Climate Change Implications on Soil Health and Agronomical Interventions to Increase Soil Carbon Sequestration under different Landuses

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***Abstract*—** *Healthy soil is the crucial factor required to meet the global demands for food and fibre for the burgoining population. However, global food security is threatened by climate change impacts. Climate change, variability, and mismanagement or misuse of resources lead to soil degradation and vulnerability. Hence, sustainable soil management aims for the services of soil to be maintained without significantly impairing the soil functions that enable those services or biodiversity. Sequestering higher carbon in soils will help the soil increase its resilience to climate change in the long run. Therefore, every step towards sustainable soil health management in the climate change scenario should focus on soil carbon sequestration. The soils under different land use systems have various carbon sequestration potential. Adoption of the best management practices like conservation tillage (minimum, zero/no-till), balanced fertilization, green mulching, crop residue management, cover cropping, organic manures and in-situ soil and moisture conservation measures in agricultural lands can improve the carbon sequestration potential. The amount of carbon stored in forest soils is often greater than aboveground in living and dead plant biomass. Managing forests to optimize carbon sequestration is also essential to increase the carbon in forest soils. Carbon sequestration is the global mission achieving this is possible only through local vision involving the farmers, researchers and common public as agricultural/ forest soils and trees have the tremendous potential to sequester atmospheric carbon. Focus on soil health management to mitigate the climate change impacts is indispensable to have a sustainable ecosystem with high biodiversity.*

Keywords*— climate change, soil health, soil degradation, soil carbon sequestration, sustainable soil management, land use systems, soil organic carbon, carbon loss, conservation tillage.

I. INTRODUCTION

Soil is a storehouse of nutrients and water essential for crop production, hydrological cycle and atmospheric gas exchange. It is the foundation for plant establishment, growth, agriculture, and forest and livestock production. The soil's biodiversity and abundance of biological activity are more incredible than in any other terrestrial ecosystem. Soil contributes about 98% of our food directly or indirectly (Lal et al., 2021). Climate change, variability, and mismanagement or misuse of resources lead to soil degradation and vulnerability. The SOC pool in 1 m depth of soil is 30 tons ha^{-1} in arid regions, whereas in organic soils of temperate areas, it is 800 tons ha^{-1}. But it is also an alarming message that most agricultural soils have lost 30 to 75% of the soil organic carbon pool that accounts 30 to 40 t C ha^{-1}. This carbon loss is more significant in soils prone to accelerated erosion due to human activities, resulting in soil quality degradation and productivity decline. The optimum organic carbon level is necessary for the soil to hold water and nutrients, decrease soil erosion and degradation risks, improve soil structure, and provide energy to soil microorganisms.

In contrast, soils have more potential to store carbon than other terrestrial ecosystems as agriculture, deforestation, and other anthropogenic activities have reduced their organic carbon content. Practices like intensive agriculture, high chemical input farming, and clean cultivation have drastically depleted the soil's organic carbon content and adversely affected soil health. The critical limit of SOC concentration for tropical soil is 1.1%, but they have a very low organic carbon content level of 0.1 to 0.2 %. Accomplishing the critical organic carbon content level in these regions will be arduous for farmers and scientists. But agricultural soils have the potential to sequester carbon to their original capacity. The effect of carbon sequestration is more prominent in degraded soils regarding soil health improvement. Soil C sequestration is an effective food and nutrition security strategy through soil quality improvement. SOC sequestration in soils is an effective climate change mitigation option (Lal 2004), and the 4 per 1000 initiative suggested that 20–35% of global anthropogenic greenhouse gas emissions could be reduced by increasing global SOC stocks in the top 40 cm by 0.4% per year (Minasny et al. 2017). Therefore, every step towards sustainable soil health management in the climate change scenario should focus on soil carbon sequestration.

II. SOIL HEALTH

Soil health is the state of the soil being sound in physical, chemical, and biological conditions, having the capability to sustain the growth and development of plants. Soil is one of the most precious resources has a vital role in the water cycle. Healthy and biologically active soil are what we need for healthy food and clean water.

