Assessment of Carbon Sequestration in Agriculture and Agroforestry Systems

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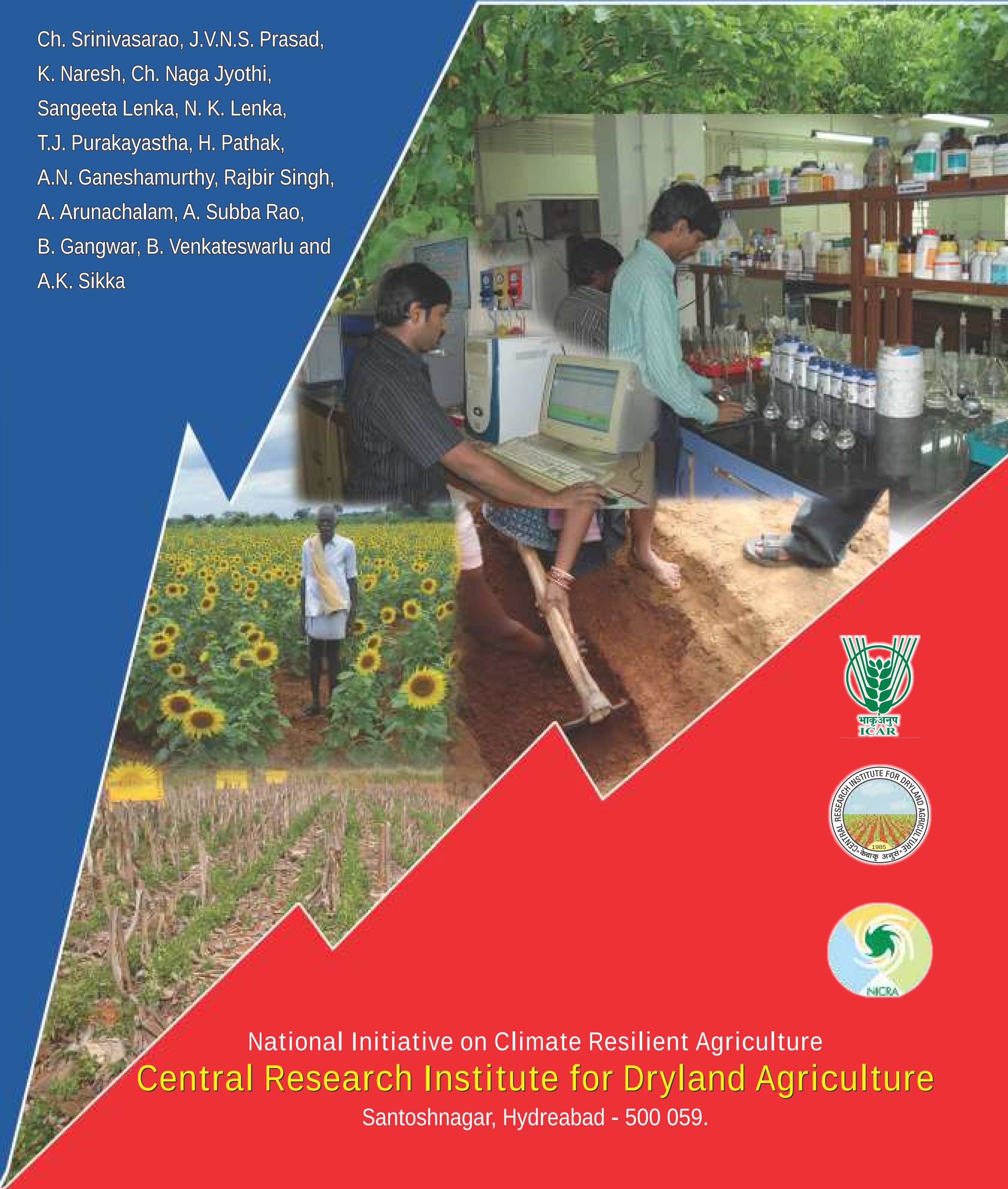

National Initiative on Climate Resilient Agriculture
Central Research Institute for Dryland Agriculture
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Partners

Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh
Indian Institute of Soil Science, Bhopal, Madhya Pradesh
Indian Agricultural Research Institute, New Delhi
Project Directorate for Farming Systems Research, Modipuram, Uttar Pradesh
Indian Institute of Horticultural Research, Bengaluru, Karnataka
NRM Division, ICAR, KAB-II, New Delhi

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FOREWARD

Climate change is the biggest threat to rainfed agriculture in the years to come. Rainfed agriculture characterized by high rainfall variability, inherently less fertile soils with low productivity levels and poor coping capacity are more vulnerable to the effects of climate change. Sequestering carbon either into soil or into the vegetation is one of the effective means of mitigation of green house gas (GHG) emissions. Carbon sequestration also contributes towards climate change adaptation by prolonging the availability of moisture to crops and enhance income by way of improved yields and also through trees which can provide additional income during the years of drought. There are several strategies which can enhance carbon sequestration viz. reduced tillage, residue retention, application of manures, integrated nutrient management, green manuring, etc. whereas tree systems such as agrisilviculture, agri-horticulture, silvi-pastures, etc. can store substantial quantities of carbon.There is a significant scope to enhance carbon sequestration in both the irrigated and rainfed systems as there are several proven practices for varied climatic regions which when taken up in a systematic manner can contribute towards enhancing the agricultural productivity in the country in a significant manner.

A number of long-term experiments were initiated in our country to quantify the effect of best management practices on carbon sequestration and enhancing productivity. Several tree based systems are being established in various parts of the country in various network programs. Research programs were initiated under NICRA by various partner institutions to identify the best practices and identify promising tree systems for enhancing carbon sequestration. There is a need to quantify the buildup of carbon in these experiments from time to time with a robust methodology so that results are accurate, verifiable and comparable.

I am happy to note that several institutions of the NARS under the NICRA umbrella have collectively brought out this practical bulletin on carbon sequestration. The bulletin provides step by step guidance for quantifying carbon in both the arable and tree systems in a clear and concise manner. I am sure this bulletin will be useful to all the researchers involved in carbon sequestration research. I complement the authors for this unique effort.

B. Venkateswarlu

PREFACE

Agriculture and forestry sectors can be sinks for CO_2 through carbon sequestration into biomass and soil organic matter and is considered as a win-win strategy for sustainable crop productivity and environmental protection. Soil organic carbon plays a critical role in cycling of essential nutrients, improve the soil physical, chemical and biological properties, reduce soil erosion, arrests land degradation, prolongs the moisture availability thus contributing to soil health, agriculture growth and environmental services. Carbon content of majority of Indian soils is low and there is vast potential to enhance the soil carbon stocks. Restoration of degraded lands can sequester up to 9 Tg C annually and part of the potential can be realized with the current technology and by integrating with the developmental programs. Out of the 120 m ha of degraded area of the country, adoption of appropriate land use and management practices can arrest further degradation thus results in higher biomass and promotes higher soil C accumulation.

Maintaining or enhancing organic carbon is a slow process particularly in tropical regions where rapid decomposition of organic matter results in loss of carbon. Results of a number of experiments conducted in India and abroad conclusively proves the potential, however the rates of sequestration have been low. There is a need to develop location specific management practices for enhancing the carbon stocks for various production systems and studies on strategies for enhancing soil carbon stocks and developing appropriate tree systems are at a nascent stage in India. A number of experiments were initiated in network mode by several organizations in the country and C sequestration potential and C stocks inventory is in progress under NICRA. This bulletin outlines brief overview of carbon sequestration and step by step procedure for quantification of carbon in soils and tree systems in a simple manner. We firmly believe that this publication will be very useful for researchers, academicians, policy makers and students and for estimating C stocks in NICRA long term experiments. We thank all those who have contributed towards the completion of this publication.

Authors

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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
$FeSO_4 7H_2O$	Ferrous Sulphate
$FeSO_4 (NH_4)_2SO_4 6H_2O$	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
$K_2Cr_2O_7$	Potassium Dichromate
NaOH	Sodium Hydroxide
NATCOM	National Communication
OC	Organic Carbon
SIC	Soil Inorganic Carbon
TC	Total Carbon
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

1. Introduction

1. Introduction

Carbon is the fundamental building block of life and an important component of many chemical processes on the planet earth. Carbon is exchanged and cycled among earth's oceans, atmosphere, ecosystems and geosphere. It is present in the atmosphere primarily as carbon dioxide (CO_2). In recent years there has been a consistent and continuous increase in the emission of greenhouse gases (GHGs) in to 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). The CO_2 concentration in the atmosphere has increased from 280 ppm in 1850 to 391 ppm in 2012 (WMO, 2012; CDIAC, 2012). There has been increase in the atmospheric methane (CH_4) and nitrous oxide (N_2O) concentrations over the same period resulting in increase in the radiative forcing leading to global warming (IPCC, 2007). Global climate change and warming may lead to greater variability in rainfall, rise in sea level, increased incidence of extreme weather events, heavy and intense storms, decrease in crop yields in some of the tropical regions threatening the livelihoods of communities living in the climatically vulnerable regions of the world. The GHGs emissions should be reduced by 50 to 80% by 2050 to avoid the adverse consequences of global warming. There are three strategies of lowering CO_2 concentration from the atmosphere: (i) reducing the global energy use, (ii) developing low or no-carbon fuel, and (iii) sequestering CO_2 from point sources or from atmosphere through natural (vegetation/soils) and engineering techniques (Schrag, 2007).

