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8. Carbon Sequestration: Mitigating Climate Change Through Agriculture

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Abstract:

The Industrial Revolution, beginning in the late 1700s in Great Britain, marked a significant transition from agrarian economies to industrialized and mechanized production. This era of rapid industrialization and innovation led to the mechanization of agriculture, growth of factories, mass production, and new transportation modes. However, it also resulted in increased greenhouse gas (GHG) emissions, contributing to the greenhouse effect and atmospheric warming. The main sources of GHG emissions were fossil fuel combustion and deforestation. Consequently, global temperatures have risen, sea levels have increased, and extreme weather events have become more frequent, threatening biodiversity and ecosystems. Carbon sequestration emerges as a vital strategy to mitigate these effects. This process involves capturing and storing atmospheric CO_2 *through terrestrial, geological, and oceanic methods. Terrestrial sequestration, particularly in plants and soil, offers a natural, cost-effective approach. Implementing improved agricultural practices, such as conservation tillage, crop rotation, and agroforestry, can enhance soil carbon storage and contribute to climate change mitigation. Additionally, carbon trading and credits under the Kyoto Protocol provide economic incentives for reducing GHG emissions. Thus, soil carbon sequestration presents a practical solution to sequester atmospheric* CO_2*, improve soil health, and ensure sustainable agricultural productivity in the face of climate change.*

Keywords:

Carbon sequestration, mitigation measures.

8.1 Introduction:

A period of major industrialization and innovation during the late 1700s and early 1800s which was first began in Great Britan, saw the mechanization of agriculture, growth of factories, mass production of manufactured goods and introduction of new modes of transportation like steamships, automobiles, and airplanes. It is responsible for creating capitalism and the modern cities of today. It marked a shift from agrarian and handcraft-based economies to industrialized and mechanized production. However, unintended consequences of the Industrial Revolution were the rapid increase in the emission of greenhouse gases (GHGs) into the atmosphere leading to the greenhouse effect, GHGs act as the glass planes of a greenhouse which absorb and emit radiation at specific wavelengths within the spectrum of infra-red radiation and thereby trapping the heat radiated from the ground.

This, process is generally referred to as greenhouse effect, adds to net energy of the lower atmospheric temperature, therefore results in Atmospheric Warming.

The main sources of GHG emissions during this period were from the burning of fossil fuels (coal, oil, and natural gas) to power factories, transportation, and homes. Also, deforestation for industrial purposes and agricultural expansion also contributed to increased GHG levels as trees play a vital role in absorbing CO_2 from the atmosphere. This led to serious effects like global temperature rise (by 1.1°C above pre-industrial levels (Delmotte, 2018), Rising sea levels, ocean acidification, shrinking ice sheets and extreme weather events such as hurricanes, droughts, heatwaves, and heavy rainfall which threatened biodiversity. Before the Industrial Revolution atmospheric carbon dioxide was 280 ppm or less, now in 2022 it was 417.06 ppm. The increase between 2021 and 2022 was 2.13 ppm—the 11^{th} year in a row where the amount of carbon dioxide in the atmosphere increased by more than 2 ppm. It is now reaching levels 50% higher than before the industrial revolution. And, 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019 (Lan *et al*., 2024). The global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99°C higher than 1850–1900. So, changes in temperature, CO_2 and increase in concentration of GHGs in the atmosphere may be natural or human driven altered earth's climate and showed its impact on the environment, ecosystems, and human societies called climate change (Soeder, 2021)

Table 8.1: Sources of GHGs

Natural Sources	Anthropogenic Sources
Volcanic eruptions	Agriculture
Ocean release	Land use change
Soil respiration and decomposition	Deforestation
Wetlands	Transportation
Earthquake	Industries
	Fossil fuel burning
	Electricity generation

8.2 Greenhouse Gases Potentials:

1. Carbon Dioxide (CO_2): CO_2 is the reference gas with a GWP of 1 over all time frames. This means that other gases are compared to CO_2 in terms of their warming potential.

