jimenez et al., 2007). Biotic soil C sequestration on the other hand depends on management practice, climate and activities of soil organisms (Lal et al., 2007 & Abdullahi et al., 2014).

4.3. Carbon stock in forest soils

Carbon is stored in forest ecosystems mainly in biomass and soil and to a lesser extent in coarse woody debris (Ngo et al., 2013). The carbon stock in forest soils play a large role in global carbon cycle due to the large expanse of forest ecosystems estimated at 4.1 billion hectares globally (Dixon & Wisniewski, 1995). It has been estimated that, globally, the forest ecosystem contains about 1240 Pg C (Dixon et al., 1994). Out of this amount, the plants (vegetation) contain about 536 Pg C while the soil is believed to contain up to 704 Pg C. This is a very significant amount. The forest ecosystems contain more than 70% of global soil organic carbon (SOC) and forest

soils are believed to hold about 43% of the carbon in the forest ecosystem to 1 m depth (Jobbagy & Jackson, 2000). However, unfortunately this high carbon content inherent in natural forest soils is easily depleted by decrease in the amount of biomass (above and below ground) returned to the soil, changes in soil moisture and temperature regimes and degree of decomposability of soil organic matter (due to difference in C:N ratio and lignin content) (Post & Kwon, 2000). Anthropogenic activities such as conversion of forests to agricultural land also deplete the soil organic carbon (SOC) stock by 20–25% (Lal, 2005). Deforestation is reported to emit about 1.6–1.7 Pg C/year (about 20% of anthropogenic emission (Watson et al., 2000).

5. The role of soil carbon in different ecosystems

The carbon in soil plays significant roles in different ecosystems. Some of these include:

5.1. Sustainable land management

Apart from reducing the concentration of greenhouse gases (GHGs) in the atmosphere, soil carbon sequestration also complements efforts geared at improving land (forest or agricultural land) productivity. This is because all strategies that sequester carbon in soil also improve soil quality and land productivity by increasing the organic matter content of the soil. Organic matter improves soil's structural stability, water-holding capacity, nutrients availability and provide favorable environment for soil organisms (Lal, 2004). Carbon sequestration activities offer an opportunity for regaining lost productivity especially under agricultural systems. It has been reported that managed ecosystems such as agriculture have lost 30–55% of their original soil organic carbon stock since conversion (Batjes, 2013). The lost productivity of agricultural and degraded lands together offers an opportunity for recovering 50–60% of the original carbon content through adoption of carbon sequestration strategies (Lal, 2004).

5.2. Carbon inventories

The obligation on countries, that are parties to the UNFCCC, to deposit their independent nationally determined contributions (INDCs)

requires a comprehensive estimation and valuation all carbon sink and sources in the terrestrial and other sectors. These estimation and valuation of carbon in the LULUCF sector will be incomplete if the contribution of soil carbon is excluded due to its large percentage (36–46%). Carbon inventory is a process of estimating changes in the stocks (emission and removals) of carbon in soil and biomass periodically for various reasons (Pacala & Socolow, 2004).

5.3. Mitigation of climate change

The continuous increase in the concentration of carbon dioxide (CO₂) and other GHGs in the atmosphere largely due to anthropogenic sources is believed to be responsible for climatic changes and related consequences being experienced across the globe (IPCC, 2001 & Jimenez et al., 2007). This situation has generated interest in developing strategies for reducing GHGs build up in the atmosphere. Out of the approximately 8.7 Gt C/year being emitted into the atmosphere, from anthropogenic sources, only 3.8 Gt C/year remains (Lal, 2008 & Denman et al., 2007). The unaccounted difference of 4.9 Gt C/year is believed to be sequestered in terrestrial (oceans, forests, soils, etc.) bodies which is referred to as the 'missing sink' (Hansen et al., 2013 & Denman et al., 2007). This realization has generated interest on the potential of terrestrial sector (including soil) to sequester carbon in long-lived pools thereby reducing the amount that is present in the atmosphere (Guo & Gifford, 2002).

5.4. Ancillary benefits

Apart from climate change mitigation and improving forest land productivity, carbon sequestration in soils (of different ecosystems) also have several ancillary benefits. Some of these include: improvement in water holding capacity and infiltration, provision of substrate for soil organisms, serving as a source and reservoir of important plant nutrients, improvement of soil structural stability among others (Post & Kwon, 2000). According to (Fung, 2000) the environmental benefits associated with soil carbon sequestration is 40–70% higher than the productivity benefits.

Based on these reasons, therefore, any policy, strategy or practice that increase soil carbon sequestration also generates these benefits.

6. Challenges of carbon sequestration in soils

Although there are a lot of opportunities in leveraging carbon stock and sequestration potential in the soil of different ecosystems, there are numerous challenges making this difficult in reality.

Some of these challenges include:

a. Carbon pools: sequestered carbon exists in the soil in different pools with varying degree of residence time in the ecosystem.