1.1. Carbon sequestration

Carbon sequestration is fixing atmospheric CO_2 by physical, chemical or biological processes into long-lived carbon pools such as ocean, soil, vegetation (especially forests) and geologic formation in a manner that it is not re-emitted into the atmosphere in the near future. Although oceans store most of the earth's carbon, soils contain approximately 75 to 80 % of the terrestrial carbon pool and higher than the biotic pool (i.e. the increased amount stored in

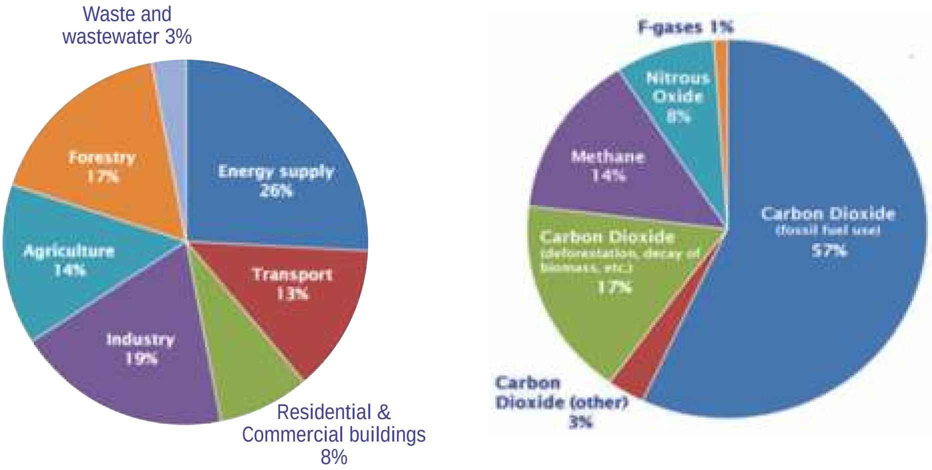


Fig 1. Contribution of various greenhouse gases to global warming (IPCC 2007)

living plants and animals). Therefore, soils play a key role in maintaining a balanced global carbon cycle. Depending on the processes and technological innovations, there are three main types of carbon sequestration (i) those based on the natural process of photosynthesis and conversion of atmospheric CO_2 into biomass, soil organic matter or humus and other components of the terrestrial biosphere; (ii) those involving engineering techniques and (iii) those involving chemical transformations (Lal, 2008). Atmospheric enrichment of CO_2 can be moderated by reducing anthropogenic emissions and by adopting proper management practices in agriculture, forestry systems which will enhance storing or sequestering carbon either in to plant or in to the soil.

1.2. Importance of soil carbon sequestration in agriculture

The soil organic matter, the seat of soil organic carbon, is the most complex, dynamic and reactive soil component. It contributes to plant growth and development through its effect on the chemical, biological, and physical properties of soil. It has nutritional function that it profoundly affects the activities of microflora and macrofauna and promotes good soil structure, thereby improving the tilth, aeration and water retention (Stevenson, 1994). In addition, organic matter in soils is involved in cementing soil particles into structural units (aggregates), chelating metals, provide buffer action, contribute to the cation exchange capacity and mineralization of important plant nutrients and affect the bioactivity, persistence, and biodegradability of pesticides (Fig. 2).

Fig 2. Carbon enriched soil profile

Soil can potentially store 2-4 times higher carbon compared to the atmosphere and vegetation and hence potentially can play a significant role in reducing CO_2 emissions. The total soil carbon consists of the soil organic carbon and inorganic carbon, estimated to be approximately over 2250 Giga tons (Gt) in the top one meter depth (Batjes, 1996). The soil organic carbon (SOC) is a mixture of plant and animal residues at various stages of decomposition and substances synthesized microbiologically and or chemically from the breakdown products, and of the bodies of live microorganisms and small animals. The soil inorganic carbon (SIC) consists of elements of carbon and carbonates. There is a potential of increasing SIC pool through formation of secondary carbonates in arid regions. In addition, there is also the potential of leaching of bicarbonates, especially in soils irrigated with good quality water. However, the rate of formation of secondary carbonates is low (e.g., 5–10 kg $ha^{-1} yr^{-1}$) (Lal, 2004; 2008).

Carbon sequestration through enrichment of SOC stocks in arable systems is gaining importance because of its potential to climate change mitigation and the associated benefits to crop productivity and sustainability. In general, Indian soils are poor in soil organic carbon (< 5 mg kg^{-1} soil or 0.5%) due to prevailing high temperature facilitating faster decomposition. Organic carbon content of some of the important soil groups under rainfed conditions is presented in Fig. 3. Other soil properties such as clay content and CEC (Fig. 4) also governs soil carbon accumulation and stabilization.

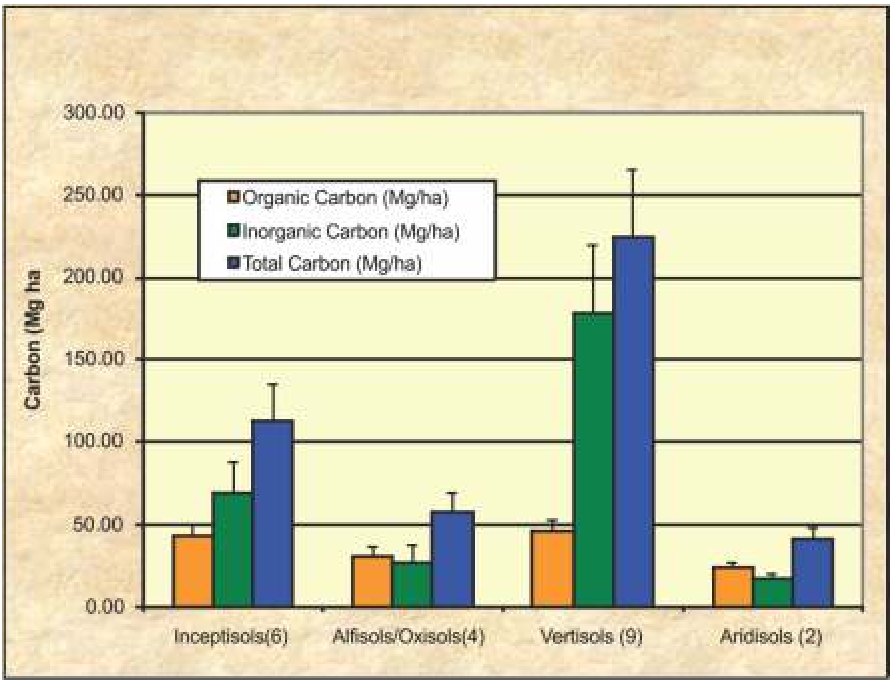


Fig 3. Carbon stocks in different soil types under various rainfed production systems of India

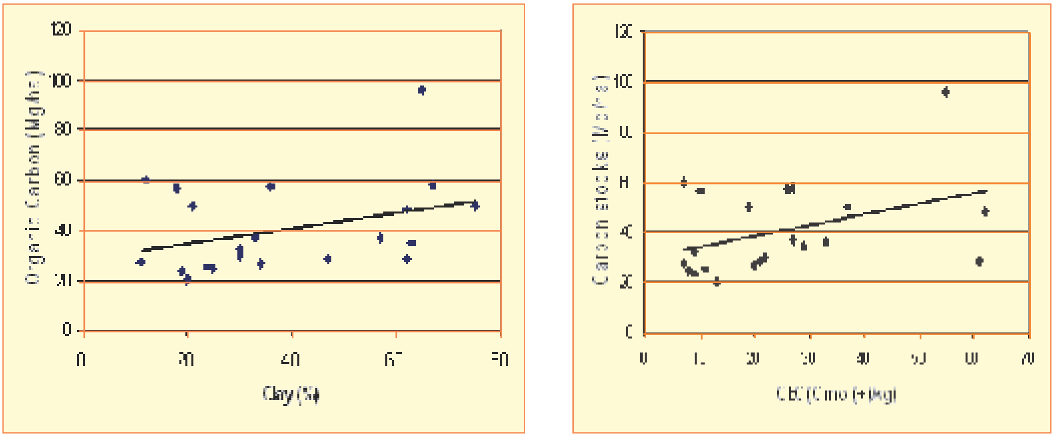


Fig 4.Relationship between the clay content and cation exchange capacity (CEC) with that of the organic carbon

Soil management practices such as reduced tillage, balanced fertilizer application, irrigation and crop residue management, etc. help to build soil carbon stocks to varying degrees. Reducing the intensity and frequency of tillage operations and leaving crop residues on the soil surface as mulch are important strategies for enhancing soil organic carbon content. Judicious nutrient management is crucial to carbon sequestration in tropical soils. Long-term manure application increases the carbon pool and the effects may persist for longer periods. Although both organic and inorganic forms of carbon are found in soils, land use management typically has a larger impact on organic carbon (Srinivasarao et al., 2013).

