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Carbon Sequestration as Influenced by Cropping Practices: A Review

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ABSTRACT

Global warming has been a serious concern in recent times with regards to declining productivity which will soon emerge as a major challenge for future of agricultural systems. The major contributors to the global warming are the atmospheric carbon dioxide, methane and nitrous oxide. Agriculture has the vast potential for the carbon sequestration. Certain modifications in agricultural practices can efficiently reduce atmospheric carbon dioxide. In this paper the role of conservation tillage, cropping pattern including crop rotation and intercropping, nutrient management, livestock management in agriculture, cover crops in sequestering the atmospheric carbon dioxide has been reviewed along with evidences of the work carried out across the nations.

Key words: Carbon sequestration, Conservation tillage, Cover crops, Cropping pattern, Global warming, Livestock.

Global warming is causing a serious concern for the scientists all over the world. The interest in the field is deepening with time. Before the Industrial Revolution started in the mid-1700s, the global average amount of carbon dioxide was about 280 ppm and it was reported to be 409.8 ppm in 2019 (Lindsey, 2020). The rising levels of carbon dioxide and the consequent increase in the temperature can cause a serious threat to the infrastructure, human health, businesses *etc.* Climate change will impact the economy of all the countries negatively; however, the developing and underdeveloped countries of South Asia and Sub Saharan Africa are at greater risk. According to a simulation study (GTAP INT calculations), it is concluded that with each degree rise in temperature, there is increase in the net negative loss of GDP per year, however, this loss is more for the countries located in South Asia and Africa (Kompas *et al*., 2018). The losses in the long run varies from the -0.383 per cent/ year for Finland and -0.885 per cent/ year to -17.437 per cent/ year for Sri Lanka to -26.556 per cent/ year for Togo with rise of 4°C in temperature. (Kompas *et al.*, 2018). The change in climate can also influence the human health both directly and indirectly. The effect of heat stress is direct one whereas, the changes in the nature of vectors and pathogens *vis a vis* susceptibility of the human will increase the susceptibility. Agriculture is an important sector where the impact of rising carbon di oxide can take heavy toll. Increase in the carbon dioxide concentration will increase the net rate of photosynthesis (Cure and Acock, 1986; Allen *et al.,* 1987). However, the increase in carbon dioxide levels will also lead to decrease in the transpiration due to closure of stomata which can interrupt the growth and development. The reduction in transpiration can be up to 30 per cent in certain crops (Kimball, 1983). Rise in carbon dioxide level will also be accompanied by the rise in average temperature which may have both direct and indirect effect on the crop yield. Rising temperatures and changes in rainfall patterns have direct effects on crop yields, as well as indirect effects through changes in irrigation water availability (Nelson *et al.,* 2009). A search was carried out for the effect of climate change under various models on the yield of important crops over different locations and are presented in Table 1.

Rise in CO_2 levels in atmosphere has positive influence on the photosynthesis by the plant. The increase is higher in the C3 plants when compared to CAM and C_4 plants as the photorespiration which operates in C_3 plants is suppressed. The increase in net photosynthesis in C_3 species has been reported as high as 50-100% when CO_2 concentration doubles compared to 10% in C4 species (Unsworth and Hogsett, 1996) and photosynthesis in C_3 plants increases up to 800-1000 ppm (Amthor, 2001). However, rise in CO_2 levels causes greenhouse effect leading to an increase in temperature. The rise in temperature leads to the reduction in transpiration leading to closure of stomata. The rise in temperature after the flowering/panicle initiation in crops lead to the increase in growth rate. This reduces the total duration of the grain filling leading to the reduction in the yields. Thus, it becomes important to reduce or retain the atmospheric CO_2 concentration to limit the global warming.

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Carbon sequestration is a process of capturing and storing atmospheric CO_2 in solid or liquid form through natural or artificial process. SOC is classified into three fractions, according to their rate of mineralization or turnover. Three major organic carbon pools are represented below (Table 2).

Plants serve as an important medium of fixing atmospheric carbon through the process of photosynthesis. This fixed carbon is utilized for the formation of leaves, stems, roots *etc.* which later get added to soil as litter and thus, increases the soil carbon content. However, the agricultural practices in the form of tillage, nutrient management, irrigation management and cropping pattern also lead to the loss of the soil organic carbon. It has been estimated that 30-50 per cent of SOC has been lost after the initialization of agriculture (Kucharik *et al.,* 2001). Modifying agricultural practices can be an effective measure to enhance the carbon sequestration in soil. Approximately 12% of soil C is held in cultivated soils (Schlesinger, 1991), which cover around 35% of the terrestrial land area of the planet (Betts *et al.,* 2007). In agriculture, carbon sequestration can also be enhanced through reducing the loss of soil organic and inorganic carbon from soil to the atmosphere. It has been suggested that, relative to other negative emission options, soil C sequestration may offer one of the least expensive and most readily implementable near-term options (NASEM, 2018). Increasing the soil carbon pool will also have multiplier effect on the soil fertility, better soil structure and reduced erosion.

