



**National Research Centre for Agroforestry**  
Gwalior Road, Jhansi-284 003 (U.P.)  
Ph: 91-510-2730214 Fax: 91-510-2730364  
Email: [director@nrcaf.org.in](mailto:director@nrcaf.org.in)



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# National Initiative on Climate Resilient Agriculture

Methodologies for Assessing Biomass, Carbon Stock and Carbon Sequestration in Agroforestry Systems



Ram Newaj, S.K. Dhyani, S.B. Chavan, R.H. Rizvi, Rajendra Prasad, Ajit, Badre Alam and A.K. Handa



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Director  
National Research Centre for Agroforestry,  
Gwalior Road, Jhansi-284003 (U.P.)  
Tel.: 0510-2730214  
Fax:0510-2730364  
Email:krishivaniki@nrcaf.res.in  
Website:http://www.nrcaf.res.in

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## Foreword

Agroforestry is a viable alternative for reducing atmospheric carbon dioxide by sequestering into plant parts and soil. To offset carbon emissions, there are several programmes have been initiated by the scientific organizations in the Country. Greening India is one of them. Since agroforestry is very complex system and monitoring carbon storage is the major constraints in carbon offset programme due to lack of reliable, accurate and cost-effective methods. Now carbon is internationally traded commodity and monitoring of carbon storage by the agroforestry/forestry project is major issues for their assessment. There are several project at national and international level in which methodology for assessing carbon have been discussed. Now the efforts are being made by the scientists involved in agroforestry research to develop reliable methods to assess biomass, soil carbon and carbon sequestration in agroforestry system. In this direction, the scientists of National Research Centre for Agroforestry have made some efforts to compile the methods developed by Centre and elsewhere to assess changes in four carbon pools: above and belowground biomass, soil carbon and standing litter crop over a specific period of time in the form of bulletin.

The bulletin entitled "Methodologies for Assessing Biomass, Carbon Stock and Carbon Sequestration in Agroforestry Systems" is an attempt made by Ram Newaj, S.K.Dhyani, S.B.Chavan, R.H.Rizvi, Rajendra Prasad, Ajit, Badre Alam and A.K. Handa to address the methodology for assessing carbon storage in agroforestry system. I am confident that this attempt will be helpful to students and researchers those are involve in carbon sequestration study under agroforestry systems.

## Preface

In agroforestry system, monitoring and verifying carbon storage may be expensive depending upon level of scientific validity needed. This bulletin on "Methodologies for Assessing Biomass, Carbon Stock and Carbon Sequestration in Agroforestry Systems" is the response of the suggestions made by the Experts of National Initiative on Climate Resilient Agriculture (NICRA) to develop methodology for monitoring carbon storage in agroforestry systems. It describes simple methods and procedures for measuring organic carbon stored by agroforestry land uses over time. Such monitoring effort assesses the net difference in organic carbon stored in soil and tree biomass for project and non project (pre -project) sites over specific period of time.

Based on methods and procedures developed by National Research Centre for Agroforestry and elsewhere for monitoring the changes in carbon storage in agroforestry, a bulletin has been prepared and it will be helpful for students, researchers, NGOs and others those are interested in carbon sequestration study in agroforestry.

Ram Newaj  
S.K.Dhyani  
S.B.Chavan  
R.H.Rizvi  
Rajendra Prasad  
Ajit  
Badre Alam  
A.K. Handa

# Contents

Foreword

Preface

1.	Introduction
2.	Importance of monitoring carbon stock changes in agroforestry and present status of its assessment
3.	Carbon monitoring and its role in carbon trading through Clean Development Mechanism (CDM) project
4.	Field approach to quantify carbon sequestration
5.	Biomass estimation
5.1	Aboveground biomass
5.1.1	Survey procedure
5.1.1.1	Transect walk
5.1.2	Tools required for carbon monitoring during field survey
5.1.3	Destructive Sampling
5.1.3.1	Harvest method
5.1.3.1.1	Analysis of dry oven mass and wood density
5.1.3.1.2	Laboratory analysis
5.1.3.2	Mean tree technique for biomass estimation
5.1.4	Non-destructive method
5.1.4.1	Biomass estimation of main stem based on their volume
5.1.4.2	Estimation of main stem volume/ biomass using volume/biomass equation
5.2	Estimation of floor vegetation, dead wood, and litter biomass
5.2.1	Measurement of floor vegetation
5.2.2	Measurement dead wood biomass
5.2.3	Measurement of litter biomass
5.3	Belowground biomass
5.3.1	Destructive method
5.3.2	Non-destructive method
6.	Soil organic carbon
6.2	Procedure for soil organic carbon analysis

7.	Different simulation models for quantification of Agroforestry carbon sequestration
7.1	CO2FIX 3.1 model
7.1.1	Input Parameters for the CO2FIX model
7.1.2	Basic data required for running the CO2FIX model
7.1.3	Parametrization of the tree cohorts
7.1.4	Parametrization of the crop cohort
7.1.5	Parametrization of the soil module

8.	Assessment of Carbon Sequestration using Geospatial Technologies
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9.	References
	Annexure-I
	Annexure-II
	Annexure-III
	Annexure-IV
	Annexure-V

## 1. Introduction

Climate Change is a serious global environmental concern and increasing atmospheric carbon dioxide level and its potential effects on climate has become a serious problem in recent years. Carbon sequestration is promising means for reducing atmospheric carbon dioxide. To offset carbon emissions, there are several programmes have been initiated by the scientific organizations in the Country. The Greening India is one of them, which having targeting to achieve 33% tree cover of the total geographical area through agroforestry and social forestry. These systems can offset the atmospheric carbon dioxide by sequestering it in plant parts and soil. As we know agroforestry is very complex system and in tree based system, the major constraints in carbon offset programme is the lack of reliable, accurate and cost-effective method for monitoring carbon storage. Now carbon is internationally traded commodity and monitoring of carbon storage by the agroforestry/forestry project is major issues for their assessment. There are several project at national and international level in which methodology for assessing carbon have been discussed. For example, Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance 2003 for Land Use Land Use Change and Forestry (LULUCF), Forest Carbon Monitoring programme, Winrock International Institute and Methodology for Assessing Carbon Stock for Reduction Emission from Deforestation and Degradation (REDD) by Ministry of Environment and Forests and Tata Energy and Resource Institute (TERI), India. But in case of agroforestry, such types of methodologies are very sporadic and scanty. Now the efforts are being made by the scientists involved in agroforestry research to develop reliable methods to assess biomass, soil carbon and carbon sequestration in agroforestry system. In this technical bulletin, we have made some efforts to compile the methods developed by the National Research Centre for Agroforestry and elsewhere to assess changes in four carbon pools: aboveground biomass, belowground biomass, soil carbon and standing litter crop over a specific period of time.

The United Nations Framework Convention on Climate Change (UNFCCC) defines carbon sequestration as the process of removing carbon (C) from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric  $\text{CO}_2$  and its secure storage in long-lived pools (UNFCCC, 2007). The carbon cycle in plants is driven by the process of photosynthesis (Fig. 1). Photosynthesis converts the energy gained from sunlight to nutrients that the plant requires. It utilizes carbon dioxide, water, and energy and converts it to oxygen and glucose. Plants retrieve molecules of carbon dioxide from the atmosphere and convert it to usable molecules that are stored in plant parts, including limbs, leaves, roots, and the stem (Gorte, 2009).

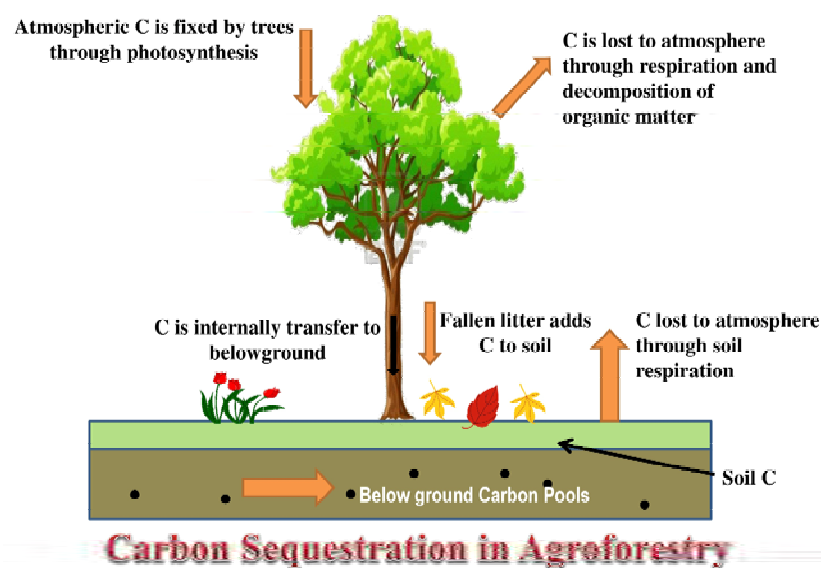


Fig. 1 The carbon cycle in plants is driven by the process of photosynthesis

It is well known that terrestrial ecosystems are important global carbon sinks and the size of this sink depends on the cropland of the world, the most feasible and cost-effective approach to carbon sequestration is in restoring the massive sink in woody biomass and soils

## 10. Importance of monitoring carbon stock changes in agroforestry and present status of its assessment

- It sequesters carbon in vegetation and in soils depending on the pre-conversion soil C,
- the more intensive use of the land for agricultural production reduces the need for slash-and-burn or shifting cultivation,
- the wood products produced under agroforestry serve as substitute for similar products unsustainably harvested from the natural forest,
- to the extent that agroforestry increases the income of farmers, it reduces the incentive for further extraction from the natural forest for income augmentation, and finally,
- agroforestry system (AFS) may have dual mitigation benefits as fodder species with high nutritive value can help to intensify diets of methane-producing ruminants while they can also sequester carbon.

The assessment of carbon sequestered in agroforestry project was done by the researchers at National and International level and evidence is now emerging that agroforestry system are promising land use system to increase and conserve aboveground and soil C stock to mitigate climate change. The average potential of agroforestry has been estimated to be 25 tonnes C/ha over 96 m ha (Sathaye and Ravindranath, 1998). In this way the total potential of agroforestry in India to store C is about 2400 million tonnes. The C sequestration potential of tropical agroforestry system (Table 1) in recent studies is estimated between 12 and 228 t C ha<sup>-1</sup> with a mean value of 95 t C ha<sup>-1</sup> (Pandey, 2007). Therefore based on global estimates of the area suitable for agroforestry (585-1215 x 10<sup>6</sup> ha), 1.1-1.2 Pg C (1 Pg= 10<sup>9</sup> tonnes) could be stored in the terrestrial ecosystems over the next 50 years (Albrecht and Kandji, 2003). In another estimate, the area under agroforestry in India is 8.2% of total reported geographical area (305.6 m ha) and it contribute 19.3% of total C stock under different land uses is 2755.5 million tonnes. Carbon stocking in agroforestry is about 532.5 million tonnes besides the scattered trees available in field or on farm/field bunds (Table 2) Although there is variation in the estimation of area under agroforestry and C stock made by scientist involve in this area but there is good indication of agroforestry for gaining popularity for mitigating climate change because desired tree cover can only be achieved by including tree in farm field/bunds.

**Table 1. Potential carbon storage for agroforestry systems in different eco-regions of the world**

Region	Eco region	Agroforestry systems	Carbon storage (MgCha <sup>-1</sup> )
Africa	Humid tropical high	agrosilviculture	29-53
South America	Humid tropical low Dry lowlands		30-102
			39-195
Southeast Asia	Humid tropical dry lowlands		22-228
Australia	Humid tropical low	silvopastoral	68-81
North America	Humid tropical high		28-51
	Humid tropical low dry lowlands		133-154
			104-198
Northern Asia	Humid tropical low		90-175
			15-18

Source: Dixon *et al.*, 1993; Krankina and Dixon, 1994 and Winjum *et al.*, 1992

Note: Carbon storage values were standardize to 50 year rotation

Table 2. Area, biomass and carbon stock in trees under different land uses

Land-use classes	Area (m hectare)	Biomass (m tonnes)	Carbon (m tonnes)
Forests	69.70	2,398.46	1,085.16
Cultivated land	140.88		
<b>A) Irrigated</b>			
Pure cropping area with scattered trees on bunds/fields	56.4	280	140
Agroforestry	7.0	420	210
Total (A)	63.4	700	350
<b>B) Rainfed areas</b>			
Pure cropping area with scattered trees on bunds/fields	64.5	967.5	483.8
Agroforestry	13.0	520	260
Total (B)	77.5	1487.5	743.8
<b>C) Fallow &amp; Wasteland</b>			
Fallow/culturable wastes /pastures/groves	50.0	800	400
Agroforestry	5.0	125	62.5
Total (C)	55	925	462.5
<b>D) Unfit for vegetation</b>			
	40		
<b>Total (A+B+C+D)</b>	<b>305.60</b>	<b>5510.96</b>	<b>2755.5</b>

Source: NRCAF, 2006

In India, a number of studies have indicated that the tree component in agroforestry has a capacity for biomass production at least as great as that of natural vegetation. Carbon sequestration potential (CSP) of agroforestry systems is given in Table 3, which indicated that CSP varied from region to region. Plethora of workers *viz.*, Kaushal *et al.*, 2014; Prasad *et al.*, 2012; Rizvi *et al.*, 2012; Swami and Puri 2005; Chauhan *et al.*, 2010; Ram Newaj *et al.*, 2008 are reported carbon sequestration potential of agroforestry.