2. Methane (CH4): Methane is a potent greenhouse gas with a GWP of approximately 25 over a 100-year period. This means that methane has around 25 times the warming potential of CO_2 over a century.

3. Nitrous Oxide (N_2O): Nitrous oxide is another potent greenhouse gas with a GWP of about 298 over a 100-year period.

4. Hydrofluorocarbons (HFCs): HFCs are synthetic gases used in various applications, including refrigeration and air conditioning. Different HFCs have varying GWP values, but many of them are significantly more potent than CO_2. Some HFCs have GWP values in the thousands or even tens of thousands.

5. Perfluorocarbons (PFCs): PFCs are industrial gases used in certain manufacturing processes. They have high GWP values, ranging from hundreds to thousands.

6. Sulfur Hexafluoride (SF6): SF6 is used in electrical equipment and has an extremely high GWP, estimated to be around 23,500 times that of CO_2 over a 100-year period.

Table 8.2: GHGs: contributions on global warming

Greenhouse gases	**Contributions on global warming**
Carbon dioxide (CO2)	50%
Methane (CH4)	16-20%
Chlorofluorocarbons (CFC)	13-18%
Ozone (O3)	7-8%
Nitrous oxide (N2O)	4-5%
Water Vapor	2%

8.3 Effects of Climate Change:

Global Temperature Rise- The average global temperature has increased significantly over the past century, primarily due to human activities such as burning fossil fuels and deforestation.

Warming Oceans- Oceans have absorbed about 90% of the excess heat from global warming, resulting in higher sea surface temperatures. This warming affects marine ecosystems, disrupts weather patterns, and contributes to the bleaching of coral reefs, which are critical to marine biodiversity.

Shrinking Ice Sheets- Ice sheets in Greenland and Antarctica are losing mass at an accelerating rate. Greenland lost an average of 286 billion tons of ice per year between 1993 and 2016, whereas, Antarctica lost 127 billion tons of ice per year (Anonymous, 2024). The melting of these ice sheets contributes to sea level rise and poses a threat to coastal communities worldwide disrupting habitats for species that depend on ice-covered regions.

Glacial Retreat- Glaciers around the world are retreating at unprecedented rates contributing to sea level rise impacting freshwater resources. Many regions rely on glacial meltwater for drinking water, agriculture and hydropower their loss can lead to water shortages.

Sea Level Rise- Rising Sea levels, caused by the melting of ice sheets and glaciers and the expansion of seawater as it warms. Higher sea levels lead to increased flooding, erosion, and saltwater intrusion into freshwater supplies, affecting millions of people living in coastal regions.

Declining Arctic Sea Ice- Arctic Sea ice is declining in both extent and thickness. This loss of ice accelerates warming in the Arctic, disrupts local ecosystems and affects global weather patterns.

Extreme Weather Events- Climate change is linked to an increase in the frequency and intensity of extreme weather events such as hurricanes, heatwaves, droughts, and heavy rainfall. These events can lead to devastating impacts on communities, economies, and ecosystems, causing loss of life, displacement, and significant economic costs.

8.4 Effect of Climate Change on Agriculture:

The dependency of agriculture on climate is indicated by the fact that cultivation is mostly in rainfed area out of total net sown area, which is dependent on uncertainties of monsoon and temperature fluctuations. Some of its key impacts listed below:

- Reduction of crop yields
- Increase in moisture stress
- Alteration in nutrient dynamics
- Reduced soil organic matter and fertility status
- Soil erosion, Salinization and alkalization
- Increase in pest and disease incidence
- Increase in weed infestation
- Migration of pollinators
- Reduced nutritional value of crops

Highly intensive agriculture in the name of green revolution notwithstanding the alarming depletion in soil organic C and increasing the production of major greenhouse gases and enhancing the contamination of ground water.

These impacts necessitate adaptive management strategies to sustain soil fertility and agricultural productivity in the face of a changing climate. Under such situation "carbon sequestration" play a key role to conserve natural resources and achieve sustainability in agricultural production, it is also known as "**carbon capture**." A geoengineering technique for the long-term storage of carbon dioxide (or other forms of carbon) for the mitigation of global warming.