Conservation tillage

Conservation tillage refers to the practices of maintaining at least 30% of the crop residue on the soil surface varies with the type of tillage, the extreme form as zero tillage. The mechanisms responsible for promotion of SOC sequestration through conservation tillage are moderation of temperature regimes, changes in soil moisture regimes and erosion control, increases the diversity and activity of soil fauna *e.g.* earthworms, reducing soil and water loss by protecting against rain drops, enhancing stable aggregates, soil aggradations and reduces degradation (Lal and Kimble, 1997). No till studies has shown that there is increase in the SOC in the shallow depths and lesser SOC in deeper layers when compared to the conventional tillage and equivalent for both when whole soil profile is considered owing to reduced temperature regimes, increasing soil strength and bulk density under no till conditions (Baker *et al*., 2007; Yang *et al*., 2014). Similar results were reported by Deen and Kataki (2003) where higher SOC was reported with zero tillage in 0-20 cm depth when compared to spring and fall

Table 1: Effect of climate change under various models on the yield of important crops over different locations.

Crop	Location of study site	Changes simulated	Change (%) in yield	Source
Wheat	Iran	Global temp change 1.1 to 3.8°C;	-1 to -37	Valizadeh *et al.,* 2014
	South Australia	CO_2 change 51-125%; Local rainfall	-13.5 to -32	Luo *et al.,* 2005
		changes in growing season (-8.6to +4.6%)	-41 to + 6.3	Seino, 1995 (as cited in Luo *et al.,* 2005)
	Japan	NA	-30 to +7	Delecolle *et al.,* 1995 (as cited in Luo
	France	NA		*et al.,* 2005)
Rice	Egypt	RCP 8.5 (Irrigated condition)	-19	Pepijn *et al.,* 2017
	East Africa	RCP 8.5 (Irrigated condition)	-20	…….do……
	West Africa	RCP 8.5 (Irrigated condition)	-20	…….do……..
	Malaysia	1% rise in temperature	-3.44	Alam *et al.,* 2014
	Phillipines	1°C increase	-10	Peng *et al.,* 2004
	India	Each 1°C increase in temp	-7.2	Krishnan *et al.,* 2007
Maize	Iowa State	1°C increase	-10	Ummenhofer *et al.,* 2015
	(USA)	1°C increase	-15	Ummenhofer *et al.,* 2015
	SE Australia	RCP 8.5	-3.8	Petersen, 2019
	USA	RCP 4.5	-1.8	Petersen, 2019
	USA		-3.3 to -5.9	Luhunga, 2017
	Tanzania	RCP 4.5	-10.2 to -11.2	Luhunga, 2017
	Tanzania	RCP 8.5	-20 to -40	Singh *et al.*, 2010
	India	5°C increase		

Table 2: Major functional pool, their composition, per cent share of total and turnover time (Lal and Kimble, 1997; Stavi and Lal, 2010).

Type of fraction	Composition	Per cent share (%)	Turnover time (year)
Labile/ Active	Soluble carbohydrates, exocellular enzymes and microbial biomass	15-20	0.2-1.4
Intermediate/ Slow	Particulate organic matter	20-40	8-50
Recalcitrant/ Passive	Humic and fulvic acids; organo-mineral complex	60-70	400-2200

