Chapter 10
Carbon Sequestration in Agroforestry: Enhancement of Both Soil Organic and Inorganic Carbon

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Abstract In India owing to its gradation in climatic conditions from temperate to humid tropics, the agroforestry systems (AFS) and practices are highly diverse within the country. The agroforestry practices followed in India range from intensified simple monoculture systems of planting, such as block and boundary plantations, to more specific, diversified, and complex systems, such as home gardens. In the era of changing climate, the role of trees, and other vegetation, its abatement is of paramount significance. Agroforestry as a sustainable land management system has a major role in carbon conservation and sequestration. Agroforestry practices sequester carbon both above ground as well as belowground. The above ground carbon sequestration by vegetation which sequester atmospheric carbon undergoing various physiological process and conserve it as biomass. The sole terrestrial pool where carbon (C) may be intentionally increased by agroforestry practices is the soil organic carbon (SOC) pool, which has been able to store some carbon for millennia. Agroforestry systems sequester about 2233 g carbon both above and below ground during the period of 50 years, but estimates of the amount of land they occupy globally are highly uncertain.

Keywords Agroforestry · Carbon sequestration · Climate change · Soil organic carbon

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10.1 Introduction

Agroforestry can be defined as a sustainable land management system in which trees are deliberately integrated with agriculture crops, fodder crops, pastures, and poultry in some form of special arrangement or temporal sequence. Climate change is considered as a potent environmental concern in the twenty-first century. Land Use, Land Use Change, and Forestry (LULUCF) under Kyoto Protocol recommended afforestation and reforestation as the potent Green House Gas (GHG) offset activity to mitigate climate change. But as per the Paris climate agreement, every developed and developing nation shows reduction in carbon emission in order to reduce the global warming of the atmosphere by about 2 °C, whereas the global warming is directly related with carbon emission. Therefore, studies on the carbon sequestration potential of trees are gaining momentum for reducing the global temperature. According to LULUCF, agroforestry became recognized as a carbon sequestration activity under the afforestation and reforestation programmes, and agroforestry systems attracted attention as a carbon sequestration strategy from both industrialized and developing countries. Under the Paris agreement for climate change, the Nationally Determined Contribution (NDC) for India is to sequester 2.5–3.0-billion-ton carbon dioxide equivalent by 2030 (Chavan et al. 2022). A study of the change in forest carbon stock between the years 2019 and 2021 showed an increase of 79.4 million tonnes of carbon (FSI 2021). According to India's Restoration Opportunities Atlas, 87 million hectares (25% of total land) have the potential for carbon reduction through agroforestry (Singh 2021). According to the IPCC's Fifth Assessment Report, agroforestry will have a significant potential to sequester carbon in developing nations by the year 2040 (Nair et al. 2009a, b, c, d; 2010).

The variation in land use sectors have varying carbon emissions and sequestration. Agriculture alone is assumed to be responsible for 10–12% of all global anthropogenic GHG emissions, with non-CO_2 GHG emission estimates of 5120–-6116 Mt CO_2 eq/year in 2005. Agricultural lands frequently undergo extensive management, which presents numerous chances to enhance agronomic techniques, fertilizer and water management, and land use techniques to meet the goals of carbon sequestration. The total carbon sequestration capacity of agricultural lands worldwide is 0.75 to 1 Pg/year, or roughly 50% of the 1.6 to 1.8 Pg/year lost to deforestation and other agricultural activities. Thus, switching from lower biomass land uses like crop fallows, grasslands, etc., to tree-based systems like agroforestry, forests, and plantation forests can result in significant increases in carbon storage. IPCC (2007) defined carbon sequestration as the process of uptake of carbon containing substances, predominantly carbon dioxide, into a secondary reservoir with a long residence time. In agroforestry, carbon accumulation has been estimated to range from 0.29 to 15.2 Mg C ha1 year1 above ground and from 30 to 300 Mg C ha1 year1 for soils that are at least 1 m deep (Nair et al. 2009a, b, c, d).