2.1 Climate change implications on soil:

Climate change is an essential factor in the planning and management of natural resources. Climate change, land degradation and biodiversity loss made the soil one of the world's most vulnerable natural resources. Projected temperature changes and rainfall patterns are likely to affect the SOC stock directly and indirectly. Directly, the temperature and moisture regime will affect microbial decomposition. Indirectly, it will affect the crop growth, productivity, above and below-ground biomass. Due to global warming, rainy days are expected to decline in many regions with more extreme events, and evaporation and transpiration rates are projected to increase. These changes may reduce the soil moisture availability for plant growth. The higher temperatures will also accelerate the rate of soil organic matter decomposition (mineralization), especially near the soil surface, which will affect the soil's potential capacity to sequester carbon and retain water. Many experiments showed that an increase in soil temperature would result in a significant loss of organic matter in agricultural and forest soils (Heikkinen et al., 2013; Melillo et al., 2017).

Higher soil temperatures increase the microbial decomposition and control of SOM storage in soil. Moist but well-aerated soils support microbial activity, and decomposition rates decrease as soils become drier. Flooded/submerged soils have lower rates of organic matter decomposition due to restricted aeration and thus, with very high amounts of soil C. High precipitation will transport the carbon down to the soil profile as dissolved or particulate organic matter. During drought, SOM decomposition may initially decrease but subsequently increase after rewetting. Soil physical properties are crucial in deciding the soil response or resilience to climate change. The inherent soil property, like texture, is resistant to change or changes very slowly over time, but soil organic carbon content, structure, CEC, nutrient availability, soil biodiversity and pH are more easily affected by climate and management practices. The proper soil management practices that keep the ideal soil's physical properties are inevitable to deliver soil ecosystem services, such as storing water, supplying nutrients to plants, sequestering carbon and reducing greenhouse gas emissions. Understanding these properties will enable the farmers to understand the climate change effects and mitigate its impacts.

2.2 Healthy soil:

Soil is no more an inert medium to physically support plant but a living entity has "health" that nourishes billions of lives in it. Soil system always responds to the way it has been treated and managed. A good soil management programme would involve the practices and techniques that augment the soil health by increasing key soil properties, recycling nutrients, sequestering carbon, and encourage soil biological population to flourish and diversify to keep the ecosystem functioning well. It also helps in absorbing, retaining rainwater for use during dry periods and draining the excess rainwater, filtering and buffering water to remove any toxic pollutants. Once soil health is lost it is very tough to regenerate, globally soil health is maintained with five soil health principles and each one is equally significant. Farmers can even customise the techniques according to their region, crop cultivation practices and feasibility to achieve the objective of these basic principles.

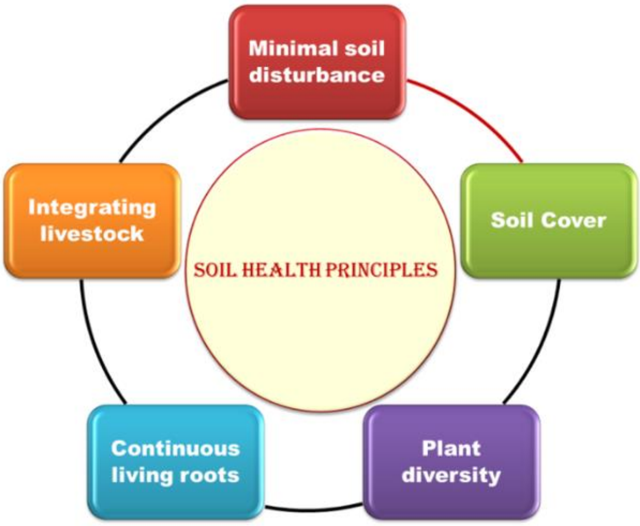

FIGURE 1: Principles of Healthy soils

2.3 Sustainable Soil Health Management:

Sustainable soil management aims the supporting, provisioning, regulating, and cultural services of soil are maintained without significantly impairing either the soil functions that enable those services or biodiversity. The four types of ecosystem services and the soil functions explained are (FAO, 2015)

- Supporting services - primary production, nutrient cycling and soil formation
- Provisioning services - supply of food, fibre, fuel, timber and water; raw earth material; surface stability; habitat and genetic resources
- Regulating services - water supply and quality, carbon sequestration, climate regulation, control of floods and erosion
- Cultural services - aesthetic and cultural benefits derived from soil.