8.5 Types of Carbon Sequestration:

- In plants and soil “terrestrial sequestration” (“carbon sinks”)
- Underground “geological sequestration”
- Deep in ocean “ocean sequestration”
- As a solid material (still in development)

Terrestrial Carbon Sequestration:

- The process through which CO_2 from the atmosphere is absorbed naturally through photosynthesis & stored as carbon in biomass, latter litter/ dead plants upon addition to soil contributed to enhancement of soil organic carbon.
- Terrestrial sequestration involves plant sequestration (biomass) and soil carbon sequestration (Soil organic carbon and soil inorganic carbon).
- Deforestation is responsible for world’s annual CO_2 emissions, though offset by uptake of atmospheric CO_2 by forests and agriculture.
- Carbon accumulation eventually reaches saturation point where additional sequestration is no longer possible (when trees reach maturity, or when the organic matter in soils builds back up to original levels before losses occurred).
- After saturation, the trees or agricultural practices still need to be sustained to maintain the accumulated carbon and prevent subsequent losses of carbon back to the atmosphere.
- The potential of soil carbon sequestration in India is estimated at 10-14 Tg C/y for restoration of degradable soils and ecosystem (Lal *et al.* 2004)

Soil carbon sequestration is a natural, cost effective and environment friendly process.

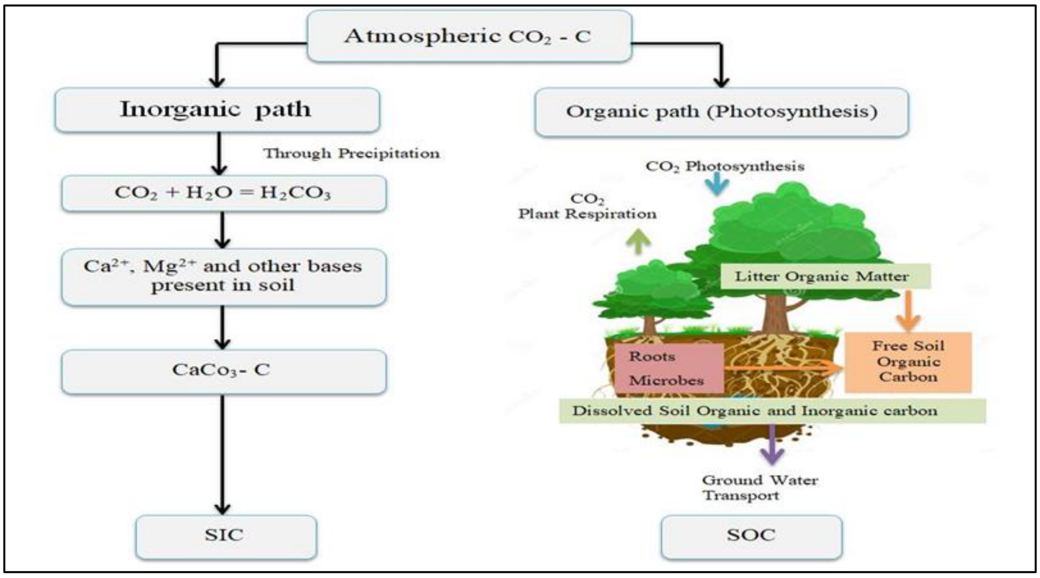

Figure. 8.1: Carbon Sequestration Mechanism in Plants and Soil (Anonymous, 2021)

Table 8.3: The Potential of Carbon Sequestration in Soil of India

Region	Area (M ha)	C sequestration potential (Tg C yr^{-1})
Arid	52.0	0.67-1.34
Semi-arid	116.4	2.33-4.66
Sub-humid	86.4	3.46-5.18
Sub-humid/humid	33.3	2.06-2.72
Per humid	20.2	2.42-3.03
Sub-humid/semi-arid	8.5	0.34-0.51
Humid/Perhumid	11.9	1.43-1.79
Total	328.7	12.71-19.23
Secondary carbonates	328.7	21.78-25.6
Erosion control	--	4.80-7.20
Total	328.7	39.29-52.03

Tg= Teragram Lal (2004)

Geological Sequestration:

- Storing of CO_2 underground in rock formations able to retain large amounts of CO_2 over a long time period.