1.3. Soil carbon sequestration in agriculture systems

Most of the agricultural soils contain lower SOC pools than their counterparts under natural ecosystems. The reduction of SOM, during conversion of natural to agricultural ecosystems along with drainage of wetlands, intensive tillage of soils and burning or removal of crop residues has reduced the soil sink capacity. Thus conversion to a restorative land use and adoption of recommended management practices can enhance the SOC pool. In general, SOC sequestration rate can be up to 0.5 to 1.5 t $ha^{-1}yr^{-1}$ in cool and humid climates and 0.05 to 0.5 t $ha^{-1}yr^{-1}$ in warm conditions and in arid regions (Lal, 2004). The rate of decomposition of SOM is generally higher in tropical than in temperate climates. However, crop species also play an important role in maintaining SOC pools, through the quality and quantity of the residues that are returned to the soil (Mandal et al., 2007). Increasing the SOC pool by one Mg C ha^{-1} yr^{-1} can enhance agronomic production in developing countries by 32 and 11 million tons per year in case of cereals and food legumes respectively (Lal, 2011; Srinivasarao et al., 2012c).

Some of the strategies for improvement of carbon sequestration potential are no-till farming with crop residue mulch and cover cropping (conservation agriculture), integrated nutrient management (INM) including use of compost and manure, and liberal use of bio-solids. A number of long-term experiments were initiated long back in this country to quantify the effect of the best management practices on carbon sequestration and for improvement of productivity in various agro-ecoregions. There is a need to quantify the buildup of soil carbon in these experiments from time to time and with a robust methodology so that the results are accurate, inter-comparable and verifiable (Srinivasarao et al., 2013).

The objective of any carbon sequestration strategy is to enhance the carbon stocks in the vegetation in case of tree systems and to retain it for longer time and to increase the soil organic carbon, improve depth wise distribution of SOC and to stabilize the SOC by encapsulating it within stable micro-aggregates so that carbon is protected from microbial processes. Adoption of appropriate land use coupled with best management practices are important elements of such a strategy. However, the exact sink capacity depends on the kind of land use and the antecedent level of SOM, climate, soil profile characteristics and the management practices adopted (Lal, 2004). The carbon sequestration rates related to important rainfed production systems of India are presented in Table 1.

Table 1: Carbon sequestration rates in different rainfed production systems of India

Location	Rainfed production system and location	Rate of carbon sequestration (Mg C ha^{-1} yr^{-1})	Organic materials used	Quantity of organic carbon matter applied (Mg ha^{-1} yr^{-1})	Reference
Anantapur (Andhra Pradesh)	Groundnut, Alfisols	0.57	Groundnut shells	1.78	Srinivasarao et al., 2012a
Bangalore (Karnataka)	Finger millet mono cropping Alfisols	0.51	FYM	1.64	Srinivasarao et al., 2012b
Solapur (Maharashtra)	Rabi Sorghum, Vertisols	0.89	Sorghum stover, Leucaena clippings	3.40	Srinivasarao et al., 2012d.
Indore (Madya Pradesh)	Soybean-Safflower, Vertisols	1.18	Soybean residue	3.48	Srinivasarao et al., 2012e
Varanasi (Uttar Pradesh)	Rice- Lentil, Inceptisols	0.31	FYM	3.55	Srinivasarao et al., 2012f
Bangalore (Karnataka)	Fingermillet – Groundnut rotation, Alfisols	0.32	FYM	2.03	Srinivasarao et al., 2012c
SK nagar (Gujarat)	Pearlmillet-Clusterbean-Castor rotation, Entisols	-0.36	FYM	3.95	Srinivasarao et al., 2011

Arresting land degradation reduces the erosion and soil displacement. The predominant form of land degradation in arid and semi-arid regions of India is water erosion. Erosion displaces the fertile surface layer which contains relatively higher organic carbon. The displaced carbon eventually gets oxidised to CO_2 and released in to the atmosphere. It has been estimated that carbon sequestration to the extent of 7.2 to 9.8 Tg C yr^{-1} (Table 2) can be achieved by arresting land degradation in India (Lal, 2004).

Table 2. Soil organic carbon sequestration through restoration of degraded soils (Lal, 2004)

Degradation process	Area (M ha)	SOC sequestration rate (kg ha^{-1}yr^{-1})	Total SOC sequestration potential (Tg C yr^{-1})
Water erosion	32.8	80-120	2.62-3.94
Wind erosion	10.8	40-60	0.43-0.65
Soil fertility decline	29.4	120-150	3.53-4.41
Waterlogging	3.1	40-60	0.12-0.19
Salinization	4.1	120-150	0.49-0.62
Lowering of water table	0.2	40-60	0.01-0.012
		Total	7.20-9.82

Reducing tillage intensity is one of the options for enhancing the soil carbon sequestration. The conventional tillage practices disrupt the soil aggregates and exposes the carbon resulting in loss of carbon (Fig. 5). In recent years, zero tillage along with the conservation agricultural practices have been suggested for enhancing the soil carbon status.

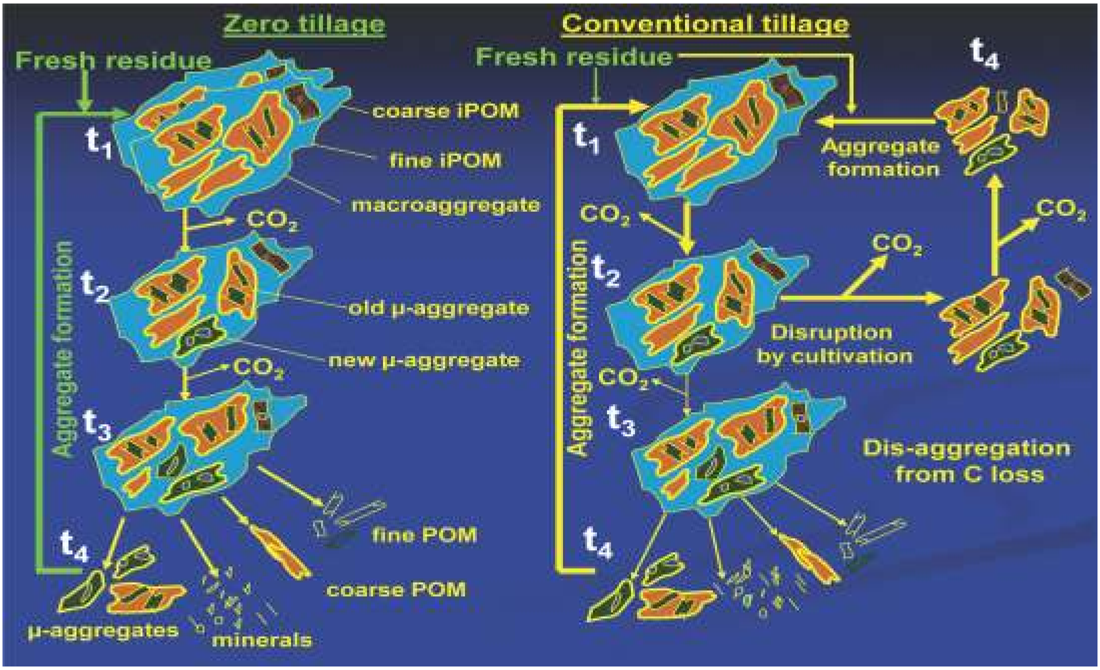


Fig 5. Illustration of soil carbon sequestration and stabilization in relation to soil tillage management

1.4. Carbon sequestration in agroforestry/ perennial/horticultural systems

Agroforestry is defined as a land-use system that involves the deliberate introduction, retention of mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock to exploit the ecological and economic interactions of different components for enhancing the productivity in unit area and time. Several studies have conclusively proved that inclusion of trees into the agricultural landscapes often improves productivity of the system while providing opportunities to create carbon sinks. The amount of C sequestered largely depends on the kind of agroforestry system, management practices adopted, soils and the climate of the region (Prasad et al., 2012).

Carbon sequestration in agroforestry systems can be broadly divided into sequestration in above ground and below ground plant parts. The above ground carbon sequestration rates in some major agro-forestry systems around the world are highly variable, ranging from 0.29 - 15.21 Mg $ha^{-1}yr^{-1}$ (Nair et al., 2010) and differs greatly depending on a number of factors, like the agro- climatic region, the type of system, site quality, previous land use, management practices adopted, etc. In general agroforestry systems on the arid, semi-arid and degraded sites have a lower carbon sequestration potential than those on fertile humid sites; and the temperate agroforestry systems have relatively lower sequestration potential compared with the tropical systems. The carbon sequestration rates in some of the predominant agroforestry systems in India are presented in Table 3.