Table 3. Carbon sequestration potential (CSP) of various agroforestry systems in India

Location	Agroforestry System	Tree species	No. of tree per hectare	Age (year)	CSP (Mg C ha <sup>-1</sup> yr <sup>-1</sup> )	References
Uttarakhand	Agrisilviculture	<i>D. hamiltonii</i>	1000	7	15.91	Kaushal <i>et al.</i> , 2014
Himachal Pradesh	Agrihorticulture	Fruit trees	69	-	12.15	Goswami <i>et al.</i> , 2014
Khammam, Andhra Pradesh	Agrisilviculture	<i>L. leucocephala</i>	4444	4	14.42	Prasad <i>et al.</i> , 2012
			10000	4	15.51	
Uttarakhand	Agrisilviculture	<i>P. deltoids</i>	500	8	12.02	Singh and Lodhiyal, 2009
SBS Nagar, Punjab	Agrisilviculture	<i>P. deltoids</i>	740	7	9.40	Chauhan <i>et al.</i> , 2010
Dehradun, Uttarakhand	Silviculture	<i>E. tereticornis</i>	2500	3.5	4.40	Dhyani <i>et al.</i> , 1996
			2777*	2.5	5.90	
Kurukhkheta, Haryana	Silvipasture	<i>A. nilotica</i>	1250	7	2.81	Kaur <i>et al.</i> , 2002
		<i>D. sissoo</i>	1250	7	5.37	
		<i>P. juliflora</i>	1250	7	6.50	
Chandigarh	Agrisilviculture	<i>L. leucocephala</i>	10666	6	10.48	Mittal and Singh 1989

Tripura	Silviculture	<i>T. grandis</i>	444	20	3.32	Negi <i>et al.</i> , 1990
		<i>G. arborea</i>	452	20	3.95	
Tarai Region Uttarakhand	Silviculture	<i>T. grandis</i>	570	10	3.74	Negi <i>et al.</i> , 1995
			500	20	2.25	
			494	30	2.87	
Jhansi, Uttar Pradesh	Agrisilviculture	<i>A. procera</i>	312	7	3.70	Ramnewaj <i>et al.</i> , 2008
Jhansi, Uttar Pradesh	Agrisilviculture	<i>A. pendula</i>	1666	5.3	0.43	Rai <i>et al.</i> , 2002
Jhansi, Uttar Pradesh	Silviculture	<i>A. procera</i>	312	10	1.79	Rai <i>et al.</i> , 2000
		<i>A. amara</i>	312	10	1.00	
		<i>A. pendula</i>	312	10	0.95	
		<i>D. sissoo</i>	312	10	2.55	
		<i>D. cinerea</i>	312	10	1.05	
		<i>E. officinalis</i>	312	10	1.55	
		<i>H. binata</i>	312	10	0.58	
		<i>M. azadirach</i>	312	10	0.49	
Hyderabad, Andhra Pradesh	Silviculture	<i>L. leucocephala</i>	2500	9	10.32	Rao <i>et al.</i> , 2000
		<i>E. camaldulensis</i>	2500	9	8.01	
		<i>D. sissoo</i>	2500	9	11.47	
		<i>A. lebbeck</i>	625	9	0.62	
		<i>A. albida</i>	1111	9	0.82	
		<i>A. tortilis</i>	1111	9	0.39	
		<i>A. auriculiformis</i>	2500	9	8.64	
Hyderabad, Andhra Pradesh	Agrisilviculture	<i>L. leucocephala</i>	11111	4	2.77	Rao <i>et al.</i> , 1991
			6666	4	1.90	
Raipur Chhattisgarh	Agrisilviculture	<i>G. arborea</i>	592	5	3.23	Swami and Puri 2005
Coimbatore Tamilnadu	Agrisilviculture	<i>C. equisetifolia</i>	833	4	1.57	Viswanath <i>et al.</i> , 2004
Kerala	Home garden	Mixed tree spp.	667	71	1.60	Saha <i>et al.</i> , 2009

## 11. Carbon monitoring and its role in carbon trading through Clean Development Mechanism (CDM) project

The Clean Development Mechanism (CDM) of Kyoto Protocol is one of the most flexible mechanisms for project-based emission reduction activities in developing countries. The Kyoto Protocol establishes legally binding emissions cuts at 5.2 per cent below 1990 levels by 2012. The uncertainty about the second commitment period of this protocol is now over. The agreement in Durban extended Kyoto Protocol for the second commitment period. Parties willing to join second commitment period will take commitment to reduce emissions below 1990 levels by 2020 in accordance with their Copenhagen pledges. The second commitment period under the Kyoto Protocol is set to begin on January 1, 2013 and end either on December 31, 2017 or December 31, 2020. The commitments and the length of commitment period will be decided in Doha during COP 18 of the UNFCCC (ICFRE, 2012).

The number of new CDM projects approved each month has steadily risen, from less than 40 in mid-2007 to over 170 by mid-2011. India and China now account for over two-thirds of all CDM projects. By July 2011, 3021 projects had been approved. Of these, just 61 related to forestry schemes and one to agriculture (Pye-Smith, 2012). The CDM of the Kyoto Protocol enables businesses and organizations in developed countries to meet their emission quotas by financing mitigation activities in developing countries. In spite of all these obvious potential advantages of agroforestry systems in terms of ecology and CO<sub>2</sub>-mitigation they are not really accepted within the framework of the “Clean Development Mechanism” under the Kyoto protocol because most of carbon market trade involve emission reduction credit but there is also growing interest in the use of trees for absorbing carbon dioxide from the atmosphere. In India, some of the promising tree species are being grown by the farmers as commercial agroforestry in different agro-climatic region and they are managing the trees with their own ways and it does not come under afforestation/reforestation/improvement of degraded lands. These are the problems to measure and calculate the carbon flows and to estimate potential “leakages” of carbon from the projects. There are some positive ecological and socio-economic benefits of such projects make them especially attractive for companies who focus on advertising by funding such projects (Kursten, 2007). So there are really good chances to get funding for well managed projects which do not only mitigate climate change but also improve the livelihood of rural villages by planting and using economically important woody plants. Small scale CDM projects related to agroforestry and forestry in cultivated and forest lands in India is given in Table 4. The challenges faced by the agroforestry for getting CDM projects are as follows;

- Agroforestry system incorporate tree by its nature. Therefore, such systems presently occur even without additional incentives associated with selling of carbon credits.
- The amount of carbon stored in AFS depends upon tree density and in general it provides small unit of certified emission reduction (CER) over a specific period of time. If agroforestry enter for carbon market and land is shifted to AFS, the increase in income from carbon credit sale must be offset the declines in crop production due to space occupied by trees and competition for growth resources.
- In agroforestry, C sequestration is a dynamic process. In case of short rotation trees, the system follow quick accumulation of carbon and at end of rotation period, trees are harvested and land return to sequential system, part of C would be released back to the atmosphere.
- Legal, social and institutional challenges such as land and tree tenure and government policies. Very few countries have regulatory frameworks in place for governing carbon rights.
- Limited access to carbon markets
- Logistical issues associated with defining and demarcating individual/family plots. The costs associated with doing this will likely be high; however, sampling approaches used for group certification may be able to reduce costs if multiple smallholders are grouped together to achieve economies of scale. In the cases of coffee and cocoa this may work through existing organizations.
- The costs associated with measuring and monitoring carbon stock changes are very high and the farmers cannot efforts such cost.
- There is still global uncertainty on REDD policy/mechanisms which is limiting investment.

**Table 4. Small scale CDM projects related to agroforestry and forestry in cultivated and forest lands in India**

S. No	Name of Project	State	Area (ha)	Annual (ha) Reductions (t of CO <sub>2</sub> )
1	Small scale cooperative afforestation CDM pilot project activity on private lands affected by shifting sand dunes in Sirsa	Haryana	369.87	11596
2	Reforestation of severely degraded landmass in Khammam under ITC social forestry project	Andhra Pradesh	3070.19	53392
3	Carbon sequestration by adopting environment friendly technology based agroforestry practices	Orissa	1607.7	4896
4	International small group and tree planting program (TIST)	Tamil Nadu	106.7	7367
5	Bagepalli CDM Reforestation Programme, Chickballpur	Karnataka	8933.34	92103
6	Himachal Pradesh Reforestation Project Improving Livelihoods and Watersheds	Himachal Pradesh	4,0003.07	41400
7	Reforestation of degraded land by Mangalam Timber Product Ltd.	Orissa, Andhra Pradesh & Chhattisgarh	14969.46	146998

Source: UNFCCC, 2013

## 12. Field approach to quantify carbon sequestration

There are different methods to quantify carbon sequestration from agroforestry systems. Consequently, estimation of C sequestration creates practical errors due to absence of standardized methodologies in AFS. Agroforestry considered as integrated, intensive, interactive and imperative which makes researcher difficult to measurements of diverse tree species on farmer's field. While, there is no simple, easy, fast and realistic solution for monitoring carbon in AFS. However, most estimation protocols, methodologies and standards are available to address trees in forests, not on farms. Forestry protocols for afforestation, forest management, and reduced deforestation of forested land do not address the specific barriers and opportunities for carbon sequestration in agroforestry systems on agricultural land (Sloke, 2010). Spatial variability and farm to farm differences in management are the greatest challenges for monitoring agroforestry or farm forestry areas. Most projects of this type will include farms that are widely dispersed and managed in different ways. The methods used to assess biomass and carbon stock available in trees under natural forests can be directly applied to trees available in agroforestry, but there are some important differences. These include;

- Agroforestry plantings require intensive labor inputs, and are typically small in size.
- Agroforestry plantings are often widely scattered over the landscape.
- Trees in agroforestry plantations are often widely spaced to provide light for associated crops. As a result, the tree canopy is discontinuous and may be highly variable.
- In some agroforestry systems, trees are arranged in regularly spaced rows. This could introduce bias into systematic sampling schemes arranged in linear grid-like patterns.
- Agroforestry plantings are usually established and maintained by small land holders. Thus, any measurement of an agroforestry plantation necessarily involves professional interaction with farmers that may not occur in other types of land use.

The methods describe in this technical bulletin will help to monitor carbon stock changes in agroforestry project for which farmers to the benefit of carbon credit in the scenario of CDM projects. The Kyoto Protocol recognizes forestry and agroforestry sectors as potential sinks and paved the way for creation of 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 5. But there is still a need to educate the farmers about carbon market and to provide technical guideline for agroforestry project so that the project should be accordance of CDM project.

**Table 5. Approved small scale methodologies related to agroforestry and forestry in cultivated and forest lands**

S. No	Methodology	Applicability
1	<b>AR-AMS001:</b> 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 and silvipasture
2	<b>AR-AMS002:</b> Simplified baseline and monitoring methodologies for small-scale afforestation and reforestation project activities under CDM implemented on settlements	Agroforestry systems, silvipasture, horticultural crops and energy crops
3	<b>AR-AMS004:</b> Simplified baseline and monitoring methodologies for small-scale agroforestry afforestation and reforestation project activities under CDM	Agroforestry systems
4	<b>AR-AMS005:</b> 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	<b>AR-AMS006</b> (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.

Source: UNFCCC, 2013

In any land uses, carbon sequestration study consisted with three steps; first is to determine, second one is analyze and third one is to calculate. Each step consists of different activities which is presented and described briefly in a simple flowchart (Fig. 2).

The IPCC has generated a number of methodology reports on national greenhouse gas inventories with a view to providing internationally acceptable inventory methodologies. The IPCC methodology is designed to calculate the emissions and removals from land use and land use change for a national inventory. IPCC Guidelines provide methodologies for estimating national inventories of anthropogenic emissions by sources and removals by sinks of greenhouse gases. The IPCC has so far developed following guidelines which content approved methods by IPCC for monitoring carbon change in Land Use Land Use Changes and Forestry (LULUCF).