These pools include:

i. Passive, recalcitrant or refractory pool: organic carbon held in this pool has a very long residence time ranging from decades to thousands of years.

ii. Active, labile or fast pool: carbon held in this pool stays in the soil for much shorter period due to fast decomposition. The residence time normally ranges from 1 day to a year.

iii. Slow, stable or humus pool: carbon held in this pool has long turnover time due to slow rate of decomposition. The residence time typically ranges from 1 year to a decade.

b. Measurement and verification: the stock of carbon in soils is difficult, time-consuming and expensive to measure. Changes within the range of 10% are very difficult to detect due to sampling errors, small-scale variability and uncertainties with measures and analysis (Sparling, 2006). The annual incremental stock of carbon in soil is very small usually within 0.25–1.0 t/ha (Ravindranath & Ostwald, 2008). It is even more difficult to account for little gains or losses in soil carbon at various scales due to methodological difficulties such as monitoring, verification, sampling and depth (Trumbore & Torn, 2003). Even if these small changes (gains or losses) are detected, it is not easy to link such changes to management or land use practice in a given context. The capacity of the soil to sequester and retain carbon is also finite as it reaches a steady state after sometime.

c. Separation: it is very difficult to isolate and differentiate the portion of carbon sequestered in the soil as result of management activities or land use and that which occurred naturally. The principle of separation requires that the carbon sequestered or GHGs emission prevented as a result of management intervention be distinguished from that which would have occurred due to natural causes. Methods are therefore needed that can differentiate naturally sequestered carbon from that captured due to human management (Swift, 2001).

d. Permanence: another challenge of carbon sequestration in soil is non-permanence of the sequestered carbon as it can be released back to the atmosphere as easily as it is gained as a result of decomposition or mineralization. It is for this reason that sequestered carbon is considered a short-term option for removing carbon from the atmosphere. The rate of carbon loss depends on several climatic, land use and management factors.

7. Management techniques for carbon sequestration in soils

The stored soil carbon is vulnerable to loss through both land management change and climate change. The important strategies of soil C sequestration include restoration of degraded soils, and adoption of improved management practices (IMPs) of agricultural and forestry soils. Management techniques, which are successful in providing a net carbon sink in soils, include the following:

a. Conservation agriculture: According to Hobbs (2007), conservation agriculture (CA) is defined as minimal soil disturbance (no-till) and permanent soil cover (mulch) combined with rotations. It is a more sustainable cultivation system for the future than those presently practiced. According to Food and Agricultural Organizations (FAO) of the United Nations, conservation agriculture is defined as a concept for resource saving of agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment and minimizing or eliminating manipulation of the

soil for crop production. It involves an application of modern agricultural technology to improve production, by maximization yields as well as maintaining the health and integrity of the ecosystem unlike the traditional systems which mainly aim to maximize yields often at the cost of the environment (Dumanski et al., 2006). Conservation agriculture has a proven potential of converting many soils from source of C to sinks of atmosphere C by sequestering it into soil (FAO/CTIC, 2008; & Lal et al., 1998). CA improves agriculture by reducing erosion, increasing water infiltration, improving soil surface aggregates, reducing compaction through promotion of biological tillage, increasing surface soil organic matter and carbon content, moderating soil temperatures, and suppressing weeds. It also helps in reducing costs of production, saves time, increases yield through more timely.

b. Minimum/zero tillage: The main purpose of tillage is to provide favourable soil environment for plant growth. It is one of the major factors responsible for reducing carbon stocks in soil. SOM is oxidized when it is exposed to the air by tillage, resulting in a reduction in organic matter (OM) content, unless additional OM is returned to the soil as residues, compost, or other means. Tillage disrupts the pores left by roots and microbial activity. The effect of this on below ground biology is not well known. The bare surface exposed after tillage is prone to breakdown of soil aggregates as the energy from raindrops is dissipated. This results in clogging of soil pores, reduced infiltration of water and increased runoff, leading to soil erosion. When the surface dries, it crusts and forms a barrier to plant emergence (Hobbs, 2007).

c. Cover crops: Cover crop is the use of crops such as legumes and small grains for protection and soil improvement between periods of regular crop production. Cover crops improve carbon sequestration by enhancing soil structure and adding organic matter to the soil. Wang et al. (2010) in their studies on six winter and summer cover crops each grown in two soils, gravelly loam soil (GL), and fine sandy soil (FS), in phytotrons at

three temperatures reported that among winter cover crops, the highest and the lowest amounts of C accumulated were 0.597 kg/m² by *Vicia faba* L. and 0.149 kg/ m² by white clover (*Trifolium repens*) respectively in the FS soil. Among summer cover crops, sun hemp (*Crotalaria juncea* L.) accumulated the highest quantity of C (0.481 kg/ m²), while that by castor bean (*Ricinus communis*) was 0.102 kg/m² at 30° C in the GL soil. Following a whole cycle of winter and summer cover crops grown, the mean SOC increased by 13.8 and 39.1% in the GL and FS soils, respectively as compared to the respective soils. Pulses add a significant amount of organic carbon to soil because of their ability for atmospheric nitrogen fixation, leaf shedding ability and greater below-ground biomass (Ganeshamurthy, 2009). The changes in the soil organic carbon pool due to the inclusion of pulses in an upland maize-based cropping system in Inceptisols of Indo-Gangetic plains were studied after seven cropping cycles (Venkatesh et al., 2013). The results indicated that inclusion of pulses improved the total soil organic carbon content. It was more in surface soil (0-0.2 m) and declined with increase in soil depth. Maize-wheat-mungbean and pigeonpea-wheat systems resulted in significant increase of 11 and 10%, respectively in total soil organic carbon, and 10 and 15% in soil microbial biomass carbon, respectively, as compared with a conventional maize-wheat system. The application of crop residues along with farmyard manure at 5Mg/ha and bio-fertilizers resulted in greater amounts of carbon fractions and higher carbon management index than in the control and there commended inorganic fertilizers (N, P, K, S, Zn, B) treatment, particularly in the system where pulses were included.