season tillage. However, highest SOC was reported with no till followed by chisel plough and MB plough in 0-75 cm soil depth (Olson *et al.,* 2013). No till and reduced till had significantly higher SOC sequestration when compared to conventional tillage, with increasing trend towards zero till (Alvarez, 2005). Soil respiration plays a key role in determining the carbon balance (Li *et al.,* 2010). Soil aggregates has key role in the conservation of soil organic carbon. Tilling of soil leads to losses of SOC as cultivation breaks up the soil and exposes organic matter previously protected within soil macro aggregates to microbial decay. No till always protect the C mineralization cannot be generalized as it depends on the soil climatic conditions, amount and location of crop residues and soil organic matter and higher CO_2 emission has also been reported with not till than conventional tillage (Yang *et al*., 2014; Rong-Kan *et al*., 2020). The beneficial impact of the reduced tillage in terms of carbon sequestration is realized with the residue incorporation. The combination of reduced tillage and residue incorporation is the practice of conservation tillage. No tillage with straw mulching reported highest net ecosystem carbon balance (NCF) followed by rotatory tillage with straw incorporation and chisel plough with straw incorporation whereas the conventional moldboard ploughing tillage without crop straw reported negative NCF in rainfed winter wheat-summer maize cropping system (Lu *et al.,* 2018). Long term No till with straw incorporation reported highest SOC sequestration as it improves the aggregation of macro-aggregate (Rong-Kan *et al.,* 2020). In the residue management, it was also observed that the type of straw also influence the carbon sequestration. Basch *et al*. (2010) reported that under no till system, the significantly higher SOC was reported with the 5000 kg/ha wheat straw, when compared with 2500 kg/ha wheat straw and 750 kg/ha chickpea residue. The difference is attributed to the higher C: N ratio in wheat when compared to chickpea. Similarly, Cha-un *et al.* (2015) studied the crop rotation with residue incorporation for 4 year period and concluded that Rice-rice had highest SOC level when compared to Corn-rice and Sweet sorghum-rice which was attributed to higher C: N ratio present in rice stubbles. Powlson *et al.* (2014) and Baker *et al*. (2007) reported that the majority of studies on no-till and conservation tillage primarily demonstrate differences in carbon concentrations at the soil surface, while ignoring lower depths where more aggressive tillage systems, such as moldboard plowing, may actually be relocating carbon.

Cropping pattern

Cropping pattern refers to the arrangement of crops over a unit area in spatial and temporal context referred as inter/mixed cropping and crop rotation, respectively. The crop which adds more biomass (both above ground and below ground) is effective in carbon sequestration. The photosynthates in leaves are transported to the roots and are also secreted in the soils in the form of various organic compounds. Cropping pattern can be effective in carbon sequestration as cropped land occupies 35 per cent of the total global area. Shrestha *et al.* (2013) reported that wheat-oilseed-pulses recorded highest SOC level in both 0-7.5 cm and 0-15 cm fallow-crop-crop rotation (crop includes canola, wheat and pulses). Njaimwe *et al.* 2016 reported that maize-oats-maize rotation enhanced the carbon sequestration as compared to maize-wheat-maize and maize-fallow-maize rotation. In the Indo-Gangetic plains of India, Rice-wheat-mungbean system resulted in 6 per cent increase in SOC and 85 per cent increase in soil microbial biomass carbon as compared to conventional Rice-wheat cropping system (Ghosh *et al*., 2012). Lötjönen and Ollikainen (2017) conducted an analytical model study on cereal monoculture and cereal-legume rotation (clover based rotation) and reported that latter led to average decrease in the GHG emission per year by 4705 kg CO_2-eq/ha (31%). Pikula and Rutkowska (2014) reported that crop rotation without legumes reported drop of SOC to 0.61 per cent whereas, the rotation with legumes (clover-grass mixture) reported the highest value of SOC up to 0.79 per cent. Drinkwater *et al*. (1998) reported that the corn-soybean rotation system had the greatest productivity and returned the largest crop residues to the soil compared to monoculture of corn or soybean.

Intercropping is practiced by the farmers for the efficient utilization of resources, harnessing complementary interaction between the component crops and higher yields as compared to single cropping. The crops intercropped produce more biomass (both above ground and below ground) which leads to the more fixation of carbon in soil. Hu *et al.* (2015) reported that wheat and maize intercropping emitted 10 per cent lower carbon than sole maize cropping. Ferreira *et al.* (2019) reported that the intercropping systems along with minimum soil tillage were more effective in maintaining and sometimes increasing the levels and stocks of SOC as compared with native vegetation.

Agro forestry is the other system which is effective in carbon sequestration. In a modeling study in the seven districts of Central Plateau and hill agro climatic zone in India, it was estimated that total carbon sequestered was 2.141 MtC (Rizvi *et al.,* 2019). Winans *et al.* (2016) reported that tree based intercropping (TBI) system had 33-36 per cent more C storage than adjacent non-TBI system. In addition to C sequestration, agroforestry also increases the net income of farm and changes the microclimate of the crop field which has positive influence on crop growth and development.