Above ground carbon sequestration in agroforestry (Fig. 10.1) is by trees and other vegetation (above ground biomass) and below ground carbon sequestration is

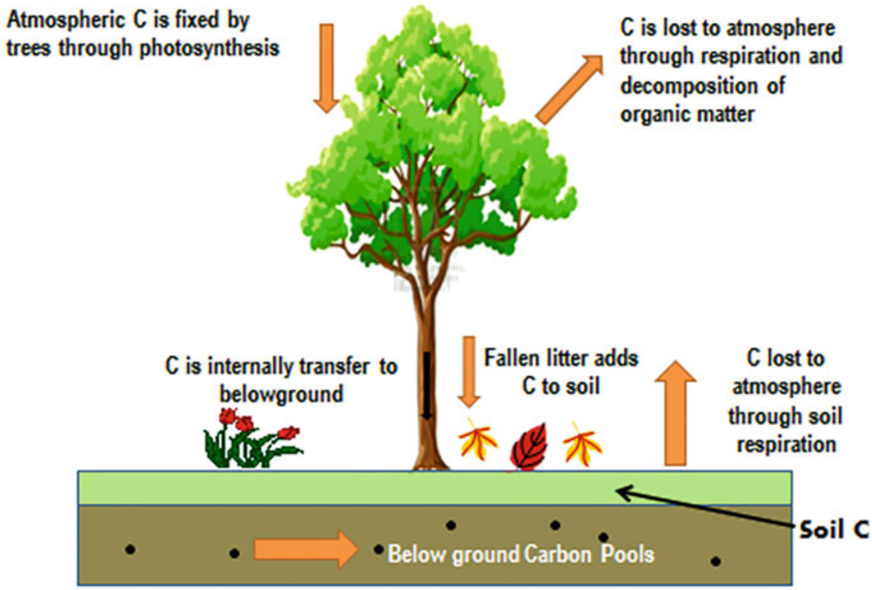

Fig. 10.1 Carbon sequestration in agroforestry

by roots biomass and soil pool. According to the Soil Science Society of America (SSSA), carbon sequestered in the soil is in two ways, direct and indirect (SSSA 2001). Chemical processes that transform carbon dioxide into inorganic soil molecules like calcium and magnesium carbonates directly sequester carbon in the soil. Plants photosynthesize atmospheric carbon dioxide into plant biomass, resulting in indirect carbon sequestration.

10.2 Mechanisms of Carbon Sequestration in Agroforestry Systems

The mechanism of carbon sequestration is through biologically mediated uptake and conversion of atmospheric carbon dioxide into inert, long lived carbon containing substances and hence it is also called as bio sequestration (U.S. DOE 2008). Carbon sequestration in an agroforestry system can be above ground carbon sequestration and below ground carbon sequestration (Fig. 10.2). Over geological time scales of more than 100,000 years, the atmospheric carbon dioxide concentration is regulated by the long-term global carbon cycle, which explains the biogeochemical cycling of atmospheric carbon among surface systems including oceans, the atmosphere, biosphere, and soil.

The carbon dioxide in the atmosphere is fixed in plants through the physiological process of photosynthesis and a small amount of carbon dioxide is released back