d. Crop rotations or crop sequencing: Crop rotation is a sequence of crops grown in recurring succession on the same area of land. It improves the soil structure and fertility by alternating deep rooted and shallow rooted plants. A crop that leaches one kind of nutrient from the soil is followed during the next growing season by a dissimilar crop that

returns that nutrient to the soil or draw different ratio of nutrients. Varying the type of crops grown can increase the level of soil organic matter. However, effectiveness of crop rotation depends on the type of crops and crop rotation times. The main component of crop rotation is replenishment of nitrogen through the use of green manure in sequence with cereals and other crops. Organic crop rotation includes cultivation of deep rooted legumes which increase the carbon content in deeper soil layer by rhizo-deposition and deep root biomass. It also leads to more effective use of nitrogen and integrated livestock production. Various long term field experiments were conducted to compare crop sequencing with mono-cropping. Continuous maize cultivation with a legume-based rotation was studied by Gregorich et al. (2001). After 35 years, the difference between monoculture maize and the rotation was 20 tonne C/ha. In addition to this, the SOC present below the ploughed layer in the legume-based rotation appeared to be more biologically resistant, indicating the deep rooted plants were useful for increasing carbon storage at depth. Santos et al. (2011) reported on the basis of research done for 17 years that the forage-based rotations of semi-perennial alfalfa and annual rye grass for hay production contributed more to soil organic C sequestration than rotations based on cover crops (oat or vetch). It was concluded that the roots, either in for age based or cover crop-based rotations, played a more relevant role in building up soil C stocks in no-till Ferralsol than shoot residues. Higher rates of carbon sequestration were observed in those systems that included legume crops (Rochester, 2011).

e. Crop residue: According to Ministry of New and Renewable Energy (MNRE, 2009), Govt. of India approximately 501.76 Mt of crop residues are generated every year. Depending on the crops grown, cropping intensity and productivity in different regions of India, there is a large variability in generation and end use of these crop residues. The crop residues generation is the highest in Uttar Pradesh (60 Mt) and followed by Punjab (51 Mt) and Maharashtra (46 Mt). Estimated

total crop residues unutilized in India is 92.81 Mt annually, which is burnt on-farm primarily to clear the fields to facilitate planting of succeeding crops (Pathak et al., 2010). The problem of on-farm burning of crop residues has intensified in recent years due to use of combines for harvesting and high cost of labours in removing the crop residues by conventional methods (NAAS, 2012). Burning of crop residues produces CO, CH₄, N₂O, NO_x, NMHCs (non methane hydro carbons), SO₂ and many other gases (Anonymous, 2012). About 0.23 million tonnes of CH₄ and 0.006 million tonnes of N₂O were emitted from burning of crop residue in India in 2007. Burning disturbs the microbial population present in the soil, leads to moisture loss and increases the pH of soil due to production of ash, which contains Ca, Mg and K ions. Leaving crop residue on the field is another practice which will have an important impact on the sequestration of carbon. Siligrama and Chambers (2002) reported that more organic carbon was present in the plough layer where straw was incorporated (10.9 g/kg) rather than burnt (8.9 g/kg). Instead of burning the residues it should be converted to biochar. Duxbury and Lauren (2004) on the basis of crop residue management experiments conducted at Bhairahawa in Nepal reported that carbon stocks at a depth of 40 cm ranged between 26.9 and 28.8 t/ha. The fertilizer input without residue had no effect on the soil carbon stock, indicating that the increased productivity of rice and wheat (average of 5.1 *versus* 3.4 t/ha for rice and 3.0 *versus* 1.2 t/ha for wheat for fertilized and control treatments, respectively) did not impact soil C contents. On an average, soil C stock increased by 1.48 t/ha when residues were added. The total amount of residues added over the period of 7 years was 29.5 t/ha or 14.75 tC/ha. Thus, C retention was 10% of that added or 0.21 tC/ha/year. In some farming systems, all above-ground production may be harvested, leaving only the root biomass. The actual quantities of residue returned to the soil will depend on the crop, the growing conditions and the agricultural practices. Below-ground

residues and root turn-over represented direct inputs into the soil system, and as such had the potential to make major contributions to SOM stocks (Sanderman et al., 2010).

f. Organic agriculture: According to the Codex Alimentarius Commission (2001), organic agriculture is the holistic production management system that avoids use of synthetic fertilizers, pesticides and genetically modified organisms, minimizes pollution of air, soil and water and optimizes the health and productivity of interdependent communities of plants, animals and people. Organic agriculture offers a unique combination of environmentally sound practices with low external inputs while contributing for the food availability. The total area under organic agriculture in the world was 37 Mha during 2010 which had 0.85% share of the total agricultural land (Willer & Kilcher, 2012). Organic farming is not new to the Indian farming community. India has diverse climate and different forms of organic farming are successfully practiced. In 2003, only 73,000 ha of cultivated land were certified organic. In 2010, this rose to 780,000 ha with 0.43% share of total agricultural land. The highest shares of organically managed land are in Europe, Liechtenstein, Austria and Switzerland (Willer & Kilcher, 2012).

g. Grasses and forages: Photosynthetic assimilation of atmospheric carbon and the translocation of photo-assimilate to roots by deep-rooted grasses, not only help to trap the excess CO₂ in deeper soil layer but partly replenish the SOC in the long run. The efficiency of photosynthetic carbon trap could be greater where roots grow faster and deeper and root architecture is fibrous penetrating a larger soil volume. Grasses sequestered more C than leguminous cover crops (Lal et al., 1999a). Lavania and Lavania (2009) studied the importance of Vetiver grass [*Vetiveria zizanioides* (L.)] in sequestering carbon. Its root penetrates deep into the soil with an initial growth rate of 3 cm per day reaching over 2m in just 6 months to 6m in three years. It has an annual biomass production potential of 100-120t/ha. Because of fibrous nature of the roots,

uniform dispersal of stored carbon occurs into the soil. It is also non-competitive with other crops. Strategic plantation of vetiver grass in crop fields, tree lines, river, road and rail-line embankments as hedgerows could potentially contribute to carbon sequestration.