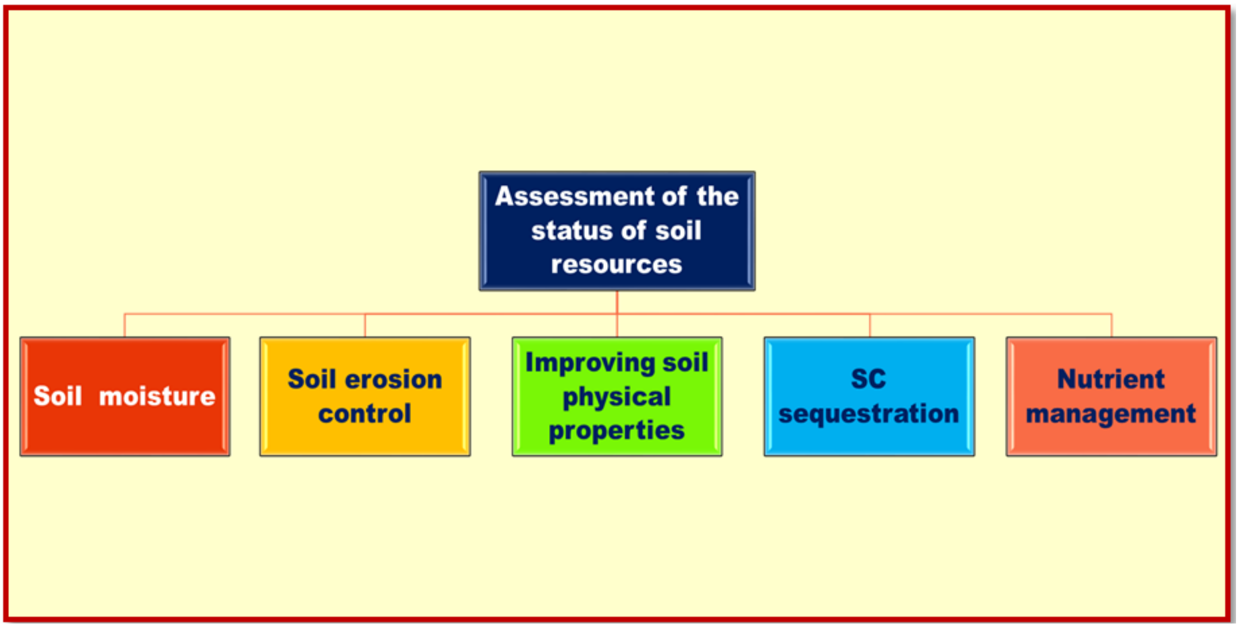

FIGURE 2: Sustainable soil management strategies

2.4 Soil Management interventions for carbon sequestration:

Carbon sequestration in soils will contribute directly to climate change adaptation and mitigation. This will also make agricultural production systems more sustainable; increase the overall resilience of agricultural ecosystems; and maintain the ecosystem services of soils. Sustainable soil and land management practices adapted to the local biophysical and socio-economic conditions can enhance the interactions among soil, water, plants and livestock which can prevent, slow or stop soil degradation as the impacts of climate change (Lal, 2013). The ninth principles from the World Soil Charter (FAO, 2015) say that soils that degradated can, in some cases, have their core functions and contributions to ecosystem services restored by applying appropriate rehabilitation techniques. This increases the area available to provide services without necessitating land-use conversion. Many already proven soil management practices can help farmers to mitigate the adverse effects of increasing weather variability and climate change. The widespread adoption of these practices can contribute to the global carbon sequestration and maintain the soil health.

The soil carbon sequestration depends on a number of factors like

1. **Abiotic** - clay content, mineralogy, structural stability, land slope, soil moisture and temperature regimes
2. **Biotic –** land use, management practice, activities of soil organisms

The best management practices should consider all these biotic and abiotic factors for improving the efficiency of any land use to store the soil carbon.

III. CLIMATE CHANGE AND LAND USE CHANGES

Several land uses are prevalent in the earth that are often changing due to increasing population pressure and climate change. The dynamics of these changes are complex to understand and cause the degradation of natural resources. Many processes are responsible for the rapid land use changes over space and time. Due to increasing population pressure in the hilly regions, deforestation has increased, bringing the forest land under annual cultivation/habitat construction. It also exerted pressure on farmers to go for intensive cultivation without leaving time for green manuring or a fallow period to replenish the soil. These changes have resulted in soil and water quality degradation. Climate change and inadequate rainfall distribution also brought many fertile agricultural lands under real estate. Hence, deriving land use-specific management options to enhance the soil carbon sequestration potential is necessary to mitigate future climate change impacts on soils.

