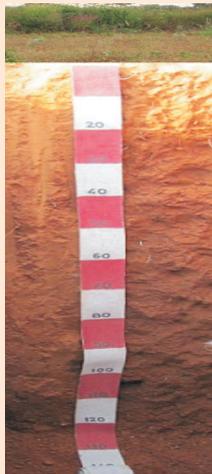


A Practical Manual on Estimation of Carbon Sequestration



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सत्यमेव जयते

त्रिलोचन महापात्र, पीएच.डी.

एफ एन ए, एफ एन ए एस सी, एफ एन ए ए एस
सचिव एवं महानिदेशक

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Foreword

The “4 per Thousand” initiative was launched at the 21st Conference of Parties (COP21) in December 2015 to address global climate change through the aspirational goal of increasing SOC stock of the world to a 40 cm soil depth by an average annual rate of 0.4% to keep space with food security by 2050. In India, extreme weather events are costing approximately \$9-10 billion annually and climate change is further projected to impact agricultural productivity with increasing severity by the end of the century. World wide carbon (C) sequestration is considered as a win-win-win strategy because it advances food security, improves the environment and mitigates global warming *vis-a-vis* climate change.

Soil organic carbon (SOC) stock of India was last estimated in the year 2000 and a recent map was brought out, but the depletion of the carbon stock has not been fully averted mainly owing to faulty soil management practices, deforestation, inappropriate land uses and climate change. The rate of C depletion is faster in the small land holders (SLHs), who often failed to implement best management practices (BMPs). For successful implementation of Reducing Emissions from Deforestation and Degradation (REDD+) payment mechanism of C credit in forest ecosystem and inclusion of C credit farming policy issue in Intergovernmental Panel on Climate Change (IPCC) protocol under changing climate scenario, uniform and accurate SOC estimation is required. Implementation of identical methodologies and *in-situ* measurement of SOC and use of uniform terminology are important. Hence, an effort has been made in this document to define different terminologies of C sequestration, and method to determine/compute them with proper illustrations. The information provided in the document will be useful to assess the performance of the identified region-specific BMPs for technology transfer under climate change and C credit policy issue.

The technical manual entitled “*A Practical Manual on Estimation of Carbon Sequestration*” has been developed by the collaborative effort of ICAR-IISWC, Dehradun; ICAR-IARI, New Delhi and ICAR-NBSS&LUP, Nagpur. This technical manual will help not only the students and researchers, but also it would assist the planners. I congratulate the authors for their initiative, commitment and excellent efforts for bringing out this manual to help capacity building for the students, scientists and all those engaged in Soil Organic Carbon Research.

Dated the 17th May, 2018
New Delhi


(T.MOHAPATRA)

Director Desk



Soil organic carbon (SOC), a key component of the global C pool, plays an important role in C cycling, regulating climate, water supplies and biodiversity, and therefore in providing the ecosystem services that are essential to human being. The global soil carbon (C) pool amounts to 2500 Gt, whereas the biotic pool is only 560 Gt. Most agricultural soils in temperate regions have lost as much as 60% of SOC and as much as 75% in tropical regions, mainly due to conversion of natural ecosystems to agricultural uses. On a global scale, C loss from soils is mainly associated with soil degradation, including accelerated erosion and mineralization, and land use change, and has amounted to 78 ± 12 Gt since 1850.

Consequently, the present organic carbon pool in agricultural soils is much lower than their potential capacity. Results showed an increase in atmospheric CO₂ from about 280 to more than 400 ppm, over the last 250 years, is causing measurable global warming. The most important challenges were how to bring back these emitted atmospheric CO₂ to vegetation and soil profile to establish soil as a sink to prove the hypothesis that soil can store 2-2.5 times more carbon than the atmosphere. Challenges of policy issues of C credit farming in field cropping system require accuracy and uniform methodology follow up.

Managing soils to obtain multiple economic, societal and environmental benefits requires integrated policies and technologies that maintain and enhance soil C. Developing effective policies capable of growing terrestrial C sinks is a serious challenge in tropical and subtropical soils. The implementation of improved land management practices is the need of the hour to build-up C stocks in tropical and subtropical soils. Decisive actions are to be implemented to limit soil C loss due to erosion and emissions of carbon dioxide and other greenhouse gases to the atmosphere. The tropical and subtropical soils need technically sound and economically feasible strategies to enhance SOC pools in a sustainable manner. Although there are many literatures available related to SOC pools and stocks, scattered information are available on this aspect. Moreover, estimation protocol, depth of soil sampled, terminology used and methodology adopted are often different with different researchers. It will be better to follow uniform estimation, terminology and methodology to identify best management practices and their impacts on changes in SOC stocks and C sequestration potentials.

I congratulate the authors for their initiative, commitment and excellent efforts for bringing out the manual to help capacity building of the stakeholders, planners, scientists, students and all those engaged in C sequestration research and land use planning.

A handwritten signature in black ink, appearing to read 'P.K. Mishra', with a long horizontal stroke extending to the right.

(P.K.Mishra)

Preface

Carbon (C) sequestration is a win–win–win strategy because it advances food security, improves the environment and mitigates global warming vis-a vis climate change. The first ever estimate of organic carbon (OC) stock in Indian soils was 24.3 Pg (1 Pg = 10^{15} g) based on 48 soil series of the major soils. Latter on the SOC stock has been estimated at 63.2 Pg in the first 150 cm soil depth and 21.0 Pg in 0-30 cm, considering five major physiographic regions. Most agricultural soils in temperate regions have lost 60% of soil organic C (SOC) and 75% of SOC in tropical regions. At the 21st Conference of Parties (COP21) in December 2015 to address global climate change through the aspirational goal of increasing SOC stock of the world to 40 cm depth by an average annual rate of 0.4% initiative was launched. Small land holders (SLHs), often faced with difficult bio-physical and socio-economic conditions, are the principal managers of soils in India. Government of India harmonized database showed 120.7 million hectare (Mha) land is degraded, 70% of which is due to water erosion and C loss thereby is unknown. Human-induced soil degradation results from mostly deforestation and inappropriate agricultural practices. Extreme weather events are costing India \$9-10 billion annually and climate change is projected to impact agricultural productivity with increasing severity from 2020 to the end of the century. Of these, nearly 80% of the total financial losses remain uninsured. Major sustainable soil management options for curbing degradation were climate ready-crops, changing planting date, crop insurance, conservation agriculture with tree/vegetative buffer strips and participatory integrated watershed management for soil and water conservation using land resource inventory based land use planning in larger scale. To achieve the entire task, a strong research group is required who would monitor SOC and its pools using harmonized methodology, with accuracy, in-situ measurements and with a uniform terminology. In Indian perspective, different terminologies are often being used in the literature. This often misleads the researchers and policy makers. Hence, effort has been given in this document to define different terminologies and to compute them with examples, so that one could properly assess the performances of the identified region-specific best management practices for technology transfer under changing climate scenario and under C credit policy issue. The IPCC has made protocol for C credit payment of the tree growers for the developing countries through REDD+ mechanism. However, IPCC is yet to decide the payment mechanisms for soil C sequestration in favour of the other categories of farmers. The major causes for this are mostly concerned with the accurate estimation and quantification of short- and long-lived C pools. In addition, limited research works have been conducted about the potentiality of C sequestration in the arable lands of the SLHs due to non-adoption or inappropriate adoption of best management practices (BMPs). There are 117 million SLHs representing 85% of the total operational holdings, cultivating over 72 Mha of land, and meeting 50–60% of India's food requirement. The agricultural soils of SLHs are strongly depleted of OC and nutrient reserves. Therefore, the challenge of feeding 1.7 billion people in India by 2050 will depend on increasing the current productivity levels by restoring the depleted soils of SLHs. In this practical manual, we outline methodology for computing C sequestration in lands to fulfil the dual objectives of advancing food security, the “4 per Thousand” target and mitigating climate change in India through accurate quantification of C sequestration. It will guide in formulating policy issue on soil C credit in lands of small holders.

(Authors)

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The technical manual entitled “A Practical Manual on Estimation of Carbon Sequestration” was written in a collaborative mode with the institutions involved, ICAR-Indian Institute of Soil and Water Conservation, Dehradun, ICAR-Indian Agricultural Research Institute, New Delhi and ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur.

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We are also indebted to all contributors who directly or indirectly helped in bringing out this manual. We sincerely hope that this publication would immensely benefit the students, researchers, officials and policy makers engaged in carbon sequestration research *vis-a-vis* natural resource management to combat land degradation

Contents

| Sl.No. | Description | Page No. |
|---------------|---|-----------------|
| 1. | Introduction | 1 |
| 1.1 | Climate change and carbon sequestration | 1 |
| 1.2. | Soil quality and carbon sequestration (CS) | 3 |
| 1.3. | Concept of soil carbon sequestration | 4 |
| 1.4. | Soil organic carbon pools | 4 |
| 1.5. | Role of C pools in C sequestration | 5 |
| 2. | Soil survey, sampling, and preparation | 5 |
| 2.1. | Sampling from the experimental plots | 5 |
| 2.2. | Soil sampling from the district or block level areas: | 6 |
| 2.3. | Soil sampling in watersheds | 7 |
| 2.4. | Management history of the study sites | 7 |
| 2.5. | At field laboratories | 7 |
| 2.6. | At instrumentation laboratory (Central Laboratory) | 8 |
| 2.7. | Sampling leaf litter fall | 8 |
| 2.8. | Fine root | 8 |
| 3. | Laboratory measurements | 9 |
| 3.1. | Walkley-Black C | 9 |
| 3.2. | Total soil carbon, total soil organic carbon and total inorganic carbon | 10 |
| 3.3. | Soil organic matter determination by Loss-on-Ignition method | 13 |
| 3.4. | Labile and recalcitrant C pools | 13 |
| 3.5. | Water soluble C and hot water soluble C | 13 |
| 3.6. | Carbohydrate C | 13 |
| 3.7. | Particulate organic C and soil aggregates carbon | 14 |
| 3.8. | Determination of Total SOC/SOM (using SOC Conversion factor) | 14 |
| 3.9. | In situ measurement of soil carbon | 15 |
| 4. | Computation of carbon sequestration rates | 17 |
| 4.1. | Estimation of gross C inputs (field crops /arable lands) | 17 |
| 4.1.1. | Determination of mummification rate constant | 17 |
| 4.1.2. | Estimation of carbon input (Agroforestry and forestry systems) | 18 |
| 5. | Different terminology and estimation | 20 |
| 5.1. | Carbon stocks | 20 |
| 5.2. | Carbon sequestration potential (CSP) | 22 |
| 5.3. | Carbon stabilization | 22 |
| 5.4. | Determination critical carbon values for soils | 22 |
| 5.5. | Carbon saturation deficits | 23 |
| 5.6. | Carbon balance | 23 |
| 5.7. | Carbon sink | 23 |
| 5.8. | Carbon emission factor | 23 |
| 5.9. | Carbon management index (CMI) | 23 |
| 5.10. | Carbon budgeting | 23 |
| 5.11. | Carbon credits/trading | 24 |
| 6. | Soil organic carbon prediction using some models (Indian scenario) | 24 |
| 6.1. | Roth-C model | 24 |
| 6.2. | EX-ACT Model | 25 |
| 6.3. | Comparative features of some carbon estimation models- (India) | 26 |
| 6.4. | Carbon storage estimation in trees-past and present | 26 |
| 7. | Annexure | 27 |
| 8. | References | 29 |

Abbreviations

| | |
|---|---|
| AFS | Agro Forestry Systems |
| CDIAC | Carbon Dioxide Information Analysis Centre |
| CDM | Clean Development Mechanism |
| DBH | Diameter at Breast Height |
| DBGU | Diameter Below Graft Union |
| EFA | Education For All |
| $\text{Fe}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$ | Ferrous Sulphate |
| $\text{FeSO}_4 (\text{NH}_4)_2 \text{SO}_4 \cdot 6\text{H}_2\text{O}$ | Ferrous Ammonium Sulphate |
| FYM | Farm Yard Manure |
| GHG | Green House Gas |
| GT | Giga Tonnes |
| H_2SO_4 | Sulphuric Acid |
| INM | Integrated Nutrient Management |
| IPCC | Intergovernmental Panel on Climate Change |
| $\text{K}_2\text{Cr}_2\text{O}_7$ | Potassium Dichromate |
| NaOH | Sodium Hydroxide |
| NATCOM | National Communication |
| OC | Organic Carbon |
| SIC | Soil Inorganic Carbon |
| TC | Total Carbon |
| TOC | Total Organic Carbon |
| UNFCCC | United Nations Framework Convention on Climate Change |
| WMO | World Meteorological Organization |
| GEFSOC | Global Environmental Facility Soil Organic Carbon |

1. Introduction

Soil organic carbon (SOC), a key component of the global carbon (C) pool, plays an important role in C cycling, regulating climate, water supplies and biodiversity, and therefore in providing the ecosystem services that are essential to human well-being. The global SOC mass is relevant for the C cycle budget and thus atmospheric C concentrations. The Intergovernmental Panel on Climate Change (IPCC) identified five C pools of the terrestrial ecosystem involving biomass, namely the above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter (SOM).