h. Rotational grazing: Grazing is expected to decrease the availability of residues that can be used to sequester C, especially as the quantity of C returned in manure is less than that consumed. However, if proper grazing management is followed, it will have a positive effect on the C stock of soil. For improved grasslands, high rates of sequestration can be achieved through introduction of more productive grass species and legumes. Improved nutrient management and irrigation can also increase productivity and sequester more carbon (Verchot & Singh, 2009).

i. Growing plants on semi-arid lands: It has been suggested as a way to increase carbon storage in soils. However, the fossil fuel costs of irrigating these lands may exceed any net gain in carbon sequestration. Additionally, in many semi-arid regions surface and groundwater contain high concentrations of carbonate and bicarbonate ions of Ca, Mg and Na. As these are deposited in the soil, they release CO₂ into the atmosphere. On degraded croplands, an increase of 1 tonne of soil carbon pool may increase crop yield by 20 to 40 kg/ha of wheat, 10 to 20 kg/ha for maize, and 0.5 to 1.0 kg/ha for cowpeas. Trees could also make significant contribution in increasing C content of soils of dryland. N-fixing trees in particular leads to increased accumulation of soil C. *Prosopis* and *Acacia* adapted to subtropical semi-arid lands were reported to increase the level of soil C by 2 tonne/ha (Geesing et al., 2000).

j. Bio-char or Black carbon: Bio-char is gaining importance as a viable option of storing carbon permanently. It is a solid material obtained from the carbonization of the biomass. According to Lehmann et al. (2006), the term “bio-char” is a relatively recent development and evolved in conjunction with issues such as soil management and carbon

sequestration. Bio-char differs from charcoal in regard to its purpose of use, which is not for fuel, but for atmospheric carbon capture and storage, and application to soil. Durenkamp et al. (2010) described bio-char as charcoal produced by pyrolysis of biomass feedstock (e.g. plant material), an excellent soil amendment that offered a cheap, easily accessible source of organic carbon (OC) and improved water retention as well as provided habitat for microbes. Verheijen et al. (2010) defined bio-char as charcoal (biomass that has been pyrolysed in a zero or low oxygen environment), for which, owing to its inherent properties, scientific consensus exists that application to soil at a specific site is expected to sustainably sequester carbon and concurrently improve soil functions (under current and future management), while avoiding short and long-term detrimental effects to the wider environment as well as human and animal health. Modern bio-char is a product that can be manufactured from almost any uncontaminated organic matter, such as crop residues, bark, stem timber (logs), nonstem logging residues (bark, branches, tree-tops), various grasses and agricultural plant residues. According to Zimmeman (2010) and Roberts et al. (2010), soil application of bio-char, charcoal created by low temperature pyrolysis of biomass under anaerobic conditions, is also being considered as an option to increase the SOC. The conversion of biomass carbon to bio-char leads to sequestration of about 50% of the initial carbon as compared to low amounts retained after burning (3%) and biological decomposition (less than 10-20% after 5-10 years) (Lehmann et al., 2006). This efficiency of carbon conversion of biomass to bio-char is highly dependent on the type of feedstock, but is not significantly affected by the pyrolysis temperature (within 350-500°C).

k. Inorganic fertilizer: Fertilization is one of the most important crop inputs in the production system. It is the primary means of increasing plant population and crop yield. Any increase in plant biomass ultimately increases the scope of carbon sequestration.

Lal et al. (1999 b) recommended fertilizer application as a successful method of sequestering carbon. Nitrogen can increase soil organic matter because it often limited in agro-ecosystems. However, the CO₂ released from fossil fuel combustion during the production, transport and application of nitrogen fertilizer can reduce the net amount of carbon sequestered. Nitrogen from fertilization on agricultural lands can also run-off into nearby waterways where it may have serious ecological consequences. Wilson and Al-Kaisi (2008) conducted experiment to examine the short-term effects of crop rotation and N fertilization on soil CO₂ emissions. It was found that soil CO₂ emissions were greater in continuous corn than from corn-soybean rotation. This difference was attributed to the fact that the continuous corn plots received a greater amount of crop residue than the plots in a corn-soybean rotation. They also reported that soil CO₂ emission rate was decreased, with the increase of N application rate. It has been observed that increased N can cause a depression in soil CO₂ emissions not only in agricultural soils but also in forest soils. This is because there is decrease in extracellular enzyme activity and reduced root activity, decrease rhizo-deposition, due to increased N application. The findings of this research indicate that changes in cropping systems can have immediate impacts on both the rate and cumulative soil CO₂ emissions. Although N fertilizers reduce carbon dioxide emission but it leads to emission of nitrous oxide another GHG. Kukal et al. (2009) conducted research on rice-wheat and maize-wheat cropping systems and concluded that application of FYM or balanced fertilization with NPK resulted in higher carbon sequestration. Rice-wheat system has greater capacity to sequester C as compared to maize wheat because of greater C input through enhanced productivity.

8. Measurement of Carbon Dioxide Emission

Field CO₂ measurements: Four PVC rings 10 cm in diameter are placed in each plot after emergence of crop, two in the row and two between the rows. Carbon dioxide emissions is

measured at each PVC ring with a Li-Cor 6400 (Li-Cor Corp., Lincoln, NE) equipped with a 6400-09 soil chamber. Measurements of soil CO₂ emission rate is taken every 7–10 days until harvest. Soil temperature and soil moisture were measured in the top 5 cm outside the ring at the time of measuring CO₂ emission. Soil temperature was measured with a thermometer provided with the Li-Cor 6400. Cumulative CO₂ emission at a given time was calculated using the following relationship:

$$\text{CO}_2\text{-C (kg/ ha)} = \text{“}X_i + (X_{i+1}) N + (X_{i+2}) N + \dots + (X_{i+n}) N$$

Where,

i = first week of the growing season when first CO₂ rate was taken.

n = the last week of the growing season when last CO₂ rate was taken.