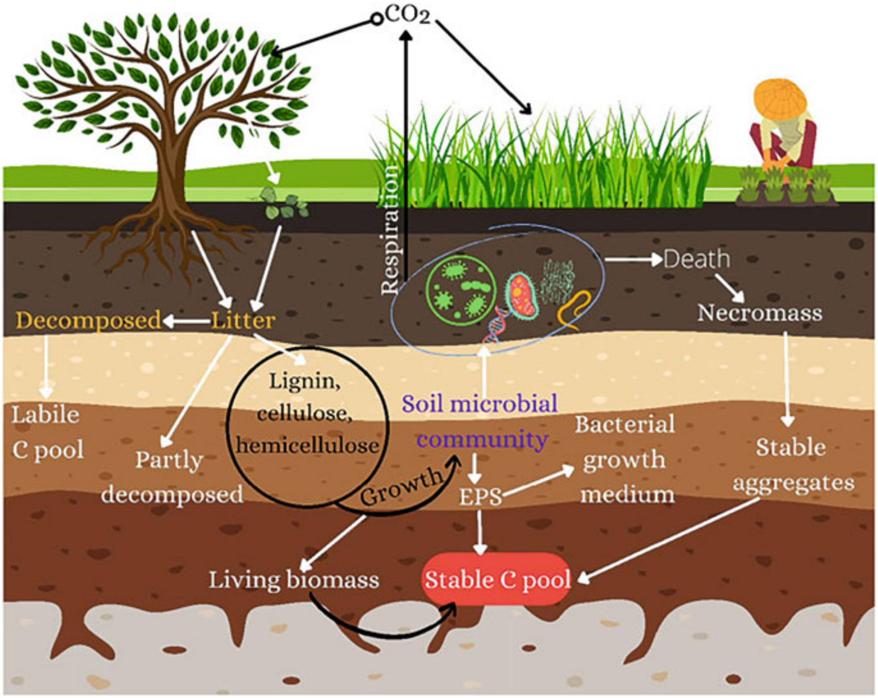

Fig. 10.2 Mechanism of bio carbon sequestration in agroforestry

through plants, animals, and microbes through aerobic respiration as carbon dioxide and anaerobic respiration as methane. A large amount of carbon dioxide and methane is released into the atmosphere during the burning of fossil fuels, forest fire, vehicular exhaust, land clearance for agriculture and other purposes. The plants store carbon both in above ground and belowground biomass. The above ground biomass encompasses leaves, twigs, stems, and branches and belowground as roots. The biomass on decomposition by the activity of microbes will transfer the carbon to a labile carbon pool. The lignin, hemicellulose, and cellulose content of the plant biomass is used for the growth and nourishment of soil microbes which in turn fixes carbon in the dead necromass to the soil stable carbon pool, and such carbon sequestration in the soil is called indirect soil carbon sequestration. Direct carbon sequestration occurs through direct chemical reaction of carbon dioxide with soil minerals and is converted into stable inorganic compounds such as calcium and magnesium carbonates and is stored in the soil pool. According to estimates, the soil and aboveground components of tree-based land-use systems carry the majority of the carbon (C), or around 60% and 30%, respectively.

10.3 Soil Carbon Sequestration

Soil carbon sequestration is one of the significant greenhouse gas (GHG) removal strategies and is estimated at about 4.8 Gt CO_2 eq/year. Soil carbon sequestration is also addressed as negative emission technology is through two ways, direct and indirect carbon sequestration (Fig. 10.3). Direct carbon sequestration occurs through direct chemical reaction of carbon dioxide with soil minerals and converted into inorganic compounds such as calcium and magnesium carbonates and is stored in the soil pool. The carbon thus formed is called as inorganic carbon or bound carbon which is in stable form and can be stored for a long period of time. The indirect carbon sequestration occurs when the dead or living plants biomass is acted upon by soil active microorganisms through the process of decomposition. The lignin, hemicellulose, and cellulose content of the plant biomass is used for the growth and nourishment of soil microbes which in turn fixes carbon in the dead necromass to the soil stable carbon pool (Nair et al. 2009a, b, c, d).

The pool of carbon in the soil is made up of 750 Pg of soil inorganic carbon and 1550 Pg of soil organic carbon, both at a depth of 1 m. According to an average calculation, the total soil carbon pool (2300 Pg) is more than both the atmospheric pool (770 Pg) and the vegetation pool (610 Pg) combined (Murthy et al. 2013; Lorenz and Lal 2014, b; Shi et al. 2018).

In an agroforestry system, the growth of the crop is a function of soil fertility, and soil organic carbon is an important factor determining the fertility of the soil. The litter from the tree decomposition is responsible for the enrichment of soil fertility for crop growth under an agroforestry system. The organic carbon content in the soil is a pool of atmospheric carbon dioxide that is sequestered indirectly contributing toward