3.1 Improving soil carbon sequestration potential of Agricultural land use:

Some of the best management practices for agricultural lands to improve the carbon sequestration potential are listed below

- Organic Manure application
- Balanced fertilization
- Conservation tillage (minimum, zero/no-till)
- Mulching
- Crop residue management
- Cover cropping

3.2 Organic manure application:

The application of organic manure add carbon and other nutrients in the soil. The addition of organic manures in agricultural lands increases SOC stocks. Carbon stocks in the world at 0–20 cms depth improved 240–460 Kg C $ha^{-1}yr^{-1}$ after ten years of manure addition (Gattinger *et al.,* 2012). Further, a 30% increase in SOC at plough layer (0-15 cm) due to organic manure addition (Zavattaro *et al.,* 2017). Manure application could further add SOC concentration due to added organic C inputs in manure (Zhao *et al.,* 2014). Continuous addition of manure for four years, a 25% C was stored in the soil carbon pool (Eghball, 2002).

3.3 Balanced Fertilisation:

The Green Revolution transformed India into self-sufficient in food grain production; no other activity had such an immense impact on the country's economic development. The fertilization approach was one of the best field management practices to achieve high crop yields in intensive agriculture with high yielding varieties. But recently, farmers forgot the 4:2:1

ratio of NPK application and urea as a nitrogen fertilizer is used much more than the recommendation. Indiscriminate application of fertilizers also degrades the soil quality (Lin et al., 2014). Hence balanced nutrient application combining chemical fertilizers and organic manures will help enhance microbial activity and carbon sequestration.

3.4 Conservation Agriculture:

Intensive and conventional agricultural practices challenged agriculture's sustainability through soil degradation, declining soil organic matter, loss of soil biodiversity, depletion of groundwater, and greenhouse gas (GHG) emissions (Parihar et al., 2018). Decreased land availability and increased cropping intensity, urging the farmers to remove the crop residues from the field immediately after harvest. Intensive cultural operations with farm equipment break the natural soil aggregates and modify the soil structure. This practice leaves the soil surface bare and highly prone to erosion and soil degradation (Doraiswamy et al., 2007). Minimum soil disturbance and maximum crop residue returns will improve soil organic carbon (SOC) storage and maintain soil health. Conversion to no-till practice on the lands under corn-soybean cropping rotation could sequester about 2% of the annual anthropogenic emissions of CO_2 emissions in the United States (Bernacchi, Hollinger, & Meyers, 2005). Conservation agriculture supports soil in adapting to climate change by improving its resilience against extreme climatic situations (Maity et al., 2021).

3.5 Mulching:

Mulching with organic materials can effectively change the soil microclimate, enhance microbial activity, and release soil nutrients to plants (Vogel et al. 2015). Mulching will change the nutrient cycle and energy flow between the soil and plants and alter SOC dynamics. It improves soil properties by adding carbon and nutrient sources through the decomposition of organic matter; and directly increases SOC.

3.6 Crop residue management:

Crop residues contribute to the maintenance of soil organic carbon (SOC), a key component of soil fertility and soil-based climate change mitigation strategies. Crop residues are essential for maintaining soil organic matter content and sustaining crop production. They are also a vital energy source for soil macro- and microorganisms, stabilizing soil aggregates, enhancing nutrient cycling, and improving soil physical properties (Canqui and Lal 2009). In regions with >20°C annual temperature decomposition rate of crop residue is higher than in the cooler regions. Hence, a threshold level of residue retention in soils of the tropics to increase the SOC pool should be determined. Crop residue retention in fields should be an integral part of crop cultivation to increase the soil's organic carbon level

3.7 Cover cropping:

Cover crops are an important soil carbon sequestration strategy usually used as green manure and ploughed into the soil before the subsequent crop is sown important cover crops belong to cereals, brassicas, and legumes to fit almost any cropping system. Apart from reducing the erosion and carbon loss cover crops enhance the growth of soil organisms, which increases soil carbon levels over time. Nine years of cover crop addition contributed 10–20 Mg C ha^{-1} organic carbon in soils compared to no cover crop experiment (Chahal et al., 2020). Cover crops should be fast growing and produce higher biomass for serving both the purpose of erosion control and soil carbon sequestration.

3.8 Carbon sequestration in forest soils:

Forests are a major terrestrial ecosystem which occupies 30–43 % of the world's land surface. They serve the purpose of habitats for wildlife, clean water and carbon storage, and climate mitigation. Forest biomass is the major pool of green carbon, and the total amount is estimated at approximately 359 billion tons (Allen et al. 2010). Forest soil is the largest carbon pool among the soils of various land uses. Overall, the forest ecosystems store twice as much carbon as the atmosphere. The carbon sequestration and the role of forests in curbing climate change are remarkable. Worldwide, forests store approximately 47% of total global carbon (Malhi et al. 2002). The carbon sequestered in soil can stay in the ground for a long period of time. Carbon is released due to microbial decomposition for energy. This process depends largely on soil drainage, climate, natural vegetation, and soil texture.