Nutrient management

Soil acts as a store house of the nutrients. Good nutrient management is essential for higher yields, which will spare the additional use of land in agriculture. Crop plants use these nutrients for their growth and development and accumulate biomass. The potential biomass in the crop plants is determined by the solar radiation and consequent

photosynthesis, however, the realization of potential is dependent of the nutrient supply. This biomass (both above ground and below ground) when incorporated in to the soil leads to enhancement of the SOC status. In addition, the better nutrient status of the soil also encourages the growth of the various other plants and micro-organisms which are contributor of the organic carbon. The nutrient management and soil carbon sequestration can be achieved by knowing the source of nutrient, time and method of application and reducing the nutrient loss from soil *e.g.* denitrification in form of nitrous oxide from the rice fields ultimately lead to the global warming. The other forms in which it can be conserved are reducing leaching losses and volatilization losses. Nutrients are supplied through both organic and inorganic sources. The management of nutrients combining both organic and inorganic sources is found to be more effective in carbon sequestration. Therefore, nutrient management in agriculture can play an important role in the carbon sequestration. Nutrients are classified into primary, secondary and micro nutrients. It is reported that to sequester 10 Mg C in crop residues, 833 kg of Nitrogen, 200 kg of phosphorus and 143 kg of sulphur is required (Hussain *et al.,* 2021). Carbon stocks of the soils were higher when organic inputs were combined with mineral fertilizer, compared to only organic inputs or only mineral fertilizer (Hijbeek, 2019; Trivedi *et al.,* 2020). Zhang *et al.* (2012) reported that application of organic amendments for 25-28 years increased SOC by 7-45 per cent when compared to mineral fertilization.

Increasing nutrient use efficiency is essential to offset the release of Green house gases in agriculture through their use. Time and method of application of nutrient fertilizer have a larger role in determining the nutrient use efficiency. Agriculture contributes 70-90 per cent of N_2O emissions mostly from the nitrogen fertilizers which can be prevented by the site specific nutrient management as the total nutrient to be applied will be reduced, thus reducing the N loss in form of volatilization, runoff and leaching loss (Richards *et al.,* 2015). Site specific adaptive research is needed to identify recommended management practices (RMPs) that optimize soil N use efficiency while improving crop yield and C sequestration thereby curbing greenhouse gas (GHG) emissions (Christopher and Lal, 2007). Practices that improve N use efficiency includes adjusting application rates based on precise estimation of crop needs (*e.g.,* precision farming); using slow-or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); applying N when least susceptible to loss, often just prior to plant uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops roots; or avoiding N applications in excess of immediate plant requirements (Smith *et al.,* 2007).

Cover cropping

The production of higher biomass under cover crops and its subsequent addition to the soil leads to the enrichment of SOC in soil. The roots of these crops add the organic matter which promotes the aggregate formation and thus conserves the soil carbon. The reduction of temperature under cover crops lead to the reduced decomposition, thus, loss of SOC is prevented. Adding organic matter through crop and other residues moderate soil temperature, which further reduces the rate of carbon loss (Melillo *et al.,* 2017). The associated increase of SOC with the cover crops is also attributed to the reduced erosion. A regression analysis revealed that changes in SOC from cover cropping is correlated with improvements in soil quality, specifically decreased runoff and erosion and increased amount of mineralizable carbon, mineralizable nitrogen and soil nitrogen (Jian *et al.,* 2020). McDowell, 2019 reported that the rye cover crop and cover crop mix increased the percentage of macro aggregates by about 4.1 to 5.1 per cent and total particulate organic matter (POM), the labile or easy to degrade organic matter, by 14 per cent as compared to control. Poeplau and Don, 2015 concluded that the cover crop treatments had a significantly higher SOC stock than the reference croplands. Jian *et al.* 2020 in a meta analysis and regression studies concluded that cover cropping increases SOC in near surface soils by an average of 15.5 per cent. Whereas medium-textured soils had highest SOC stocks (overall means of 39 Mg ha^{-1} with and 37 Mg ha^{-1} without cover crops), fine-textured soils showed the greatest increase in SOC after the inclusion of cover crops (mean change of 39.5%). Coarse-textured (11.4%) and medium-textured soils (10.3%) had comparatively smaller changes in SOC, while soils in temperate climates had greater changes (18.7%) than those in tropical climates (7.2%). Sainju *et al.* (2006) also reported that SOC increased by 6-8% with cover crops at 0 to 10 cm and by 0.4% with rye in monoculture and 3% with vetch and rye in biculture at 0-30 cm.

Inclusion of livestock in agriculture systems

Livestock management has become an essential component of agriculture systems. This is more important for the countries like India where majority of farmers are having marginal land holding owing to more profitability per unit land area. In some developing countries, livestock contributes 50-80 per cent of GDP (World Bank, 2007). In terms of SOC sequestration, livestock is an essential source of organic matter, grassland management is essential for conserving SOC and inclusion of ley farming can add to the more biomass and thus, higher SOC will be added. Livestock themselves release large amount of GHG due to enteric fermentation. Improved feeding practices, use of specific dietary additives, long term changes in management and animal breeding can reduce the CH_4 and N_2O emissions (Smith *et al.,* 2007). Grasses due to their high density of root biomass and quick regenerative ability improve the aggregate formation and add to SOC sequestration. Conversion of land use from grassland to farmland leads to loss of soil organic carbon.