Carbon sequestration is a win–win–win strategy because it advances food security, improves the environment and mitigates global warming. Benefits of C sequestration are manifold. It improves soil quality, increases use efficiency of inputs, reduce in soil erosion and sedimentation, decrease in nonpoint pollution, mitigate climate change by offsetting anthropogenic emissions, improve water quality, improve agronomic productivity and advances food security. Carbon sequestration implies capturing atmospheric CO₂ into long-lived pools of C. Carbon sequestration is also known as “carbon capture” which is a geo-bio-engineering technique for the long-term storage of carbon dioxide (or other forms of carbon) for the mitigation of global warming. There are four major ways by which C can be stored (sequestered): i) in plants and soil “terrestrial sequestration” (carbon sinks), ii) underground “geological sequestration”, iii) deep in ocean “ocean sequestration” and iv) as a solid material (still in development). Our topic of interest is C sequestration in plants and soils i.e. terrestrial C sequestration. Terrestrial C sequestration is the process through which CO₂ from the atmosphere is absorbed naturally through photosynthesis and stored as carbon in biomass and soils. Tropical deforestation is responsible for 20% of world's annual CO₂ emissions, though largely offset by uptake of atmospheric CO₂ by forests and agriculture.

The accurate estimation of soil carbon (C) stocks and dynamics is a necessary for understanding the global C budget. The soil carbon consists of organic and inorganic components. The SOC pool is derived from remains of plants and animals. SIC pool is described as parent materials of primary carbonates (lithogenic) and atmospheric CO₂ as secondary carbonates (pedogenic). Characteristics and dynamics of SIC pool in arid and semi arid regions soils of India has been reported by Pal et.al. (2003) and found that aridity in the climate is responsible for the formation of pedogenic calcium bicarbonate and this is an adverse condition for the enhancement in SOC. Increase in C sequestration via SOC enhancement in the soil would induce dissolution of native calcium carbonate and it's leaching, resulting in SIC sequestration. Thus there may be a synergy in SOC and SIC sequestration.

Estimation of the total SOC stock of different eco-regions of India is essential to monitor SOC changes over the years and over adoption of appropriate management practices. The first ever estimate of organic carbon (OC) stock in Indian soils was 24.3 Pg (1 Pg = 10¹⁵ g) based on 48 soil series (Gupta et al.,1984). Assessing the impact of land use conversion, soil management and cropping/farming systems on SOC pools in diverse spatial scales is essential to understand the magnitude of the depletion of SOC, to establish the cause-effect relationship, and to identify BMPs for re-carbonization of soils following a specific protocol. The past estimates of SOC pools in soils of India were 24 Pg (Pg = petagram = 10¹⁵ g = 1 billion metric tonne) and 63 Pg in the 0-30 cm and 0-150 cm depth, respectively (Bhattacharyya et al., 2000). They considered five major physiographic regions of India, of which the highest was in peninsular plateau and the least in the costal plains and Islands. Using the GEFSOC Modeling System and comparing it with the mapping technology, Bhattacharyya et al. (2008) estimated SOC pool of the Indo-Gangetic Plains (IGP) at 1.27-1.32 Pg for 0-20 cm depth. Other estimates of SOC pool for IGP ranged from 0.57-1.44 Pg. For the central Western Ghats, covering an area of 8.8 million hectare (Mha), and stretching between Goa and the Palghat Gap, SOC pool has been mapped for forests at varying levels of degradation (Krishnan et al.,

2007). Wani et al. (2010) estimated SOC pool to 0.3 m depth for the state of Madhya Pradesh (M.P.) for the year 2005-2006. These estimates were based on the remote sensing data, district boundaries, the agro-ecological sub-regions and the geographic information system (GIS) using the FAO/UNESCO soil map. Total biomass and SOC pool of M.P. were 34.9 and 790.6 Tg C (Tg= teragram = 10^{12} g = 1 million metric tonne), respectively. The ecosystem C pool of the Kolli Hills, parts of the eastern Ghats of Tamil Nadu, were estimated by Ramachandran et al. (2007) at 2.74 Tg and 3.48 Tg for biomass and SOC pool, respectively. Similarly, C pool for soils of Rajasthan was estimated at 1.23 Pg for SOC and 0.90 Pg for soil inorganic C (SIC) in the 1 m depth (Singh et al., 2007). Of these, the surface 0-25 cm layer stored 31% of the total C pool.

Walkley –Black recovery factor (WBRF) studies by Bhattacharaya et al. (2011) which showed wide variation with rainfall region, soil types and ranges between 78- 87% (factor 1.15 to 1.28) for the surface soil (0-15 cm depth) in IGP region whereas 76- 78% (factor 1.29 to 1.31) in BSR. These factors also varied with different depth of soil. Considering a universal correction factor (assuming 1.29, 77% recovery) in all soil types and depths will over or underestimates the SOC stock estimation,

Comparing the carbon stock simulated through GEFSOC modeling system and with mapping techniques, estimated SOC pool of the IGP at 1.27– 1.32 Pg for 0-20 cm for rice-wheat system of IGP, revealed that GEFSOC modeling estimated higher than mapping techniques. It may be because of crop input parameter (crop management) inclusion by model which does not happen in mapping technique (texture and wetness). Evaluation of Century model in long term experimental data set consisting two contrasting climate (semi-arid, dry <800 mm rainfall and humid, >1600mm) of IGP physiographic region was accomplished and found that model overestimates by 15% in SOC in overall stock estimation in predicting at national and sub-national scale. It has also been reported that model performed well in semi-arid dry region and less in humid IGP and identified lowland flooded rice and triple cropping as the major constrain for less performance of Century model. Comparative soil organic carbon modeling studies with Roth-C, Denitrification and Decomposition (DNDC) and Century model at NBSS&LUP revealed average to modest performance in different physiographic region but the estimation potential of Roth-C model found higher accuracy (observed vs. measured) than DNDC and Century model under diverse physiographic and soil management conditions in India. Work on Roth-C model identified factors for differences in SOC stock in modeling and soil mapping techniques mentioning inclusion of crop input factor in model as major variant for differences. The study emphasized the importance of Roth-C model (using soil survey data base) for SOC estimation, land use planning, and identifying BMP, to mitigate climate change in India (Bhattacharyya et al., 2011)

Thus, the basic objective of the manual is to harmonize all methodologies of C estimation, to estimate changes in SOC stocks under different land uses, management practices and changing climate scenarios. Another idea is that in India, researchers may use the uniform terminologies to identify the impacts of BMPs on C sequestration. In this manual, only C sequestration protocols are discussed.

1.1 Climate change and carbon sequestration

The CO₂ concentration in the atmosphere has increased from 280 ppm in 1850 to 408 ppm in 2018. There have been increases in the atmospheric methane (CH₄) and nitrous oxide (N₂O) concentrations over the same period resulting in increased radiative forcing, leading to global warming (IPCC, 2007). The green house gas (GHG) emissions should be reduced by 50 to 80% by 2050 to avoid the adverse consequences of global warming. There are three major strategies of lowering CO₂ concentration from the atmosphere: (i) reducing the global energy use, (ii) developing

low or no-carbon fuel, and (iii) sequestering CO₂ from point sources or from atmosphere through natural (vegetation/soils) and engineering techniques. In 2010, world emitted 50 billion tonnes CO₂ equivalent, of which India emitted 5% of global GHGs. The major sources of CH₄ emission are ruminants, rice field and manure management and sources of N₂O and CO₂ are soil, fertilizer, manure management, tillage, soil erosion and residue burning (Schrag, 2007). In recent years there has been a consistent and continuous increase in the emission of GHGs into the atmosphere, due to the anthropogenic activities, viz. burning of fossil fuels for energy, deforestation, land-use change, biomass burning and draining of peat and wetlands (Fig. 1).

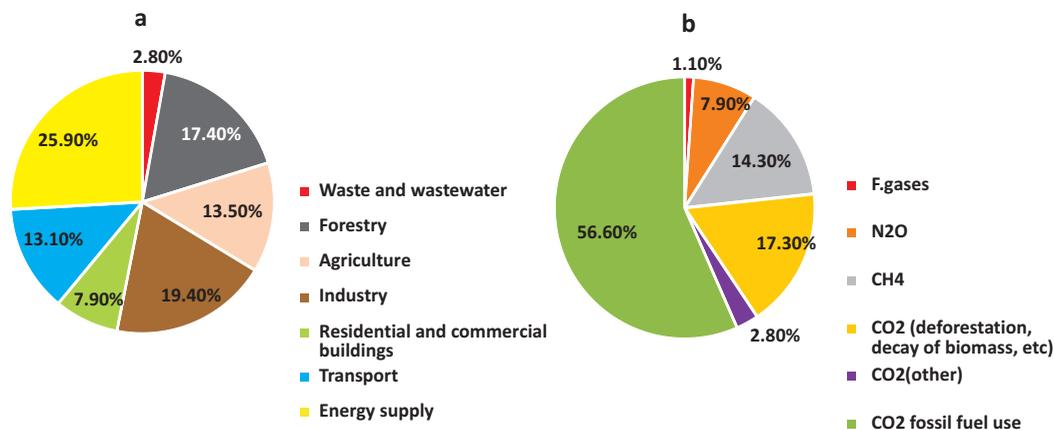


Fig.1 : Contribution of various sources in GHG emission (a) and share of various GHG in global warming (b) (IPCC, 2007).

1.2. Soil quality and carbon sequestration (CS)

Carbon sequestration plays an important role on soil quality. It influences soil physical, chemical and biological functional properties. It regulates energy and nutrients for soil biota, influences aggregate stability, water retention, hydraulic properties, resistance or resilience to compaction, buffering capacity, cation exchange capacity and formation of soluble and insoluble complexes with metals. More recently, a greater range of labile soil organic matter (SOM) attributes such as light fraction of organic matter (LF), particulate organic matter (POM, >53- <2000µm), water soluble carbon, acid hydrolysable carbohydrates and potentially mineralizable fraction of C are more sensitive to changes in management. Little attention has been paid towards estimation of labile pools of C compared to total SOC in most agricultural soils. However, labile fraction has a disproportionately large effect on nutrient supplying capacity and structural stability of soils. In agricultural soils, the light fraction typically contains 2-18% of total SOC and POM contains 20-45% of total SOC in the whole soil. Particulate organic carbon is the precursor for formation of soil microbial biomass C (MBC).

Humic and non-humic fraction of C in soil is a key attribute of soil quality. It is the major source of cellular C and energy for the heterotrophic microorganisms. The POM accumulation is also the major pathway by which nutrients are recycled from crop residues back to the soil and release nutrients by mineralization during decomposition of POM. The large POM maintains soil structure and macro-aggregation. The large amount of microbial community associated with the decomposing POM produces binding agents, such as exo-cellular mucilaginous polysaccharides. Particulate organic matter acts as a major food and energy for endogenic soil fauna. Thus, POM is associated with a magnitude of soil process and functions and is, therefore, a key attribute of soil quality. Acid hydrolysable carbohydrate (AHC) (32-37% of total SOC) is a labile C fraction and has been found changing more rapidly in response to changes in management than total SOC concentration. The KMnO₄-oxidizable C fraction accounts for 5-30% of SOC. This oxidizable fraction usually is more

sensitive to soil management than total SOC. Simple measurement of soil aggregate stability, POM, light fraction of C, and acid hydrolysable carbohydrates have to be evaluated on their sensitivity to change in different soils and crop management systems to estimate soil quality deterioration.

1.3. Concept of soil carbon sequestration:

Carbon sequestration in soil implies transfer and storage of atmospheric CO₂ into the SOC pool as recalcitrant humus and into the SIC pool as secondary carbonates. Its importance lies in the urgent need to offset increases in atmospheric enrichment of CO₂ and its benefits to agronomic yield and soil quality. Judicious land use and novel land management practices for a reasonably long time period generally are the means for attaining increased soil C sequestration (Bhattacharyya et al., 2012a, b; Bhattacharyya et al., 2013). Long-lived pools of SOM are time dependent turn over fractions of added C inputs. It mostly represents passive pool with a turn over period of centuries to millennium (800-2000 years) and represents mineral associated organic C (<53 µm clay+ silt size fraction, MAOC). The POM-C represents slow pool with turnover period of decades (20-50 years). The last pool is active pool with turnover period of months to year. It mostly represents soil microbial biomass carbon (SMBC).