- The Revised 1996 Guidelines for National Greenhouse Gas Inventories, IPCC (1997), known as the “1996 IPCC Guidelines”,

- Good Practice Guidance and Uncertainty Management, IPCC (2000), known as the “GPG2000”,
- Good Practice Guidance for Land-Use, Land-Use Change and Forestry, IPCC (2003) known as the “GPG-LULUCF” and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC (2006) known as the “2006 IPCC Guidelines”.

Before describing the methods for assessing C in different land uses, it is necessary to understand the major carbon pool which needs to determine. There are five carbon pools and it consists of aboveground biomass, belowground biomass, litter, dead wood and soil (Table 6).

**Table 6. Carbon pools in agroforestry**

Pools		Descriptions
Living biomass	Above-ground biomass	All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage. Note: In cases where forest understory is a relatively small component of the above-ground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it, provided the tiers are used in a consistent manner throughout the inventory time series.
	Below-ground biomass	All biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead Organic Matter	Deadwood	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps, larger than or equal to 10 cm in diameter (or the diameter specified by the country).
	Litter	Includes all non-living biomass with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for deadwood (e.g. 10 cm), lying dead, in various states of decomposition above or within the mineral or organic soil. This includes the litter layer as usually defined in soil typologies. Live fine roots above the mineral or organic soil (of less than the minimum diameter limit chosen for below-ground biomass) are included in litter where they cannot be distinguished from it empirically.
Soils	Soil organic matter <sup>1</sup>	Includes organic carbon in mineral soils to a specified depth chosen by the country and applied consistently through the time series <sup>2</sup> . Live and dead fine roots within the soil (of less than the suggested diameter limit for below-ground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.

The IPCC Guidelines use six broad land-use categories to report emissions and removals from land use and land use conversions (strictly these are a mix of “land use” and “land cover”). The methodologies are required to estimate emissions and removal of CO<sub>2</sub> and non-CO<sub>2</sub> emissions for both situations, also taking account the long term average carbon stock associated with mentioned land uses:

- |                |               |
|----------------|---------------|
| 1) Forestland  | 2) Cropland   |
| 3) Grassland   | 4) Wetlands   |
| 5) Settlements | 6) Other land |

In IPCC report, agroforestry is considered as a subject of agriculture so it is included in the section of cropland. In this manual we are emphasizing on different land uses consist of perennial plantations, coffee, fruit orchards and rubber plantations. Before entering in to topic need to discuss important issues of IPCC report.

An estimation of C pools from various aspect of change from one state to other e.g. forest land converted to crop land; makes use of IPCC GPG volumes I, II, III & IV. Based on these volumes following methodologies are prepared. These top-level categories can further be subdivided (or “stratified”) depending on national circumstances to capture the differences between climate, ecological zones or management practices etc. The methods contained in the IPCC Guidelines require information on activity data such as area and area changes of different land use categories, population (e.g. livestock), biomass (e.g. biomass burnt, amount of fertilizer applied) and emission factors or the data and parameters that are used for estimating these emission factors such as biomass stocks per unit area, growth rates, biomass losses per unit area, biomass expansion factors, and livestock parameters etc. FAO is the main source of activity data and emission factors for forest and other land-use categories in Tier 1 level calculations.

The countries may use different methods for obtaining area data such as annual census, periodic surveys and remote sensing. The 2006 IPCC Guidelines provide guidance on the three approaches that may be used for obtaining and representing information on area and area changes for national GHG inventories. **Approach 1** identifies the total area under individual categories but does not provide information on land use conversions between land uses. **Approach 2** allows for tracking of conversions between land-use categories while **Approach 3** tracks on a spatially explicit basis. As opposed to the methodological tiers, these approaches are not hierarchical in nature and countries may use a mix of approaches for different regions over time. IPCC provides different tiers

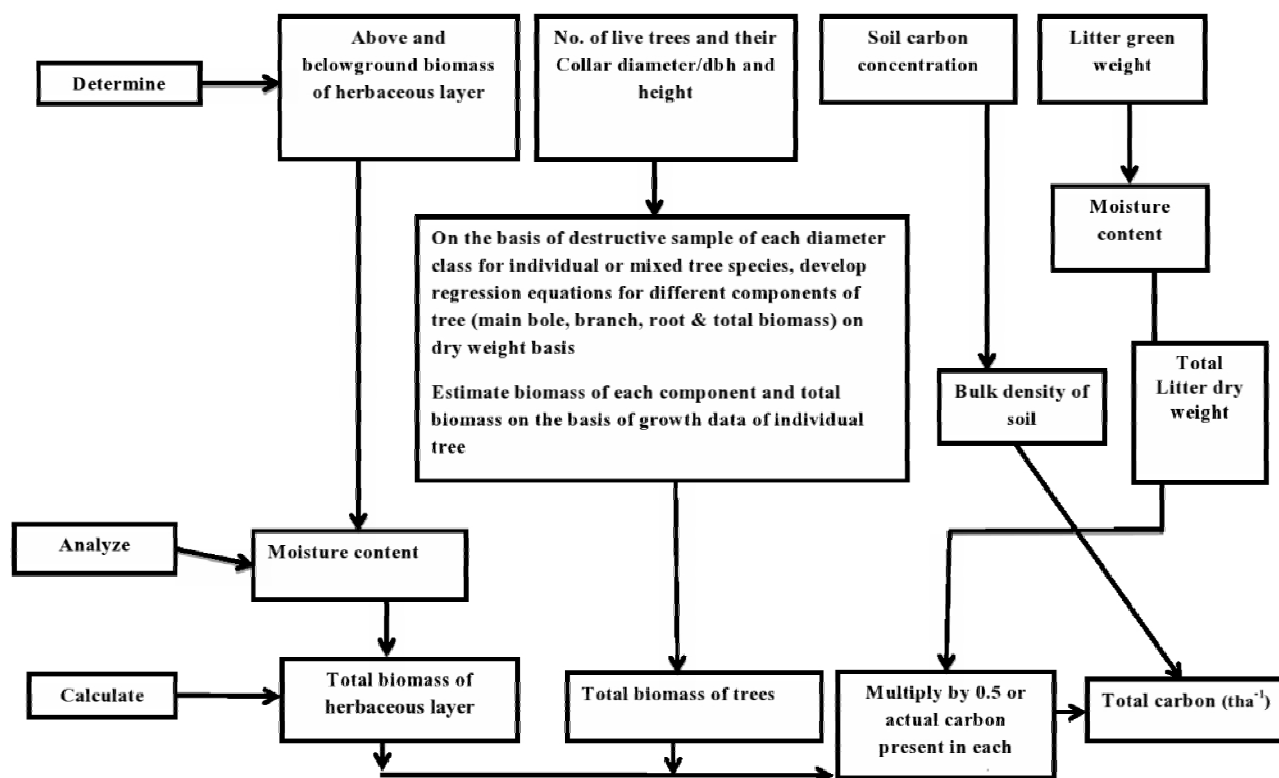


Fig. 2 Flowchart for monitoring changes in major carbon pools in agroforestry system

to estimate removal and emission of carbon from systems and these tiers are suggesting the level of complexity applied in estimating the GHG emissions from a particular source category. The tiers of estimate range between tiers I, II & III. Higher Tier implies a more data intensive effort (See box 1).

### Box 1 Concept of Tier in IPCC

#### *Tier 1*

Tier 1 methods are designed to be the simplest to use, for which equations and default parameter values (e.g., emission and stock change factors) are provided in IPCC Volume 4. Country-specific activity data are needed, but for Tier 1 there are often globally available sources of activity data estimates. The FAO stat, FSI reports, & Volume tables are important Tier 1 parameters.

#### *Tier 2*

Tier 2 can use the same methodological approach as Tier 1 but applies emission and stock change factors that are based on country- or region-specific data. Country-defined emission factors are more appropriate for the climatic regions, land-use systems and livestock categories in that country. Tier 2 to corresponds with country-defined coefficients for specific regions and specialized land-use or livestock categories.

#### *Tier 3*

At Tier 3, higher order methods are used, including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level. These higher order methods provide estimates of greater certainty than lower tiers. Such systems may include comprehensive field sampling repeated at regular time intervals and/or GIS-based systems of age, class/production data, soils data, and land-use and management activity data, integrating several types of monitoring.

## 13. Biomass estimation

Carbon sequestration in agroforestry system is quantified through biomass estimation of trees and herbaceous layer. There are different methods to estimate above and belowground biomass (Fig. 3).

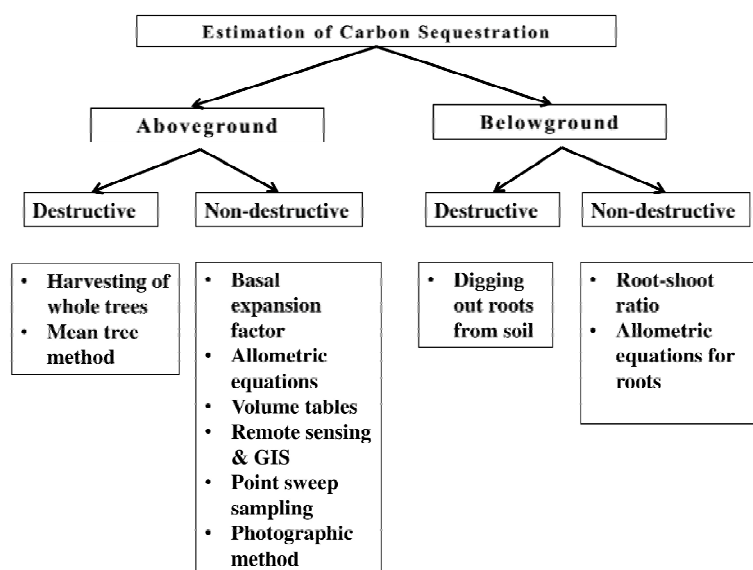


Figure 3. Methods for estimating above and belowground biomass

## 5.1 Aboveground biomass

The total standing above-ground biomass of woody perennials is often considered as one of the largest carbon pools. The above-ground biomass comprises all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes as well as herbaceous undergrowth. For agricultural lands, this includes crop and weed biomass. The dead organic matter pool (necromass) includes dead fallen trees and other coarse woody debris. Agroforestry is the form of scattered trees on farm which makes difficult to analysis of carbon sequestration potential in field. As in research plots trees are arranged in definite structure and spacing, it's easy to carry out inventory procedures and possible to get result in a short moment.

Against this backdrop need to set some accepted procedure to carry out measurements on farmer's field. Transect analysis is an important geographic tool for studying changes in land use or vegetation or diversity from one place to another. Select the transect route carefully and identify the start and end points. It is important to be familiar with the transect route to ensure that it passes through a variety of zones so that the completed transect will provide meaningful information.

### 5.1.1 Survey procedure

#### 5.1.1.1 Transect walk

- 1) Line transect run 100m to 1km based on species distribution, time, accuracy and surface. Every 100 m set out quadrat to analyze species distribution along the transect line.
- 2) Sampling quadrates of regular shape of dimensions  $10 \times 10$  m (For trees),  $5 \times 5$  m (For shrubs) and  $1 \times 1$  m (For herbs), nested within each other, were defined as the units for sampling the landscape and measuring biomass.
- 3) Identify trees and record its local as well as scientific name and girth at breast height (GBH) or diameter at breast height (DBH) of the trees ((Kumar *et al.*, 2006; Gillespie *et al.*, 2000).
- 4) Another important issue with reference to the girth measurement is the size of tree, which is responsible for including and excluding the tree species while taking measurements. For better understanding they classified the stems into;
  - a) trees (stems  $\geq 10$  cm DBH),
  - b) saplings (stems  $\geq 1$  m tall and  $< 5$  cm DBH: stem diameter at 1.37 m), and
  - c) seedlings (stems  $\geq 0.2$  m tall and  $< 1$  m tall).

Note: Ferreira and Prance (1998) suggested that minimum recommended DBH for tree is 10 cm, as it is becoming standard for quantitative inventories for many ecologists, but again, if resources permit a smaller minimum DBH should be included for a subsample in any floristic inventory.

- 5) For measurement, diameter or girth follow diameter measurement rules given in Box 2 and may also be referred in "Forest Mensuration" by Chaturvedi and Khanna, 1982.
- 6) For the medium-size (10 -30 cm dbh) trees, 20, 15, or 10 m wide gap between transect may be convenient, and for the shrubs and herbs, usually 2 or 1m wide gap is convenient.

- 7) Geometry of transect is no need to run perfectly straight transects except to avoid getting lost and to minimize the possibility of biasing the data against certain micro-habitats (e.g. thick tangles) or of slightly overestimating the sample area where the transect bends.
- 8) It is usually more important to stay within one habitat, such as following an elevation contour or following a curving ridge top over different elevations, even if this requires a zig-zag transect.
- 9) Kumar et al (2006) used stratified random sampling to collect tree data within 1 ha belt transect (1000 m × 10 m), which used as an alternate to 1 ha square plot.
- 10) Pacific Forestry Centre, British Columbia followed at each location surveyed that the line transects were placed end-to-end with 25-m gaps between them.
- 11) More than one transect is required per site if the primary purpose of a survey is to measure foliage projective cover. Stand basal area can be used to establish the number of replicate transects required for sampling.