Table 3: Carbon sequestration rates in different agroforestry systems*

Location	System	Carbon sequestration (Mg $ha^{-1}yr^{-1}$)
Chandigarh (Mittal & Singh, 1989)	Leucaena agri-silvi system	0.87
Jhansi (Rai et al., 2002)	Anogeissus agri-silvi system	1.36
Coimbatore (Viswanath et al., 2004)	Casuarina agri-silvi system	1.45
Bhadrachalam, AP (Prasad et al., 2012)	Leucaena agri-silvi system	13.7
	Eucalyptus agri-silvi system	7.5
Karnal (Kaur et al., 2002)	Prosopis silvi-pasture system	2.36
	Acacia silvi-pasture system	1.29
	Dalbergia sissoo silvi-pasture system	1.68

Location	System	Carbon sequestration (Mg $ha^{-1}yr^{-1}$)
Himalayan foot hills (Narain et al., 1998)	Eucalyptus silvi-pasture system	3.41
	Leucaena silvi-pasture system	3.60
Jhansi (Rai et al., 2000)	Leucaena silvi-pasture system	1.82
	Terminalia silvi-pasture system	1.11
	Albizia procera silvi-pasture system	2.01
	Dalbergia sissoo silvi-pasture system	2.90
Hyderabad (Rao et al., 2000)	Leucaena monoculture	5.65
Tripura (Negi et al., 1990)	Gmelina monoculture	3.69
U.P. (Negi et al., 1990)	Teak monoculture	2.94
Dehradun (Dhyani et al., 1996)	Eucalyptus monoculture	5.54

* Excluding soil carbon

In agroforestry systems the carbon stored in soil ranges from 30-300 Mg C ha^{-1} up to one meter depth (Nair et al., 2010). Carbon sequestered in agroforestry systems depends on the quantity and quality of biomass added through trees and soil parameters such as soil structure and aggregation. In a poplar system an increase in soil carbon to the extent of 6.07 t ha^{-1} yr^{-1} and higher carbon content was observed in 0-30 cm depth in sandy clay compared to loamy sand. About 69% of soil carbon in the profile was confined to the upper 40 cm soil layer wherein carbon stock ranged from 8.5 to 15.2 Mg C ha^{-1}. A mix of agroforestry with crop fields is a promising option to enhance C sequestration in soils (Fig. 6).

Fig 6. Mango and eucalyptus based agroforestry systems

1.5. Carbon sequestration for mitigation of climate change

In 2010, world emitted 50,101 Mt CO_2 eq. whereas India emitted 2,691 Mt CO_2 eq. i.e., 5.4% of the global greenhouse gas (GHG) emission. The global agriculture contributed 11.3% (5,677 Mt CO_2 eq.) of total global GHG. Share of Indian agriculture was 7.1% (406 Mt CO_2 eq.) of emission from global agriculture. Indian agriculture contributed 21.0% of Indian total GHG emission, but was only 1.1% of the total global emission from all the sources (Pathak H, unpublished). During 1970 to 2010, GHGs emission from Indian agriculture has increased by about 75%. Increased use of fertilizer and other agri-inputs and increased population of livestock are the major drivers for the increase in GHG emission. Relative contribution of Indian agriculture to the total GHG emission from all the sectors of the country, however, has decreased from 32.5% in 1970 to 15% in 2010. Higher growth in emission from energy, industry and transport sectors compared to that of agriculture sector are responsible for such decreasing contribution from agriculture. Emission of methane from Indian rice fields has remained almost similar during 1970 to 2010 though the rice production has increased during the period from 115 to 128 Mt. This is because of almost constant area under rice (43-44 Mha) and similar water and crop management practices followed by the farmers over the years. However, emission of nitrous oxide has increased considerably during the period because of use of more fertilizer and manure in soil.

Agriculture and forestry sectors can be the sinks for CO_2 through carbon sequestration into biomass and soil organic matter. There are multiple benefits of sequestering carbon in forest and agricultural soils and in vegetation besides the obvious benefit of offsetting CO_2 emissions. Adding value to the carbon sequestered in the vegetation and other products enhances the returns and income to the farmer in more than one way. Sequestering carbon either through arresting land degradation or through adoption of management practices is a win-win strategy for enhancing the agricultural productivity as well as towards mitigation of GHG emissions.

1.6. Community/ economic benefits of carbon sequestration

Enhancing carbon sequestration has multiple benefits which can be summarised in to benefits associated with improvement in soil quality and towards improving the environment by way of mitigating the harmful effects of CO_2. The tangible and intangible benefits associated towards each of the above are elaborated here.

1) Improvement in soil quality: Enhanced soil organic carbon content of soils results in improvement in the nutrient supplying capacity of the soil, improvement in soil physical properties and also enhanced microbial activity which improves the crop growth favourably and provide better environment for crop growth.

2) Improved water holding capacity: Water holding capacity of soil is just that, the specific ability of a particular type of soil to hold water against the force of gravity. The nature of the soil, composition of the soil, amount of organic component and size of the soil particles determine its ability to retain water. Soil organic matter compounds bind the primary particles in the aggregates, physically and chemically and this, in turn, increases the stability of the aggregates and water holding capacity of soil. Soil organic carbon build up influence the water transmission properties of the soil viz., hydraulic conductivity, infiltration and percolation through their influence on aggregation status, total porosity and the continuity of macropores present in the soil. Soil organic matter generally improves both the initial and steady state infiltration rate of soil due to the beneficial effect of it on the water stability of soil aggregates, consequent reduction in crust formation, development of a continuous soil bio-pore system and increase in hydraulic conductivity.

3) Increasing crop productivity: Organic matter affects crop growth and yield, either directly by supplying nutrients, or indirectly by modifying soil physical properties that can improve the root environment and stimulate plant growth. It was estimated that each ton of profile organic carbon stock has potential to improve crop productivity upto 400 kg ha^{-1} yr^{-1} (Srinivasarao et al., 2013).

4) Improvement in environment and mitigating GHG emissions: The Kyoto Protocol of 1997 of the United Nations Framework Convention on Climate Change (UNFCCC) provides the foundation for international efforts to reduce the greenhouse gas emissions and to ensure communities getting benefit towards the GHG emission reduction/ carbon sequestration activity. The Kyoto Protocol recognises forestry and agroforestry sectors as potential sinks and paved the way for creation of Clean Development Mechanism (CDM) for transferring the benefits to communities who contribute towards mitigation activities.

There are many approved methodologies in CDM which supports agroforestry interventions. Many of these methodologies were developed in the last three years and aims at introduction of trees in various landscapes which performs multiple roles. Some of the approved methodologies for afforestation/reforestation are given in Table 4. The existing methodologies support integration of trees in to private and community lands as agrisilviculture, silvipasture system, short rotation intensive systems and also for taking up intensive tree cultivation in highly degraded lands such as shifting sand dunes, mine spoils, ravines, homesteads and roadside plantations, etc. Soil carbon sequestration is eligible only as a part of land use change and afforestation and reforestation activities, during the first commitment period of Kyoto Protocol (2008-12). In view of the large potential existing in this sector there could be many projects that can be taken up related to agroforestry which can contribute towards improving the livelihoods of the communities besides mitigating the effects of climate change.

Table 4: Approved small scale methodologies related to agroforestry and forestry in cultivated and forest lands (UNFCCC, 2013)

S. No	Methodology	Applicability
1	AR-AMS001 (Simplified baseline and monitoring methodologies for small-scale/afforestation and reforestation project activities under CDM implemented on grasslands or croplands)	Agroforestry systems, short rotation intensive forestry systems, silvipasture
2	AR-AMS002 (Simplified baseline and monitoring methodologies for small-scale afforestation and reforestation project activities under CDM implemented on settlements)	Agroforestry systems, silvipasture, horticultural crops, energy crops
3	AR-AMS004 (Simplified baseline and monitoring methodologies for small-scale agroforestry afforestation and reforestation project activities under CDM	Agroforestry systems
4	AR-AMS005 (Simplified baseline and monitoring methodologies for small-scale afforestation and reforestation project activities under CDM implemented on lands having low inherent potential to support biomass)	Establishment of trees on sand dunes, contaminated or mine spoils highly alkaline or saline soils
5	AR-AMS006 (Simplified baseline and monitoring methodologies for small-scale silvipastoral afforestation and reforestation project activities under CDM)	Tree systems on degraded lands/ grasslands, subject to grazing activities.

2. Field procedures and sampling

2. Field procedures and sampling

2.1 Soils

Carbon in soils can be divided into two major pools: soil organic carbon (SOC) and soil inorganic carbon (SIC). Organic carbon is derived from organic matter and is important in maintenance and improvement of soil fertility. Inorganic carbon can be classified into two types: (i) carbonates derived from weathering of rocks (lithogenic) and (ii) carbonates derived from the direct absorption of CO_2 into the soils (pedogenic). The SIC can be a significant carbon pool and has been estimated to be as high as 930-1738 Gt C globally, with significant concentrations in arid regions and in degraded ecosystems. However, the magnitude of SIC sequestration rates are generally lower than that of SOC. The SIC pool is relatively stable, and is thought neither to be a net sink nor to be strongly affected by land management and hence not of much significance in the climate change perspective (Lal, 2009). Measurement techniques for assessing soil organic matter (SOM) are relatively simple and straight forward. The measurement of soil carbon requires (i) collection of soil samples depth wise (ii) determining the soil bulk density (BD) as per the depth of soil sampling and (iii) quantification of soil organic and inorganic carbon content in the collected soil samples. The mass of soil carbon per unit area is determined by multiplying the depth, BD values and the soil C content and summed up depth wise for expressing up to one meter depth.