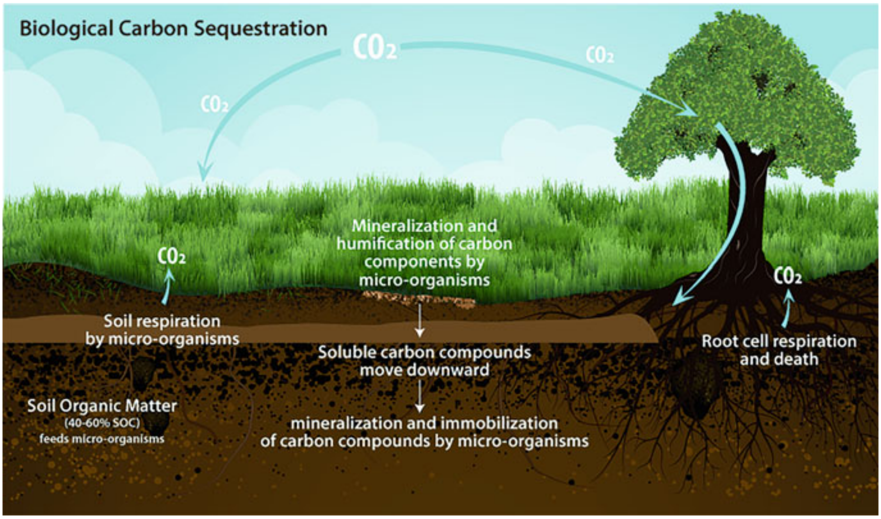

Fig. 10.3 Biological carbon sequestration in soils

the fertility of the soil and also plays a major role in determining the carbon storage in the ecosystem and regulating the concentration of carbon dioxide in the atmosphere. Hence, agroforestry can be adopted as the sustainable tool not only for the reduction in atmospheric carbon dioxide but also increases the crop productivity and enhances the sustainability of the system.

The protocols envisaged to quantify the soil carbon sequestration includes estimation of organic carbon dynamics in soil by wet digestion or dry combustion, measuring belowground living biomass, isotope measurements labelled by using either stable (^{13}C) or radio (^{14}C) isotopes and carbon dating. Apart from these various models such as CENTURY, RothC models, etc., were also developed to formulate the soil carbon pool. Recent spectroscopic methods, such as airborne spectroscopy, were also intended to assess the surface soil organic carbon utilizing multispectral and/or hyperspectral sensors mounted on aircraft, unmanned aerial vehicles (UAVs), or satellite platforms (Stefano and Jacobson 2018).

10.4 Carbon Stock Measurement

10.4.1 Aboveground

The above ground carbon sequestration is carried out by the trees' above ground biomass such as stems, leaves, branches, inflorescence, etc. The above ground carbon stock is measured in terms of harvested and standing biomass (Moraes et al. 1995; Guo and Gifford 2002). The traditional method of estimating the carbon stock is by harvesting the whole tree including roots. The method includes cutting down sample trees, separating different parts (such as the stems, leaves, inflorescence, etc.), digging out and washing the roots, calculating the dry weights of each part from samples, and adding the results to determine the total biomass. The carbon content of the harvested parts were estimated by combustion of samples.

The C content in each component was determined by combusting the samples after separating the collected representative trees into their various parts (branchlets, branches, dead branches, leaves, roots, and fine roots). A regression curve was then created using the calculated whole-tree biomass and carbon content. Such whole-tree harvesting processes need a lot of time and labour. In order to estimate whole-tree biomass, Dixon (1995) measured the volume of stem wood and multiplied it by the species-specific wood density. This result was then multiplied by 1.6. Root biomass was not included and it was assumed that 50% of the projected whole-tree biomass was made up of carbon. The worldwide forest biomass was then estimated in greater detail using this preliminary estimate. Variations in tree management can also be a problem; for example, trees in AFS may be pruned differently depending on management procedures, or they may grow in various ways because their spacing is different from that of natural (forest) systems. Agroforestry plots also differ from one another in terms of plant composition, planting patterns, and stand densities. As a result, estimating biomass output from local AFS is a tough undertaking that makes extrapolating results from one system to another exceedingly challenging.

10.4.2 Belowground Estimation

Understanding how belowground organic carbon dynamics in AFSs affect carbon stock depends on this determination, which is challenging. In addition to live root and hyphal biomass, microbial biomass, and Soil Organic Matter (SOM) in labile and more recalcitrant forms, organic C can take on a variety of distinct forms in soils. Measurement, estimation, and prediction of Soil Carbon Sequestration (SCS) are challenging tasks due to the complicated interplay of these several forms (Schulp et al. 2008). Carbon stock above ground and below ground has been presented in Fig. 10.4.