X = CO₂ rate (kg/ha/day)

N = number of days between two consecutive CO₂ rate measurements.

Soil organic carbon analysis using loss on ignition method

(LOI): The soil samples were oven dried at 105 °C for 24 hours to remove the moisture. The dried samples were grinded and sieved to 2 mm size to remove large particles (generally those particles greater than 2-mm in diameter) to make the homogenous for further analysis. The loss-on-ignition (LOI) method was used for the determination of soil organic matter content. About 20g of oven dried soil sample was added to a ceramic crucible (or similar vessel). The samples were then heated to 450° C overnight (16 h) to remove all soil carbon.

$$\% \text{ SOM (Soil organic carbon)} = \frac{\text{Weight of oven dried soil-weight of soil after burning}}{\text{Weight of oven dried soil}} \times 100$$

Finally, the loss-on-ignition (LOI) method determines only the organic matter content in the soil. For the sample burned at the temperature of 450 °C, there was the regression formula or correction factor developed by (Ball, 1964) to convert soil organic matter (%) to SOC (%). The result was calculated by using this regression formula: $Y = 0.458X - 0.4$

Where, *Y* = SOC (%) and *X* = SOM (%) or LOI (%).

Gas Analyzer: A dynamic flow system was used for measurements of CO₂. Air flowed from the soil enclosure through a Teflon lined polyethylene sample line 5 m in length and then it entered an infrared gas analyzer (Li-Cor 820). Data were stored in a computer and fluxes were calculated from the linear increase of concentration *versus* time adjusted for the ratio of chamber volume to area and the air density within the chamber (Keller et al., 2005).

Portable CO₂ Gas Analyzer: Enoch et al. (1970) informed about the gas analyzer which

could be used in the field experiments. A simple, portable instrument for the determination of carbon dioxide concentration in atmospheric air by non-aqueous titration is described. The method can be used in the range 10–10,000 ppm. 50 ml air samples containing about 300 ppm CO₂ can be analyzed with an accuracy of ± 3%. With increasing sample size the accuracy increases. A simple device is used to compensate for the influence of temperature and pressure. The time required for one titration is about 2 min.

Measurement of CO₂ in forest: It is measured through nondestructive morphometer and Allometric Equations method (IPCC, 2003 & USDA, 2007) relating to:

- Total ground biomass
- Carbon percentage
- Density of the wood of the plants

Allometry refers to the “relation between the size of an organism and the size of any of its parts, an allometric equation is usually expressed in power-law form or in logarithmic

form". The total ground biomass is determined through combined analysis of above ground biomass (AGB), below ground biomass (BGB) and tree canopy biomass values corresponding to each tree spp. measured. AGB is morphometrically measured with volume of the above ground plant and wood density.

Volume = Ab H Kc

Where,

Ab = Basal Area

H = Height

Kc = Site dependent constant

BGB is calculated by the formula given by McDicken, 1997.

The biomass of foliage of each tree was determined with the help of crown volume.

$$\text{Crown volume (Vm}^3\text{)} = \frac{\pi D_b^2 H_c}{12}$$

Where,

D_b^2 = Diameter of the crown

Hc = Height from the ground to base of the crown

9. Strategies of increasing carbon stock in soils

There are proven practices and strategies that lead to increase in soil carbon stock in different terrestrial ecosystems. Most of these strategies increases the carbon stock in biomass through photosynthesis and indirectly builds up below ground and soil carbon through increased deposition of organic matter. According to Post and Kwon in 2000, organic carbon level of soil can be improved by increasing the amount of organic matter input, changing the decomposability of organic matter, placing organic matter in deep layer and enhancing better physical protection of the soil aggregates or formation of organo-mineral complexes (Post & Kwon, 2000).

In the forest ecosystem, the following have been widely reported.

- Afforestation
- Reforestation
- Natural regeneration
- Enrichment planting
- Reduced impact logging (RIL)
- Increasing the carbon stock of existing forests using several silvicultural techniques among others (Walcott et al., 2009 & Jandl et al., 2007). In the agricultural ecosystem, some strategies that enhance carbon capture and storage in the soil include:

- Manuring and fertilizing
- Conservation tillage (minimum, zero/no-till)

- Crop residue management
- Cover cropping
- Application of farmyard manure
- Application of inorganic fertilizers
- Rotational grazing
- Perennial cropping systems, Etc.

CONCLUSION

Carbon sequestration is highly related to the soil and management system. Zero/no tillage combined with crop residue retention on the soil surface helps in sequestering carbon, increases water use efficiency and reduces fossil fuel utilization. When residues are retained on the soil surface only a small fraction of it comes in contact with soil and microbes. Due to limited oxygen availability decomposition is slow. Incorporation of crop residue into the soil leads to early decomposition and release of CO₂ hence it should be avoided. Crop rotation contributes to carbon sequestration because it can increase the rate of accumulation of SOC at various depths in the soil profile, as different crop species have different root depths.

There has been increasing interest on carbon capture and storage in the soils of different ecosystems as a climate mitigation measure. However, enhancing the carbon stock of soils also have ancillary benefits such as improving soil health and productivity, water retention, fertility enhancement among others. Although, theoretically this idea sounds appealing, however it is difficult to operationalize it in

practice due to a number of challenges. Some of these include difficulties in measurement of soil carbon stock, permanence, carbon pools with different carbon residence times, separation, the tendency of the soil to reach saturation level when the maximum attainable carbon that could be captured is reached. Advances have been made in tackling most of these challenges, however, deliberate actions to enhance carbon capture and sequestration in the soil ecosystem is yet to get wide acceptance by practitioners and policy makers alike. This chapter is written in an attempt to create more awareness on the potential of soils in capturing and storing atmospheric CO₂ in long lived pools thereby mitigating climate change in the process. Researchers should also work assiduously in finding solutions to the challenges making widespread adoption of this initiative difficult.