The basic concept of C sequestration is depicted by Jastraw and Miller (1998) that how fungal hyphae and roots play an important role with clay, silt sized fraction to form micro-aggregates that ultimately form a macroaggregate in the rizhospheric soils to protect SOM

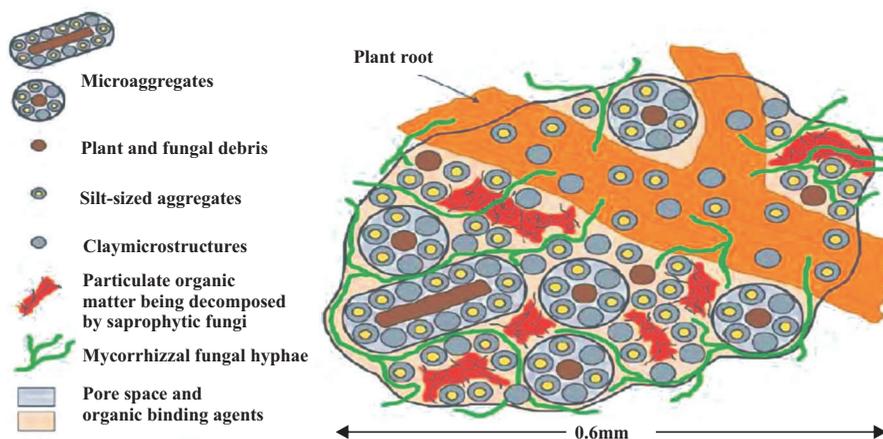


Fig. 2 :Micro-aggregate structures and the enveloping macro-aggregate under the binding influence of mycorrhizal fungal hyphae

1.4. Soil organic carbon pools

In most of the C sequestration studies in India, the oxidizable organic C fraction is considered. However, this is not the true representative of the changes in total SOC. So understanding of different C pools is required to quantify soil C dynamics and to create an inventory of C sequestration data base in a plot scale to a regional scale. Soil organic matter is generally characterized by dividing into different physical, chemical and biological pools. Labile fractions of SOM, rather than total SOM, have been proposed as sensitive indicators of changes in soil quality and soil's response to agricultural management. Several chemical and biological methods have been used to distinguish labile or biologically active and recalcitrant pools of SOM, with variable degree of success. Commonly used chemical methods include determination of dissolved organic C, hot water soluble C, potassium permanganate oxidizable C, and organic C fractions of different oxidizability. The biological methods for determination of active SOM pool include microbial biomass C and mineralizable C.

1.5. Role of C pools in C sequestration

The size of the overall C pool in soils can be misleading as an indicator of how that soil will behave, unless we understand something about the relative proportions of the different 'pools' in which C is present. The role of C pool in C sequestration has been well described by Bell and Lawrence (2009). Soils that have differing proportions of POM (relatively young, labile material), humus and recalcitrant compounds like charcoal behave very differently, both in terms of properties and the microbial communities (and resulting functions) they can support. Soils supporting open grasslands will have proportionally more char-like material in their native condition, from regular natural burning events, than similar soils under a rainforest. Similarly, soils in the sugar industry areas where regular trash burning occurs can also have high (up to 50%) soil C as charcoal, compared to much lower proportions with a long-term history of residue removal.

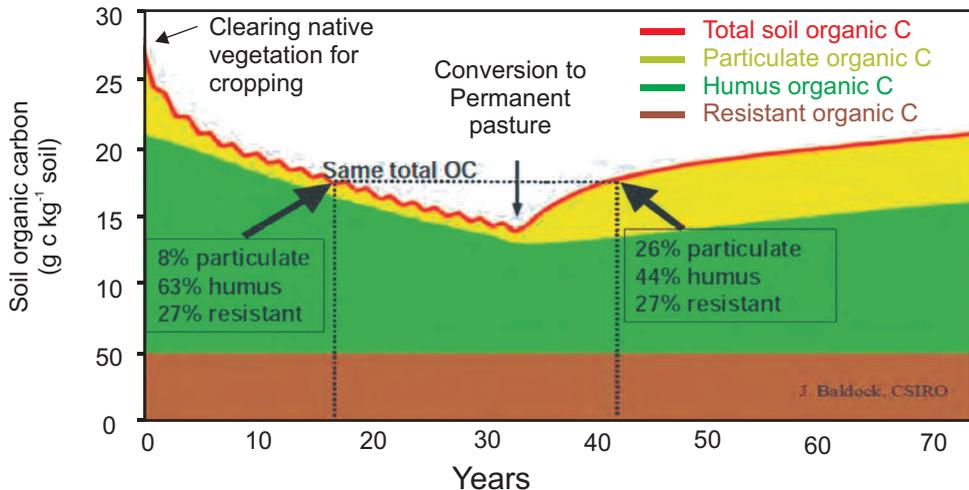


Fig. 3 : Land use effect on different carbon pools.

These proportions of different C pools are very important (Fig. 3.). Here (Fig. 3), the soil was examined twice in its management history—once during the continuous cropping phase after clearing the native vegetation and a second occasion after conversion of the cropped area to permanent pasture. If simply analyzed for total SOC, both soils would appear very similar. The amount of resistant/char like material was unchanged. However, while there had been a large increase in the particulate/labile fraction in response to the pasture, the amount of humus (decades-centuries to form) was much lower and still reflective of the end of the cropping rundown period. This means that (i) the long term soil nutrient stores had not recovered after 42 years of management, and (ii) this SOM would decline much more rapidly if the land was returned to cropping again (as the humus C was less). Research studies suggest that SOM rapidly declined after clearing the native vegetation to cropping.

2. Soil survey, sampling, and preparation

2.1. Sampling from the experimental plots

Soil sampling generally are being conducted in two ways. One in an experimental plot where different treatments are imposed and the other, in the district/block level. Composite samples have to be prepared for each treatment. Soil samples area of 25 m x 25 m is considered representative of a particular agricultural management within a plot. By sampling from a small area, errors due to encountering a soil type that is not representative of the targeted soil will be minimized. Two sets of duplicate undisturbed soil cores need to be collected after crop harvest from the 0-100 cm soil layers

2.3. Soil sampling in watersheds

The underlying basis for soil sampling in the watershed is that a soil sample taken represents the "population". Little attention seems to have been devoted to develop or evaluate a methodology for sampling at the watershed-level in rainfed agricultural production systems. It further implies that C status of the representative soil sample(s) determined in a laboratory would reflect C status of a watershed. The most important factor that influences the effectiveness of soil sampling is to minimize inherent soil heterogeneity

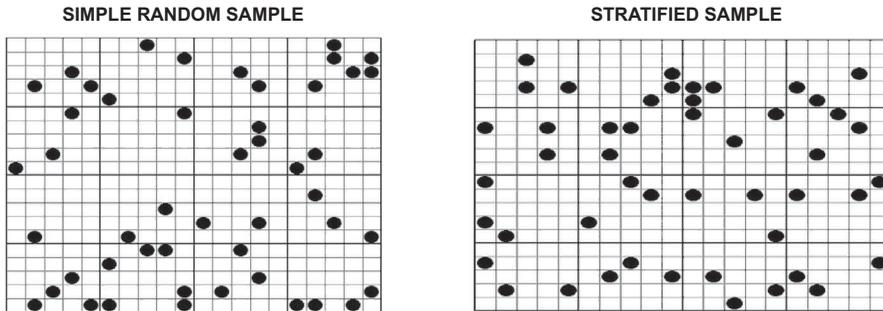


Fig. 6: Simple and Stratified random soil sampling in a watershed

Generally, land use is considered as basis for sampling. But, soil sampling strategy in a watershed should be based on taking samples to represent the entire watershed and stratified so that even a small population of the samples can represent the whole population. The soil sampling units should be stratified on the basis of crop, area covered by the crop, and number of farmers owning the land. Stratified random sampling methodology (Fig. 6) for collecting soil samples from the watershed may be followed to minimize spatial variability. A total of 100-125 soil samples from the surface (0-15cm) layer generally represent the entire watershed of 500 ha. Each sample may be a composite of 7-8 cores, randomly collected from the area represented by a crop and group of farmers. Stratified random sampling methodology can be adopted for sampling a watershed of about 500 ha in area (Sahrawat et al., 2008).

2.4. Management history of the study sites

A requisite for collecting soil from any given sampling site is that the farm owner/ manager is able to provide 10 years of detailed management history. The management history data are absolutely critical to the program of C sequestration assessment. Without these data, there is no way to ascribe differences in SOC concentration and composition within and between regions to management specific factors. The site information sheet covered major items such as crop type, yield, tillage, stubble management, irrigation, addition of fertilisers and other amendments/soil conditioners, fallow periods, residue cuts for hay, pasture type, pasture yield or stocking density and grazing management.

2.5. At field laboratories

Freshly collected field samples is initially air dried, typically at 40 °C for a minimum of 48 hours, and then the sample mass is recorded. Samples were then passed through an 8 mm sieve. Then one set of samples may be used for wet or dry sieving for analysis of soil aggregation and aggregate-associated C. Bulk soils (< 8-mm) may be ground to pass through a 0.2-mm sieve for analysis of bulk soil C.

Bulk density: Entire volumetric soil samples collected for determination of bulk density is oven dried to 105 °C to eliminate all moisture prior to weighing. Alternatively, the entire sample can be air dried and the oven dry equivalent weight may be determined on a subsample. Bulk density can be calculated according to equation

Bulk density (g cm^{-3}) = Dry mass of entire soil sample (g)/volume of the soil sample (cm^3)

2.6. At instrumentation laboratory (Central Laboratory)

The majority of samples received at the central lab as approximately 500 g of air dried soil material. Each sample may be quantitatively split down to a 30–40 g subsample using a riffle box (Civilab, 12×13 mm slotted box) to minimize bias in selecting the subsample for subsequent analyses. About 10 g of the split material is set aside in a glass scintillation vial for fine grinding and subsequent analyses.

Oven dry equivalent (ODE) mass: The residual moisture content in the soil samples after air drying should be quantified by mass loss after oven drying. A 20-g sample of the same split material should be weighed out into an aluminium foil weighing tray, placed in an oven at 105°C for 16–24 hr, allowed to cool in desiccators and then re-weighed. The difference between the initial and final mass should be recorded and used as the ODE correction factor (mass of residual water/mass of dry soil) in the calculation of all C concentrations. In high clay soils, C concentration (mg C g^{-1} of soil) measured on an air dried sample can be underestimated by up to 10–15% if a correction to oven dry equivalent soil was not performed.

Fine grinding: The 10 g subsamples should be finely ground for 3 minutes. The 180 second duration is found by Baldock et al. (2010) to be necessary to minimize variability in MIR spectra due to particle size differences between samples across a wide range of soil textures.

Fizz testing: Prior to organic C analysis, all samples should be tested for the presence soil of inorganic carbon (SIC). Approximately 0.5 g finely ground soil may be placed in a ceramic or plastic container and a few drops of 1M hydrochloric acid (HCl) should be poured directly on the sample. Visible effervescence is recorded as: 0 = none, 1 = slight, 2 = moderate, and 3 = vigorous. Any sample that scored 1–3 are then treated as containing IOC and need to pre-treated with acid to remove IOC.

2.7. Sampling leaf litter fall

The surface area under each tree species should be divided into 5 equal parts and litterfall traps of size $1 \text{ m} \times 1 \text{ m}$ should be randomly placed in parts of the stands that had comparable stand densities for each of the studied tree species. All the species should be of similar age. All together, 60 leaf litter fall traps /ha should be used for each site for collection of leaf-mass between August of previous year and July of study year on a 15 days interval basis. Estimated annual mass of leaf litter fall will be as the sum of the litter fall mass collected fortnightly during the study period. All the leaf litter from each trap should be collected in paper bags and returned immediately to the laboratory, where it should be cleaned, dried (70°C for at least 48 h), weighed and expressed in g m^{-2} on a monthly interval basis.