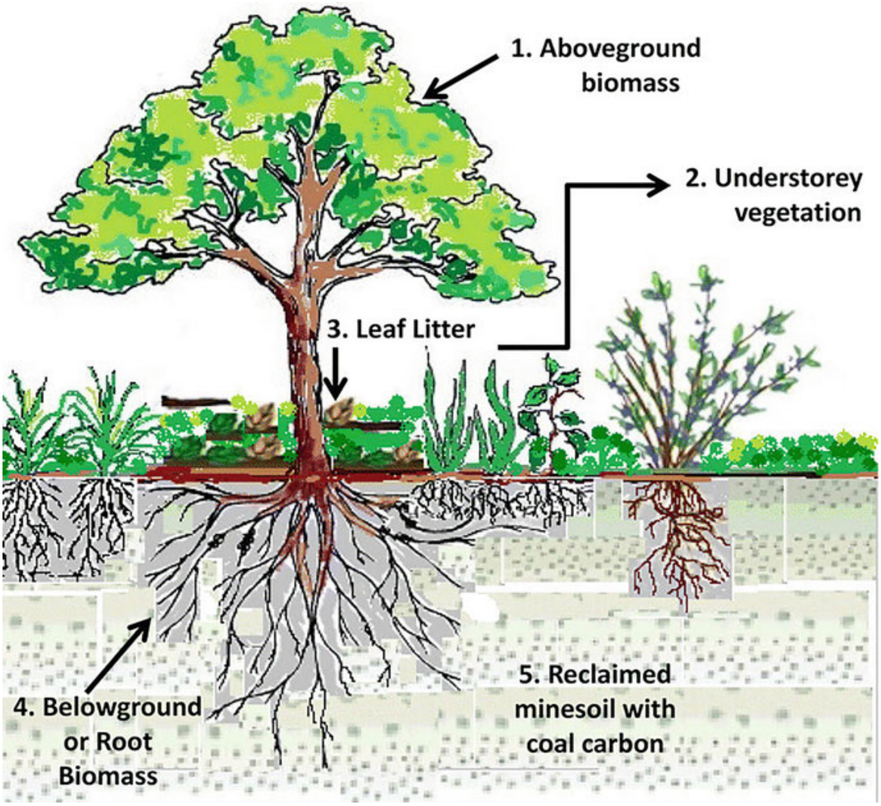

Fig. 10.4 Carbon stock above ground and below ground

10.5 Carbon Stocks in Agroforestry Systems in India

Through the enhancement of soil carbon and root biomass, carbon is stored in standing biomass above ground as well as below ground in diverse agroforestry systems. India's potential for sequestering carbon via agroforestry and other alternative land use systems was estimated to be 25 t C/ha over 96 M ha of land, or 68–228 Mg C/ha. However, this value varies by location according to biomass production. According to research by Jha et al. (2009), agroforestry can store 26% more carbon than farming in the Haryana plains, or about 83.6 t C/ha, up to a depth of 30 cm in the soil. However, the scale of the operation and the final use of the wood would determine the amount of carbon sequestration from forestry activities.

10.5.1 Agri-Silvicultural systems

Carbon sequestration in tree biomass: Maikhuri et al. (2001) projected that planted tree species on abandoned agricultural land may sequester 3.9 t/ha/year of carbon annually and 1.79 t/ha/year of carbon on degraded forest land. The intercropped *Alnus nepalensis* and *Dalbergia sissoo* plants with wheat and paddy had the maximum carbon sequestration rates of 0.256 t C/ha/year and 0.141 t C/ha/year, respectively.

10.5.1.1 Carbon Sequestration in Tree Biomass

According to Maikhuri et al. (2001), planted tree species on degraded forest land may absorb 1.79 t/ha/year of carbon and 3.9 t/ha/year of carbon on abandoned agricultural land. The highest rates of carbon sequestration were achieved by the intercropped *Dalbergia sissoo* and *Alnus nepaliensis* plants with wheat and rice, at 0.256 t C/ha/year and 0.141 t C/ha/year, respectively. Agri-silvicultural system based on *Gmelina arborea* that has been in place for 6 years sequestered 31.37 t C/ha. According to a different study, monocultures of trees and food crops sequestered 40% and 84% less carbon than agri-silviculture, showing that agroforestry systems have a greater capacity to sequester carbon. *Dalbergia sissoo*, at the age of 11 years, was able to accumulate 48–52 t/ha of biomass in an agri-silvicultural system. In an agri-silvicultural system where tree biomass ranged from 23.61 to 34.49 t C/ha with black gram-mustard, carbon dynamics involving various pruning techniques were investigated. According to studies on poplar-based agri-silvicultural systems, total biomass in the system was 25.2 t/ha, which is 113.6% more than solitary wheat cultivation. Net carbon storage in the system was 34.61 t C/ha as opposed to 18.74 t C/ha in single wheat cultivation. Albizia and mixed tree species, such as Mandarin, formed an agroforestry system that collected 1.3 t of biomass per hectare and stored 6939 kg of agricultural and tree biomass.