CO₂ is increasing at the rate of 2.3 ppm per year, which is resulting in the increase of global warming and environmental pollution. Agriculture sector is responsible for up to 30% emission of GHGs. Sustainable agriculture is essential for the survival of humankind. Adoption of different agronomic management practices can be helpful in the sequestration of carbon. Such practices include no-tillage or reduced tillage, nutrient management, cover crops, crop rotations, green manuring, application of animal manures, agroforestry, etc. Adoption of these different agronomic practices will not only improve the crops yields but will also improve farmer's income.

In addition to the different conservation practices, deep rooted grasses/crops should be developed through hybridization to increase the carbon storage at deeper soil layer. In many plants as much as 30-50% of the C is fixed in photosynthesis is initially translocated below ground. Some is used for structural growth of the root system, some for autotrophic respiration and is lost to the surrounding soil in organic form (rhizo-deposition). Biochar can hold carbon in the soil for hundreds and thousands of years. It helps in improving soil fertility that stimulates

plant growth which ultimately increases the biomass leading to higher CO₂ consumption.

REFERENCES

- Abdullahi, A. C., Siwar, C., Shaharuddin, M. I., & Anizan, I. (2014). Leveraging the potentials of soil carbon sequestration in sustaining forest ecosystems in Malaysia. *The Malaysian Forester*. 77(2), 91-100.
- Anonymuos, (2012). India Second National Communication to the United Nations Framework Convention on Climate Change. Ministry of Environment and Forests, Government of India: 65.
- Ball, D. F. (1964). Loss-On-Ignition as an Estimate of Organic Matter and Organic Carbon in Non-Calcareous Soils. *J. of Soil Science* 15, 8492.
- Batjes, N. H., & Sombroek, W. G. (1997). Possibilities for carbon sequestration in tropical and subtropical soils. *Glob. Change Biol.* 3, 161–173.
- Batjes, N. H. (2013). Reader for the soil carbon benefits module. In: Proceedings of the ISRIC Spring School; April 22-26, 2013; Wageningen University Campus, The Netherlands. pp. 1-16.
- Batjes, N. H. (1999). Management options for reducing CO₂ concentrations in the atmosphere by increasing carbon sequestration in the soil. In: NRP Report No. 410-200-031, Dutch National Research Programme on Global Air Pollution and Climate Change and Technical Paper 30. Wageningen, *The Netherlands: International Soil Reference and Information Centre*; <http://www.isric.org/isric/webdocs/docs/NRP410200031.pdf>
- Battle, M., Bender, M. L., Tans, P. P., White, J. W. C., Ellis, J. T., Conway, T., & Francey, R. (2000). Global carbon sinks and their variability inferred from atmospheric O₂ and δ¹³C. *Science*. 287, 2467-2470.

- Burras, C. L., Kimble, J. M., Lal, R., Mausbach, M. J., Uehara, G., Cheng, H. H., Kissel, D. E., Luxmoore, R. J., Rice, C. W., & Wilding, L. P. (2001). Carbon Sequestration: Position of the Soil Science Society of America. *Agronomy Publications. Paper 59*.
- Codex Alimentarius Commission, (2001). Guidelines for the production, processing, labelling and marketing of organically produced foods GL 32–1999 pp-2 www.codexalimentarius.net/input/download/standards/.
- Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P. L., Wofsy, S. C., Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H. L. editors. *Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, New York: Cambridge University Press; 2007.
- Dixon, R. K., & Wisniewski, J. (1995). Global forest systems: An uncertain response to atmospheric pollutants and global climate change. *Water, Air, and Soil Pollution*. 85, 101-110 Carbon Sequestration in Soils: The Opportunities and Challenges <http://dx.doi.org/10.5772/intechopen.7934713>
- Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler, M. C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science*. 263, 185-190.
- Dumanski, J., Peiretti, R., Benites, J. R., McGarry, D., & Pieri, C. (2006). The paradigm of conservation agriculture. *Proc. World Assoc. Soil Water Conserv. P1* 58–64.
- Durenkamp, M., Luo, Y., & Brookes, P. C. (2010). Impact of black carbon addition to soil on the determination of soil microbial biomass by fumigation extraction. *Soil Biol. Biochem.* 42, 2026-2029.
- Duxbury, J. M., & Lauren, J. G. (2004). Enhancing technology adoption for the rice–wheat cropping system of the Indo- Gangetic plains. SM CRSP Annual Report, Soil Management CRSP, University of Hawaii at Manoa, Honolulu, HI.
- Dyson, F. J. (1977). Can we control the carbon dioxide in the atmosphere? *Energy*. 2(3), 287-291. Available at: <http://linkinghub.elsevier.com/retrieve/pii/0360544277900330> [Accessed: 10th April, 2018]
- Enoch, H., Ehrlich-Rogozensky, S., Avronm, M., & Parchornik, A. (1970). A new, portable CO₂, gas analyzer and its use in field measurements. *Agric. Meteorol.* 7, 255-262.
- FAO/CTIC, (2008). Soil carbon sequestration in Conservation Agriculture – A Framework for Valuing Soil Carbon as a Critical Ecosystem Service. Conservation Agriculture Carbon Offset Consultation 2008 October 28-30, West Lafayette, Indiana, USA.
- Ganeshamurthy, A N. (2009). Soil changes following long-term cultivation of pulses. *J. Agric. Sci.* 147, 699-706.
- Falkowski, P. G., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., & Gruber, N. (2000). The global carbon cycle: A test of our knowledge of earth as a system. *Science*. 290, 291-296. DOI: 10.1126/science.290.5490.291
- Fung, I. (2000). Variable carbon sinks. *Science*. 290, 1313-13131.
- Geesing, D., Felker, P., & Bingham, R L. (2000). Influence of mesquite (*Prosopis glandulosa*) on soil nitrogen and carbon development: implications for global carbon sequestration. *J. Arid Env*, 46, 157 - 180.