2.8. Fine root

Sequential coring should be followed to determine fine root mass. Although, the sequential soil core method may lead to some underestimation in fine root production. It is one of the most widely used methods because it estimates directly fine-root biomass. The size and definition of fine root varies from study to study, because root morphology and size differ between species and even within species across sites (Fitter, 1985). Root less than 5 mm diameter is regarded as fine root. Root biomass should be determined by destructive sampling at three random locations using 5.5 cm diameter soil cores from 0–7.5, 7.5–15, 15–22.5 and 22.5–30 cm soil depths. Generally soil cores (3 samples per soil depth) should be collected from random locations within each site at monthly interval basis. Samples should be randomly taken within 2 m from the bole of mature trees in order to minimize the error in the collection of root samples. Instead of specific distances, a range should be chosen, since this procedure allows the calculation of root mass per unit area. Cores should be taken in the first

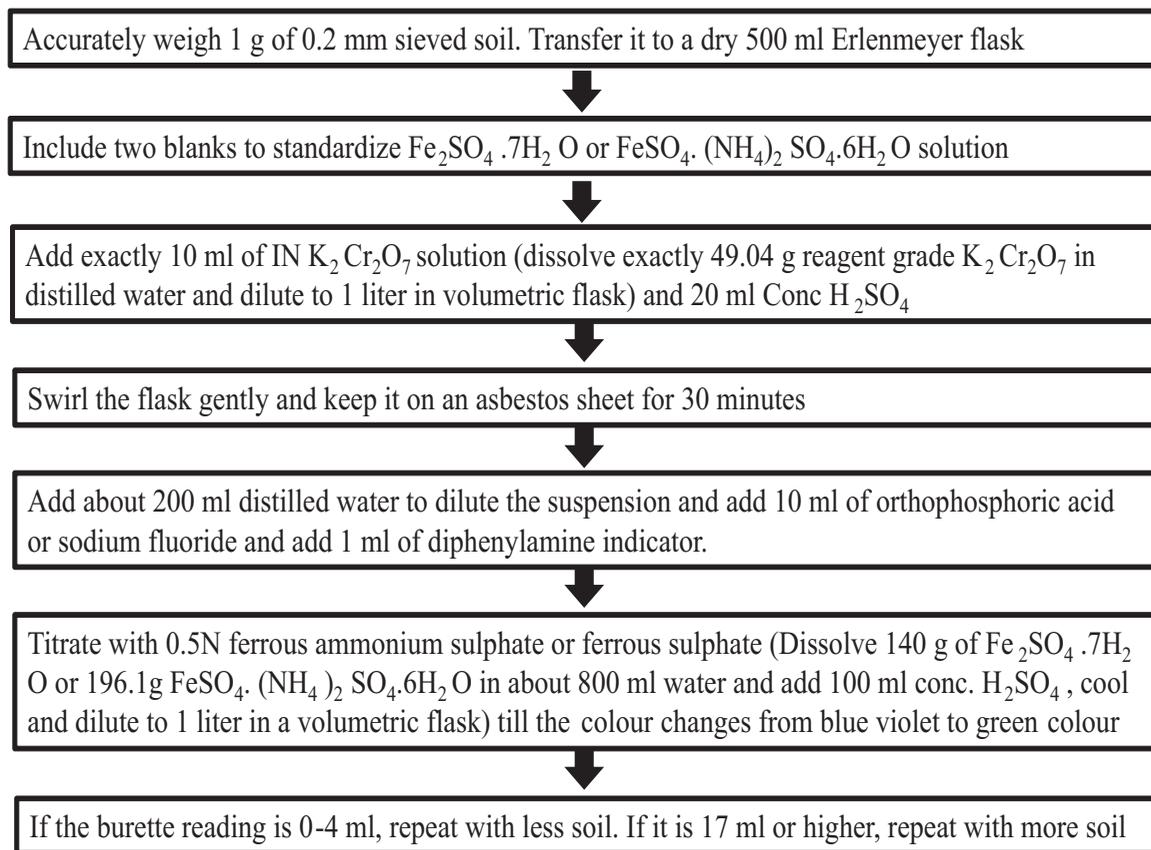
week of every month from August of the previous year to July of the next year. Fine roots collected from different depths should be summed and expressed in g m^{-2} . Roots should be separated from soil by soaking in water and then gently washing over sieves with mesh size of 5 and 0.5 mm. The roots should be washed by the same person during the experiment to minimize errors in cleaning operations. The clay particles adhering to roots should be carefully removed using forceps. Utmost care should be taken to free fine roots from soil particles through repeated washing and then it is oven dried at 70°C for 48 h.

3. Laboratory measurements

3.1. Walkley-Black C

Organic C pools can be estimated by the Walkley-Black method (Walkley and Black, 1934). In this method, organic C in the soil is oxidized with the mixture of potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) and concentrated H_2SO_4 utilizing the heat of dilution of H_2SO_4 . Unused $\text{K}_2\text{Cr}_2\text{O}_7$ is back titrated with ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) or ferrous ammonium sulphate [$\text{FeSO}_4 \cdot (\text{NH}_4)_2\text{SO}_4 \cdot 6\text{H}_2\text{O}$].

Step Wise Procedure for Estimation of Soil Organic Carbon



Calculation

$$\text{Organic carbon (\%)} = [10 (B-T)/B] \times (0.003 \times 100) / \text{Weight of soil (g)}$$

where,

B= volume (ml) of ferrous ammonium sulphate solution required for blank titration.

T= volume of ferrous ammonium sulphate solution needed for titration of soil sample

3.2. Total soil carbon, total soil organic carbon and total inorganic carbon

Total C (TC) in soils is the sum of both organic and inorganic C fractions. Total C analysis involves conversion of all forms of C in soils to CO₂ by wet or dry combustion methods and subsequent quantification of evolved CO₂ by gravimetric, titrimetric, volumetric, spectrophotometric or gas chromatographic methods (Nelson and Sommers, 1996). The dry and wet combustion methods are the two basic approaches to quantify the total C in soils. Dry combustion is conducted by heating (~1000°C) a soil–catalyst mixture in a resistance furnace or induction furnace in a stream of O₂ or CO₂ free air, followed by quantification of evolved CO₂. Through dry combustion method, oxidation of organic C and thermal decomposition of carbonate minerals is achieved. The commercially available automated instruments such as total organic C (TOC) analyzer and CHN analyzer employ the dry combustion. Loss of ignition (LOI) method can also be used where instrumentation facilities are not available for determination of SOM.

Principle of total C estimation using an elemental CHN Analyzer

Samples are combusted at elevated temperatures in a resistance or an induction furnace in the presence of a stream of pure oxygen. Combustion temperatures generally exceed 1000 °C. After oxidation, CO₂ is measured using an infrared detector. To ensure complete combustion of the sample, a pure oxygen stream is used as well as various catalysts or accelerators. Typical catalysts and accelerants include: vanadium pentoxide, Cu, CuO, and aluminum oxide. After several minutes of combustion in the pure oxygen stream, a carrier gas (helium) is turned on, the combustion chamber is swept clean, and the evolved gases are carried through the traps and scrubbers to the detector. Analyses are stopped after a known volume of gas has been collected or after a given amount of time has passed and the total SOC concentration can be determined through CHN analyzer (Fig.7). The C concentration should be reported on an oven-dry basis. So adjustments for moisture content will be necessary, if the samples are only air-dried prior to analysis.



Fig. 7: CHN analyser used for determination of TC Standards

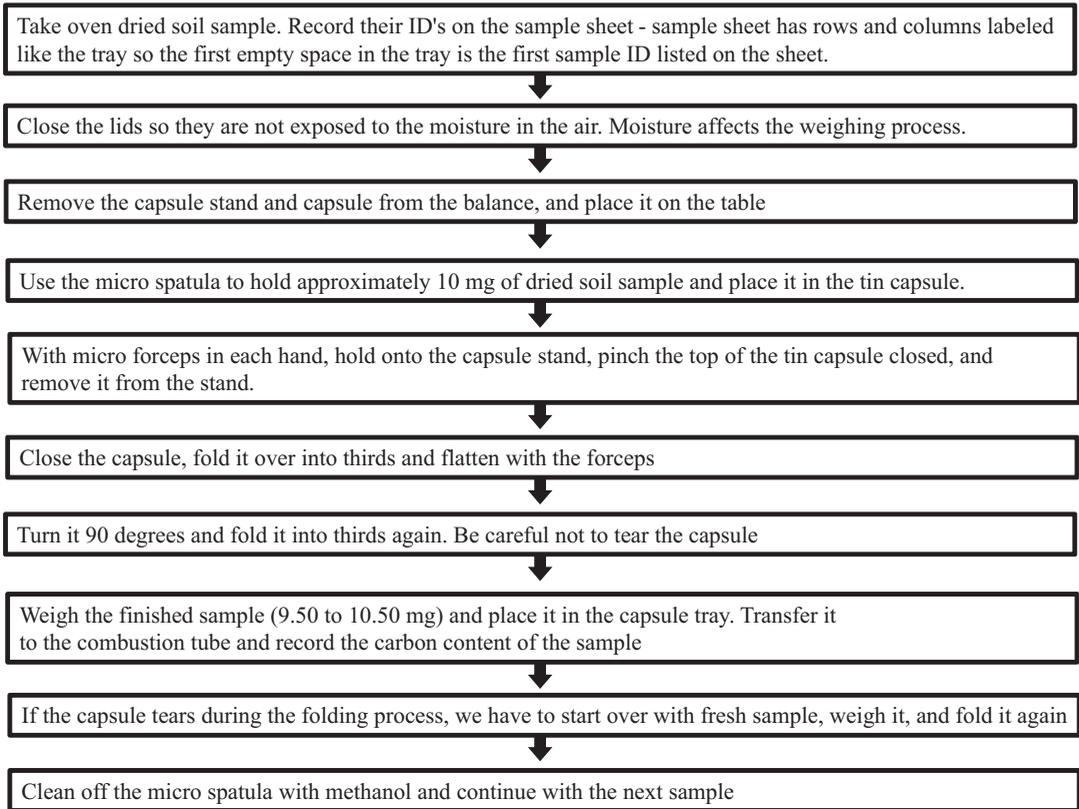
Standard 1: Calibration Standard. Potassium Acid Phthalate - KHP ($\text{KHC}_8\text{H}_4\text{O}_4$). This standard contains 47% organic C.

Standard 2: Calibration Control Standard (ICV or CCV). KHP (second source)

Standard 3: Sensitivity Check Standard (SCS). Certified soil standard

Standard 4: Soil Standard Reference Material (SRM)

Operational procedure of CHN Analyzer



Start running a conditioner sample by pushing single run. A conditioner sample is run at the beginning of each sample set in order to calibrate the machine. This sample is comprised of 1.5 to 2.5 mg of Acetanilide and run as a sample.

Inorganic carbon test

Place a small aliquot (approximately 1 g) of sample on a watch glass.

To this aliquot add 1 - 2 mL of 4 N HCl and observe for effervescence.

If effervescence is detected, or the sample is suspected of having inorganic carbon present, the sample must be treated for inorganic C removal.

Inorganic carbon (IOC) removal procedures

There are four common methods adopted by many researchers to remove Inorganic carbon from soil:

Acid rinse/ washing method: Soils are entirely mixed with diluted acid and washed with de-ionised water and dried before measurement of the organic carbon and $\delta^{13}\text{C}$ content (Midwood and Boutton, 1998).

Limitation: a. Loss of OC and change in $\delta^{13}\text{C}$ signature and loss of fine soil materials. b. time and labour consuming

Capsule method/ aqueous acid addition: Addition of stepwise diluted acid and water directly into soil which is in silver capsule and transfer to metal tray and keep on hot plate. The sample is monitored for effervescence and indicating IOC reaction. After end of reaction capsule folded and packed in tin capsule and measured OC and $\delta^{13}\text{C}$ content (Verardo *et al.*, 1990).

Limitation: soil contamination by violent effervescence and soil loss affect OC

Acid fumigation by HCL: Soil samples weighed in silver capsule and placed in microtiter tray. Add water to moisten the soils and keep tray in desiccator. Place 100 ml of Conc HCL acid in beaker inside the same desiccator. After keeping it undisturbed for 6-8 hrs, remove tray, dry in oven and cool to pack fold the capsule and measure OC and $\delta^{13}\text{C}$ (Harris *et al.*, 2001).

Limitation: N content and $\delta^{15}\text{N}$ in soil gets altered. Loss of soil due to damage of brittle capsule

Benefit: many samples can be processed, no effect on OC and $\delta^{13}\text{C}$

Loss on Ignition (LOI): LOI calculates % OM by comparing the weight of a sample before and after the soil has been ignited. Before ignition, the sample contains OM, but after ignition all that remains is the mineral portion of the soil. The difference in weight before and after ignition represents the amount of the OM that was present in the sample (Ball, 1964)

Problems with LOI:

- LOI is not accurate than elemental analysis SOC estimation for arid forest soil.
- Loss of clay structure water, and other volatile compound also takes place, it is not all SOM which ignites
- It is difficult to determine the optimal temperature and duration for heating
- LOI varies with soil type and depth of same soil
- LOI is unreliable if soil has low SOC (<1.5%)
- Conversion of LOI- OM to OC is difficult because of conversion factors may differs vegetation to vegetation

Soil pH (decide SIC removal required/not):

General concept is *that* soil pH >7.4 need to remove inorganic carbon, and recently Walthert *et al.* (2010) observed SIC at further low pH. Therefore for pH >6.00 soil samples need to be treated to remove SIC.