10.5.1.2 Enhancement of Soil Organic Carbon

Singh et al. (1989) found that *Populus deltoides* and *Eucalyptus hybrids* with Cymbopogon spp. increased SOC by 33.3 to 83.3% when planted alongside crops, with *Populus deltoides* showing the greatest increase in SOC. It has been found that agroforestry plantings with ages ranging from 6 to 20 years have boosted soil organic carbon. In an agroforestry system based on Poplars, trees were able to store more soil carbon in sandy clays than loamy sand during the first year of installation (6.07 t/ha/year) compared to the following years (1.95–2.63 t/ha/year). Traditional *Prosopis cineraria*-based systems cause SOC to rise by 50%, primarily as a result of leaf litter. After 5 years of planting, Samra and Singh (2000) noted increases in the status of soil organic carbon under *Acacia nilotica* + *Sacchram munja* of 0.39 to 0.52% and under *Acacia nilotica* + *Eulaliopsis binata* of 0.44 to 0.55%.

10.5.2 Silvipastoral Systems

10.5.2.1 Carbon Sequestration in Tree Biomass

The rate of biomass carbon storage in the silvipastoral system was 6.72 t C/ha/year in 8 years, which is two times more than the rate of 3.14 t C/ha/year from natural grassland, according to comparative studies conducted by National Research Centre for Agroforestry (NRCAF) in the year 2007 on biomass production from natural grassland and silvipastoral system composed of *Albizia amara*, *Dichrostachys cinerea*, and *Leucaena leucocephala*. Approximately 16,400 t/year of carbon is sequestered annually in farm forestry, which includes species like Eucalyptus sp., *Populus deltoides*, *Tectona grandis*, and *Anthocephalus chinensis* trees. In natural grassland in semi-arid Uttar Pradesh, species of *Eucalyptus tereticornis*, *Emblica officinalis*, *Albizia procera,* and *Albizia lebbeck* were introduced as part of a silvipastoral system.

10.5.2.2 Carbon Stored in Block and Boundary Plantations

In a study conducted by Kumar (2010) on four different agroforestry systems, including Eucalyptus hybrid boundary plantation + wheat, *Populus deltoides* block plantation + wheat, *Populus deltoides* block plantation + lemon grass and *Populus deltoides* boundary plantation + wheat it was estimated that total carbon sequestration rate [in trees] was 21.38, 70.59, 18.53, and 116.29 tonnes. For the Chirpine, Khair, mango, mixed plantations and Kino-based agricultural forestry systems in Uttaranchal, assessed a mitigation potential of 62.7, 48.5, 60.8, 61.7, and 37.6 t C/ha/year, respectively.

10.6 Estimation of Carbon Sequestration Potential for Agroforestry Systems

Under the Kyoto Protocol, agroforestry has been recognized as a viable global approach to reduce greenhouse gas emissions. And the reason for this is due to its potential in carbon sequestration. There are several agroforestry mechanisms with different carbon sequestration rates. In that aspect carbon sequestration can depend on type of climate, technology, time since land use change, and previous land use. In this regard, it is critical to understand carbon sequestration in various tree species in agroforestry technologies, as well as which agroforestry technologies offer the best value in terms of carbon sequestration. The carbon sequestration potential for any agroforestry system is estimated by the following methods:

1. Destructive method
2. Non-destructive algometric method

10.6.1 Destructive Method

The standard procedure for calculating biomass via destructive sampling is to cut down numerous sample trees and weigh their various components (e.g., branch, foliage, root, and stem). There are two methods employed for the estimation of carbon content using destructive sampling method

1. Destructive by weighing
2. Destructive with scaling

10.6.1.1 Destructive by Weighing

Carbon estimation in trees through destructive weighing methods involves measuring the biomass of the tree and converting it into an estimate of carbon content. Here is a general approach for conducting such measurements:

- Select a representative sample of trees: Choose a range of trees from the target populations that are representative of the species, age, and size distribution.
- Sample tree harvesting: Carefully select individual trees for destructive sampling. Ensure that the trees selected are healthy and not ecologically significant. Obtain necessary permissions and permits if required.
- Tree felling and sectioning: Cut down the selected trees and section them into different components, typically including the trunk, branches, and foliage.
- Weighing components: Weigh each component separately using a scale or balance with suitable precision. It is advisable to record weights in kilograms (kg) for accuracy.