2.1.1 Profile soil sampling

If the samples are to be collected from an experimental plot, representative locations away from the field boundary are to be selected for soil sampling. If the area to be sampled is large, it may be divided in to appropriate number of smaller homogeneous units for better representation. Variations in slope, colour, texture and crop growth are important factors that should be taken in to account for sampling and areas near trees, wells, compost pits and other non representative locations are to be avoided. Pits with a dimension of 1 x 1 x 1-1.5 meter are dug depending upon soil depth, soil condition and the production system. The samples are to be collected from different depths and depend on the kind of crops to be studied and their rooting habits. For deep rooted, longer duration, dryland crops and tree systems samples are to be collected at depths of 0-20, 20-40, 40-60, 60-80 and 80-100 cm. The thickness of the different horizons are to be measured and reported. A minimum number of 5 sub samples should be collected for every layer but more samples are required if the site is heterogeneous. The organic layer at the soil surface is sampled separately from the underlying mineral soil. The distinction has to be made between the organic layer and mineral layers. A record of the places sampled should be kept.

2.1.2. Soil sample collection

Samples can be drawn with core sampler, tube auger, screw type (Fig. 7), post hole or with spade and khurpi depending on the moisture status and physical condition and crop status at the time of sampling. Soil is collected from each layer and from the desired depth by means of suitable sampling tools. The soil collected from the same treatment and mixed thoroughly by hand on a clean piece of cloth or polythene sheet. From these samples, one composite sample is prepared by the method of quartering till about 500 g of sample is obtained. Generally soil samples are taken at the end of the growing season, and if the aim of the study is to detect temporal changes in carbon levels, then it is important to keep the timing of sampling uniform. Special care in collection and handling samples is required to prevent contamination. The samples are labelled carefully.

Fig 7. Collection of soil sample with (a) screw augur and (b) core sampler

2.1.3. Soil sample collection for bulk density (BD)

Bulk density of soil is the mass per unit volume of soil. Core method is widely used to measure the bulk density for stone-less and slightly stony soils. The samples are taken with core cylinders on the horizontal sections. The cores for BD measurement should be at least 75 mm and preferably 100 mm in diameter and the height of the sample should not exceed the diameter. Cylinders are inserted vertically or horizontally with force by hammering enough to fill the sampler. A single cylinder may be used with the bottom sharpened. Soil cores are carefully taken to ensure minimal compaction and disturbance to the soil structure. In hard soil layers, an impact absorbing hammer may be used for hammering the ring holder into the soil. Some headroom space is left over the ring allowing for taking an oversize sample. This prevents the sample for compaction during sampling. The ring with sample is taken vertically with its cutting edge downwards. Dig out the cylinder carefully with a trowel. A spatula or knife may be used but care has to be taken to avoid smearing the surface. General precautions to be taken during sample collection and processing are given in Table 5 Sampling date, sample reference and the exact sampling depths are recorded and each sample is labelled carefully. The samples are immediately transferred in to plastic bags or a plastic or aluminium foil to prevent drying.

2.1.4. Processing soil samples

Soil samples brought to the laboratory are spread out on an aluminium tray, plastic or a thick brown paper. Coarse concretions, stones and pieces of roots, leaves and other undecomposed organic residues are removed.

Table 5: Precautions to be taken while soil sampling and processing

Sample Collection	Sample Processing
Sample should represent the treatment/ system	Dry the samples only under the shade
Do not collect samples near water channels, near borders, trees, wells, manure heaps, etc.	Avoid using bags or boxes which are previously used for fertilisers, manures, etc.
Do not collect the sample when the field is excessively wet	Use markers and labels which do not fade
Avoid contamination while collection of samples	Store the samples in shade and dry place

Large lumps of moist soil are broken by hand. It is preferable to shade dry soils at 20-25^{0}C and at 20 to 60% relative humidity. Samples may be mixed during drying to expose fresh surface. After air-drying, the samples are crushed gently in pestle and mortar and sieved. The pestle and mortar may be of wood, porcelain/stoneware or stainless steel. The process is continued till the desired quantity of soil sample is obtained. For organic carbon estimation through Walkley and Black method, samples, passed through 0.2 mm sieve are required. Ground samples are stored in thick gauge polythene bags, screw cap jars or glass containers along with an identification number or tags (Fig. 8). Cloth bags are unsatisfactory because they are neither water proof nor dust proof.

Fig 8. Soil sample air drying, processing and proper storage

2.2. Agroforestry and perennial 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 carbon 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 carbon sequestered by an agroforestry system is the cumulative of three components (Fig. 9). They are

1) Carbon sequestered in above ground parts
2) Carbon sequestered in below ground parts (root carbon)
3) Carbon sequestered in soils in tree systems

A

B

Fig 9. A) Separation of the whole tree biomass in to individual components and B) Excavating the tree root systems for the determination of biomass in Jatropha (GR Rao)

3. Laboratory estimation and data analysis

3. Laboratory estimation and data analysis

3.1. Soils

3.1.1. Bulk density

On returning from the field, the sampler and its contents are carefully removed so as to preserve the natural structure and packing of the soil as nearly as possible. A shovel, alongside and under the sampler, may be needed in some soils to remove the sample without disturbance. The soil is trimmed extending beyond each end of the sample holder with straight-edged knife or sharp spatula. The sample volume is thus established to be the same as the volume of the sample holder. Transfer the soil to a container, weigh it and place it in an oven at 105^0C till constant weight is reached (Fig. 10). Bulk density is determined by dividing the oven dry soil sample by the volume of the sample. The soil used for the estimation of bulk density is not to be used to determine the organic carbon content. The equation for BD estimation is as follows:

Calculation

$$\text{Soil bulk density (Mg cm}^{-3}) = \frac{\text{Oven dry weight of soil}}{\text{Total volume of soil}}$$

Fig 10.Collection of samples using core sampler and transfer of samples into cans

3.1.2. Soil organic carbon

Organic carbon is estimated by the modified Walkley-Black Method (Walkley and Black 1934). Organic matter in the soil is oxidized with the mixture of potassium dichromate ($K_2Cr_2O_7$) and concentrated H_2SO_4 utilizing the heat of dilution of H_2SO_4. Unused $K_2Cr_2O_7$ is back titrated with ferrous sulphate ($FeSO_4.7H_2O$) or ferrous ammonium sulphate [$FeSO_4.(NH_4)_2SO_4.6H_2O$] (Fig. 11).

Step Wise Procedure for Estimation of Soil Organic Carbon

Accurately weigh 1 g of 0.2 mm sieved soil. Transfer it to a dry 500 ml Erlenmeyer flask

↓

Include two blanks to standardise $FeSO_4.7H_2O$ or $FeSO_4.\ (NH_4)_2SO_4$ solution

↓

Add exactly 10 ml of IN $K_2Cr_2O_7$ solution (dissolve exactly 49.04 g reagent grade $K_2Cr_2O_7$ in distilled water and dilute to 1 liter in volumetric flask)

↓

Swirl the flask gently and keep it on an asbestos sheet

↓

Add about 200 ml distilled water and add 10 ml of orthophosphoric acid or sodium fluoride and add 1 ml of diphenylamine indicator

↓

Titrate with 0.5N ferrous ammonium sulphate or ferrous sulphate (Dissolve 140 g of $FeSO_4.7H_2O$ or 196.1g $FeSO_4.\ (NH_4)_2SO_4.\ 6H_2O$ in about 800 ml water and add 100 ml conc. H_2SO_4, cool and dilute to 1 liter in a volumetric flask) till the colour changes from blue violet to green colour

↓

If the burette reading is 0-4 ml, repeat with less soil. If it is 17 ml or higher, repeat with more soil

Calculation

$$\text{Organic carbon (\%)} = \frac{10\,(B-T)}{B} \times \frac{(0.003 \times 100)}{\text{Wt.of soil (g)}}$$

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.

Organic matter (%): Organic C (%) X 1.724 (factor)

Fig 11. Weighing of soil samples by digital electronic balance and titration for organic carbon estimation

3.1.3. Soil inorganic carbon (SIC)

The inorganic carbon in the soil is represented by carbonates of calcium and magnesium. The major component of the SIC is represented by the calcium carbonate. The rapid titration method of Piper (1944) also called as acid neutralization method is generally used for estimation of SIC. The sample is treated with dilute acid and the residual unreacted acid is titrated with alkali (Fig. 12). The results are expressed as calcium carbonate equivalent.

Step Wise Procedure for the Estimation of SIC

Weigh 10 g of 2 mm sieved soil in an Erlenmeyer flak including blank

↓

Add 25 ml of 0.5 N HCl (Take about 600 ml of distilled water to a graduated Erlenmeyer flask, slowly add 18.25 ml conc. HCl under constant stirring. Cool and make to 1 litre by pipette and swirl it for half an hour)

↓

Transfer it on a water bath and heat for 5 min, cool and filter it with 2 washings

↓

Add 5 drops of Phenolphthalein indicator (Dissolve 100 mg Phenolphthalein in 100 ml ethanol 99.9%) titrate it with 0.25 N NaOH (Take about 800 ml of distilled water to a graduated Erlenmeyer flask, add 10 g of NaOH under constant stirring and make up to 1L)

Calculation

$$\mathrm{CaCO_3}\ \%\ \text{equivalent} = \frac{(a-b)}{s} \times 0.050 \times 100$$

Where

a = ml NaOH used for blank, b = ml NaOH used for sample, s = air-dry sample weight in grams.