Ocean Sequestration:

- Carbon is naturally stored in the ocean via two pumps *viz.*, solubility and biological, and there are analogous man-made methods, direct injection and ocean fertilization, respectively. Eventually equilibrium between the ocean and the atmosphere will be reached with or without human intervention and 80% of the carbon will remain in the ocean. The same equilibrium will be reached whether the carbon is injected into the atmosphere or the ocean. The rationale behind ocean sequestration is simply to speed up the natural process.
- Carbon sequestration by direct injection into the deep ocean involves the capture, separation, transport, and injection of CO_2 from land or tankers. $1/3^{rd}$ of CO_2 emitted a year already enters the ocean; Ocean has 50 times more carbon than the atmosphere.
- Carbon Sequestration is not yet viable at a commercial level. Small scale projects demonstrated (lab experiments) but Carbon sequestration is still a developing technology.

Concern with injecting carbon dioxide into ground or ocean because fear of leaks into water table or escape of CO_2 into a massive bubble that can potentially suffocate humans and animals.

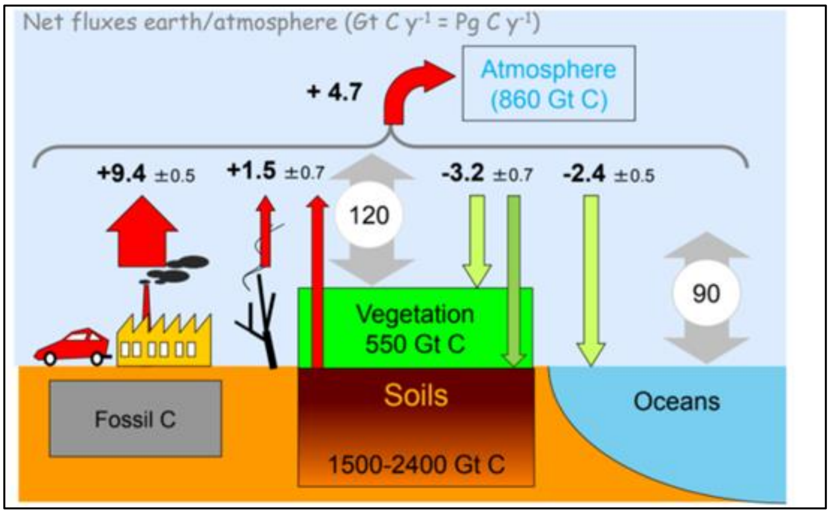

Figure 8.2: Carbon Flow Through Various Sources (Source: Le Quéré *et al.* 2018)

8.6 Measures to Offset Greenhouse Gases:

- Avoiding emissions by maintaining existing carbon storage in trees and soils.
- Increasing carbon storage by tree planting (Carbon sequestration rates differ based on the species of tree, type of soil, regional climate, topography & management practice).
- Limiting excessive grazing
- Reducing burning of crop residues
- Improved agricultural management practices

1. **Conservation tillage**- Reducing soil disturbance, permanent soil cover and diversified cropping systems improves soil properties.
2. **Retention of crop residues-** Decreases rain drop impact, decreases evaporation losses, and increase in SOC content, favoring crop yields.
3. **Mulching**- Reduces vulnerability of soils to erosion and degradation, reducing evaporation, lowering occurrence of salinity, and Weed control.