- Gifford, R. M. (2003). Plant respiration in productivity models: Conceptualisation, representation and issues for global terrestrial carbon-cycle research. *Functional Plant Biology*. 30, 171-186.
- Gregorich, E. G., Drury, C. F., & Baldock, J. A. (2001). Changes in soil carbon under long-term maize in monoculture and legume-based rotation *Can. J. Soil. Sci.* 81, 21–31.
- Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta analysis. *Global Change Biology*. 8, 345-360.
- Hansen, J. P., Kharecha, M., Sato, V., Masson-Delmotte, F., & Ackerman, D. J. (2013). Assessing “Dangerous Climate Change”: Required reduction of carbon emissions to protect young people, future generations and nature (JA Añel, Ed.). *PLoS One*. 8(12), e81648.
- Hobbs, P. R. (2007). Conservation agriculture: what is it and why is it important for future sustainable food production. *J. Agric. Sci.* 145, 127–137.
- IPCC, Climate Change (2001). The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press; p. 881. ISBN-13: 9780521807678
- IPCC [Intergovernmental Panel on Climate Change (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*.
- IPCC. Summary for Policymakers. In: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. M. editors. Climate Change (2013). The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.
- IPCC. Summary for policymakers. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Arahani, E., Kadner, S., Seboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlomer, S., van Stechow, C., Zwickel, T., & Minx, J. C. editors. Climate Change (2014). Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
- Jandl, R., Vesterdal, L., Olsson, M., Bens, O., Badeck, F., & Rock, J. (2007). Carbon sequestration and forest management. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources. 2(17), 1-16.
- Jimenez, J. J., Lal, R., Leblanc, H. A., & Russo, R. O. (2007). Soil organic carbon pool under native tree plantations in the Caribbean lowlands of cost Rica. *Forest Ecology and Management*. 241, 134-144. DOI: 10.1016/j.foreco.2007.01.022
- Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*. 10(2), 423-436.
- Kane, D. (2015). Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices. Working Paper. National Sustainable Farming Coalition. Retrieved from: http://sustainableagriculture.net/wp-content/uploads/2015/12/Soil_C_review_Kane_Dec_4-final-v4.pdf [Accessed 19th April 2018]
- Keller, M., Varner, R. K., Dias, J. D., Crill, P., de Oliveira, R. C., & Jr. & Asner, G. P. (2005). Soil-Atmosphere exchange of Nitrous Oxide, Nitric oxide,

- methane and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil. *Earth Interactions* 9(23), 1-28.
- Kirschbaum, M. U. F. (2000). Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry*. 48, 21-51.
- Kukul, S. S., Rasool, R., & Benbi, D. K. (2009). Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil Till. Res.* 102, 87-92.
- Lagomarsino, A. (2007). Structural and Functional Diversity of Soil Microbes is Affected by Elevated [CO₂] and N Addition in a Poplar Plantation. *J. Soils Sediments*. 7(6), 399–405.
- Lal, R., Hassan, H. M., & Dumanski, J. (1999a). Desertification control to sequester carbon and mitigate the greenhouse effect. In: *Carbon sequestration in soils: Science monitoring and beyond* eds. Rosenberg, N., Izaurralde, R. C., & Columbus, E. L. Ohio: Malone Battelle Press.
- Lal, R., Kimble, J. M., Follett, R. F., & Cole, C. V. (1999b). *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Boca Raton FL: Lewis Publishers.
- Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*. 123, 1-22.
- Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management*. 220(1-3), 242-258.
- Lal, R., Follett, R., Stewart, B. A., & Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*. 172(12), 943-956.
- Lal, R. (2008). Carbon sequestration. *Philosophical transactions of the Royal Society of London. Series B, Biological Sciences*. 362, 815-830.
- Lavania, U. C., & Lavania, S. (2009). Sequestration of atmospheric carbon into subsoil horizons through deep-rooted grasses- Vetiver grass model. *Curr. Sci. India* 5(10), 618-619.
- Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems - A review. *Mitigation and Adaptation Strategies for Global Change* 11, 403–427.
- MacDicken, K. (1997). *A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects*, Arlington, VA: Winrock International.
- MNRE, (2009). Ministry of New and Renewable Energy Resources, Govt. of India, New Delhi. www.mnre.gov.in/biomassresources.
- NAAS, (2012). Management of Crop Residues in the Context of Conservation Agriculture. Policy Paper No. 58, National Academy of Sciences, New Delhi. 12 p.
- Ngo, K. M., Turner, B. L., Muller-Landau, H., Davies, S. J., Larjavaara, M., Nik Hassan, N. F., & Lum, S. (2013). Carbon stocks in primary and secondary tropical forests in Singapore. *Forest Ecology Management*. 296, 81-89.
- Olson, K. R. (2014). Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. *Geoderma*. 195-196, 201-206.
- Pacala, S., & Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science*. 305, 968-972.
- Pathak, H., Bhatia, A., Jain, N., & Aggarwal, P. K. (2010). Greenhouse gas emission and mitigation in Indian agriculture – A review. In: ING Bulletins on Regional Assessment of Reactive Nitrogen, Bulletin No. 19 (Ed. Bijay-Singh), SCONING, New Delhi, 34 p.
- Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use