Fig 12.Analysis for estimation of soil inorganic carbon

3.1.4. Total carbon, total organic carbon & total inorganic carbon

Instrumental Analysis

Total C 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 CO_2 by wet or dry combustion methods and subsequent quantification of evolved CO_2 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 soil. Dry combustion is conducted by heating (~ 1000 ^{o}C) a soil – catalyst mixture in a resistance furnace or induction furnace in a stream of O_2 or CO_2 free air followed by quantification of evolved CO_2. Through dry combustion method, oxidation of organic carbon and thermal decomposition of carbonate minerals is achieved. The commercially available automated instruments such as TOC analyzer, CHNS analyzer, employ the dry combustion principles.

Principle

The commonly used method is the catalytic combustion or oxidation method. The catalytic combustion method achieves total combustion of samples by heating them to 680°C in an oxygen-rich environment inside total carbon combustion tubes in the presence of platinum catalyst. One of the important features of this method is the capacity to efficiently oxidize hard-to-decompose organic compounds, including insoluble and macromolecular organic compounds. Since this method utilizes the simple principle of oxidation through heating and combustion, the steps of pre treatment and post-treatment using oxidizing agents are unnecessary, which enhances operability. The carbon dioxide generated by oxidation is detected using an infrared gas analyzer (NDIR- non-dispersive infrared) which has high detection sensitivity, with a detection limit of 4μg L^{-1}, the highest level for the combustion catalytic oxidation method. The sample is delivered at the combustion furnace, which is supplied with purified air. There, it undergoes combustion through heating up to 680°C with a platinum catalyst. It decomposes and is converted to carbon dioxide. The carbon dioxide generated is cooled and dehumidified, and then detected by the NDIR. The concentration of TC (total carbon) in the sample is obtained through comparison with a calibration curve.

Operation

Total Carbon (TC)

The sample is initially weighed into a tin/silver boat. The boat is then placed into a quartz ladle which is introduced to the high temperature and oxygen atmosphere (typically 950°C) within the sample combustion zone. At higher temperature, all the carbon within the sample gets rapidly oxidized to CO_2. Interfering reaction products (including sulphur oxides, halides, water and nitrous oxides) are removed by the post-combustion scrubbers. The resulting carbon dioxide is then swept into the Coulometer/detector where it is automatically measured.

Total Inorganic Carbon (TIC)

Upon introducing a sample into the sample flask, the system is purged with a CO_2-free carrier gas to eliminate atmospheric carbon dioxide. At that point, the analysis is initiated by adding an aliquot of acid through the acid dispenser into the sample flask, causing inorganic carbon to be evolved as CO_2. Using the built-in heater and magnetic stirrer to facilitate the fast evolution of inorganic carbon, the CO_2-free carrier gas transports the reaction products through a post-scrubber (to remove potential interferences) and ultimately into the reaction cell within the coulometer. There, the carbon dioxide is automatically measured using absolute coulometric titration (Fig. 13). In some models, the soil sample is treated with the acid and the evolved CO_2 is carried to the detector by the carrier gas and the concentration of CO_2 is read through infrared detector.

Total Organic Carbon (TOC)

Generally the direct TOC analysis of solids is performed by subjecting the soil sample to various pre-treatment methods resulting in the release of SIC as CO_2 and the remaining as the TOC. But the TC and SIC can be estimated separately and the TOC is estimated as difference, where

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

Fig 13. Handling of TOC analyzer for estimation of total carbon and inorganic carbon

Data Handling

Analytical progress is displayed on the 10" LCD touch screen in user selectable units. Detailed analysis/ information is automatically saved to an on-board SD card after each sample. Data can also be transmitted through the standard serial and Ethernet ports to be captured on a personal computer. In addition, a detailed report can be printed while each sample is running

Elemental (CHN) Analyzer

Principle

Total C and N were measured by CHN analyzer using dry combustion technique. The dry combustion method is based on oxidation of organic carbon and thermal decomposition of carbonate mineral in a medium temperature resistance furnace (~1000°C). A sample is placed in a tin sample capsule, crimpled to confine it and introduced into a quartz combustion reactor. Flash combustion occurs when a pulse of O_2 is injected into the quartz reactor immediately after the introduction of the sample. Under these temperatures and O_2 conditions, the tin is oxidized to SnO_2 resulting in the increase of temperature from 1700°C to 1800°C resulting in complete combustion of soil carbon and nitrogen. The combustion products (CO_2, N oxides, and H_2O) a swept by the helium carrier gas and passed over CuO to convert any traceable CO to CO_2 and silver mesh to remove S and halogen gases. The gases then flow through a heated Cu (650°C) column to remove excess oxygen and reduction of N oxides to N_2. The gas mixture is separated via three columns by the purge and traps chromatography and is subsequently detected by a thermal conductivity detector (Fig. 14). It is one of the few analytical techniques that give a clear quantitative measurement of the carbon, hydrogen, nitrogen and sulphur.

Operation of CHN Analyzer

Take oven dried soil sample. Select 3 to 5 samples from the drying oven and record their ID's on the sample sheet - sample sheet has rows and columns labeled like the tray so the first empty space in the tray is the first sample ID listed on the sheet

↓

Close the lids so they are not exposed to the moisture in the air. Moisture affects the weighing process

↓

Use the micro spatula to remove approximately 10 mg of dried soil sample and place it in the tin capsule

↓

Remove the capsule stand and capsule from the balance, and place it on the table

↓

With micro forceps in each hand, hold onto the capsule stand, pinch the top of the tin capsule closed, and remove it from the stand

Close the capsule, fold it over into thirds and flatten with the forceps

↓

Turn it 90 degrees and fold it into thirds again. Be careful not to tear the capsule

↓

Weigh the finished sample (9.500 to 10.500 mg) and place it in the capsule tray. Transfer it to the combustion tube and record the carbon content of the sample

↓

If the capsule tears during the folding process, we have to start over with fresh sample, weigh it, and fold it again

↓

Clean off the micro spatula with methanol and continue with the next sample

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.

Fig 14. Handling of CHN analyser for estimation of total carbon

3.1.5. Computation of soil carbon stocks

Carbon stock for a given soil strata is estimated by multiplying SOC content with soil bulk density and soil layer depth. In order to calculate the quantities of organic carbon accumulated in different depths of soils, the values for each soil depth were multiplied with the bulk density and with the carbon content (Batjes, 1996). Generally carbon stock computation is done for one meter depth of soil profile depending upon soil type (Srinivasarao et al., 2009b).

Equation for computation of carbon stock is:

Carbon stock (Mg/ha) = A x B x C x D

Where in

The C-stock is the C stock in the mineral soil (Mg ha^{-1}), A is the area of one hectare in M^2, B is the depth in meters, C is the bulk density (Mg m^{-3}) and D is the soil organic carbon content in %. A correction factor CFst is used for stoniness, with CFst = 100 - (% stones) / 100.

The total soil carbon pool is then determined by summing the carbon mass of each of the sampled soil depths. Organic matter that is above the soil surface in the litter layer is not taken into account in the assessment of soil carbon stocks. For cultivated soils, this means that plant or crop residues are considered as a transitory phase.

3.1.6. Computation of soil carbon sequestration in cropping systems

The large potential of carbon sequestration in to soils, forestry and agroforestry systems has provided a promising approach to reduce the atmospheric concentration of CO$_2$ for mitigating climate change. However, global soil carbon stocks of agricultural land have decreased historically and continue to decline. Thus, improved agronomic practices that could lead to reduced carbon losses or even increased soil carbon storage are highly desired. Changes in soil carbon levels that result from changes in land uses or production practices are determined by a variety of relatively local factors, including climate condition, soil characteristics, historical land use pattern and current management practices. The carbon stocks of some of the predominant rainfed production systems of India are presented in Fig. 15 (Srinivasarao et al., 2009a, Srinivasarao et al., 2013). An ideal cropping system for carbon sequestration should produce and return significant quantity of biomass or organic carbon in to the soil.

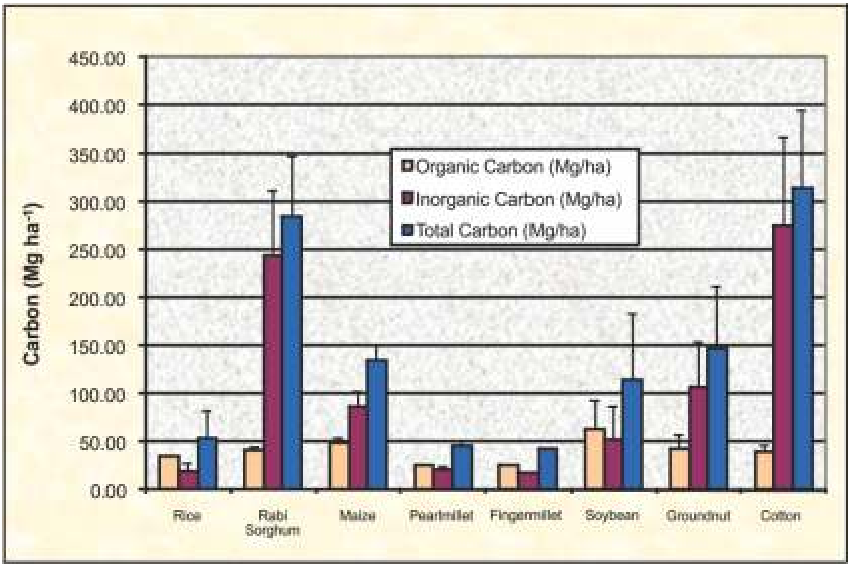


Fig 15. Carbon stocks in soils under diverse rainfed production systems

The organic carbon concentration in the surface soil (0-15 cm) largely depends on the total input of crop residues remaining on the surface or incorporated into the soil. Therefore, to improve carbon sequestration, it is critical to increase the input of plant biomass residues (Fig. 16). Biomass accumulation can be enhanced by an increase in cropping intensity, growing cover crops between main crop growing seasons, reducing fallow period of land, crop rotations and intercropping systems. Biomass return to the soil can be improved by elimination of summer or winter fallow, and maintaining a dense vegetation cover on the soil surface, which can also prevent soil loss from erosion. Under field conditions changes (build up/ depletion) in soil organic carbon does not happen in a short period. Carbon stock estimation is usually done in a long term experiments, farming system, agro forestry, grass land systems and in sites where land use change had occurred. Changes in carbon stocks after certain years of experimentation is computed by the following equation (Srinivasarao et al., 2013).