Basal area count	No. of replicates transect and length
< 3	3 × 100
3-7	2 × 100
> 7	1 × 100

- 12) Generally number of transects are decided based on area of study.

Area of the study (ha)	Number of transect
0-1	1-2 walking transect
1-10	3 walking transect + 1 quadrat per community + 1 replicate quadrat per community ≥ 5 ha.
11-50	4 - 6 walking transects + 1 quadrat per community 1 replicate quadrat per community ≥ 5 ha.
Above 50	0 walking transect + 2 quadrates per Community + 1 quadrat per community ≥ 10 ha.

(Source: Murray *et al.*, 2002)

- 13) The transect of 50m, 100m, 200m and 500m length of the transect based on time, accuracy and cost. The length of 100m transect most preferred in vegetation studies (Kuhnell *et al.*, 1998).

By transect analysis; primary observation can be recorded on tree species, no. of tree per hectare (tree density), diameter at breast height (at 1.37 m), height of trees, major intercrops, soil type, topography etc (Plate 1 & 2).

### 5.1.2 Tools required for carbon monitoring during field survey

In order to perform an inventory accurately, reliably and at minimum cost, an inventory team must have following equipment during field survey;

1. Measuring tape
2. Ravi altimeter
3. GPS with extra battery pack and charger
4. Sampling frame square
5. Marker, pencil, inventory sheet
6. Polythene bag (1 kg capacity)
7. Soil auger
8. Sheet holder
9. Calculator
10. Precision spring scale for 5 kg



Plate 1. A view of data recording by team member during survey



Plate 2. A view of soil sampling using power auger

### 13.1.3 Destructive Sampling

#### 5.1.3.1 Harvest method

Harvest method is known as destructive method of biomass estimation (Plat 3). It is the most direct method for estimation of biomass (above and belowground) and the carbon stocks stored in the agroforestry systems (Gibbs *et al.*, 2007). This method involves harvesting of whole trees and separation of tree components (stem, branches, leaves, twigs and roots) to measure the fresh weight, after they are oven dried. It is very accurate and simple method to estimate biomass. Sampling destruction can be carried out by this method due to time and resource consuming, strenuous, destructive and expensive and it is not feasible for a large scale analysis. Usually, this method is prominently used for developing biomass equation to be applied for assessing biomass on a larger-scale (Segura and Kanninen, 2005). Cost and repeatability over time, heavy manual fieldwork to collect samples were recognized as the main disadvantages of biomass-harvest techniques (Flombaum and Sala, 2007). In addition, harvests cannot be repeated over time in exactly the same place, leading to confusions between time and space variability.



Plate 3. A view of destructive sampling for estimation of above and belowground biomass and litter collection through litter trap can also be seen in last photo.

All live trees with dbh  $\geq$  5 cm and above in the sample plots will be measured. The following information needs to be collected;

- i) tree species
- ii) DBH of trees
- iii) Tree height

The following steps are suggested in destructive sampling;

1. Identifying tree species (tree name) should be done first before starting the measurement of dbh; Laborers may also assist in clearing ground vegetation for tree access.
2. Using a 1.37 m straight wooden stick, mark measuring position for dbh measurement; (See box 2).
3. Record all the information on number of stumps; buttress diameter; height of buttress etc. and note any irregularities if any.
4. Enter the data on dbh in excel spread sheet and group dbh data of trees into dbh class. The interval of dbh class is 10 cm, and dbh classes are: 5 – 15 cm; 15 – 25 cm; 25 – 35 cm; 35 – 45 cm; 45 – 55 cm; 55 – 65 cm; 65 – 75 cm; etc.
5. Select randomly the sample trees in each dbh class in the sample plots.
6. After selection of sample trees for each dbh class, use chain saw to cut down the tree at its base.
7. Once the sample tree is cut down. The following parameters need to be accurately measured:
  - a. Diameter at stump;
  - b. DBH at 1.37 m;
  - c. Total tree height from the stump to the top of the crown.
  - d. Length of tree bole - from the stump to the first main branch.
  - e. Length of tree bole-from the stump to the point where diameter becomes 10cm.
  - f. If tree with buttress, measure diameter and height of the buttress.
8. Separate the cut trees into different parts (e.g. bole, branches and leaves).
9. Use scale to measure immediately the weight of stem, branches, leaves and buttress if tree with buttress.
10. Carefully record all information on destructive measurement of sample trees.

### Box 2. DBH measurement guideline

1. For sloping ground, this distance measures from the uphill side of the stem.
2. For leaning trees (on level ground), the point will be on the under-side of the tree parallel to the axis of the stem.
3. For leaning trees on sloping ground, the point will be decided based on common sense by imagine that the earth is rotating so that the tree is vertical and then locate the point as for a sloping tree.
4. Trees forked below breast height should be treated as a double stem i.e. two separate trees.
5. Trees forked above breast height should be treated as a single stem and measured according to the position of tree on ground or hills.
6. Trees forking at breast height or slightly above are measured at the point of minimum diameter below the fork.
7. Coppice crops should be measured from ground level, not from stool level.
8. The vines, moss, loose bark and other loose material at breast height should be removed.
9. The breast height should be fixed by using a fixed height (bh) stick.
10. Measure at right angles to the stem axis. Keep tapes taut.

Figure MS word file Me Missing Ha

### 5.1.3.1.1 Analysis of dry oven mass and wood density

Sampling for dry mass analysis can be taken immediately after completion of measurement of fresh weight of each tree components. The following steps are suggested to be carried out for sampling:

1. Sample for dry mass analysis: collect three samples per tree of stem, branches and leaves. Samples taken for each tree part should be a representative sample. Therefore, when taking the sample for dry mass analysis, always be noted that:
  - a. The sample should be taken from different positions of the stem, and different parts of branches and leaves. To prepare a stem sample, take two to three discs (and if too large, radial sections of the discs) amounting to about 0.2 % of the total stem fresh weight. For branch sample, take 4 small discs from branches amounting to about 0.5 to 1.0 kg<sup>1</sup>.
  - b. Put sample of the tree parts (stem, branches and leaves) into poly bags and tightly tied to prevent moisture loss.
  - c. The estimated weight of each sample is suggested to be 0.5 – 1.0 kg for stem and branches; 0.3 – 0.5 kg for leaves.
2. Samples for wood density analysis will be four wood discs samples for the bole. The sampling procedures are as follows:
  - a. Mark the position for sampling. The sampling position is at stump level (0.0 m), at 1/4 of bole length; 1/2 of bole length and 3/4 of bole length.
  - b. Take one wood disc or radial section of the discs if big bole for each sampling position with wood disc thickness of 5 – 10 cm.
3. All samples for dry mass and wood density analysis should bear a label for later identification.
  - a. For samples for dry mass analysis, after putting the sample into poly bag, use permanent pen to write information on sample. The information should include: i) Plot code; ii) Tree name; iii) DBH size; iv) Sample name (stem, branch or leaves).
  - b. Information on samples for wood density analysis include: i) Plot code; ii) sample tree code; iii) sample position (0.0 m, 1/4 of bole length, 1/2 of bole length, 3/4 bole length)
4. The samples for dry mass analysis must be weighed immediately and carefully using a chemical scale (either on site, or off-site, but within the same day) to determine the exact fresh weight of each sample taken in the field.
5. All samples should be sent to a qualified laboratory in time for analysis and information on samples collection for dry mass and wood density analysis.

### 5.1.3.1.2 Laboratory analysis

#### 1. Total dry weight (TDW) for each organ of the sample tree

Total dry weight for each organ of sample tree is calculated based on the total fresh weight of each organ measured in field and the ratio of dry weight to fresh weight calculated for each organ in the laboratory. The formula for TDW calculation is as follows;

$$TDW = TFW * (SDW / SFW)$$

Where: TDW is total dry weight; TFW is total fresh weight; SDW is absolute dry sample weight and *SFW* is fresh sample weight.

#### 1. Wood density

Wood density of every wood disc for each sample tree species is analyzed in the laboratory and is calculated by the following formula:

$$WD = \frac{SDW_c}{SV}$$

Where: WD is wood density in g/cm<sup>3</sup>; SDW<sub>c</sub> is dry weight of sample cube and *SV* is volume of sample cube.

#### 2. Carbon stock in biomass

Carbon stock in each biomass pool will be calculated based on oven dry biomass of each pool and carbon fraction. The general formula for calculation of carbon stock in biomass is as follows:

$$CS_i = TDW_i \cdot CF_i$$

Where: CS<sub>i</sub> is carbon stock of component *i* in kg; TDW<sub>i</sub> is total oven dry weight of component *i* in kg; and CF<sub>i</sub> is carbon content in biomass of component *i* in percent.

In case there is no analysis of carbon content in each biomass component (stems, branches and leaves), it is suggested to use the default carbon fraction provided by IPCC. This value is between **0.47** and **0.50**. Total carbon stock for each sample tree will be calculated as the sum of carbon stock of each tree component.

### 5.1.3.2 Mean tree technique for biomass estimation

Allometry is an effective method for accurately estimating biomass of trees, tree components and stands. However, the labour and expense of constructing and validating the necessary equations limit the application of the allometric approach in biomass sampling. Many of the allometric equations developed in the past were published in obscure journals and furthermore have restricted applicability outside the area of their development.

The mean tree technique can be a cost-effective alternative to more time-consuming allometric methods. The mean tree technique was developed by several investigators during the 1960's and 70's. The concept behind the method is that an average-sized tree will also have an average quantity of biomass. The usual approach is to select a tree or trees of mean basal area. Basal area tends to be a good predictor of total biomass, since diameter, basal area and sapwood area; all have a similar functional relationship to the quantity of live foliage and branches in the crown. The selected trees are then destructively sampled to determine their biomass. Sub-sampling may be used in the case of large trees. The mean tree weight is then multiplied by the number of trees in the stand to obtain an estimate for the total stand biomass. This basic technique can be modified by including stratified random sampling, the basal area ratio method or by using weighted average values (MacDicken, 1997). The advantages and disadvantages of the method are given below;

#### Advantages

- It is fast, it can be accurate and it does not require elaborate computations.
- It is most appropriately applied in homogenous, even aged and well-spaced stands.
- The accuracy of this technique declines in diverse stands with a wide array of bole diameters and tree sizes.
- Most agroforestry plantings with their systematically spaced trees of near-uniform age and size biomass estimates within 2-10% of the true value appear realistic based on literature.

## Disadvantage

- There is no estimate of the error.
- Without replication, there is no way to detect a poor estimate.
- There is no statistical method to compare sequential samples.
- Almost all applications of the mean tree technique have been on coniferous species, which tend to be more uniform in shape than deciduous species.
- Tree size is related exponentially to diameter, the mean tree technique tends to be biased towards an underestimation of the actual stand biomass.
- If substantially more than five trees per size class need to be sampled, the mean tree technique loses any advantage over standard allometric approaches.

The largest challenge in using the mean tree technique in the field is to select trees for biomass determination that are truly of average size. This requires careful measurement of stand diameters and simple mathematical calculation computations that could be a source of error by inexperienced technicians. Biomass measurement is a tedious process. If the trees of a stand have a uniform size and structure and reliable allometric equations for biomass are not available, the mean tree technique may provide rapid estimates of the biomass of the stand.

### 5.1.4 Non-destructive method

An allometric relation is one whereby one measured parameter is a good estimate of another unmeasured parameter in the same organism (Marc Janssens *et al.*, 2003). A less harmful way to carry out biomass estimate is to develop an allometric equation that will allow us to estimate the mass of a tree from a few simple measurements of it and then to apply this equation to the trees in a forest/agroforestry. The term allometry is defined as “the measure and study of relative growth of a part in relation to an entire organism or to a standard”. It is based upon a principle first described by Galileo Galilei in the 1630's about how the proportions of an organism must change as it gets bigger. Allometric equations, relating biomass with one or more tree dimensions, are frequently used to compute average tree biomass (Kale *et al.*, 2004). Component-wise biomass estimation based on non-harvest technique is desirable as against the techniques, which involve harvest of different parts of trees, including felling of entire tree for generation of equations for estimating biomass. Allometric equations that relate tree diameter at breast height (1.37 m) to other attributes such as standing carbon stock and leaf area are an important and often-used tool in ecological research as well as for commercial purposes. Such tools represent the primary method for estimating above-ground forest dry matter or carbon (Cabrera, 2003).