Table 8.4: Effect of Legume Mulching on Chemical Properties of Soil

Treatment	Organic C (%)
Legume mulching	
Control	0.56
Sunhemp (S)	0.67
Leucaena (L)	0.66
S+L	0.72
Initial	0.57

Sharma *et al.* (2010)

Table 8.5: Effect of Tillage and Mode of Mulch Application on Runoff (%) and Soil Loss (Mg ha^{-1})

Mode of Mulch	Runoff (%)		Soil Loss (Mg ha^{-1})	
	Minimum Tillage (Tm)	Conventional Tillage (Tc)	Minimum Tillage (Tm)	Conventional Tillage (Tc)
Mulch on whole plot	**17**	**21**	**2.1**	**3.1**
Mulch on lower 1/3rd plot	26	29	6.3	6.8
Mulch in strips	31	34	8.1	10
Mulch in vertical holes	44	51	15.5	21.4
No mulch (control)	**47**	**55**	**17.2**	**25**
Mean	33	38	9.8	13.2

Bhatt and Khera (2006)

4. **Cover cropping-** They are defined either as additional crops planted on the field postharvest or crops intercropped with the main crop.

- In cases of leguminous cover crops, they can supply considerable stocks of nitrogen (N) to the soil, which are available for uptake by the subsequent main crops.

5. **Perennial pastures-** Can be grown as an integral component of the multi-year cropping sequence, include a range of native or introduced grasses and legumes for fodder or forage production.

- These are efficient in reclaiming degraded agricultural lands while providing a range of ecosystem services, such as the increase in species diversity, supporting complex food webs, and boosting soil health.
- Their deep root systems enhance soil carbon sequestration.

Table 8.7: SOC (%) after 15 Years of Planting of the Different Perennial Fodder Grasses

Fodder Species	SOC (%) at 0-15 cm Soil Depth	SOC (%) at 15-30 cm Soil Depth	SOC (%) at 30-45 cm Soil Depth
Broom grass	**1.75**	**1.33**	**1.42**
Setaria	2.40	**2.31**	2.15
Perennial ground nut	2.30	1.99	2.08

Fodder Species	SOC (%) at 0-15 cm Soil Depth	SOC (%) at 15-30 cm Soil Depth	SOC (%) at 30-45 cm Soil Depth
Congosignal	**2.55**	1.96	**2.20**
Guinea var. Makunia	2.54	2.23	1.92
Guinea var. Hamil	2.25	1.89	1.83
Napier	1.93	1.77	2.05
Paspalum	2.21	1.97	1.49
Control (no fodder)	1.63	1.12	1.38

Ghosh *et al*. (2009)

6. Crop rotation:

Crop rotation, as opposed to continuous monoculture, it is a practice of growing a series of different types of crops in the same area across a sequence of growing seasons.

- It affects soil quality by altering the SOC content, soil structure, soil aggregation and nutrient cycling.
- Amount of crop residues returned to the soil during crop rotation plays a crucial role in SOC sequestration, with different crop rotations having varying effects.
- Crop rotations and intercropping with nitrogen-fixing crops will enhance soil fertility and enrich nutrient supply to subsequent crops, leading to increased crop yields.

Table 8.8: Effect of Medium-Term Tillage Practices and Intensified Cropping Systems on Total Soil Organic Carbon at Different Depths after Harvest of Winter Season Crops in The Sixth Year

Treatment	SOC g Kg^{-1} Depths (cm)		
	0-5	5-15	15-30
Tillage practices			
PB	**7.74**	6.28	5.41
ZT-flat	7.49	**6.31**	**5.52**
CT-flat	5.46	4.71	4.35
LSD (P<0.05)	0.33	0.29	0.58
Cropping pattern			
MWMb	7.48	6.04	5.32
MCS	**7.52**	**6.25**	**5.64**
MMuMb	6.30	5.33	4.50

Treatment	SOC g Kg^{-1}		
	Depths (cm)		
	0-5	5-15	15-30
MMS	6.30	5.45	4.90
LSD (P<0.05)	**0.35**	**0.40**	**0.41**

PB-permanent bed; ZT-zero tillage; CT- conventional tillage; MWMb- maize–wheat–mungbean; MCS- maize–chickpea–*Sesbania;* MMuMb- maize–mustard–mungbean; MMS-maize–maize–*Sesbania*

Patra *et al*. (2023):

7. **Agroforestry-** An important conservation farming option, encompasses several practices such as alley cropping, multi-story cropping and silvo-pastoral systems, where trees or shrubs are intercropped with grain crops, vegetables, or forages.