3.2. Carbon Stock estimation in agroforesty/ perennial systems

Carbon stock in the tree systems is estimated by quantifying the carbon the above ground biomass, below ground biomass and by quantifying the carbon stored in the soil. The above ground biomass can be directly quantified by destructive sampling and measurement of the entire tree and the individual components. Harvesting of the entire tree for estimation of biomass is an old approach (Nair et al., 2010). The second method has been to estimate volume of the trees with the help of allometric equations and

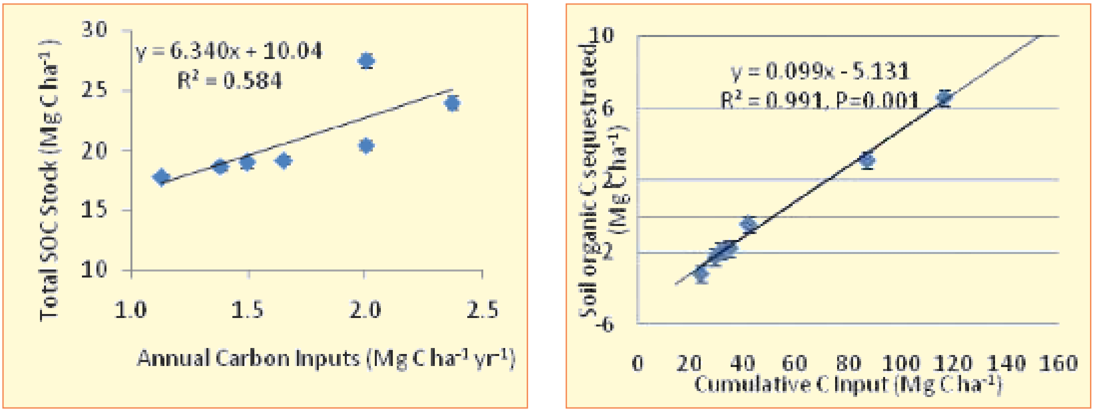


Fig 16. Crop residue C inputs influence soil organic carbon and SOC sequestration

C sequestered (Mg C ha^{-1}) = SOC$_f$- SOC$_i$ for year

Where SOC$_f$ – current year of carbon stock and SOC$_i$ – Initial year of carbon stock

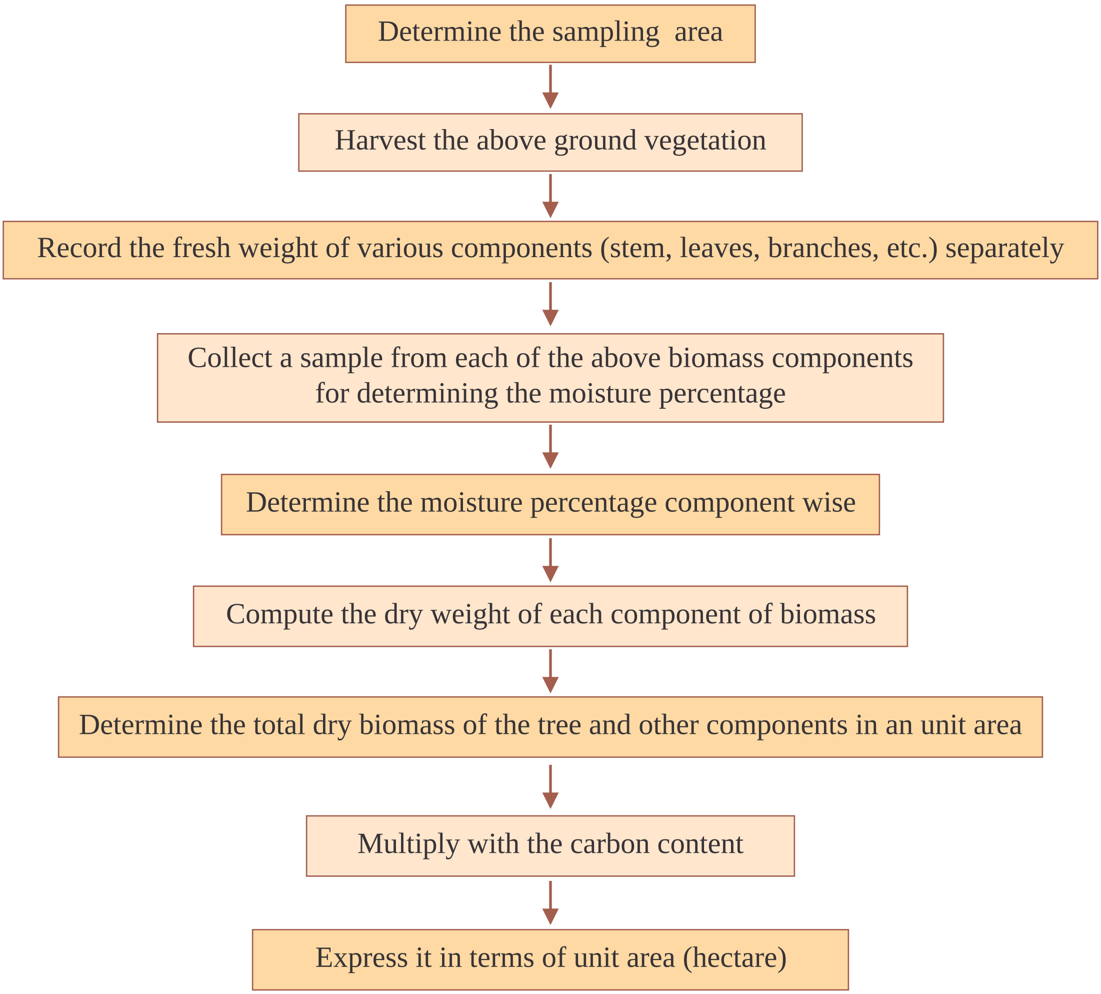
$$\textbf{Carbon sequetration rate (t ha}^{-1}\textbf{ yr}^{-1}\textbf{) = } \frac{\textbf{Carbon sequestered (total)}}{\textbf{number of years experiment}}$$

estimate the weight of the tree using the species specific wood density. The entire tree biomass is then estimated by multiplying with biomass expansion factors to obtain whole tree biomass. The third approach has been to use species specific allometric equations for estimation of the whole tree biomass using the allometric equations. If species specific allometric equations are not available for biomass estimation, general equations (Brown 1997, UNFCCC 2006) can be used.

The procedure for assessing these components is as follows:

3.2.1. Determining the carbon in above ground biomass

The aboveground biomass comprises of all woody stems, branches and leaves of trees and shrubs. Aboveground biomass can be measured in two ways. One of the methods is through destructive sampling where in all the above ground vegetation in a unit area is harvested and the biomass is quantified. The step wise procedure for estimating carbon in the above ground biomass through destructive sampling is as follows:



Estimation of Carbon in above Ground Biomass

One of the precise ways to quantify carbon sequestration in tree systems is through destructive sampling at regular intervals. It is often used to validate other, less invasive and costly methods, such as the estimation of carbon stock using non destructive in situ measurements and remote sensing (Nair, 2012). Unfortunately, cutting and weighing sufficient number of trees to represent the size and species distribution in a system is complex and time consuming and it is also tedious and labour intensive. Therefore, non-destructive techniques have to be used to determine aboveground biomass of forest and agroforestry tree species. These methods are based on regression models that relate biomass to easily measurable growth parameters by allometry. Published allometric relationships are available for some of the commonly grown tree species and they can be used for determining the biomass.

Step Wise Procedure for Estimation of Carbon in Above Ground Biomass using Allometric Equations

Determine the sampling area

↓

Measurement of the diameter at breast height (DBH)/ tree height of all the trees in the sampling area

↓

Use the allometric equation for the estimation of tree biomass

↓

Convert the fresh wood biomass in to oven dry weight basis with the help of moisture percentage

↓

Estimate the carbon content of the biomass (in case facilities are not available use the IPCC default value of 0.47) for converting in to carbon

↓

Express the carbon content for unit area

Published allometric equations are available in literature for many of the commonly grown agroforestry tree species for Indian conditions (Annexure- 1) and they can be used after ascertaining their suitability for a specific location. Majority of the allometric equations use the easily measurable tree growth parameters such as the DBH or tree height or both for higher accuracy. In case species specific equations are not available for Indian conditions, generic equations for different rainfall regimes are available and they can be used for determining the biomass (Annexure - 2). In case volume tables are available, then the tree biomass can be estimated using the wood density values. The dry biomass can to be estimated by with the help of moisture percentage and accordingly the carbon content can be determined.