- change: Processes and potential. *Global Change Biology*. 6, 317-327.
- Ravindranath, N. H., & Ostwald, M. (2008). Generic methods for inventory of carbon pools. In: Carbon Inventory Methods: Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Round wood Production Projects. Netherlands: Springer; pp. 99-111.
- Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimated the energetics, economic and climate change potential. *Environ. Sci. Technol.* 41, 827–833.
- Rochester, L. J. (2011). Sequestering Carbon in minimum tilled clay soils used for irrigated cotton and grain production. *Soil Till. Res.* 112, 1-7.
- Sanderman, J., Farquharson, R., & Baldock, J. (2010). Soil carbon sequestration potential: A review for Australian agriculture. A report prepared for the Department of Climate Change and Energy Efficiency *CSIRO National Research Flagships*.
- Sanderman, J., Farquharson, R., & Baldock, J. (2010). Soil Carbon Sequestration Potential: A Review of Australian Agriculture. CSIRO Publication; Available: <https://www.mla.com.au/globalassets/mla-corporate/blocks/research-and-development/csiro-soil-c-review.pdf> [Accessed: 20th April 2018]
- Santos, N., JefersonDieckowCime´lio, BayerMolin, R., Nerilde Favaretto Volnei Pauletti & Jonatas Thiago Piva. (2011). Forages cover crops and related shoot and root additions in no-till rotations. to C sequestration in a subtropical Ferralsol. *Soil Till. Res.* 111, 208–218.
- Sedjo, R. A., & Solomon, A. M. (1989). Climate and forests. In: Rosenberg, N. J. editors. Greenhouse Warming: Abatement and Adaptation. Washington, DC: Resources for the Future; pp. 105-119 12 Carbon Capture, Utilization and Sequestration.
- Siligrams, M., & Chambers, B J. (2002). Effects of long term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. *J. Agric. Sci.*, 139, 115-127.
- Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., & Lomas, M. (2008). Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*. 14, 2015-2039.
- Soil Science Society of America, (2001). Carbon Sequestration: Position of the Soil Science Society of America (SSSA). SSSA, Madison, WI. Available at www.soils.org/pdf/pos_paper_carb_seq.pdf.
- Smith, P. (2008). Land use change and soil organic carbon dynamics. Nutrient Cycling in Agroeco systems. 81, 169-178.
- Sparling, G. P., Wheeler, D., Vesely, E. T., & Schipper, L. A. (2006). What is soil organic matter worth? *Journal of Environmental Quality*. 35, 548-557.
- Stockmann, U., Adams, M., Crawford, J. W., Field, D. J., Henakaarchchia, N., Jenkins, M., Minasnya, B., McBratneya, A. B., de Courcelles, V. D., Singha, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Birde, M., Brookes, P. C., Chenug, C., Jastrow, J. D., Lal, R., Lehmann, J., O'Donnell, A. G., Parton, W., Whitehead, D., & Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment*. 164(20), 80-90.
- Swift, R. S. (2001). Sequestration of carbon by soil. *Soil Science*. 166(11), 858-871.
- Trumbore, S. E., & Torn, M. S. (2003). Soils and the global carbon cycle. In: Holland EA, editor. Soils and Global

- Change. Belgium: NATO Advanced Study Institute.
- USDA, (2007). Measurement Guidelines for the Sequestration of Forest Carbon USDA Forest Service, General Technical.
- Venkatesh, M. S., Hazra, K. K., Ghosh, P. K., Praharaj, C. S., & Kumar, N. (2013). Long-term effect of pulses and nutrient management on soil carbon sequestration in Indo-Gangetic plains of India. *Can. J. Soil Sci.* 93, 127-136.
- Verchot, L. V., & Singh, V. P. (2009). Carbon Sequestration Opportunities with Smallholder Communities: Forestry, Agriculture and Agro-Forestry. In: 4th World Congress on Conservation Agriculture 4-7th February, 2009 at New Delhi: 351-361.
- Verheijen, F. G. A., Jeffery, S., Bastos, A. C., van der Velde, M., & Diafas, I. (2010). Biochar Application to Soils. Key note lecture at Biochar Workshop, New Zealand Biochar Research Centre, Massey University, Palmerston North, 11th- 12th February, 2010. <http://www.biochar.co.nz/workshop.html>
- Walcott, J., Bruce, S., & Sims, J. (2009). Soil Carbon for Carbon Sequestration and Trading: A Review of Issues for Agriculture and Forestry. Canberra: Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry;
- 14 Carbon Capture, Utilization and Sequestration.
- Wang, Q., Yuncong, L. I., & Ashok, A. (2010). Growing Cover Crops to Improve Biomass Accumulation and Carbon Sequestration: A Phytotron Study. *J. Environ. Protection* 1(2), 145-149.
- Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J., & Dokken, D. J. (2000). Land Use, Land-Use Change and Forestry. Cambridge, UK: Cambridge University Press; p. 375. ISBN-13: 9780521800839.
- Willer, H., & Kilcher, L. (2012). Eds. The World of Organic Agriculture - Statistics and Emerging Trends 2012. Research Institute of Organic Agriculture (FiBL), Frick, and International Federation of Organic Agriculture Movements (IFOAM), Bonn.
- Wilson, H. M., & Al-Kaisi, M. M. (2008). Crop rotation and nitrogen fertilization effect on soil CO₂ emissions in central Iowa. *Appl. Soil Ecol.* 39, 264 – 270.
- World Bank. Agricultural land (% of land area). 2015. Available from: <http://data.worldbank.org/indicator/AG.LND.AGRI.ZS/countries?display=graph> [Accessed 21 April 2018]
- Zimmeman, A. R. (2010). Abiotic and microbial oxidation of laboratory-based black carbon (biochar). *Environ. Sci. Technol.* 44, 1295–1301.