- Additional agroforestry practices include windbreaks, to reduce wind erosion.
- It also provides a range of products, including food for human consumption, fodder for livestock, timber for building, wood for fuel, and pollen for honey bees.
- Sustain many ecosystem services such as increasing species diversity, enhancing wildlife habitats, fostering natural food webs, fostering water infiltration, improving soil and ecosystem health, augmenting long-term C sequestration, and decreasing emissions of CO_2.
- Reclaiming degraded lands.

Table 8.9: The Potential for C Sequestration in Agroforestry Systems

Agro-Forestry systems	System Characterstics	Soil carbon (Mg C ha^{-1})		Time Frame for Realizing the Potential (yr)
		Stock to 50 cm Depth	Potential for Sequestering Additional C to 100 cm Soil Depth	
Alley cropping	E>5 yr	20-45	25-75	>5
	N or young<5 yr	20-70	30-120	>10
Silvipasture (grazing systems)	E, TD low < 50 ha^{-1}	20-80	50-100	>20
Shaded perennial systems	E>15-yr-old	100-200	20-50	10

E-existed, N-new, TD- tree density

Nair *et al*. (2010)

8. **Biochar**- Biochar is a carbon-rich coproduct of pyrolyzing biomass subject to high-temperature and oxygen-deprived conditions for biofuel production (Liu *et al.*, 2016).

- Highly resistant to microbial activity
- Augmenting the recalcitrant fraction of SOC and decreasing emissions of CO_2 from soil
- Lesser leaching of nutrients, and smaller contamination of off-site water sources.
- Increase in CEC is attributed to the existence of carboxylic groups on the surfaces of the biochar itself, as well as due to exposed carboxylic groups of organic acids absorbed by the biochar, both of which contribute negative surface charge to the biochar. Enhance adsorption of nutrients in the rooting zone.
- In addition, the high porosity of biochar augments physical quality of the soil, increasing its water-holding capacity and hydraulic conductivity.

Table 8.10: Effect of biochar application on mitigating GHG emissions under field conditions

Biochar feedstock	Pyrolysis temp. (◦C)	Application Rate (Mg ha^{-1})	Cultivated Crop	GHG emissions Rate (%) Compared with Control		
				CO_2	N_2O	CH_4
Wheat	550	20	Corn-wheat	0.13	20.79	-
		40		-5.40	31.54	-
Corn straw	550	26.0	Cabbage + carrot	-20.12	11.19	-
		64.0		-59.98	-18.33	-
		128.0		-87.21	5.58	-
Rice straw	600	20	Rice	9.87	15.75	-7.37
		40		25.36	43.60	15.07
Cattle feedlot waste	550	10	Ryegrass	0.27	-13.67	-
Pig manure	-	15	Soybean	-	-49.49	-

Mosa *et al*. (2023)

9. Precision Nutrient Management:

It is a management strategy utilizing innovative, site specific techniques for management of spatial and temporal variability for enhancing output, efficiency and profitability of agricultural production in an environmentally responsible manner."

Table 8.11: Soil Biological Properties Under Nutrient Management Practices

Nutrient management	Active Carbon (mg kg^{-1} Soil)	Microbial Biomass Carbon (µg C g^{-1} Soil)	Soil Dehydrogenase Activity (µg TPF Rel g^{-1} Day^{-1})
Farmers field practices	37.1	390	28.7
Site-Specific Nutrient Management	39.8	420	30.2
Green Seeker based management	40.1	414	30.0
LSD ($p \leq 0.05$)	2.8	20	1.3

Pramanick *et al*. (2022)

10. Integrated Nutrient Management: By combining chemical fertilizers, organic manures, crop residues, green manuring, agro-industrial by-products, and biological fixation, INM promotes the efficient use of natural resources and increases crop production. This holistic approach maintains soil fertility and improves soil physical conditions. Moreover, INM reduces soil and water erosion, controlling soil, water, and air pollution. These benefits collectively contribute to mitigating climate change by fostering a healthier and more resilient agricultural ecosystem.