Allometry is used to describe the morphological evaluation of species and is based on the relation between a tree biomass, volume and of any part of the tree component (Table 7, 8 & annexure 1). The general form of the allometric equation is  $y = ax^b$  where  $y$  = measure/ process in question *viz* volume/biomass,  $x$  is size (usually DBH),  $b$  is the allometric exponent (which about the relationship between  $x$  &  $y$ ) and  $a$  = a constant (the allometric coefficient). Allometric scaling equations on the basis of total tree height ( $H$ ) and basal diameter. General allometric equation for biomass based on climate type and rainfall is given in Table 7. Species specific allometric equations for biomass developed by the NRC for Agroforestry, Jhansi is given in Table 8.

Preparation of allometric equations needs information on tree diameter with different classes and height; also destructive sampling of selected trees gives better prediction of allometric equations. The procedure of diameter and height measuring is given in destructive sampling of trees.

### 5.1.4.1 Biomass estimation of main stem based on their volume

For each tree measured in lower diameter class ( $\text{dbh} \leq 15 \text{ cm}$ ) and those having only one diameter measurement, calculate the stem volume using equation 1 (cylinder taper function)

$$V = d^2 * (\pi h \div 4)$$

Where  $V$  = volume of stem  $\text{m}^3$ ,  $\pi = 3.14$ ,  $h$  = height of the stem (m) and  $d$  = diameter (cm)

- ❖ For each tree in higher diameter class ( $\text{dbh} \geq 15 \text{ cm}$ ) and those having several diameters measured calculate the volume of each measured section having each the height of 1.0 m using Equation 2 (truncated cone taper function) and sum to obtain the stem volume

$$V = (\pi h \div 12) (d_1^2 + d_2^2 + d_1 \cdot d_2)$$

Where  $V$  = volume of stem  $\text{m}^3$ ,  $\pi = 3.14$ ,  $h$  = height of the stem (m),  $d_1$  = the greater diameter (cm) and  $d_2$  = the smaller diameter (cm)

- ❖ Convert the stem volume into stem biomass using wood density  
Biomass (tons) = Volume ( $\text{m}^3$ )  $\times$  Specific gravity ( $\text{tons}/\text{m}^3$ )

### 5.1.4.2 Estimation of main stem volume/ biomass using volume/biomass equation

A volume model or biomass model is a mathematical function which links the volume or the biomass of the trees to their biophysical properties (usually  $\text{dbh}$  & height). Examples of model that were fitted to observation on volume, biomass,  $\text{dbh}$  and height and tested using statistical computing software R (Guendehou *et al.*, 2014) are presented below.

$$\ln(X) = \chi_0 + \chi_1 \ln(\text{dbh})$$

$$\ln(X) = \chi_0 + \chi_1 \ln(\text{dbh}) + \chi_2 \ln(H)$$

$$X = \chi_0 (\text{dbh})^{\chi_1} + \chi_2 (H)$$

$$X = \chi_0 (\text{dbh})^{\chi_1} \chi_2 (H)^{\chi_2}$$

$$X = \chi_0 + \chi_1 \ln(\text{dbh})$$

$$X = \chi_0 (\text{dbh}^2 * H)^{\chi_1}$$

$$X = \chi_0 (\text{dbh} * H)^{\chi_1}$$

Where  $X$  = biomass (kg) or Volume ( $\text{m}^3$ ),  $\text{dbh}$ : diameter at breast height (cm),

$H$ : stem height (m),  $\chi_0, \chi_1$ , &  $\chi_2$  are model parameters

**Table 7. General allometric biomass equation**

Climate type based on annual rainfall	Equation	$R^2$ value
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
	$y = \exp[-3.1141 + 0.9719 \ln(D^2 H)]$	0.97
	$y = \exp[-2.4090 + 0.9522 \ln(D^2 H S)]$	0.99
	$H = \exp[1.0710 + 0.5677 \ln D]$	0.74
Wet (>4000 mm)	$y = 13.2579 - 4.8945 D$	0.90
	$y = \exp[-3.3012 + 0.9439 \ln(D^2 H)]$	0.90
	$H = \exp[1.2017 + 0.5627 \ln D]$	0.72

Source: Brown *et al.*, 1989

Where:  $\exp [ ]$  means raised to power of  $[ ]$ ,  $y$  = aboveground biomass in kg,  $H$  = height in m,  $D$  = diameter at breast height in cm,  $S$  = wood density ( $\text{tonnes m}^{-3}$ )

**Note:** These equations are valid only for stems with  $\text{dbh} > 5 \text{ cm}$ .

Table 8. Species specific allometric biomass equations developed by the NRC for Agroforestry, Jhansi

Tree species	Tree component	Equation	R <sup>2</sup>
<i>Dalbergia sissoo</i> (n =42)	Bole	$0.832(\text{DBH})^{1.593}$	97
	Branch	$0.026(\text{DBH})^{2.332}$	99
	Leaves	$0.041(\text{DBH})^{1.845}$	97
	Root	$0.198(\text{DBH})^{1.760}$	99
	Total biomass	$0.904(\text{DBH})^{1.760}$	99
<i>Albizia procera</i>			
(i) 70% canopy pruning (n =32)	Bole	$0.038(\text{DBH})^{2.505}$	98
	Branch	$0.012(\text{DBH})^{2.690}$	96
	Leaves	$0.025(\text{DBH})^{2.237}$	97
	Root	$0.031(\text{DBH})^{2.494}$	99
	Total biomass	$0.102(\text{DBH})^{2.494}$	99
(ii) 50% canopy pruning (n =31)	Bole	$0.415(\text{DBH})^{1.538}$	95
	Branch	$0.147(\text{DBH})^{2.016}$	97
	Leaves	$0.062(\text{DBH})^{1.947}$	97
	Root	$0.234(\text{DBH})^{1.836}$	98
	Total biomass	$0.743(\text{DBH})^{1.836}$	98
(iii) Unpruned (n =29)	Bole	$0.061(\text{DBH})^{2.113}$	94
	Branch	$0.241(\text{DBH})^{1.968}$	94
	Leaves	$0.057(\text{DBH})^{2.034}$	95
	Root	$0.173(\text{DBH})^{2.014}$	96
	Total biomass	$0.525(\text{DBH})^{2.014}$	96
<i>Hardwickia binata</i> (n= 30)	Bole	$0.232(\text{DBH})^{2.046}$	99
	Branch	$0.002(\text{DBH})^{3.142}$	98
	Leaves	$0.0002(\text{DBH})^{3.514}$	99
	Root	$0.036(\text{DBH})^{2.337}$	99
	Total biomass	$0.158(\text{DBH})^{2.338}$	99
<i>Emblica officinalis</i> (n =30)	Bole	$0.056(\text{CD})^{2.000}$	99
	Branch	$4.262(\text{CD})^{0.941}$	99
	Leaves	$0.152(\text{CD})^{1.605}$	99
	Root	$0.622(\text{CD})^{1.313}$	99
	Total biomass	$2.994 (\text{CD})^{1.285}$	99
<i>Jatropha curcas</i> (n =30)	Branch	$0.004(\text{CD})^{2.678}$	99
	Leaves	$0.001(\text{CD})^{2.678}$	99
	Root	$0.001(\text{CD})^{2.667}$	99
	Total biomass	$0.05 (\text{CD})^{2.677}$	99

## 5.2 Estimation of floor vegetation, dead wood, and litter biomass

### 5.2.1 Measurement of floor vegetation

#### 1. Tools and material

- Measuring tape (20 m long)
- Measuring scale 50 kg, with 0.05 kg precision
- Chemical scale 600 g, with 0.01 g precision
- Materials: Scissors, permanent pens, poly sheet, stake, ropes, poly bags and field data forms for record keeping etc.

#### 2. Destructive sampling of floor vegetation

- Set out 1 m x 1 m quadrat in selected areas by using iron frame.
- Cut the herbaceous vegetation by use knife and/or scissors.
- Separate cut vegetation into: stems, branches and foliage.
- Use scale to measure fresh weight of each component. Carry out quickly.
- Take representative samples from each component (stems, branches and foliage).
- Use chemical scale to measure the weight of samples and place the samples into poly bags.
- Tightly seal poly bags and label each sample. All samples should be promptly sent to a qualified laboratory for dry mass analysis.

### 5.2.2 Measurement dead wood biomass

#### 1. Measurement of standing dead wood

- In the sample plot delineated, mark all standing dead trees.
- Use measuring tape and height measurement tool to measure dbh and tree height.
- Take wood sample for each density state (sound, intermediate and rotten) for wood density analysis for later calculation of dead wood biomass. The samples should be promptly sent to a qualified laboratory for analysis.

#### 2. Measurement of fallen dead wood

- Along the length of the line drawn, measure the diameter of each intersecting piece of coarse dead wood with diameter of or over 10 cm.
- Classify each piece of dead wood into one of three density states: **sound, intermediate, or rotten**. To determine the density class of a piece of dead wood, strike each piece with a heavy knife.

### 5.2.3 Measurement of litter biomass

#### 1. Tools and materials

- Litter trap
- Knife

- Hanging scale
- Materials: Permanent marking pens, poly sheet, stake, ropes, poly bags, field data forms for record keeping etc.

## 2. Measurement of litter

The litter layer is defined as all dead organic surface material on top of the mineral soil. Some of this material will still be recognizable (dead leaves, twigs, dead grasses, and small branches) and some will be unidentifiable decomposed fragments of organic material. Note that dead wood with a diameter of less than 10 cm is included in the litter layer. The measurement of litter is as follows:

- The litter traps of 1 m x 1 m set out in each agroforestry system to determine tree litter production.
- Collect the accumulated litter by fixed interval like 15 to 30 days interval for 1 year.
- The litter samples bring to the laboratory and separate into leaf litter, woody litter and miscellaneous litter (flowers and fruits, bark, unrecognizable remains of leaves and fine particles) fractions.
- The samples are dried at 80°C temperature and weight it and results present in dry ratio basis.

Note: Annexure II is provides detailed format for estimation of litter and dead matter

## 5.3 Belowground biomass

There are two prominent methods: Non-destructive sampling & destructive sampling.

### 5.3.1 Destructive method

There are several methods to measure roots directly. Destructive estimation of root provides opportunity of more accuracy than allometric or formula method. Root biomass is estimated by using following methods (Mac Dicken, 1997 and Raul Ponce-Hernandez. 2004):

1. excavation
2. auger cores
3. monolith method

Following points keep in consideration for accuracy are:

- Samples should be taken from representative volumes of soil- usually 0-30 cm soil depth unless otherwise specified.
- Samples should be taken during the time when expected standing root biomass is highest (e.g., avoid the late part of the growing season).
- The methods for sampling, storing, and washing samples will always lead to some loss of dry weight and nutrients. A correction factor of 1.25 - 2.0 should be applied to the final data, with the correction factor based on the estimated losses due to sampling and processing.

#### I) Root excavation

Root excavation method gives accurate and premised estimate of root biomass but it is costly, cumbersome and laborious to carry out. The Winrock International Institute of

Agriculture (Mac Dicken, 1997) reported core sampling and monolith are economically feasible so elaborately explained. Plate 4 shows the root architecture and biomass accumulation in field.

## 2. Core sampling (auger cores)

- The soil auger core method uses a cylindrical tube 15 cm in length and 7–10 cm in diameter, with an extension of about 1m (Plate 4).
- It removes or displaces a known volume of soil from a soil profile of known depth. A core of 50–80 mm in diameter is considered sufficient.
- The auger corer can be inserted manually or mechanically. Manual insertion of the auger corer is not practical for depths greater than 50 cm or for clayey or stony soils.
- In sandy dry soils, a small diameter core may be necessary in order to reduce soil losses while extracting the core. In very stony soils, and particularly where these have many woody roots, coring may not be possible.
- Ideally, the sample of the profile should be to the limit of the depth of the root system. Rooting intensity changes with soil depth, but the spatial variability of root intensity is typically high.
- As far as possible, soils must be sampled to a minimum depth of 30 cm.
- The best approach to root extraction is to wash roots from the cores immediately upon return from the field. Core samples can be stored in sealed polyethylene bags in a refrigerator for a few days or deep freeze until processed.
- If deep freeze facilities are not available, samples can be stored air-dried and re-wetted before washing. Losses of dry weight due to the methods used for storage should be checked.
- The texture, the structure, degree of compaction and the organic matter content have great influence on the precision and time required to extract the roots from the cores.
- The extraction involves a sieve or strainer of 0.3–0.5 mm mesh. The work can be simplified by a superficial washing and by combining strainers with 1.1 and 0.3 mm mesh.
- The first strainer will contain most roots, the second will contain the rest. The material taken from the strainers can also be mixed with water and the suspended material poured off (live roots of most species have a specific gravity near to 1.0).
- The remainder can be classified manually in a container under water (to remove fragments of organic matter and dead roots).
- This residue should then be hand sorted in shallow dishes under water to remove fragments of organic matter and dead roots; normally it is better to pick live roots from the sample and leave debris behind in the dish.
- Presoaking samples overnight in 5% sodium hexametaphosphate expedites the process of washing roots from clay soils, but the chemical discolors the roots (particularly in soils with high organic matter content) and may disrupt the tissue, making subsequent identification of live roots more difficult.
- Fine roots are the most important part of the root system for water and nutrient uptake, as they form the largest part of total root length or root surface area. For woody perennial vegetation there is a fairly

obvious distinction between the more or less permanent, secondarily thickened roots and the ephemeral, unthickened roots. This functional distinction usually falls somewhere between 1 and 3 mm root diameter. Roots above 10 mm diameter are not adequately sampled by coring.