Acid Selection:

HCL is better than other acids (H_3PO_4 – C contamination, viscous and hygroscopic and H_2SO_4 too weak to remove dolomite type IOC).

Advantages and disadvantages of C analysis using a CHN analyser (by dry combustion method)

Advantages:

- The elevated temperatures ensure combustion of all carbon forms present in the sample
- The sample preparation time and analysis time is minimal.

Disadvantages:

- A leak-free gas flow path must be maintained, else a false positive value will be obtained due to cross-contamination with atmospheric CO_2

- The initial expense of purchasing the equipment may be high.
- Pure oxygen and carrier gases must be purchased for the analysis
- Drying of the sample or pre-treatment to remove carbonates may result in the loss of volatile organic compounds or the decomposition and loss of other organic compounds present in the sample.

Calculation

Total Soil Organic Carbon (SOC) = Total Carbon (TC) – Soil Inorganic Carbon (SIC)

3.3. Soil organic matter determination by Loss-on-Ignition method

The loss-on-ignition (LOI) method for the determination of SOM involves the heated destruction of all organic matter in the soil or sediment. A known weight of sample is placed in a ceramic crucible (or similar vessel) which is then heated to between 350 and 440° C overnight (Nelson and Sommers, 1996). The sample is then cooled in desiccators and weighed. Organic matter content is calculated as the difference between the initial and final sample weights divided by the initial sample weight times 100%. All weights should be corrected for moisture/water content prior to organic matter content calculation.

3.4. Labile and recalcitrant C pools

Different SOC pools can be determined by the modified Walkley–Black method as described by Chan *et al.* (2001) using 5, 10, and 20 mL of 18.0 mol L⁻¹ H₂SO₄ that get diluted to 6, 9 and 12 mol L⁻¹, respectively after mixing with 10 ml dichromate solution (Bhattacharyya *et al.*, 2011a). The total SOC is, thus, divided into four different pools according to their decreasing order of stability (Chan *et al.*, 2001). Soil organic C oxidized by 6 mol L⁻¹ H₂SO₄ was termed the very labile pool (Pool I), the difference in SOC oxidized by 9 mol L⁻¹ H₂SO₄ and that by 6 mol L⁻¹ H₂SO₄ was termed the labile pool (Pool II), the difference in SOC oxidized by 12 mol L⁻¹ H₂SO₄ and that by 9 mol L⁻¹ H₂SO₄ was termed the less labile pool (Pool III), and the difference between total SOC (measured by a CHN analyzer) and the SOC oxidized by 12 mol L⁻¹ H₂SO₄ was termed the non-labile pool (Pool IV) or recalcitrant pool.

3.5. Water soluble C and hot water soluble C

Cold-water-soluble soil organic C is determined following the method of Liang and MacKenzie (1992). In brief, 20-g fresh soil was extracted with 50 ml ultra-pure water in a centrifuge tube by shaking the mixture for 30 min on a reciprocal shaker, and then centrifuging it at 6000 rpm for 15 min. The supernatant was filtered through a 0.45 µm glass fiber filter.

Hot-water-soluble soil organic C is extracted by the method of Sparling *et al.* (1998). In brief, 4 g air-dry soil is extracted with 20 ml ultra-pure water in a capped test-tube at 70° C for 18 h. The tubes should be shaken by hand to re-suspend the soil at the end of the incubation and then should be filtered through a 0.45-µm glass fiber filter. The organic C concentrations in the filtrate can be measured using an element analyzer.

3.6. Carbohydrate C

Extraction procedure: An easily extractable carbohydrate fraction is determined in air-dry aggregates. Carbohydrates are extracted according to the methods described by Ball *et al.* (2011), with minor modifications. Soil is shaken with hot-water (80°C) using a 1:6 soil: extractant ratio (wt/vol). The hot-water extract is centrifuged (5800 rpm, 10 min) and filtered through a 0.45-mm membrane filter. Before extraction, highly soluble substances and floating debris should be removed by shaking the soil with cold water (1:5 soil: extractant ratio, wt:v) for 1 h.

Carbohydrate determination: The carbohydrates extracted by hot water should be hydrolyzed with 12 M H₂SO₄ and 1% thymol (3-hydroxy-4-isopropyl toluene) dissolved in ethanol. The mixture should be shaken well, covered with aluminum foil, and placed in a boiling water bath for 35 minutes. During that time samples may be shaken two or three times. After cooling and transfer to colorimeter tubes, the absorbance is read at 490 nm. As equal amounts of sample and glucose standard are hydrolyzed and diluted in the same manner, the amount of carbohydrate present in the sample could be calculated by directly comparing the absorbance of the unknown samples with the absorbance of the glucose standards using the relationship:

Sample glucose wt: equivalent = (sample absorbance) x (wt glucose standard)/(glucose absorbance)

The calculation of total carbohydrate carbon is based on the assumption that carbohydrates contain 40% (wt/wt) C. Coefficient of variation for carbohydrate concentration of repeated soil samples (n=10) ranges from 1.4–3.4%.

3.7. Particulate organic C and Soil aggregates carbon

The POM-C can be determined using a physical fractionation method. 20 gram subsamples of bulk soil (8-mm sieved) from each depth and plot should be dispersed in 100 mL of 5 g L⁻¹ Na (PO₃)₆ for 15 h on a reciprocal shaker. The samples are then passed through a 53- μ m sieve and flushed with distilled water, one by one to separate the POM. The fraction retained on the sieve is collected and dried overnight at 50°C. The C concentrations in the POM fractions are then analyzed using a CHN analyzer following the dry-combustion method.

Aggregate size separation is performed by a wet-sieving method. Briefly, a 100-g air-dried (8-mm sieved) soil sample should be placed on the top of a 2000- μ m sieve and submerged for 5 min in deionized water at room temperature to allow slaking. The sieve nest is then clamped and secured to a drum. The sieve assembly was oscillated up and down by a pulley arrangement for 20 min at a frequency of 30 to 35 cycles min⁻¹ with a stroke length of 4 cm in salt-free water inside the drum. A series of three sieves (2000, 250, and 53 μ m) is used to obtain four aggregate fractions: (i) >2000 μ m (large macroaggregates), (ii) 250 to 2000 μ m (small macroaggregates), (iii) 53 to 250 μ m (microaggregates), and (iv) <53 μ m (silt- and clay-sized particles). Soil aggregate fractions retained on the different sieves are oven dried (50°C), weighed, and stored in glass jars at room temperature for organic C analysis.

3.8. Determination of Total SOC/SOM (using SOC Conversion factor)

Studies have shown that the recovery of organic C using the Walkley-Black procedure ranged from 60 to 86% with a mean recovery being 76% (Walkley and Black, 1934). Oxidizable C * 1.2 = Total SOC (De Vos *et al.* (2007), under cool temperate condition at 0-15 cm depth.

Depth wise conversion factor is required because of differential rates of humification in different layers with the variations of soil temperature. Ghosh *et al.* (2001), under sub- temperate condition have reported the following factors of conversion.

Oxidizable C * 1.18 = Total SOC (0-15 cm depth), Oxidizable C * 1.24 = Total SOC (15-30 cm depth) and Oxidizable C * 1.32 = Total SOC (30-45 cm depth),

Total C = Total SOC + SIC,

Total organic matter = Total SOC * 1.724 (58 % of the mass of organic matter exists as carbon).

3.9. *In situ* measurement of soil carbon

Development of methods for soil C analysis that address and minimize the uncertainties associated with conventional methodologies are important for improving estimates of terrestrial C inventories and fluxes. Recently, several advanced analytical methods have been utilized for soil C research. Mid- and near-infrared reflectance spectroscopy has each been assessed as a means to determine SOC concentration (McCarty et al., 2002). Analytical pyrolysis has also been evaluated as a mean to determine the composition of SOC (McCarty et al., 2002). Carbon isotope techniques have been used to estimate retention time and C turnover rates in soils (Paul et al., 2001). Conventional laboratory analysis involves a substantial amount of resources to make relatively few measurements of soil C. *In situ* methods for determination of soil C are important due to the comparatively rapid and potentially cost-effective benefits of these methods, and the reduction in sampling and laboratory errors. The greatest benefit of field analysis of soil C may lie in the potential to minimize soil disturbance while increasing the ability to analyze soils of large areas. Advanced field methods of C analysis should be capable of providing repetitive, sequential measurements for evaluation of spatial and temporal variation at a scale that was previously unfeasible.

The increased interest in assessing C inventories and dynamics has resulted in the advent of several new technologies for soil C measurement in the field. Research attempts to measure soil C *in situ* have included Laser Induced Breakdown Spectroscopy (LIBS, Ebinger et al., 2003), Near-Infrared spectroscopy (NIRS, Sudduth and Hummel 1996; Christy et al. 2003), Inelastic Neutron Scattering (INS, Wielopolski et al., 2003) (Table 1), and remote sensing imagery (Chen et al., 2000). The relatively recent advances in *in situ* soil C determination are given below:

Laser Induced Breakdown Spectroscopy (LIBS):

- Based on atomic emission spectroscopy
- Portable
- A laser pulse is focused on a soil sample, creating high temperatures and electric fields that breaks all chemical bonds and generate a white-hot plasma.
- The spectrum generated contains atomic emission peaks at wavelengths characteristic of the sample's constituent elements
- A calibration curve is required to predict soil C concentration

Inelastic Neutron Scattering (INS):

- *In situ, non-destructive* technique that consists in directing fast neutrons (14 MeV) produced by a neutron generator into the soil, where they interact with the nuclei of atoms including ¹²C and other atoms (H, N, O, Si, K, Ca, P, etc).
- Fast neutrons collide with C, H, and N atoms and release gamma rays with energies of 4.4, 2.2, and 10.3 MeV, respectively
- Soil mass interrogated: >200 kg. The INS was tested in stationary and scanning modes.

Near-Infrared Reflectance Spectroscopy (NIRS):

- Unlike LIBS and INS, NIRS probes the bond identities of a sample's molecules, offering the possibility of directly distinguishing inorganic from organic C, thus eliminating the need for acid pretreatment to remove inorganic C.
- Yet for the same reason, quantifying soil C must be done indirectly, by recourse of advanced data-fitting routines that require libraries of soil spectra vs. soil C data



Table 1: Comparison of field instrumentation for determination of soil C

| Method | Principle | Approximate detection limit | Sampling time | Sampling attributes |
|--------|---|---|-------------------------------|---------------------|
| LIBS | Intense laser pulse is focused on in-tact sample core, microplasm emission spectrally resolved | 300 mg total C kg ⁻¹ | <60 s | Invasive |
| INS | Inelastic scattering of neutrons from C nuclei emits gamma rays that are detected and analyzed for C peak intensity | 0.018 g C cm ⁻³ , or 1.2% C for 1.5 g cm ⁻³ bulk density sample | - | Non-invasive |
| NIRS | Diffuse reflectance properties in the 700 to 2500 nm spectrum are correlated to soil C content | 0.6% organic C | 200 ms spectrum ⁻¹ | Invasive |

Remote sensing

Remote sensing offers the possibility of spatial and temporal estimates of land cover, land management practices, cropping and tillage practices, net plant productivity, and plant residue—all of which impact soil C dynamics. The capacity for remote sensing to characterize these features is of particular interest due to the relative ease in periodic sampling and potential reduction in cost associated with verification and monitoring soil C sequestration. The breadth of such analyses can extend to the field and watershed scales, allowing for repeatable evaluation of large land areas. There have been limited studies on the direct measurement of soil C using remote sensing. However, a strong relationship between soil color, or visible reflectance, and SOC has long been recognized, suggesting that this type of analysis may be possible. Research has been conducted on the relationships between soil color and organic matter, although many of these studies were based on Munsell color properties of hue, value, and chroma. Fernandez et al. (1988) reported a high correlation ($r = 0.94$) between SOC content and soil Munsell value calculated from visible-reflectance data within a landscape. Problems have been encountered in establishing correlations of SOC and soil reflectance because soil color and reflectance properties are a function of many factors in addition to organic matter, including soil moisture, texture, chemical composition, parent material, and surface conditions. These problems are complicated when soils are analyzed from large geographic areas (Sudduth and Hummel 1996).