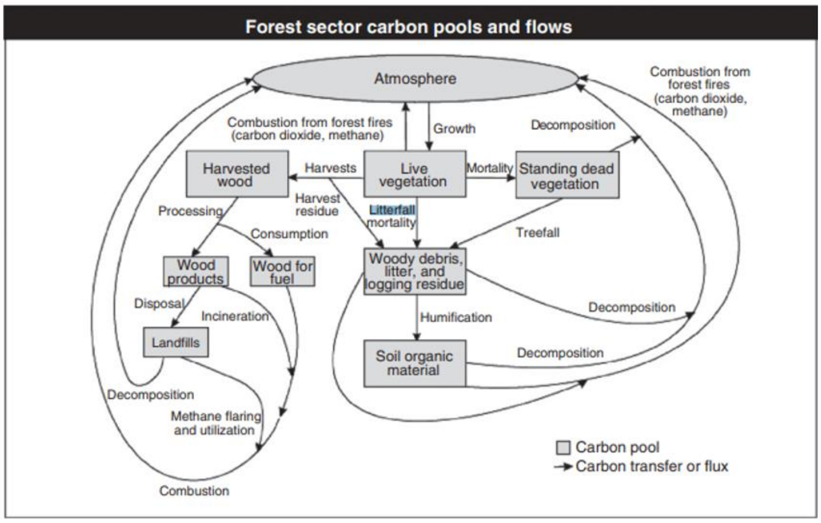

FIGURE 3: Forest carbon sequestration cycle
Source: EPA (2010).

There are many approaches to increase the carbon content of forest soils

1. The most obvious approach is afforestation: Simply planting trees on a previously unforested site/wastelands
2. Proper forest management to increase the biomass
3. Extending the harvest rotation for the joint production of carbon and timber
4. Carbon credit system
5. Forest fire can accelerate carbon loss from soils, hence proper fire management system should be derived and executed

Management practices that maintain forest cover, create forests where they did not exist previously (afforestation) and avoid drainage of systems with deep organic soils (which contain substantial carbon stores), are likely to have the best results for keeping carbon in forest soils.

3.9 Involving farming community and public in carbon sequestration:

The farming community's involvement is essential in achieving the potential soil carbon sequestration rate. Government initiatives to sequester the soil carbon will motivate the farmers to recognize the importance of carbon in sustainable soil health management

- **Incentives:** Farmers applying all best management practices to improve the soil carbon have to be given incentives such as money or inputs
- **Priority in subsidies and insurance:** The farmers who sequester carbon on their farm should be given preferences in subsidies and crop insurance claim
- **Recognitions and awards:** Farmers should be recognized with awards and certificates for their contribution to carbon sequestration
- **Community Carbon parks:** The establishment of village level carbon parks with carbon sequestering potential and fast-growing tree and grass species in community lands
- **Convergence with Corporate social responsibility:** Corporate sector can adopt a village under CSR to improve the carbon status of degraded land
- **Carbon tax:** Farmers who are not improving the carbon status of their land should be taxed
- **Creating awareness:** Awareness to sequester the carbon in soil and farm through mass awareness and skill development programmes.

IV. CONCLUSION

Soil health management will continue to play a prominent role in any land use systems and will be influenced by climate change. Healthy soil is more resilient against fluctuations in climatic parameters. The resiliency of the soil ecosystem needs to be enhanced to cope with climatic variations. Building and improving soil health through SCS in agricultural and forest soils will ensure continued productivity, enhance farmers' incomes, and holistically promote food security. Building and maintaining healthy soil is not easy, especially in the arid and semi-arid regions. Carbon sequestration is the global need to combat the impacts of climate change through greenhouse gas emissions. Achieving this global mission is possible only through local vision involving the farmers, researchers and common public as agricultural/ forest soils and trees have the tremendous potential to sequester atmospheric carbon. Focus on soil health management to mitigate the climate change impacts is indispensable to have a sustainable ecosystem with high biodiversity.

REFERENCES

[1] Allen CD, Macalady AK, Chenchouni H et al (2010) A global overview of drought and heatinduced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684.

[2] Bernacchi, C. J., Hollinger, S. E., & Meyers, T. (2005). The conversion of the corn/soybean ecosystem to no-till agriculture may result in a carbon sink. Global Change Biology, 11, 1867–1872.