- Moisture content determination: Measure and record the moisture content of each component, as this can affect the carbon content. This can be done by weighing a subsample of each component before and after drying in an oven.
- Carbon content determination: Convert the dry weight of each tree component to carbon content. The conversion factors differ for different tree components. For example, the carbon content of dry wood is usually assumed to be around 50% by weight.
- Summing carbon estimates: Sum up the carbon estimates of all the tree components to obtain the total carbon content for each tree.
- Extrapolation: Scale up the carbon estimates from the sampled trees to the entire population using appropriate statistical methods, considering the size and composition of the forest.

  Formula

$$W(f) = WW(f) \times DW(s)/WW(s)$$

  where,

- DW (f) = field dry weight in g
- WW (f) = field wet weight in g
- DW (s) = sample dry weight in g
- WW (s) = sample wet weight in g.

10.6.1.2 Destructive with Scaling

Estimating carbon content in trees through destructive sampling and scaling methods involves measuring the biomass of a tree and then converting it into carbon equivalents. Here is a step-by-step process for estimating carbon using destructive sampling and scaling:

- Select the trees: Choose a representative sample of trees from the target population. The sample size should be statistically significant to ensure accurate estimation.
- Destructive sampling: Cut down the selected trees and carefully measure the different components of the tree, including the stem, branches, leaves, and roots. Divide the tree components into sections or categories for easier measurement and analysis.
- Biomass measurement: Weigh each component of the tree using a scale or balance. It is important to separate the different components for accurate biomass determination. Measure the fresh weight of each section.
- Moisture content correction: Determine the moisture content of each tree component by collecting a subsample and drying it in an oven until it reaches a constant weight. Calculate the moisture content as a percentage of the fresh weight. Subtract the moisture content from the fresh weight to obtain the dry weight.

- Carbon content determination: Use conversion factors specific to the tree species to convert the dry weight biomass of each component into carbon equivalents. These conversion factors represent the average carbon content of different tree components.
- Scaling: Scale up the carbon content of the sample trees to estimate the carbon content of the entire population or a larger area. This involves applying appropriate statistical techniques to extrapolate the results from the sample to the population.
- Statistical analysis: Analyse the data collected from destructive sampling to estimate the mean carbon content per tree or per unit area, along with measures of uncertainty such as confidence intervals.
- Reporting: Present the estimated carbon content in a suitable format, such as tons of carbon per hectare or per individual tree, depending on the objectives of the study.

  Formula

$$V_{\mathrm{b}} = (\mathrm{SA}_1 + \mathrm{SA}_2)/2 \times L$$

where,

- V_{cc} – volume with bark in m^3
- SA_1 – sectional area of the stem lower part in m^2
- SA_2 – sectional area of the upper stem in m^2
- L – stem section length in m

It is important to note that destructive sampling involves cutting down trees, which may not be feasible or desirable in certain situations. Alternative non-destructive methods, such as allometric equations based on tree measurements (e.g., diameter, height), can also be used to estimate carbon content without harming the trees.

10.6.2 Non-destructive Algometric Method

Non-destructive carbon estimation methods in trees allow for the assessment of carbon content without the need to cut down or harm the trees. These methods rely on various measurements and equations based on tree characteristics, such as diameter, height, and biomass allocation patterns. Non-destructive methods are widely used due to their efficiency, minimal ecological impact, and the ability to estimate carbon content in a non-invasive manner. They are particularly useful for large-scale assessments of carbon stocks in forests, ecological research, and monitoring efforts.

One commonly used non-destructive method for carbon estimation is the use of allometric equations. Allometry refers to the relationship between different tree parameters and biomass or carbon content. By measuring easily obtainable tree characteristics, such as diameter at breast height (DBH) and height, allometric equations can estimate the carbon content of the tree without the need for destructive sampling. These equations are developed using statistical analysis of data collected from destructive sampling and scaling methods. They provide a reliable and efficient means of estimating carbon content across different tree species and ecosystems.