3.2.2. Quantification of carbon in below ground parts (root carbon)

Trees, by virtue of deep root systems, produce large quantities root biomass. In arid and semi arid regions where soil moisture is the principal limiting factor, trees produce large root systems to obtain water from deeper layers and from larger volumes of soil mass. Quantification of root biomass is laborious and time consuming. Allometric equations for quantification of root systems are limited to a few tree species and may not be available for many trees. Hence, it has been suggested to use a factor of 0.25 of the above ground biomass (GPG, 2006) to determine the below ground biomass. Based on this, the below ground biomass of a tree 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 by using a factor of 0.45 (GPG, 2006).

3.2.3. Quantification of soil carbon in tree systems

The quantum of biomass addition to the soil is much higher in tree systems and often the quantity of litter added to soil can reach up to 10 t $ha^{-1}yr^{-1}$ (Nair et al., 2010) which contributes towards soil carbon sequestration. In some tree systems, leaves get dropped at regular intervals and often the interspaces between tree rows are subjected to ploughing and the added residues gets recycled in to the system.

Soil samples have to be collected from the experimental units as suggested in the earlier chapters of this volume. After collection, the samples are to be processed and carbon can be determined either by Walkley Black (1934) method or by dry combustion method either with TOC or with carbon analyser. The sequestration rate of the agroforestry system is obtained after adding the carbon sequestered in the above ground and below ground and in the soil system and the total being divided with land area and number of years.

3.2.4. Calculation of carbon stocks in production systems and in ecoregions

The impact of any mitigation activity can be seen when it is taken up in a large area. Often scaling up of any mitigation activity can be achieved when it has been integrated with the developmental programmes and has become part of the policies of the line departments. The impact of such activities on the carbon sequestered can be calculated with the following formula.

The equation for estimating the carbon stock for ecoregion is

$$\text{C sequestered (Mg C ha}^{-1}\text{)} = \text{SOCr} * \text{area (ha)}$$

Where SOCr – rate of carbon sequestration per ha and area = area of the production system/ eco region in ha.

4. Conclusions

Enhancing sequestration of atmospheric CO_2 either in to the soil or trees is an important strategy which has multiple benefits. In recent years, several long-term experiments were initiated in different ecoregions involving integrated nutrient management, tillage practices, tree systems, horticulture etc. which can sequester carbon in a significant manner. An uniform methodology for accounting carbon sequestration is important for accurate quantification and to make the measurements comparable and reproducible at regional as well as for national inventory. Soil sampling up to one meter depth at 20 cm interval is preferable. The Walkley and Black method is still the widely used method which is acceptable and can be used when resources are a constraint. Carbon sequestration is generally expressed on total organic carbon. Use of TOC and carbon analyser will give information about the TC and TOC contents which will help in accurate quantification and comparison among the treatments/systems more meaningful.

In case of tree systems, it is preferable to use the allometric equations for the above and below ground (root) biomass estimation wherever possible. Allometric equations for the estimation of the tree volume are available for some of the forest trees and the biomass of the bole can be estimated with the help of the wood density values. However, biomass expansion factors are needed for the estimation of total tree biomass. As allometric relationships for the commonly grown fruit trees are not available, general equations may be used and efforts should be made to develop biomass based allometric equations for the economically important tree species.

5. Wayforward

If more food is to be produced sustainably for the coming years from both the irrigated and rainfed systems, we need to develop approaches which can build the organic matter status of our soils. Developing suitable agricultural practices which retains residues to increase the SOC is the need of the hour. Conservation agriculture practices have potential to enhance soil carbon and practices needs to be developed for different production systems. Diversification of arable cropping systems by integration of trees under rainfed conditions has several advantages and contributes towards the enhancement of income and livelihood opportunities of communities. In view of the degraded nature of rainfed soils and also due to the fact that it is a source of livelihood for the poorest of the poor, restoration of degraded soils and ecosystems in the tropics and sub-tropics is of paramount importance. The realisable potential of SOC sequestration in degraded soils and ecosystems of the tropics is high, and realization of this potential is challenging. However, the quantum of carbon sequestration depends largely on the farmers' adoption of environmentally friendly land use and management practices. Large scale adoption of these practices is challenging given the realisation of yield advantages due to sequestering carbon are not visible immediately and adoption of these practices requires additional cost. Moreover, additional global benefits towards the environmental services by way of CDM are also not forthcoming. Hence, a suitable mechanism has to be devised to support the efforts of the farmers towards sequestering carbon and environmental services rendered.

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Annexure I

Allometric equations for the estimation of above ground biomass (dry in kg/tree) for some of the important tree species in India

Species group	equation	R^2 Value	Source	Data origin
Tectona grandis	$y = 0.0904\ (DBH)^{2.551}$	0.94	Buvaneswaran et al., (2006)	Southern zone
Tectona grandis	$y = 0.0785\ (DBH)^{2.578}$	0.97		Western zone
Mangifera indica	$y = -2.43 + 0.154\ DBH + 0.193H^{a}$	0.95	Chavan and Rasal 2012	Maharashtra
Bambusa bamboos$^{@}$	$y = -3225.8 + 1730.4\ DBH$	0.83	Devagiri et al., 2013	Karnataka
Azadirachta indica	$y = \exp\{-2.4090 + 0.9522\ \ln (DBH^{2} \times H \times S)\}$	-	Chavan, 2010	Maharashtra
All dicot trees for kerala	$y = \exp\{-2.134 + 2.530 \times \ln (DBH)\}$	0.97		
Coconut palms	$y = 5.5209\ DBHz + 89.355$	0.89		
Other palms (Areca catechu, Borassus flabellifer etc.	$y = 4.5 + 7.7\ H$	-	Mohan Kumar (2011)	Central Kerala
Bamboo (Bambusa spp.)	$y = 4.437 + 2.576\ \ln (DBH)$	-		
Inland sites, Coastal sites	$y = -12.05 + 0.876\ (BA)$ $y = 11.27 + 6.03(BA) + 1.83(H)$	0.98 0.94	Mani and Parthasarathy, 2007	Peninsular India
Dendrocalamus strictus	$y = 2.487 + 0.414\ DBH$	0.97	Chaturvedi et a., (2012)	Uttar Pradesh
Dalbergia sissoo	$y = 0.1984 + 1.3756\ DBH$	0.99		
Acaccia catechu	$y = 0.3014 + 1.182\ DBH$	0.99	Singh et al.,	Uttarakhand
Albezzia lebbeck	$y = -0.7516 + 1.3805\ DBH$	0.96	(2011)	
Avenue trees	$y = -1.689 + 8.32 \times B.A$	0.50	Desai and Nandikar (2012)	Kolhapur
Natural forest and Plantation forest	$y = \exp [-0.37 + 0.33\ \ln(DBH) + 0.933\ \ln(DBH)^{2} 0.122\ \ln(DBH)^{3}$	0.93 and 0.91	Baishya et al., (2009)	Northeast India

@ in case of bamboo the biomass is of the clump, DBH = diameter in breast height in cm, H= tree height in meters, a = Tree height in foot, S = Wood density in g/cm^3, z = tree age in years, BA = Basal area in cm^2

General equations for quantifying the biomass of trees which can be in the absence of species specific equations (Brown *et al.*, 1989).

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

Where: exp [...] means "raised to the power of [...]"
Y = above ground biomass in kg
H = height in m
D = diameter at breast height (1.3 m)
S = wood density in tons/m^3

Annexure III

Carbon Stock estimation in mango orchards

Quantification of above ground biomass using mango specific allometric equation:

The above ground biomass in mango is quantified by estimating the volume of the trees with the help of allometric equations and estimate the weight of the tree using the wood density of 0.55. The entire tree biomass is then estimated by multiplying with biomass expansion factors to obtain whole tree biomass. In mango and other fruit trees where grafted plants are grown, measurement of DBH is not possible as the tree branches just at the graft union. In such cases fruit crop specific allometric equations have to be developed. The equation developed for mango is:

$$Y = A*X*(B/X)$$

Where Y = tree biomass and X is the diameter below the graft union (DBGU),

A=0.1784E+04, B=-0.1630+02. $R^2 = 0.95366$

Step wise Procedure for the Estimation of Carbon in above Ground Biomass

Determine the sampling area

↓

Measurement of the diameter below graft union (DBGU) of all the trees in the orchards in the sampling area

↓

Use the allometric equation for the estimation of mango biomass

↓

Convert the fresh wood biomass in to oven dry weight basis

↓

Estimate the carbon content of the biomass

↓

Express the carbon content for unit area

In case volume tables are available, then the tree biomass can be estimated using the wood density values (Mango wood density = 0.55). The dry biomass can to be estimated by with the help of moisture percentage and accordingly the carbon content can be determined.

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 by using a factor of 0.45 (GPG, 2006).

National Initiative on Climate Resilient Agriculture

Central Research Institute for Dryland Agriculture

Santoshnagar, Hydreabad - 500 059.