In order to make accurate, direct assessments of SOC using remotely-sensed imagery, it is necessary to understand the influence of soil organic fractions on soil reflectance properties in specific wavebands. Henderson et al. (1992) evaluated the effects of SOC on soil reflectance across the visible, NIR, and MIR spectral regions and the effects of SOM constituents on spectral reflectance of soil. Their results indicated the potential of high dimensional reflectance data to provide information about SOC content, but not SOM composition. On soils formed from similar parent materials, reflectance in the visible bands (425–695 nm) resulted in the highest correlations with SOC. However, MIR bands (1955–2495 nm) resulted in the highest correlation with SOC for soils formed on different parent materials. Further, the influence of SOC on soil reflectance appeared much stronger than any effects of SOM composition, and reflectance response was dominated by soil factors other than SOM content.

Research reporting the direct quantification of SOC or SOM content using remote sensing has been limited. Landsat imagery and ground truth site information were used in part to develop the North American Soil Organic Carbon Digital Database to determine C stocks for North America and variations in existing estimations (Lacelle et al., 2001). Chen et al. (2000) used bare-soil aerial photographs (color slides) to map surface SOC for a 115-ha field in Georgia. Soil organic carbon distribution was predicted using two approaches. The first approach was to apply the statistical

relationship between surface SOC and image intensity values in the red, green, and blue bands to individual pixels and then determine the distribution of 8 separate classes. The second approach was to initially classify the image and then apply the statistical relationship to determine means and class boundaries. Predicted and measured surface SOC concentrations were compared using linear regression ($r^2 = 0.97$ and $r^2 = 0.98$ for the two approaches, respectively) and concentrations were correctly classified in 77 and 74% of cases for the two approaches. The area of each class from the two approaches were compared using a paired *t*-test for the area distribution and were found to be very similar ($P > 0.99$). They concluded that high resolution (1063 lines per cm), remotely sensed imagery of bare soil could be quantified to accurately describe spatial variation of surface SOC for a field in Georgia.

Limitations of this methodology included effects of noise from other soil properties (e.g., Fe concentration) and consistency in image-intensity values. The use of digital multi-spectral images could minimize these limitations. Palacios-Orueta et al. (1999) used hierarchical foreground and background analysis and AVIRIS (Airborne Visible / Infrared Imaging Spectrometer) data to predict SOM and Fe contents in California. Their results indicated that the ranges of predicted organic matter were consistent with the magnitude and distribution of field samples, although the presence of vegetation and steep terrain adversely affected the ability to resolve soil properties. Increased adoption of management practices that maximize C sequestration (i.e., conservation tillage or no-till) will limit the potential for direct measurement of soil C by remote sensing, since surface residues will limit the applicability of this method (reduced potential for bare soil imagery). For future success of remotely sensed inventories of soil C, calibration and ground truthing of spectral imagery will be necessary. Assessment of SOM content using sensor data is most likely to be successful if calibration is done on a field by field basis rather than utilizing relationships over a large geographic area. Improvements in calibration procedures may allow for the projection of C sequestration dynamics to various land uses and management practices across a range of spatial scales, although the most applicable use of remotely-sensed data may remain in the collection of data such as plant productivity, residue cover, tillage, etc., that can be used in C models to estimate C sequestration.

4. Computation of carbon sequestration rates

4.1. Estimation of gross C inputs (field crops /arable lands)

It refers to the sum of all left-over C inputs from any source i.e. in- situ, leaf litter, root biomass, stubble, rhizodeposition (root exudates) and ex-situ through FYM or crop residue or compost etc. for the field crops. Gross C input for agroforestry and forestry plantations includes all the pools which include above ground biomass, below ground biomass, leaf litter and external addition of C through manures/composts.. When these undergoes decomposition, a fraction is entered into different pool of SOC based on time scale where as remaining is lost as CO₂-C. Gross C input estimation is very essential to understand how much of these C input has entered into stable SOC or sequestered.

4.1.1. Determination of mummification rate constant

In any agro-ecosystem, even after the removal of harvestable above ground biomass, considerable amount of C input is added to the soil inadvertently though leaf-fall, root, nodules and left-over stubble. Besides if the system is receiving any external sources of C input such as FYM and crops residues should also be included.

Many studies indicated strong relationship between addition and storage of SOC. The relationship between C addition to the soil by different sources and storage within the soil has been determined. The rate constant of annual C inputs incorporated into TOC (h) and decay rate constant (k) of native TOC were calculated from the following equation (Jenkinson, 1988) assuming a single-pool, first order kinetic relationship between C addition and storage

$$\delta C_s / \delta t = hA - k \cdot TOC$$

where C_s is carbon stored in soil, TOC is the initial total soil organic C, t is time, and A is annual C input to soil, 'h' as carbon storage fraction constant, k - decay rate constant.

Example:

| Initial TOC stock $t\ ha^{-1}$ (A) | Annual C input added through crops residue $t\ ha^{-1}$ | Annual C input added through FYM (C) ₋₁ $t\ ha^{-1}$ | Annual total C input (B+C) $t\ ha^{-1}$ | “h” determined from relationship say, $h = 0.2$ $D = (B+C) \cdot h$ | “k” determined from relationship (E) $k = 0.01$ | Annual C stock/store (Cs) (D-E) $t\ ha^{-1}$ | Total Carbon stock (A + D - E) $t\ ha^{-1}$ |
|------------------------------------|---|---|---|--|--|--|---|
| 15.0 | 8.0 | 10.0 | 18.0 | $(8+10) \times 0.2 = 3.6\ t\ ha^{-1}$ | $0.15\ t\ ha^{-1}$ | $3.6 - 0.15 = 3.45$ | $15 + 3.6 - 0.15 = 18.45$ |

4.1.2. Estimation of carbon input (Agroforestry and forestry systems)

In general, agroforestry systems when taken up in crop lands, trees/shrubs are planted in a definite spatial arrangement. If the trees are uniformly spaced, a part of the total area or treatment can be selected as a sampling area representing all components of the system, and the quantity of C has to be expressed in terms of unit area or per one hectare. If the trees are widely spaced, the population of trees is enumerated and a representative sample consisting of trees and the under storey components are to be assessed and expressed in terms of unit area. The quantity of C input by an agroforestry system/ forestry system is the cumulative of four components. They are

- i) Carbon present in above ground parts
- ii) Carbon present in below ground parts (root carbon) and rhizodeposition
- iii) Carbon present in litter fall
- iv) Change in SOC

Carbon present in above ground parts (stem, branches and twigs) only the C present in woody biomass should be considered as sequestered if wood is converted to furniture any other things which is long-lived. Other components of C input should be considered as C stock in respect to reference time. Turnover of other C input (fine root, rhizodeposition, leaf litter etc.) into SOC should be estimated using above mentioned methodologies to quantify C sequestration.

The key pools included in forestry activities are defined in Table 2.

Table 2: Key carbon pools for forests and their definition

| Carbon Pools | Definition |
|----------------------------|--|
| Live trees | Live trees: above ground, Live trees: below ground |
| Understory vegetation | Tree seedlings, Shrubs, herbs, forbs, grasses |
| Standing dead trees | Standing dead trees: above ground, Standing dead trees: below ground |
| Down dead wood | Down dead wood, Stumps and dead roots |
| Forest floor | Fine woody debris, Litter, Humus |
| Soil carbon woody products | Soil carbon, Wood products harvested wood mass |

Above-ground biomass –Trees

The C stocks of trees are estimated most accurately and precisely by direct methods, e.g., through a field inventory, where all the trees in the sample plots above a minimum diameter are measured. The minimum diameter often is 5 cm (d.b.h), but it can vary depending on the expected size of trees. For arid environments in which trees grow slowly, the minimum d.b.h. may be as small as 2.5 cm; for humid environments in which trees grow rapidly, the minimum d.b.h. may be up to 10

cm. Biomass and C stock are estimated using appropriate allometric equations applied to the tree measurements (Table 3). Tree biomass often is estimated from equations that relate biomass to d.b.h. only. Although the combination of d.b.h. and height as the independent variables is often superior to d.b.h. alone, measuring tree height can be time consuming and will increase the cost of a monitoring program. Further, the empirical database of trees shows that highly significant biomass regression equations can be developed using d.b.h. only.

Table 3: Climate type allometric equations for the tree measurements

| Climate type based on annual rainfall | Equation | r ² |
|---------------------------------------|--|----------------|
| Dry (< 1500 mm) | $y = 34.4703 - 8.0671 D + 0.6589 D^2$ | 0.67 |
| Moist (1500 – 4000 mm) | $y = 38.4908 - 11.7883 D + 1.1926 D^2$ | 0.78 |
| | $y = \exp [-3.1141 + 0.9719 \ln (D^2H)]$ | 0.97 |
| | $y = \exp [-2.4090 + 0.9522 \ln (D^2HS)]$ | 0.99 |
| | $H = \exp [1.0710 + 0.5677 \ln (D)]$ | 0.61 |
| Wet (> 4000mm) | $y = 13.2579 - 4.8945 D$ | 0.90 |
| | $y = \exp [-3.3012 + 0.9439 \ln (D^2H)]$ | 0.90 |
| | $H = \exp [1.2017 + 0.5627 \ln (D)]$ | 0.74 |

Y = above ground biomass in kg, H = height in m

D = diameter at breast height (1.3 m), S = wood density in tonnes/m³

Below-ground Biomass

Measuring above-ground biomass is relatively established and simple. Measuring below-ground biomass (coarse and fine roots) is time consuming so it is more efficient to apply a regression model to estimate below-ground biomass (living and dead) as a function of above-ground biomass. General equations for quantifying the biomass of trees can be used in the absence of species specific equations (Brown *et al.*, 2000).

Quantification of carbon in below ground parts (root carbon)

Allometric equations for quantification of root systems are limited to a few tree species and may not be available for many trees. For grafted mangos a factor of 0.29 has been developed through destructive sampling. Based on this, the below ground biomass of mango can be determined and the total root biomass for one hectare area can be estimated. The carbon sequestered in the below ground biomass can be determined from the above ground biomass using a factor of 0.45 (GPG, 2006).

Table 4: Tabulation of change in carbon stock in forest system

| Total afforested area (ha) Say, 500 ha | Homogenous tree density (Trees/ ha), say | Initial stock (t ha ⁻¹) | | | | Total |
|--|--|-------------------------------------|-----|-------------|-------|---------|
| | | AGB | BGB | Leaf litter | Soil | |
| P1 | Ti | nil | nil | nil | X1i | Xi |
| P2 | Tii | | | | X1ii | Xii |
| P3 | Tii | | | | X1iii | Xiii |
| --- | -- | | | | -- | -- |
| -- | -- | | | | - | |
| Pn | - | | | | ΣX1n | ΣX1n=Y1 |

| Total afforested area (ha) | Homogenous tree density (Trees/ ha) Say | After 5 or ten years | | | | Total |
|----------------------------|---|----------------------|--|-------------|-------|------------------|
| | | AGB | BGB | Leaf litter | Soil | |
| Say, 500 ha | | | | | | |
| Each sub-plot | | | | | | |
| P1 | Ti* | Ai | Bi | Li | X2i | Total |
| P2 | Tii* | Aii | Bii | Lii | X2ii | Total |
| P3 | Tiii* | Aiii | Biii | Lii | X2iii | Total |
| --- | -- | -- | - | -- | -- | |
| -- | -- | -- | -- | -- | -- | |
| Pn | ΣTn | ΣAn | ΣBn | ΣLn | ΣX2n | ΣAn+Bn+Ln+X2n=Y2 |
| | | | Net change | | | T=Y2-Y1 |
| | | | Net change ha ⁻¹ yr ⁻¹ | | | T/5 or 10=T1 |
| | | | Net change in 500 ha yr ⁻¹ | | | T1*500 ton |

Example -Calculating net change in the forest eco system

Suppose, in afforestation programme of 500 ha, the initial total soil organic carbon stock in 500 ha was X ton. After 5 years, the biomass of different plantation will increase carbon stock in above ground biomass (AGB) + root biomass (BGB) + forest litter+ soil carbon (AGB+BGB+ dead organic matter+ soil organic carbon). After five or ten years, the different trees contributed significantly carbon in all the components. Carbon stock in tree biomass have to be calculated and added in AGB+BGB+litter for homogenous trees as per trees density (X2). Then in the homogenous areas, soil samplings have to be conducted and measured total organic carbon. Then total carbon stock will be X= (X2-X1) t in 500 ha. Dividing the X with 500, we will get C stock per ha. The following table 4 will illustrate net change in carbon stock in forest ecosystem. Estimation of these values is very much useful for decisive carbon credit payment in IPCC protocol under REDD+ mechanism.