[3] Canqui. HB., and Lal R (2009). Crop Residue Management and Soil Carbon Dynamics. In Soil Carbon Sequestration and the Greenhouse Effect, 2nd edition. SSSA Special Publication. Pp. 291-309.

[4] Chahal, I., Vyn, R.J., Mayers, D. et al. (2020). Cumulative impact of cover crops on soil carbon sequestration and profitability in a temperate humid climate. Sci Rep 10, 13381

[5] Doraiswamy, P.C., McCarty, G.W., Hunt, Jr.E.R., Yost, R.S., Doumbia, M. and Franzluebbers, A.J. 2007. Modeling soil carbon sequestration in agricultural lands of Mali. Agricultural Systems 94: 63-74.

[6] Eghball. B (2002). Soil properties influenced by phosphorus and nitrogen based manure and compost applications. Agron. J., 94: 128-135

[7] Environmental Protection Agency (EPA). 2010. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008. Rep. 430-R-10-006. https://www.epa.gov/ghgemissions/ inventory-us-greenhouse-gas-emissions-and-sinks-1990-2008

[8] FAO, 2015. Revised World Soil Charter. (Available at https://www.fao.org/3 /I4965E / i4965e.pdf)

[9] GattingerA. , A. Muller, M. Haeni, C. Skinner, A. Fliessbach, N. Buchmann, P. Mäder, M. Stolze, P. Smith, N.E.H. Scialabba, U. Niggli (2012). Enhanced top soil carbon stocks under organic farming Proc. Natl. Acad. Sci. U. S. A., 109: 18226-18231.

[10] Heikkinen, J., Ketoja, E., Nuutinen, V., & Regina, K. (2013). Declining trend of carbon in Finnish cropland soils in 1974–2009. Global Change Biology, 19(5), 1456–1469.

[11] Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123(1–2):1–22.

[12] Lal, R. 2013. Soil carbon management and climate change. Carbon Management. 4(4) : 439–462.

[13] Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D. J., Glaser, B (2021). Soils and sustainable development goals of the United Nations (New York, USA): an IUSS perspective. Geoderma Reg. 25.

[14] Lin, H., Jing, C.M., Wang, J.H., 2014. The influence of long-term fertilization on soil acidification. Adv. Mater. Res. 955–959: 3552–3555.

[15] Maity PP , Somasundaram J, Datta A , Mondal S., Parihar C.M., Madhu C , Pramod Jha , Bhattacharyya R., Bandyopadhyay K.K. and Debashis Chakraborty 2021. Conservation Agriculture for Soil Health and Carbon Sequestration. Journal of Agricultural Physics. 21(1) : 145-164.

[16] Melillo, J., Frey, S. D., DeAngelis, K. M., Werner, W. J., Bernard, M. J., Bowles, F. P., Grandy, A. S. (2017). Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science, 358, 101–105

[17] Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S et al (2017) Soil carbon 4 per mille. Geoderma 292:59–86.

[18] Parihar, C.M., Parihar, M.D., Sapkota, T.B., Nanwal, R.K., Singh, A.K., Jat, S.L., Nayak, H.S., Mahala, D.M., Singh, L.K., Kakraliya, S.K., Stirling, C.M. and Jat M.L. 2018. Long-term impact of conservation agriculture and diversified maize rotations on carbon pools and stocks, mineral nitrogen fractions and nitrous oxide fluxes in Inceptisol of India. Science of the Total Environment 640–641: 1382-1392.

[19] Vogel JG, He D, Jokela EJ, Hockaday W, Schuur EAG (2015) The effect of fertilization levels and genetic deployment on the isotopic signature, constituents, and chemistry of soil organic carbon in managed loblolly pine (*Pinus taeda* L.) forests. For Ecol Manag 355: 91–100.

[20] ZavattaroL. , L. Bechini, C. Grignani, F.K. van,Evert, J. Mallast, H. Spiegel, T. Sandén, A. Pecio, J.V. GiráldezCervera, G. Guzmán, K. Vanderlinden, T. D'Hose, G. Ruysschaert, H.F.M. ten Berge (2017). Agronomic effects of bovine manure: a review of long-term European field experiments. Eur. J. Agron., 90: 127-138.

[21] Zhao S. , P. He, S. Qiu, L. Jia, M. Liu, J. Jin, A.M. Johnston (2014) . Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. Field Crops Res., 169: 116-122.