In grassland systems, there is balance between the above ground biomass, grazing and belowground root biomass. The grazing by the cattle leads to the pruning back of green biomass, thus, the equivalent belowground root

biomass dies off leading to the addition of SOC. After certain period remaining shoot and root rejuvenates in to the grassland. Poor grassland management disrupts this cycle. Removal of large amounts of aboveground biomass, continuous heavy stocking rates and other poor grazing management practices are important human-controlled factors that influence grassland production and have led to the depletion of soil carbon stocks (Conant, 2010). The composition of the species in the grassland also influences the SOC sequestration. The restoration of grassland with high plant diversity may greatly increase carbon capture and storage rates on degraded and abandoned agricultural lands (Yang *et al.,* 2019).

While grassland management is perennial activity, ley farming provides opportunity to include SOC enriching forage species in between the annual crop rotations. The pasture phase during the crop rotation provides inputs of organic matter and has reduced tillage, with less erosion, fertilizer and herbicides application (Edwards *et al.,* 2019). Ley farming is a viable alternative to burning crop residues to clear a field, which is a common practice in Africa and causes considerable loss of SOC (Jarecki and Lal, 2003). Lugato *et al.* (2014) reported that highest SOC sequestration was when the land use is changed from arable to grassland, followed by ley crop in rotation and cover crops and these both were superior over residue management and straw incorporation. Prade *et al.* (2017) observed that under modified scenario (including a year of grass rotation in the four year cereal based rotation leaving all straw in the field and pig manure as part of fertilizer requirement), the SOC reached 5.1 per cent after 140 years whereas, it was only 3 per cent in current scenario (similar to modified scenario except grass in rotation).

Challenges and Opportunities

Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emission increase of about 60 $MtCO_2$-eq yr^{-1} (Smith *et al.* 2007). The global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be ~5500-6,000 Mt CO_2-eq yr^{-1} (medium agreement, medium evidence) (Smith *et al.,* 2007).

There are various challenges to the carbon sequestration in agriculture. The foremost challenge is to measure the amount of amount of C sequestered in the soil. The addition and removal of the carbon in soil is a continuous process. It is also difficult to measure if, the carbon sequestered in the soil is due the management practices followed. Carbon sequestered in the soil is amenable to the immediate loss. It can only be held if the soil is not disturbed for a longer period. Global penetrance of conventional tillage rather than minimum and zero tillage is another challenge. Worldwide area under zero-tillage in 1999 was approximately 50 m ha, representing 3.5% of total arable land (Smith *et al.,* 2007).

According to the IPCC agricultural soils have the potential of sequestering up to 1.2 billion tonnes of carbon per year. Mineralization of only 10% of the soil organic carbon pool globally is believed to be equivalent to about 30 years of anthropogenic emissions (Abdullahi *et al.* 2018). This becomes more important when 30 per cent of the total geographical area of the world is under agriculture systems. The carbon markets if extended to the agriculture can make carbon sequestration in agriculture more attractive. The combine value of markets for green house gases (GHG) emission reduction increased to more that US $100 billion, however, agriculture has largely been excluded from formal and informal carbon markets (De Pinto *et al.,* 2010). All the activities in the agriculture are having the complementary benefits in form of increased fertility and nutrient status, soil and moisture conservation, improved physical and chemical properties of soil and will lead to the sustainable increase in the agriculture productivity. Reducing soil disturbance is also fuel efficient. However, it is to be ensured that major work is to be carried out on the measuring parameters of sequestered carbon, permanence of the sequestered carbon and developing favorable policy environment for it.

CONCLUSION

Soil carbon sequestration involves transferring atmospheric carbon into the soil via plant photosynthesis and keeping those soil-based carbon pools protected as effectively as possible from microbial activity that will release the carbon back to the air. There are agricultural management practices that show promise for restoring soils and sequestering a very significant portion of atmospheric carbon. The need for drawdown strategies is increasingly urgent and soil carbon sequestration through agriculture warrants far greater attention from policymakers, climate negotiators, farmers, ranchers and scientists. Most, if not all, of the management regimes that promote carbon sequestration also improve soil aggregation, water retention, soil fertility and food security.

Conflict of interest

All authors declare that they have no conflicts of interest.

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