Table 8.12: Organic Carbon Status After Two Cycle of Rice-Mustard Cropping System

Treatments	Organic C content (%)	
	0-15cm	**15-30 Cm**
T_1 – Absolute control	0.42	0.30
T_2 – FYM@10 t ha^{-1}	0.50	0.33
T_3 – FYM@10 t ha^{-1} +50 kg P_2 O_5 ha^{-1}	0.49	0.32
T_4 – FYM@ 10 t ha^{-1} + 50 kg N + 25 kg P_2O_5 ha^{-1}	0.48	0.33
T_5 – FYM@ 10 t ha $^{-1}$ + + 50 kg N + 50 kg P_2 O_5 ha^{-1}	0.48	0.32
T_6 –FYM@ 10 t ha^{-1} + 75kg N +37.5 kg P_2 O_5 ha^{-1}	0.50	0.31
T_7 – FYM@ 10 t ha^{-1} +75kg N +50 kg P_2 O_5 ha^{-1}	0.49	0.32
T_{8-} FYM@ 10 t ha^{-1} +100kg N ha^{-1}	0.51	0.33
T_9 – FYM@ 10 t ha^{-1} +100 kg N + 25 kg P_2 O_5 ha^{-1}	0.52	0.32
T_{10} – FYM@ 10 t ha^{-1} + 100 kg N + 37.5 kg P_2O_5 ha^{-1}	**0.52**	**0.34**
T_{11} – FYM@ 10- t ha^{-1} + 100 kg N + 50 kg P_2 O_5 ha^{-1}	0.53	0.32
T_{12} – 100 kg N + 50 kg P_2 O_5 ha^{-1}	0.43	0.31
CD at 5%	0.05	NS

Goud and Konde, 2009

Table 8.13: Effect of INM on Organic Carbon in Inceptisols

Treatment	Organic carbon (%)	
	After 1 year	After 3 year
T1-RDF OF NPK (120:26:50)	0.41	0.40
T2-FYM@10 t ha-^{1}+NPK (90:20:37)	0.65	0.70
T3- VC@5 t ha^{-1}+NPK (90:20:37)	0.63	0.65
T4-GM+NPK (90:20:37)	0.55	0.58
T5-FYM@10 t ha^{-1}+AB+PB+NPK	**0.68**	**0.74**
T6-VC@5 t ha^{-1} +AB+PB+NPK	o.64	0.67
T7-GM+AB+PB+NPK	0.56	0.64
T8-GM+AB+PB+B+NPK	0.57	0.58
CD(P=0.05)	0.09	0.15

AB=Azatobacter,PB=Phosphate solubilizing bacteria; VC=Vermicompost GM=Green manure of dhaincha Srinivasarao *et al*. (2008)

Table 8.14: Carbon Stock in Different Land Use System

Land Use	Carbon Stock (Mg/ha)		
Depth	**0-15**	**0-30**	**0-50**
Agriculture	18.8	33.1	48.5
Horticulture	22.2	37.5	53
Forestry	**44.5**	**79.6**	**116.3**

Chandran *et.al. (*2009)

8.7 Protocols of C Sequestration:

Carbon Trading:

- Carbon sequestration is one of the important mitigation strategies to cope with the impact of climate change.
- The kyoto protocol brought the mechanism of trading carbon unit as a global mechanism to address the issue of reducing emission by various countries to meet the mandatory requirement.

Carbon Credit:

- Carbon credit is a concept that a incentivizes countries which reduce their GHG emission and disincentivises those who do not reduce their GHG emission.

- Under the kyoto protocol each company that shifts to cleaner technologies obtains to it account one credit per ton of CO_2 emission reduction. This credit to the company obtains is called carbon credit.
- The protocol imposes target commitment upon a country who in turn set emission quota on companies in their country to fulfill their quota.

8.8 Conclusions:

Soil carbon sequestration is an effective resource to sequester atmospheric CO_2 with better practical application than other approaches. Crop a land use management practice can be employed to sequester more carbon in plant and soil to enhance soil health, and sustainability and secure food productivity with changing climate in rainfed areas.

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