- For herbaceous perennial and short-lived vegetation, roots should be separated into <2 mm and > 2 mm classes. In mixed vegetation, separation of roots of different species is difficult and is not necessary.

### 3. Monolith sampling

- The monolith method requires cutting a monolith of the soil, from which the roots are separated by washing using shovel or machinery. This method is frequently used for quantitative determinations of roots.
- Generally, the volume of a monolith varies between 1 and 50 cm<sup>3</sup>. The samples of the monolith can be obtained with a board of stainless steel pins nailed in wood. The size of the pinboard is determined by the type of pins, based on previous observations of depth and distribution of rooting (Plate 4).
- The soil collected with the pinboard is heavy (a sample of a block of 100 cm x 50 cm x 10 cm of soil can weigh almost 100 kg).
- The soil is washed away, exposing the roots for observation. If rough soil fragments are shown in the mesh before putting the board in the ground, it will be of help to maintain the roots in the original location while the sample is washed.
- The washing of the sample can be facilitated through cold water soaking for clayey soils and soaking in oxalic acid for calcareous soils. Washed root samples can be stored in polyethylene bags for a short time in a refrigerator, but preferably they should be stored in a freezer.
- The samples are dried at 70°C in an oven till constant weight. The results can be expressed in dry matter per unit of volume of soil.



Root excavation



Monolith sampling



Core sampling

Plate 4 showing different methods of below-ground root biomass estimation

### 5.3.2 Non-destructive method

Below-ground biomass is defined as the entire biomass of all live roots, although fine roots less than 2 mm in diameter are often excluded because these cannot easily be distinguished empirically from soil organic matter. Below-ground biomass is an important carbon pool for many vegetation types and land-use systems and accounts for about 20% (Santantonio *et al.*, 1977) to 26% (Cairns *et al.*, 1997) of the total biomass. The measurement of root biomass is time consuming and expensive due to the wide variability in the way that roots are distributed in the soil. Knowledge of root biomass dynamics is fundamental to improving our understanding of carbon allocation and storage in terrestrial ecosystems (Cairns *et al.*, 1997). Root:shoot ratios may be applied to individual plants, but more often are applied to stands of vegetation at varying scales from local, to landscape, region or biome.

Non-destructive methods rely on calculations of belowground biomass for similar types of vegetation and coefficients as reported in the literature. They are derived from the measurement of the aboveground biomass. Santantonio *et al.*, (1977) suggest that the biomass is close to 20 per cent of the total aboveground biomass and indicate that the majority of the underground biomass of the forest is contained in the heavy roots – generally defined as those exceeding 2 mm in diameter. However, it is recognized that most of the annual plant growth is dependent on fine or thin roots. The data available and recorded in the literature are limited, owing to the high costs involved in the collection and measurement of root biomass. Root:shoot ratios are routinely used to partition plant biomass into aboveground and root component. Cannell (1982) reported root: shoot of 0.26, 0.25 and 0.31 for coniferous, deciduous and tropical tree species respectively. According to MacDicken (1997), the ratio of belowground to aboveground biomass in forests is about 0.2, depending on species. A conservative estimate of root biomass in forests would not exceed 10–15 percent of the aboveground biomass. IPCC default factor for root:shoot ratio is 0.26. A reasonable estimate from the literature is:

$$\text{Belowground biomass} = \text{aboveground biomass} \times 0.26$$

Kittredge (1944) and Satoo (1955), who proposed the use of allometric regression equations of the weight of a given tree component on dbh, such as those of the form:

$$\log W = a + b \log dbh$$

Where, W represents the weight of a certain component of tree, dbh is the diameter at breast height (1.37m), and a and b are regression coefficients. The equations develop by various authors are given in Table 9. National Research Centre for Agroforestry, Jhansi has developed root : shoot ratio of important agroforestry tree species for biomass estimation and presented in Table 10 also refer annexure I.

**Table 9. Equations for estimation of root biomass**

Method	Formula	Applicability
(MacDicken, 1997; Bohm, 1979)	Species x 5:1 More loss than outlined in literature	Tree and shrubs
Santantonio <i>et al.</i> , (1997)	BGB = Volume AGB x 0.2	Tree and shrubs
Kittredge (1944); Satoo (1955)	$\log W = a + b \log DB$	Tree and shrubs
Ogawa <i>et al.</i> , (1965)	$\log W = a + b \log d^2$	Tree and shrubs
Unattributed	$\log W = a + b \log (d^2 + h + d^2h)$	Tree and shrubs
IPCC default factor	Aboveground biomass * 0.26	Tree and shrubs

Where W = dry weight of tree component; d = DBH; h = height of tree; a and b are regression coefficients

**Note:** the lowest shoot : root ratio ever reported for Species X is 5:1. To develop a conservative estimate without measuring roots, an inventory could calculate root biomass as not less than 10 or 15% of above-ground biomass.

**Table 10. Root : shoot ratio of some tree species grown under agroforestry system and/or naturally grown in wastelands**

Name of Tree	Age (yr)	DBH/CD (cm)	ABG (kg tree <sup>-1</sup> )	BGB (kg tree <sup>-1</sup> )	Root : shoot Ratio
<i>Dalbergia sissoo</i>	14	22.80	174.28	49.08	0.28
<i>Albizia procera</i>	8	23.25	204.65	100.42	0.49
<i>Emblia officinalis</i>	12	17.48 (CD)	76.84	27.03	0.35
<i>Hardwicia binnata</i>	17	20.07	140.78	40.17	0.29
<i>Acacia nilotica</i>	6	11.78	116.26	25.52	0.22
<i>Annogiessus pendula</i>	14	8.12	108.04	24.85	0.23
<i>Butea monosperma</i>	23	34.08	396.10	106.95	0.27
<i>Azadirachta indica</i>	8	21.02	245.20	62.53	0.26
Average					0.29

## 6. Soil organic carbon

Through the process of photosynthesis, plants assimilate carbon and return some of it to the atmosphere through respiration. The carbon that remains as plant tissue is then consumed by animals or added to the soil as litter when plants die and decompose. The primary way that carbon is stored in the soil is as soil organic matter (SOM). Carbon can remain stored in soils for millennia, or be quickly released back into the atmosphere. Climatic conditions, natural vegetation, soil texture and drainage affect the amount of carbon and storing period. Soils hold more carbon than plant biomass (or vegetation) and account for 81 per cent of the world's terrestrial carbon stock. Soils are often large storage pools for carbon, both organic and inorganic. Pal *et al.*, (2000) and Nordt *et al.*, (2000) reported that the soil carbon sequestration potential in different eco-regions (Table 11).

**Table 11. The potential of soil organic carbon buildup in different ecoregions**

Sr. No	Ecoregions	Temperature	Area (million ha)	Rate of SOCbuildupn (kg/ha/year)	Total SOC (TgC/year)
1	Arid	Cold	15.2	20–40	0.30–0.60
		Hot	36.8	10-20	0.37-0.74
2	Semi-arid	Hot	116.6	20-40	2.33-4.66
3	Sub-humid	Hot	86.4	40-60	3.46-5.18
4	Sub-humid /humid	Warm	21.2	40-60	0.85-1.27
		Moist	12.1	100-120	1.25-1.45
5	Pre-humid	Moist	20.2	120-150	2.42-0.30
6	Subhumid/semi-arid	hot	8.5	40-60	0.34-0.51
7	Humid/perhumid	hot	11.9	120-150	1.43-1.79
	Total		328.7		12.71-16.50

Source: Pal *et al.*, 2000; Nordt *et al.*, 2000

Note: Tg =10<sup>6</sup> tonnes

Soils are critically important in determining global carbon cycle dynamics because they serve as the link between the atmosphere, vegetation, and oceans. As per World Bank report (2012) globally, the soil carbon pool (also referred to as the pedologic pool) is estimated at 2,500 Gt (Gt =  $10^9$  tonnes) up to 2 meters deep. Out of this, the soil organic carbon pool comprises 1,550 Gt, while the soil inorganic carbon and elemental pools make up the remaining 950 Gt (Batjes, 1996). The soil carbon pool is more than three times the size of the atmospheric pool (760 Gt) and about 4.5 times the size of the biotic pool (560 Gt).

Soil carbon assessment methods can be broadly classified into direct and indirect methods depending on whether carbon content in soil samples is directly measured or inferred through a proxy variable (Table 12). Soil carbon sequestration is calculated from soil organic carbon and bulk density. Soil organic carbon includes plant, animal and microbial residues in all stages of decomposition. Measurement techniques for assessing soil organic matter (SOM) are relatively simple and straight forward. The measurement of soil carbon requires:

- a. collection of soil samples depth wise
- b. determining the soil bulk density (BD) as per the depth of soil sampling
- c. quantification of soil organic and inorganic carbon content in the collected soil samples

$$\text{Soil Organic Carbon (t C ha}^{-1}\text{)} = \text{SOC} \times \text{BD} \times \text{SD} \times 10$$

Where SOC= Soil organic carbon ( $\text{g kg}^{-1}$ )

BD= Bulk density ( $\text{g cc}^{-1}$ )

SD= Soil depth (m)

10 is conversion factor

The mass of soil carbon per unit area is determined by multiplying the depth, bulk density values and the soil C content and summed up depth wise for expressing up to one meter depth. It is the weight of dry soil per unit of volume typically expressed in  $\text{grams cm}^{-3}$ . Total volume of surface soil is about 50% solids, mostly soil particles (45%) and organic matter (generally < 5%). When determining bulk density, water-filled pore space and porosity can also be calculated.

## 6.1 Materials Needed to Measure Bulk Density

- |   |                          |
|---|--------------------------|
| 1. 3-inch diameter aluminum ring (Core) | 5. Wood block            |
| 2. Flat-bladed knife                    | 6. Scale (1 g precision) |
| 3. Ceramic box/stainless steel box      | 7. Oven dry              |
| 4. Balance                              | 8. Hammer                |

### 1. Procedure

2. Carefully clear all residue then drive ring to a depth of 3 inches (2 inches from top) with small mallet or weight and block of wood or plastic cap (same process as used for infiltration test).
3. Shift the core soil sample in stainless still or ceramic box, weigh the fresh soil sample. Record empty weight of box before keeping soil sample.
4. Keep ceramic box in oven dry at a constant weight at  $105^\circ\text{C}$  for 72 hours.

5. Weigh the dry soil with the box.
6. Calculate the internal volume of the core cutter, in cubic centimeters from its dimensions measured to the nearest 0.5 mm.

## 2. Calculation

1. Volume of soil core ( $\text{cm}^3$ ) =  $\pi r^2 \times \text{height}$
2. Bulk density ( $\text{g cm}^{-3}$ ) =  $\frac{\text{Mass of the dry soil (g)}}{\text{volume of core (cm}^3\text{)}}$

## 6.2 Procedure for soil organic carbon analysis

Soil organic carbon (SOC) 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 ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) and concentrated  $\text{H}_2\text{SO}_4$  utilizing the heat of dilution of  $\text{H}_2\text{SO}_4$ . 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 [ $\text{FeSO}_4 \cdot (\text{NH}_4)_2 \text{SO}_4 \cdot 6\text{H}_2\text{O}$ ]. Box 3 states the step wise procedure for estimation of Soil organic carbon.