5. Different terminology and estimation

5.1. Carbon stocks

Carbon stock in soil refers to presence of total carbon (total SOC + total SIC, i.e. CaCO₃) in soil in a particular depth/profile/area. Total SOC is comprised of oxidizable organic carbon + non-oxidizable organic carbon. Oxidizable organic carbon is determined by K₂Cr₂O₇ (Walkley and Black, 1934) method. Total SOC is determined by autoanalyzer (CHN/CNS) following dry combustion technique as well as platinum crucible muffle furnace technique.

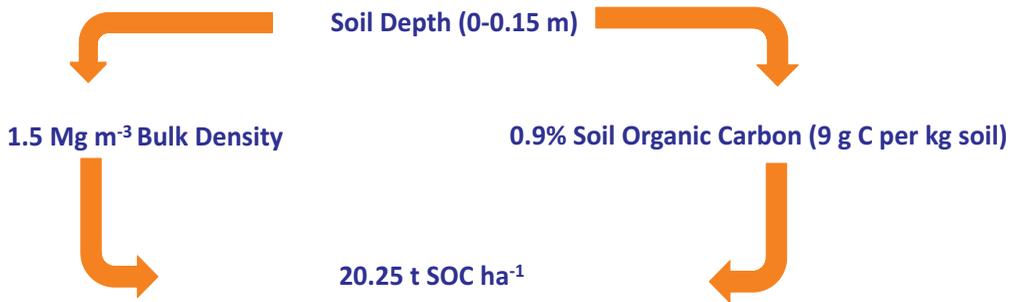
Carbon stock (Kg/ha) in depth Di= Total SOC (fraction) x BD (kg m⁻³) x Di (m) x 10000 (m²)

Where, BD: bulk density, SOC: Soil organic carbon, D: thickness of soil layer

Example,

Total SOC of any plot is 0.9%, BD – 1.5 Mg m⁻³ and depth 0.15m

Total SOC stock for 0-15 cm soil= 20.25 t ha⁻¹ (one depth layer SOC stock estimation details in below fig .8)



i.e. $10000 \text{ m}^2 \text{ per ha} * 0.15 \text{ m soil depth} * 1.5 \text{ Mg m}^{-3} \text{ BD} = 2250 \text{ t soil ha}^{-1}$

$9 \text{ g SOC per Kg soil} * 2250000 \text{ kg soil ha}^{-1} = 20250000 \text{ g SOC ha}^{-1} = 20.25 \text{ t SOC ha}^{-1}$

Fig.8: Stepwise SOC stock estimation model (< 2mm mass need to be used for calculating BD)

In order to determine the soil organic carbon stock in a profile, sum up the respective value upto desired depth.

Carbon Stock (Kg/ha) up to desired depth

$$= \sum \text{Total SOC}_i (\text{fraction}) \times \text{BD}_i (\text{kg m}^{-3}) \times D_i (\text{m}) \times 10000 \text{ m}^2$$

Where as $i = 1$ to n , n is number of layer sampled, D_i is the thickness of individual layer.

Example for SOC estimation upto desired depth

| Soil depth (cm) | OC % | BD (g/cm^3) | Thickness of the layer (m) | BD (kg/m^3) | OC in each layer of 1ha area(Kg) |
|-----------------|------|------------------------|--|------------------------|---|
| 0-15 | 0.8 | 1.35 | 0.15 | 1350 | $(0.8/100) * 1350 * 0.15 * 10000 = 16200$ |
| 15-30 | 0.6 | 1.42 | 0.15 | 1420 | 12780.0 |
| 30-45 | 0.3 | 1.46 | 0.15 | 1460 | 6570.0 |
| 45-60 | 0.25 | 1.45 | 0.15 | 1450 | 5437.5 |
| 60-75 | 0.21 | 1.48 | 0.15 | 1480 | 4662.0 |
| 75-100 | 0.20 | 1.46 | 0.25 | 1460 | 7300.0 |
| | | | Total OC in one hectare up to depth of 1m. | | 52949.5 kg = 52.65 tonnes |

It is required to estimate of per cent coarse fragment to determine C stock in non-arable land. Percent coarse fragment (>2 mm size) in soils is estimated by morphological examination of soils upto desired depth. Small amount of soil (approx. 100-200 g) from pit were taken out and placed on palm and visually examined that how much quantity of coarse fraction exist in that sample. The sizes of coarse fragments (CF) by type were gravels (G, 2-75 mm), cobbles (C, 75-250 mm) and stones (S, >250 mm).

Then, soil organic carbon stock is calculated as

Carbon stock (Kg/ha) up to desired depth

$$= \sum \text{Total SOC}_i (\text{fraction}) \times \text{BD}_i (\text{kg m}^{-3}) \times \text{D}_i (\text{m}) \times 10000 \times (1 - \text{G}_i)$$

Where as $i = 1$ to n , n is number of layer sampled, D_i is the thickness of individual layer and G_i represents volume of coarse fraction

5.2. Carbon sequestration potential (CSP)

Carbon sequestration potential is the annual rate of change of total SOC from its initial value. Strictly this may be termed as C retention potential, and only long-lived pools are considered for using the term 'sequestration'. As determination of all C fractions is comparatively difficult in most of the production system assessment, the term CSP is also used synonymously with C retention potential, more so for long term fixed-plot experiments (>10 years). This is determined by estimating annual rate of change of total SOC from its initial value.

Carbon sequestration potential in soil (CSP, $\text{t ha}^{-1} \text{yr}^{-1}$) of a particular treatment is calculated as:

$$\text{CSP} (\text{Total SOC}_{\text{treatment}} - \text{Total SOC}_{\text{initial}}) / n$$

Where, $\text{Total SOC}_{\text{treatment}}$ and $\text{Total SOC}_{\text{initial}}$ represent Total SOC content (t C/ha) in the treated and initial plots, respectively, and 'n' indicates years of experimentation.

5.3. Carbon stabilization

Carbon stabilization refers to how much SOC is retained with respect to C input received in the system. The amount of total SOC remained and stabilized in the desire depth is estimated as:

$$\text{Total SOC stabilization (\%)} = \text{CSP} / \text{ECI} \times 100$$

Where, ECI is the estimated amount of C ($\text{t C ha}^{-1} \text{yr}^{-1}$) input through crop residues, applied manure (FYM) and or any other sources.

5.4. Determination critical carbon values for soils

Oxidizable SOC (Walkley-Black) is considered as one of the key parameters for assessing soil health/quality. Maintenance of SOC at a reasonable level is thus essential for upkeeping the soil health. Conceptually the critical limit of SOC is the desirable range of its values required for normal functioning of soil and maintaining its health for sustainable crop production (Biswas, 2012). It is determined by plotting relative yield (RY)/ relative soil quality (RSQ) in Y axis and oxidizable SOC in X axis. Values in X axis in 50% RY and values in Y axis 80 % of RY/RSQ is the threshold and optimum carbon values in soil. For example Biswas (2012) reported 7.3 and 4.4 g kg^{-1} in Alfisols the optimum and threshold values of SOC in some soils of West Bengal.

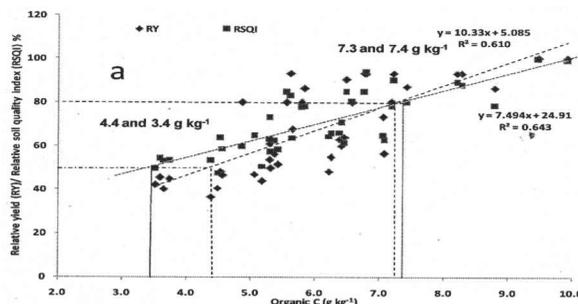


Fig. 9. Critical limits (optimum and threshold) of oxidizable SOC in Alfisols with rice-rice cropping systems (Adopted from Mandal et al., 2011)

5.5. Carbon saturation deficits

The capacity of a soil to store carbon is finite. It depends mainly on the abundance of fine particles (clay+silt) in soils and also on quantity and stability of their aggregates - both micro and macro. It is known that C associated with the fine particles is more stable with residence time varying from decades to century compared to that held by other soil components. The magnitude of additional quantity of C that a soil can store or sequester to be saturated with it on a long-term basis depends on the current status of its storage capacity *i.e.* how much of the said capacity has already been attained (Hassink 1997).

C saturation deficit = Estimate of SOC saturation value - Measured quantity of SOC in fine fractions

5.6. Carbon balance

It should be considered for a specific project (or scenario of action) in comparisons with a reference, as the net balance of all GHG emissions expressed in CO₂ equivalent (sources and sinks) with the atmosphere interface and the net change in C stocks (biomass, soil etc.).

5.7. Carbon sink

It is system that absorbs naturally a part of the CO₂ emitted in the atmosphere and store carbon for long term.

5.8. Carbon emission factor

It is a normalized coefficient that allows for calculating the emission fluxes of GHG. Global warming potential (GWP) is a measure of how much a given mass of GHG is estimated to contribute to global warming. It is a relative scale which compares the gas in question to that of the same mass of carbon dioxide (whose GWP is by definition 1).

The GWP of methane (CH₄) and nitrous oxide (N₂O) were 28 and 298 times more than CO₂. It is very essential to estimate the GWP to identify the BMPs in a conservation agriculture system.

5.9. Carbon management index (CMI)

The CMI was designed to give an indication of the C dynamics of the system.

Carbon management index (CMI) was calculated using the procedure given by Blair *et al.* (1995)

CMI = CPI x LI x 100,

$$\text{Where, CPI} = \text{carbon Pool Index} = \frac{\text{Total Carbon in Sample (mg g}^{-1}\text{)}}{\text{Total carbon in reference (mg g}^{-1}\text{)}} = \frac{\text{C T sample}}{\text{C T reference}}$$

$$\text{LI} = \text{Lability Index} = \frac{\text{Lability in Carbon in Sample soil}}{\text{Lability in Carbon in Reference soil}}$$

$$\text{Lability of C L} = \frac{\text{Labile}}{\text{Non - labile}} = \frac{\text{CL}}{\text{CNL}}$$

5.10. Carbon budgeting

Carbon budgeting refers to balance of input and output of carbon in a system. More complicated dynamic methodologies exist for calculation of total SOC budgeting. Two simplest ways of calculation are as follows:

For the field crops system, the below mentioned method is mostly followed total SOC budgeting for the study period is calculated as:

$$\text{Total SOC buildup rate (t C/ha/year)} = (\text{Total SOC}_{\text{treatment}} - \text{total SOC}_{\text{control}}) / n$$

Where, total SOC control represent SOC content (t C/ha) in the unfertilized control treatment and 'n' indicates years of experimentation (Bhattacharyya et al., 2009).

This method can also be followed for tree based system if control plot - exists.

5.11. Carbon Credits/Trading

Net gain in soil carbon after offsetting emission with reference to a baseline can be traded under the Clean Development Mechanism (CDM) of Kyoto protocol. It is vouched to be a win-win proposition for the poor farming community of developing countries for earning credits as well as serving to the cause of humanity by providing a better niche for living. There is a huge potential for such C trading in tropical and sub-tropical countries like India where soils are hungry for storing C and sunlight is abundant for photosynthetic activity. However, because of some uncertainties and inherent weakness in precise accounting of C sequestered in soils following emission offsetting practices, agricultural systems has not been covered with such trading of C credits under the Kyoto protocol. Moreover, getting credits from soil carbon sequestration through project activities presents several challenges: the need to monitor small incremental changes in soil carbon content relative to large carbon pools, long-time periods to accrue the full carbon benefit, high local variability of soil carbon content, and relatively costly soil carbon measurement procedures.

6. Soil organic carbon prediction using some models (Indian scenario)

6.1. Roth-C model

RothC-26.3 is a model for the turnover of SOC in non-waterlogged topsoils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total SOC (t ha^{-1}), microbial biomass carbon (t ha^{-1}) and $\Delta^{14}\text{C}$ (from which the equivalent radiocarbon age of the soil can be calculated) on a years to centuries timescale (Jenkinson and Coleman, 1994). It needs few inputs and those it needs are easily obtainable. RothC-26.3 is designed to run in two modes: 'forward' in which known inputs are used to calculate changes in soil organic matter and 'inverse', when inputs are calculated from known changes in soil organic matter. RothC-26.3 was originally developed and parameterized to model the turnover of organic C in arable topsoils from the Rothamsted Long Term Field Experiments - hence the name (Fig.9). Later, it was extended to model turnover in grassland and in woodland and to operate in different soils and under different climates. It should be used cautiously on sub soils and not at all on soils that are permanently waterlogged.