### Box 3. Step wise procedure for estimation of soil organic carbon (SOC)

- Accurately weigh 1 g of 0.2 mm sieved soil. Transfer it to a dry 500 ml Erlenmeyer flask
- Add two blanks to standardize  $\text{FeSO}_4 \cdot (\text{NH}_4)_2 \text{SO}_4 \cdot 6\text{H}_2\text{O}$  solution
- Add exactly 10 ml of 1N  $\text{K}_2\text{Cr}_2\text{O}_7$  solution (dissolve exactly 49.04 g reagent grade  $\text{K}_2\text{Cr}_2\text{O}_7$  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  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  or 196.1g  $\text{FeSO}_4 \cdot (\text{NH}_4)_2 \text{SO}_4 \cdot 6\text{H}_2\text{O}$  in about 800 ml water and add 100 ml conc.  $\text{H}_2\text{SO}_4$ , 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:

$$\text{Organic Carbon (\%)} = 10 (B - T) \times B \times (0.003 \times 100) \times \text{weight of soil (g)}$$

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. Organic matter (%): Organic C (%)  $\times 1.724$  (factor)

Table 12. Direct and indirect methods of soil carbon assessment

Direct Method	Indirect method
1) Field sampling and laboratory measurements using dry combustion or wet combustion	Accounting techniques <ul style="list-style-type: none"> <li>• Stratified accounting with database</li> <li>• Remote sensing to infer factors determining above-ground carbon inputs</li> </ul>
2) Eddy covariance; flux tower measurement	Biogeochemical/ecosystem simulation modeling to understand below-ground biological processes, for example, <ul style="list-style-type: none"> <li>• RothC</li> <li>• Century</li> <li>• DNDC</li> <li>• PROCOMAP</li> <li>• CO2FIX</li> </ul>
3) Emerging methods: <ul style="list-style-type: none"> <li>• Laser-Induce Breakdown Spectroscopy</li> <li>• Inelastic Neutron Scattering</li> <li>• Near-infrared and mid-infrared spectroscopy</li> </ul>	
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Source: World Bank Report on Soil Carbon Sequestration, 2012

## 7. Different simulation models for quantification of Agroforestry carbon sequestration

Agroforestry will be required to contribute substantially to meet the demands of rising population for food, fruits, fuelwood, timber, fodder, bio-fuel and bio-energy as well as for its perceived ecological services. In such situation biomass estimates, through sequential harvesting, are useful for quantifying net primary productivity and C-cycle. However, periodic harvesting is time consuming, labour intensive and un-economical. Model development is therefore an essential tool for evaluating the biomass stored and carbon sequestered.

Many of the process based models developed for agriculture and forestry are still first choice for use in agroforestry as well. Ravindranath and Ostwald (2008) have compiled and compared different models used in estimating changes in carbon stock for forestry and plantation projects. The model contrasted includes PROCOMAP (developed by Lawrence Berkeley National Laboratory), CO2FIX (developed as an inter-institutional collaborative project involving AL-TERRA, Netherland; The Institute of Ecology of University of Mexico, Mexico; The Centro Agronomica Tropical de Investigacion y Ensenanza (CATIE) Costa Rica and European Forest Institute, Finland), CENTURY (developed by Natural Resource Ecology Laboratory, Colorado State University) and ROTH (developed by Rothamsted Agriculture Research Station, UK) on the basis of their comparative feature, input/output and applications. The CENTURY model computes the form of carbon, nitrogen, phosphorus and sulphur. Both CENTURY (Century 1992) and ROTH concentrate on dynamics of soil carbon stocks for agriculture and forestry projects. PROCOMAP (Sathye and Mayers, 1995) is generally used for project level carbon stocks (biomass and soil) for forestry projects. CO2FIX has been extensively used for estimating biomass and changes in soil carbon stocks for forestry, agriculture and agroforestry projects. CO2FIX was preferred over others (*viz.* PROCOMAP, CENTURY and ROTH) and CO2FIX can simulate the carbon dynamics of single/multiple species simultaneously, and can handle trees with varied ages and agroforestry systems (AFS). The comparative Features of Some Carbon Estimation Models (World Bank report, 2012) is given in Table 13.

**Table 13. Comparative Features of Some Carbon Estimation Models in agroforestry**

Model	Features	Inputs	Output
CENTURY	Simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur for different ecosystems	Monthly mean maximum and minimum air temperature and total precipitation; plant N, P, and S content; soil texture; atmospheric and soil nitrogen inputs; and initial soil carbon, nitrogen, phosphorus, and sulfur levels	Total carbon, soil water dynamics, commercial crop yield, total dry matter, and carbon in plant residue
CO2FIX	Simulates carbon dynamics of single/multiple species, forests, and agroforestry systems	Simulation length, maximum biomass in stand, carbon content, wood density, initial carbon, yield tables, precipitation, temperature, and length of growing period	Carbon stocks and fluxes, total biomass and soil carbon, above- and below-ground biomass, deadwood, and litter and soil organic carbon production
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

PROCOMPAC	Equilibrium model for estimating carbon stocks	Activity data, planting rate, vegetation carbon stocks, rotation period, and mean annual increment in biomass and soil	Biomass and soil carbon stock, incremental carbon stocks, and cost-effectiveness indicators
DNDC	predicting crop growth, soil Temperature and moisture regimes, carbon sequestration, nitrogen Leaching, and emissions of nitrous oxide, nitric oxide, dinitrogen, ammonia, and carbon dioxide	Plant growth data, soil clay, bulk density, pH, temperature, rainfall, atmospheric nitrogen decomposition rate, crop rotation timing and type, inorganic fertilizer timing, amount and type, irrigation timing and amount, residue incorporation timing and amount, and tillage timing	Total carbon, total nitrogen, soil water dynamics, biomass carbon, carbon dioxide, crop yield, carbon input into soil, ?uxes of gases including N <sub>2</sub> O, nitric oxide NO, NH <sub>3</sub> , and CH <sub>4</sub>

Source: World Bank Report, 2012

## 7.1 CO2FIX 3.1 model

The CO2FIX V 3.1 is an ecosystem-level simulation model that quantifies the C stocks and fluxes in the forest using the so-called full carbon accounting approach, i.e. calculating changes in carbon stocks in all carbon pools over time (Noble *et al.*, 2000). It has been programmed in C++ using an object-oriented programming environment. The model is divided in six main modules:

- biomass module
- products module
- financial module
- soil module
- bioenergy module
- carbon accounting module

This model was used to quantify carbon potential from agroforestry system by deploying biomass module and soil module. The model can be run by using following general equation:

The total carbon physically stored in the system at any time ( $CT_t$ ) is considered to be

$$CT_t = Cb_t + Cs_t + Cp_t \text{ ((t C ha}^{-1}\text{))}$$

Where

$Cb_t$ -is the total carbon stored in living (above plus belowground) biomass at any time 't' ((t C ha<sup>-1</sup>)),

$Cs_t$ -is the carbon stored in soil organic matter (t C ha<sup>-1</sup>), and

$Cp_t$ - is the carbon stored in wood products (t C ha<sup>-1</sup>)

Moreover, CO2FIX outputs the biomass and C separately in above and below ground tree components cohorts wise (i.e. species wise) in addition to soil carbon dynamics. CO2FIXv.3.1 is a C accounting model developed as part of the CASFORII project and it has been described in detail by Namburs and Schelhaas (2002), Masera *et al.*, (2003) and Schelhaas *et al.*, (2004). In CO2FIX MODEL, the biomass and carbon credits are simulated at the hectare scale with time steps of 1 year. The biomass module converts volumetric net annual increment data to the annual carbon stock of the biomass compartment. Turnover and harvest parameter drive the ûuxes from biomass to soil. The model has a soil module known as YASOO (Liski *et al.*, 2005), which takes into account the initial litter quality and the effect of climate on decomposition. Litter enters the soil module based on the size of the litter and

is then dissociated into contents of different classes of organic compounds. The validity of its soil carbon estimates, mass loss estimates and ability to appropriately describe the effects of climate on decomposition rates has been tested within a wide range of environments (Liski *et al.*, 2003, 2005; Palosuo *et al.*, 2005). The CO2FIX model can be applied to coniferous or deciduous forests, as well as to monocultures or mixed tree stands (Schelhaas *et al.*, 2004.) A number of case studies have been made both in temperate and tropical climates, to estimate biomass and soil carbon (Mohren and Goldewijk, 1990; Nabuurs and Mohren, 1993; Mohren *et al.*, 1999; Nabuurs and Schelhaas, 2002; Masera *et al.*, 2003). The CO2FIX model has been used to estimate the dynamics of C-stocks and flows for a variety of ecosystem around the world (Schelhaas *et al.*, 2004). It is an invaluable tool that has contributed to IPCC climate assessments and estimation of C implication in the context of Kyoto–Protocol (Gaboury *et al.*, 2009). The CO2FIX model has been tested and validated for the forest ecosystem in the Philippines, mixed pine-oak forest of central Mexico, multi-strata AFS and tropical rainforest in Costa-Rica and woodlots in Zambia (Kaonga and Smith, 2012). De Jong *et al.*, (2004) has used CO2FIX model for estimating the carbon sequestration potential of live fenced pasture lands. CO2FIX has been used to estimates the carbon storage and sequestration potential of selected trees species in India (Kaul *et al.*, 2010).

### 7.1.1 Input Parameters for the CO2FIX model

The main input parameters relevant to CO2FIX model are the cohort wise values for the stem-CAI (current annual increment in  $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ ) over years; relative growth of the foliage, branches, leaf and root with respect to the stem growth over years; turnover rates for foliage, branches and roots; and climate data of the site (annual precipitation in mm and monthly values of minimum and maximum temperatures in  $^{\circ}\text{C}$ ). Other inputs to the model includes initial surface soil organic carbon ( $\text{Mg C ha}^{-1}$ ), rotation length for the tree species, per cent carbon contents in different tree parts, wood density and initial values of baseline carbon ( $\text{Mg C ha}^{-1}$ ) in different tree parts, when the simulation are being carried out for the existing tree plantations as in the present case.

### 7.1.2 Basic data required for running the CO2FIX model

For the purpose of simulating carbon stocks under AFS, the modules taken into considerations are biomass, soil and carbon accounting modules. CO2FIX model requires primary as well as secondary data on tree and crop components (called ‘cohorts’ in CO2FIX terminology) for preparing the account of carbon sequestered under AFS on per hectare basis. The primary data includes name of the existing tree species on farmlands along with their number, diameter at breast height (dbh), crops grown on farmlands along with their productivity, area coverage etc. Whereas the secondary data includes the growth rates of tree biomass components (stem, branch, foliage, root) for various species on annual basis as well as the productivity of different crops grown in that region.

The tree species being grown on farmland were classified into three categories/cohort’s *viz.* slow, medium and fast growing trees as per the nature of the species. The basic parameters (*viz.* rotation length, wood density, carbon contents) set for the tree cohorts have been given in Table 14. DBH of the surveyed trees was used to approximately find out the age of the standing trees. To derive the incremental data of tree stem growth, the volume equations published in State Forest Report-2009 (Forest Survey of India (FSI), Dehradun, Ministry of Environment and Forests) were used as the secondary data.

### 7.1.3 Parametrization of the tree cohorts

Stem volume equations, available in Forest Survey of India Report (2009) for the species found in survey, were used to generate the dbh (m) and stem volume ( $\text{m}^3/\text{tree}$ ) data. The individual species wise generated data sets

were then clubbed into single files for the slow, medium and fast growing species separately. These three data sets pertaining to slow, medium and fast growing species were independently used to fit non-linear functions for stem volume-dbh relationships. These tree wise absolute stem volume-dbh relationships were then converted into hectare wise stem volume-dbh relationships, by multiplying tree wise stem volume from the average number of trees found in the village survey in a specified category (slow/medium/fast). This dbh will be transformed back into age to obtain hectare wise stem volume–age relationships. Ultimately, these absolute stem volume values will be converted into CAI (current annual increment) values of stem volume by taking the difference of current year value from preceding year value.

The harvested data available for different tree species (classified under the slow, medium and fast growing categories/cohorts) at National Research Centre for Agroforestry (NRCAF), Jhansi was used to find out the relative growth of foliage, branch and root with respect to stem. These relative proportions were parameterized in CO2FIX model for branch, foliage and root growth.

#### 7.1.4 Parametrization of the crop cohort

In order to simulate the crop component, the crop was considered as a ‘tree’ with a very small stem volume, no branches and a lot of foliage and roots. The stem part is needed, since allocation to foliage and roots are driven by stem increment. In order to keep the influence of the stem compartment as small as possible, a very small increment was specified, in our case  $0.01 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ . The foliage (grain and straw) and root compartment receive a very high relative increment (w.r.t. stem), say for example set as 8657 and 865 respectively for Ludhiana district. When the wood density has been set at ‘0.09’, the aboveground production is  $8657 \times 0.09 \times 0.01 = 7.79 \text{ t DM ha}^{-1}$  (dry matter per hectare). Additionally, it is presumed for CO2FIX model that 5% of the above ground crop biomass (grain and straw) incorporates into the soil, while 95% is exported out from the system. Likewise, 30% of the below ground crop biomass is incorporated into the soil. Characteristic for cropland systems are the high turnover rates in foliage and roots, in this case set at 0.9 for both.

#### 7.1.5 Parametrization of the soil module

The dynamic soil carbon model YASSO describes decomposition and dynamics of soil carbon in well-drained soils. The soil module consists of three litter compartments (non-woody, coarse-woody and fine-woody) and five decomposition compartments (extractives, cellulose, lignin like compound, humus-1 and humus-2). Litter is produced in the biomass module through biomass turnover. For the soil carbon module, the litter is grouped as non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stems and stumps). Since the biomass module makes no distinction between fine and coarse roots, root litter is separated into fine and coarse roots according to the proportion between branch litter and foliage litter.

### 8. Assessment of Carbon Sequestration using Geospatial Technologies

For assessment of carbon sequestration potential in agroforestry systems at district level, we must know the area under agroforestry systems in that district. Geospatial technologies have important role in estimation of area under agroforestry at district level. For accurate estimation of area under agroforestry, high resolution data (better than 5 m) will be useful. With the use of high resolution data, we will be able to identify all types of agroforestry systems viz. scattered trees, boundary, agrisilviculture/agrihorticulture and block plantations.

By doing field survey, we can enumerate tree density per ha. From this carbon stock in trees/ha can be estimated using standard models/allometric equations. This carbon stock in trees together with soil organic carbon

would give an estimate of carbon storage under agroforestry systems. When estimated area and carbon storage under agroforestry systems is multiplied, it will give total carbon storage in a particular district. The diagrammatic representation of this methodology is given in Fig.4.

Another approach is direct estimation of biomass/ carbon for existing agroforestry systems through remote sensing methods. This approach requires very high resolution data (1m or better) so that no. of trees and tree canopy cover can be estimated. But this will require huge data processing as well extensive ground verification survey in a particular district.

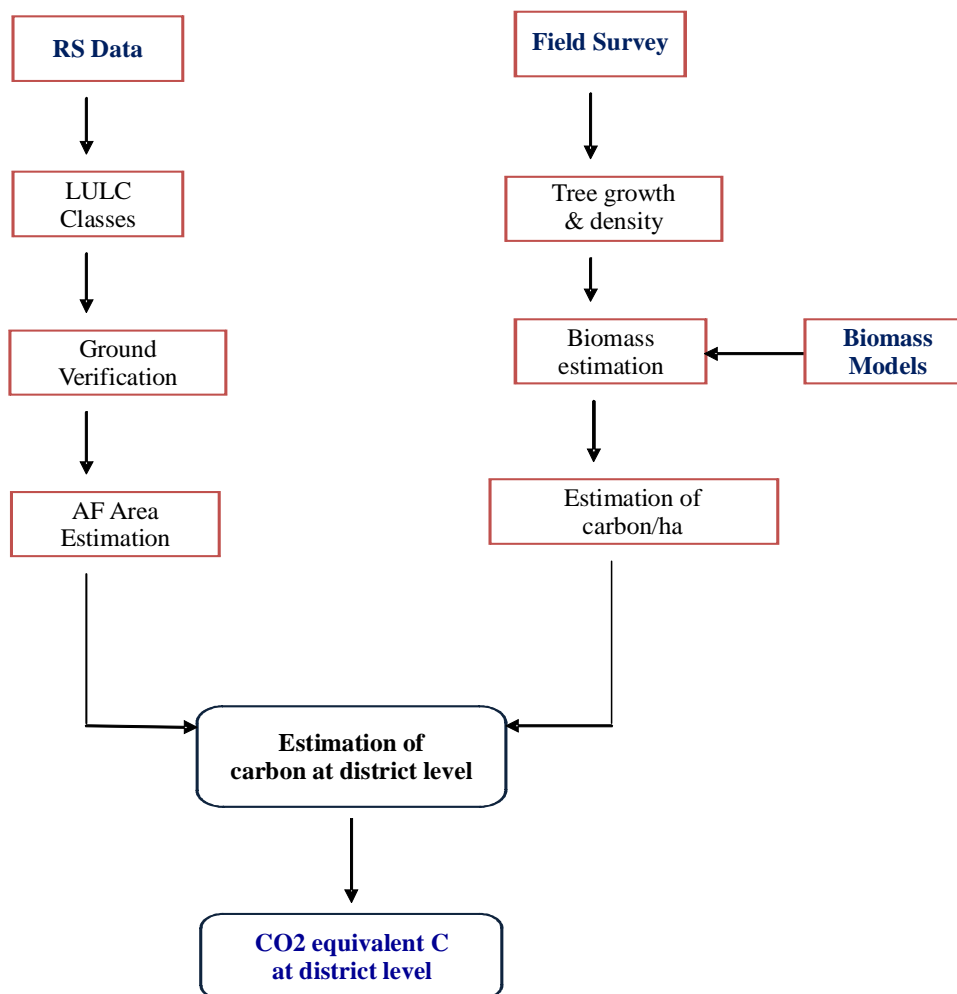


Figure 4. RS & GIS Methodology for estimating carbon sequestration at district level

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#### Annexure I. Field data sheet aboveground biomass measurement from agroforestry systems

Survey Date :		Plot area :	
Number of trees:		Altitude :	
Co-ordinates of Field plot			
Latitude :		Longitude	
Agroforestry Systems			

Tree No.	Common Name	Scientific Name	DBH (cm)	Height (m)	Remark

#### Annexure II. Field data sheet for destructive sampling of trees

Survey Date		Place	
Name of Sample tree			
DBH of sample tree at Stump 1.34m			
DBH of sample tree at 1.37 m (cm)			
DBH of sample tree at center of bole (cm)			
DBH of sample tree at top of the bole (cm)			
Height of the tree from stump to top of the crown (m)			
Height of the tree from stump to first crown forming branch (m)			

#### a) Fresh Biomass measurement of sample tree

Tree no.	Weighing time	Fresh weight of sample (kg)			
		Bole	branches	Leaves/fruits/seeds	Roots
1					
2					
3					
4					
	Total				

## b) Sample taken for dry biomass and wood density

Dry Biomass	Fresh weight of the sample (gram)			
	Bole	Branches	Leaves/fruits/seeds	Roots
1				
2				
3				
4				
Sample for wood density analysis				
			Wood disc from bole	
			Wood disc from branches	
			Wood disc from roots	

Wood density:  $SWDc \div SV$

Where:  $WD$  is wood density in  $g/cm^3$ ;  $SDWc$  is dry weight of sample cube and  $SV$  is volume of sample cube

## Annexure III. Field data sheet for floor vegetation biomass measurement

Survey Date :		Plot area :	
Place		State	
Number of trees:		Altitude :	
Co-ordinates of Field plot			
Latitude :		Longitude	
Agroforestry Systems			
Dominant floor vegetation			

## A – Fresh biomass measurement

S No	Sample name	Plot area (m <sup>2</sup> )	Floor vegetation		Fresh weight by vegetation components		
			Height (m)	Cover (%)	Stem	branches	roots

## B – Sampling for dry mass analysis

S No.	Sample name	Plot code	Fresh weight of sample		
			Stem	Branches	Foliage

**Annexure IV. Field data sheet for floor vegetation biomass measurement**

Survey Date :		Plot area :	
Place		State	
Number of trees:		Altitude :	
Co-ordinates of Field plot			
Latitude :		Longitude	
Agroforestry Systems			

**A - Measurement of standing dead wood**

S No.	Sample	Sampling plot area (m <sup>2</sup> )	Diameter (cm)			Tree height (m)	Length of bole (m)
			At 1.37 m	At base	At top		

**B - Measurement of lying dead wood**

S No	Transect length & Number	Dead wood piece no.	Diameter (cm)	Density class no.		
				S	I	R

**C - Sampling for wood density analysis**

S No.	Sample name	Type of wood density for sampling (for S, I & R)	Number of sample taken

Notes: Density class S- Solid, I- Intermediate R- rotten

**Annexure V. Field data sheet for litter biomass measurement**

Survey Date :		Plot area :	
Place		State	
Number of trees:		Altitude :	
Co-ordinates of Field plot			
Latitude :		Longitude	
Agroforestry Systems			

**Litter measurement**

S No	System name	Sampling plot area (m <sup>2</sup> )	Fresh Weight of litter (g)

**Dry mass analysis**

S No	System name	Sampling plot area (m <sup>2</sup> )	Dry Weight of litter (g)

Total dry weight (TDW) for each organ of the sample tree

$$TDW = TFW (SDW/SFW)$$

Where: TDW is total dry weight; TFW is total fresh weight; SDW is absolute dry sample weight and SFW is fresh sample weight.

**Annexure VI. Volume equation, growth rate, biomass expansion factor, Root:Shoot ratio and wood density of Important tree species in India**

S. No.	Species	Volume equation	Growth rate (t ha <sup>-1</sup> yr <sup>-1</sup> )	BEF	R:S ratio	Wood density (gm/cm <sup>3</sup> )
1	<i>Acacia catechu</i>	$V = 0.048535 - 0.183567 D + 3.78725 D^2$	2.65	2.52	0.25	0.875
2	<i>Aegle marmelos</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	2.65	1.4	0.27	0.754
3	<i>Ailanthus excelsa</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	3.59	1.63	0.27	0.356
4	<i>Albizia procera</i>	$V = -0.07109 + 2.99732 D - 0.26953 D^2$		2.90	0.27	0.579
5	<i>Albizia lebbek</i>	$V = -0.07109 + 2.99732 D - 0.26953 D^2$	6.33	2.90	0.27	0.534
6	<i>Alnus nepalensis</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	5.3	1.4	0.27	0.434
7	<i>Azadirachta indica</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$		1.74	0.28	0.693
8	<i>Bombax ceiba</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	5.43	1.4	0.27	0.329
9	<i>Toona ciliata</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	6.33	1.4	0.27	0.424
10	<i>Cedrus deodara</i>	$V/D^2 = 0.2421/D^2 - 2.68191/D + 14.77955$		1.4	0.27	0.468
11	<i>Dalbergia sissoo</i>	$V = -0.013703 + 3.943499 D^2$	5.99	1.86	0.20	0.692
12	<i>Emblica officinalis</i>	$V = 0.13734 - 2.49039 D + 15.59566 D^2 - 11.06205 D^3$		1.49	0.18	0.8
13	<i>Gravellia robusta</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	3.59	1.4	0.27	0.472
14	<i>Grewia optiva</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	3.59	2.01	0.27	0.642
15	<i>Mangifera indica</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	3.59	1.4	0.17	0.581

16	<i>Melia azadirachta</i>	$V = -0.03510 + 5.32981 D^2$		1.74	0.27	0.491
17	<i>Morus alba</i>		6.33	1.4	0.27	0.603
18	<i>Pinus roxburghii</i>	$V/D^2 = 0.167095/D^2 - 2.085944/D + 9.929936$	4.69	1.91	0.21	0.491
19	<i>Pongamia pinnata</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$		1.4	0.27	0.609
20	<i>Populus deltoides</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$		1.58	0.19	0.4
21	<i>Quercus leucotrichophora</i>	$? V = 0.240157 + 3.820069 D - 1.394520 ? D$		1.91	0.39	0.826
22	<i>Salix alba</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	8.14	1.4	0.27	0.459
23	<i>Sapindus mukorossi</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$		1.4	0.27	0.77
24	<i>Syzygium cumini</i>	$? V = -0.05923 + 2.33654 D$	5.09	2.22	0.27	0.647
25	<i>Terminalia bellerica</i>	$? V = -0.14325 + 3.07937 D$	2.65	1.56	0.25	0.628
26	<i>Terminalia arjuna</i>	$V = 0.50603 - 6.64203 D + 25.23882 D^2 - 9.19797 D^3$		1.56	0.25	0.622
27	<i>Terminalia chebula</i>	$V = -0.05004 - 0.03440 D + 6.35715 D^2$	2.65	2.37	0.25	0.642
28	<i>Tectona grandis</i>	$V = 0.08847 - 1.46936 D + 11.98979 D^2 + 1.970560 D^3$	5.43	1.74	0.20	0.57
29	<i>Terminalia tomentosa</i>	$V = 0.50603 - 6.64203 D + 25.23882 D^2 - 9.19797 D^3$	2.65	1.56	0.25	0.73
30	<i>Prunus americana</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	3.69	1.4	0.27	
31	<i>Ulmus wallichiana</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	5.43	1.4	0.27	0.435
32	<i>Pinus wallichiana</i>	$V = 0.193297 - 2.267002 D + 10.679492 D^2$	4.69	1.91	0.27	0.427
33	<i>Cassia seamea</i>	$V = 0.05159 - 0.53331 D + 3.46016 D^2 + 10.18473 D^3$		1.74	0.27	0.697
34	<i>Acacia nilotica</i>	$V = 0.0281 + 0.6872 \times ND^2 H$	6.21	2.52	0.25	0.67
35	<i>Butea monosperma</i>	$V/D^2 = 0.007602/D^2 - 0.033037/D + 1.868567 + 4.483454 D$	2.65	2.39	0.37	0.465