Model structure

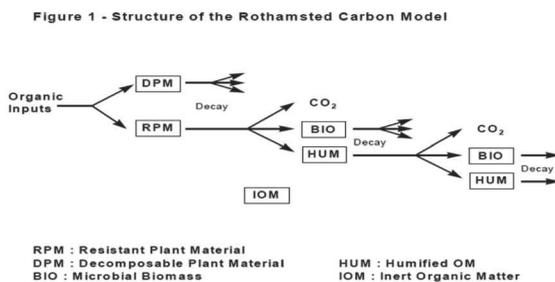


Fig.10 :Structure of the Rothamsted Carbon Model

DPM/RPM ratio used for different land use for the model is

- a. Agricultural: 1.44, b. Grassland scrub: 0.67, and c. Deciduous and tropical woodland: 0.25.

Principal

If an active compartment contains $Y \text{ t C ha}^{-1}$, this declines to $Y e^{-abck/t} \text{ C ha}^{-1}$ at the end of the month.

where a is the rate modifying factor for temperature

b is the rate modifying factor for moisture

c is the soil cover rate modifying factor

k is the decomposition rate constant for that compartment

t is 1/12, since k is based on a yearly decomposition rate.

So $Y (1 - e^{-abck/t})$ is the amount of the material in a compartment that decomposes in a particular month.

Data requirements format:

Year:-----Site, Name: ----, Sampled soil depth (top soil layer only e.g. 0-15 or 0-20 etc) (cm), Bulk density (gm/cc), Clay content (%):----

The data collection format for calibration and validation of Roth-C is as follows (Table 5).

Table 5: Data collection format for Roth-C model

| Particulars | Jan. | Feb. | March | April | May | June | July | Aug. | Sept | Oct. | Nov. | Dec. |
|---------------------------------------|------|------|-------|-------|-----|------|------|------|------|------|------|------|
| Soil cover (Crop/Fallow) | | | | | | | | | | | | |
| FYM /VC/PM (t C/ha) | | | | | | | | | | | | |
| Crop residue/plant carbon input(t/ha) | | | | | | | | | | | | |
| Irrigation(mm) | | | | | | | | | | | | |
| TOC (t/ha) | | | | | | | | | | | | |
| Precipitation (mm) | | | | | | | | | | | | |
| Temperature (Avg. °C) | | | | | | | | | | | | |

6.2. EX-ACT Model

EX-ACT (Ex-ante carbon balance tool, Bernoux et al., 2010) is used to estimate the potential contribution of agricultural and forestry sectors to climate change mitigation. It provides EX-ante measurement of GHG emissions and carbon sequestration, indication its effects on C balance. The emissions are expressed in $\text{t CO}_2 \text{ e ha}^{-1}$. It is a new simple tool which takes into account the various activities (deforestation, afforestation/reforestation, livestock, cultivation of annual crops, perennial crops and fertilization of crops) and calculates their impact on GHG fluxes and sinks from and to different pools (above and below ground biomass, soil, litter and dead wood). It computes the C balance for a specific project in comparison with a reference. It gives a clear picture of GHGs released in the current situation, in future if the project is not implemented and if implemented by comparing two scenarios “without project” and “with project' taking into account both the implementation and

capitalization phase of the project, set as 20 years. It consists of a set of Microsoft Excel sheets in which relevant data pertain to deforestation, afforestation/reforestation, forest degradation, restoration of grasslands, livestock, cultivation of annual crops, perennial crops, and fertilization of crops is entered. EX-ACT adopts a modular approach- each module described a specific land use and following a three-step logical framework (Fig.10) and calculates the C balance.

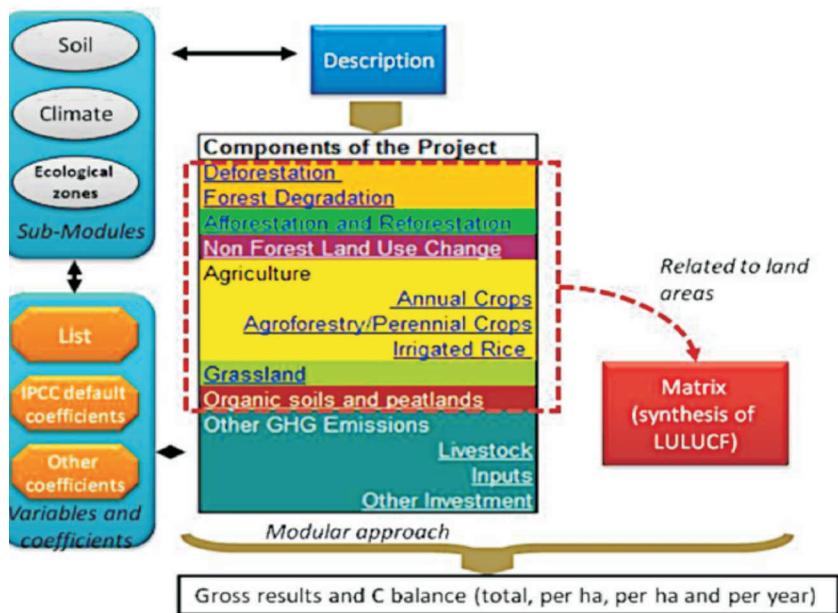


Fig.11 : General structure of EXACT tool used in the C balance study

6.3. Comparative Features of Some Carbon Estimation Models- (India)

| Model | Objective | Parameters required and Applicability | Result |
|--------|---|--|--|
| Roth C | Estimation of turnover of organic carbon in topsoil | Clay, monthly rainfall, monthly open pan evaporation, average monthly mean air temperature, and an estimate of the organic input | Total organic carbon content and carbon content in microbial biomass |
| EX-ACT | Determines GHG emissions and C sequestration | Area under agricultural land, land use management, crop and livestock management with and without project | C balance in terms of $\text{CO}_2\text{e t ha}^{-1}$ |

6.4. Carbon storage estimation in trees-past and present

The rate of carbon sequestration is different between trees depending on several factors such as age of tree, soil nutrition, speed of growth, floral diversity composition, type of soil, type of forest, size of tree and root, leaf abscission, climatic factor, etc. Tree's growth, large diameters and increasing height are itself an indicator of their large biomass contents in terrestrial carbon reservoir. Not all tree growth is equally suited for long-term carbon sequestration in biomass. Deciduous trees hold their leaves for one year while conifers can hold needles for as long as eight or more years. Fine roots live for days or years, depending on the species, but larger roots may be more important than small roots to enhance carbon pools. In contrast, tree trunks, large branches, and large roots, which remain on the tree for several decades or centuries, are the primary sites of carbon sequestration. Selected planted forests sequester more carbon than mature forests, due to their rapid carbon

sequestration rate. Short rotation tree species with regular leaf shedding patterns have more capacity for carbon sequestering in litter which decomposes more rapidly than species with annual and bimodal leaf shedding patterns, Fast-growing conifers may produce slow-decomposing litter leading to accumulation on forest floor, hence poses risk for fire damage and decline in ground flora diversity or productivity, Mixed planted forests of exotic and native species could be more efficient in sequestering carbon than monocultures, Fast-growing hardy species like Eucalyptus would be ideal choice for waste land afforestation/reforestation, and softwood species for agri-silvicultural practice in soil of fertile plain areas. Carbon sequestration is highest in young forests and will tend to reduce as forests reach maturity. Native trees like *Azadirachta indica* (Neem), *Tamarindus indica* (Tamarind), *Ficus religiosa* (Pipal) and *Madhu calatifolia* are considered ecologically beneficial as they have relatively high efficiency of carbon fixation; these species may be suitable for checking urban pollution and may provide a good option for maximum carbon fixation. Trees in urban areas also involved in stability of natural ecosystem with increased recycling of nutrient along with maintenance of climate conditions by the biogeochemical processes. The amounts of carbon sequestration by different tree species will be estimated by following the formulas as mentioned in table 4. Different researchers under Indian climatic situation reported some values (Annexure-1). These estimates have been reported excluding soil organic carbon component and utilizing a fitman factor of 0.45 C content (randomly) in each component of tress species which might have under estimated or over estimated. These value required correction (accurate estimation) by determining carbon content (through dry combustion by elemental analyser) in each part of trees at different age. Accurate estimation by following above mentioned method is very much important to implement appropriate payment protocol through REDD+ mechanism of IPCC for the developing countries.

7. Annexure- Some useful information for C research in different system

Annexure I. Carbon sequestration potential in different tree species under Indian condition

| Species | Carbon stock (t ha ⁻¹ yr ⁻¹) | Species | Carbon stock (t ha ⁻¹ yr ⁻¹) |
|--------------------------------|---|---------------------------------|---|
| <i>Acacia auriculiformis</i> | 7.7 | <i>Acacia mangium</i> Willd | 2.92 |
| <i>Dalbergia sissoo</i> | 3.6 | <i>Bamboosa balcooa</i> | 2.34 |
| <i>Casuarina equisetifolia</i> | 1.9 | <i>Ficus amplissima</i> | 2.21 |
| <i>Gmelina arborea</i> | 1.4 | <i>Tectona grandis</i> | 1.81 |
| <i>Sequoia sempervirens</i> | 5.0 | <i>Heave brazililensis</i> | 1.36 |
| <i>Cedrus deodara</i> | 4.7 | <i>Populus deltoids</i> | 1.15 |
| <i>Terminalia bellirica</i> | 3.3 | <i>Mangifera indica</i> | 1.04 |
| <i>Eucalyptus spp.</i> | 3.2 | <i>Quercus leucotrichophora</i> | 0.77 |
| <i>Albizia lebbek</i> | 11.9 | <i>Shorea robusta</i> | 8.97 |

Annexure II. Practices that sequester carbon in forest, grassland, and cropland

| FOREST | GRASSLAND | CROPLAND |
|--|---|---|
| Protection of existing forests— Avoided deforestation preserves existing soil C stocks and prevents emissions associated with biomass burning and soil exposure by land clearing | Improved grassland management— Optimize stocking rates to reduce land degradation, depletion of soil organic carbon, and methane emissions through enteric fermentation | No or reduced tillage—Reduces the accelerated decomposition of organic matter associated with Intensive (conventional or traditional) tillage |

| | | |
|--|--|--|
| Reforestation—Increasing tree density in degraded forests increases carbon accumulation | Introduction of improved pasture species and legumes to increase above- and below-ground biomass production and soil organic carbon accumulation | Mulching/residue anagement—Improves soil moisture, prevents soil erosion, and increases soil organic matter when incorporated into the soil; crop residues also prevent loss of carbon from the soil system |
| Afforestation—Establishment of new forests on nonforest land (cropland, grassland, or degraded lands) increases carbon stock through the increase in above-ground biomass as well as creating organic materials input for soil decomposition | Application of inorganic fertilizers and manure to stimulate biomass production—Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide (N ₂ O) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers | Application of inorganic fertilizers and manure to stimulate biomass production—Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide (N ₂ O) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers |
| - | Water management to increase productivity, but this has to be put in the perspective of emissions associated with the process of irrigation | Use of cover crops/green manure increases the biomass returned to the soil and thus increases soil carbon stock |
| - | Introduction of earthworms to improve aeration and aid organic matter decomposition in the soil profile | Use of improved crop varieties—Improved crop varieties help to sequester carbon in the soil through increased above- and below-ground biomass production |
| - | Establishment of pasture on degraded land reintroduces large amounts of organic matter into the soil | Agroforestry/tree-crop farming—Introduction of fruit trees, orchards, and woodlots into croplands helps to store more carbon, optimize water use, diversify production, and increase income |
| - | - | Introduction of improved crop varieties |
| - | - | Application of biochar and other soil amendments |

Annexure III. Carbon content (%) in different parts of some field crops

| Crop | Grain | Straw | Root |
|----------|-------|-------|------|
| Wheat | 28 | 42 | 30 |
| Corn | 30 | 44 | 26 |
| Cotton | 19 | 48 | 33 |
| Soybeans | 28 | 44 | .28 |

Scientific names: wheat (*Triticum aestivum*), corn (*Zea mays*), cotton (*Gossypium hirsutum*) and soybeans (*Glycine max*).

Annexure IV. Critical C input values (Mg ha⁻¹) for a zero change in SOC for soils under different AEZs of India

| Site | Critical C input | Site | Critical C input |
|------------|------------------|-----------|------------------|
| Coimbatore | 4.43 | Cuttack | 3.41 |
| Gayespur | 2.53 | Baracpur | 4.59 |
| Ludhiana | 3.46 | Mohanpur | 3.56 |
| Pantnagr | 5.16 | Almora | 0.31 |
| Phulbani | 2.31 | Bhopal | 0.89 |
| Varanasi | 2.47 | S K Nagar | 3.30 |

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