Non-destructive methods can also utilize remote sensing techniques, such as LiDAR (Light Detection and Ranging) or aerial/satellite imagery, to estimate carbon content in trees. LiDAR uses laser pulses to measure the three-dimensional structure of the forest canopy, allowing for the estimation of tree height, canopy density, and aboveground biomass. Aerial or satellite imagery provides information about the spatial distribution and density of vegetation, which can be used to infer carbon content through statistical models and algorithms.

The advantage of non-destructive methods is their ability to estimate carbon content in a non-invasive manner, reducing the ecological impact on forests and preserving the integrity of the trees. These methods also allow for rapid and efficient carbon assessments across large areas, making them valuable for monitoring changes in carbon stocks over time and space. However, it is important to note that non-destructive methods rely on statistical models and equations that are developed based on specific tree species and ecosystems, and their accuracy may vary depending on the context and conditions in which they are applied.

10.6.2.1 Calculation of Above Ground Biomass (AGB)

Above ground biomass (AGB) is defined as "the aboveground standing dry mass of live or dead matter from tree or shrub (woody) life forms, expressed as a mass per unit area", typically Mg ha^{-1}.

The biometric values measured using tree biometry was utilized for calculating the above ground biomass. The volume arrived and the density measured was used to calculate the biomass content of the wood in metric tonnes per hectare as detailed below.

Above ground biomass of the plantation is calculated by using the following formula:

$$\text{Above ground biomass (AGB)} = \text{volume}\left(\text{m}^3/\text{tree}\right) \times \text{wood density}\left(\text{g/cm}^3\right)$$

The biomass expansion factor (BEF) is a ratio that quantifies the increase in aboveground biomass of a tree or plant as it grows from one stage or size to another:

$$\text{BEF} = (\text{total volume of trees/ha})/(\text{merchantable volume of trees/ha})$$

For calculating the above ground biomass, BEF was used to convert stem biomass to above ground biomass.

10.6.2.2 Calculation of Below Ground Biomass (BGB)

Belowground biomass in trees refers to the total mass of plant material present below the ground surface, including the roots and associated structures. It encompasses the root system, which plays a crucial role in nutrient and water uptake, anchoring the tree, and providing structural support.

BGB is calculated as per the standard procedure suggested by Pandya et al. (2013):

$$\text{Below ground biomass (BGB)} = 0.26 \times \text{AGB(ton)}$$

10.6.2.3 Estimation of Total Biomass (TB)

Total biomass comprises of both above ground and below ground biomass of individual trees in a plantation. Therefore by adding both above ground and below ground biomass of the plantation the total biomass was arrived.

Total biomass was estimated by using the following formula:

$$\text{Total biomass(TB)} = \text{Above ground biomass(AGB)} + \text{below ground biomass(BGB)}$$

10.6.2.4 Estimation of Weight of Carbon (C)

The average carbon content in trees is generally considered as 50% of the tree's total biomass. Therefore, carbon content in trees was calculated by multiplying the tree biomass by 50%.

Carbon content is estimated as follows:

$$\text{Carbon content} = \text{biomass} \times 0.50$$

10.6.2.5 Estimation of Total Quantity of Carbon Dioxide

Carbon dioxide equivalent is the ratio of the total weight of one molecule of carbon (44 g) to oxygen (12 g). Therefore, weight of carbon dioxide sequestered in the tree was calculated by multiplying the carbon content of the tree by 3.67:

Table 10.1 Estimated biomass of different agroforestry systems in different agroclimatic regions

Agroclimatic regions/states	Agroforestry systems	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	TB (Mg ha^{-1})
Northern Himalayas (Himachal Pradesh, Jammu and Kashmir, Uttarakhand)	Agrisilviculture	54.93	14.87	64.67
	Agrihorticulture	40.00	13.23	57.56
	Silvipasture	43.85	19.47	87.52
Indo-Gangetic region (Punjab, Haryana, Uttar Pradesh, and Bihar)	Agrisilviculture	33.82	3.76	23.85
	Silvipasture	38.41	9.32	50.72
Eastern and Northeastern India (West Bengal, Odisha, Assam, Sikkim, Meghalaya, Manipur)	Agrihorticulture	5.57	3.63	6.41
	Home garden	52.54	34.69	121.67
	Plantation crop-based agroforestry	40.46	13.36	87.16
	Boundary plantation	16.96	2.52	19.48
	Block plantation	186.20	25.33	220.20
Western and central India (Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh)	Agrisilviculture	11.91	–	33.63
	Agrihorticulture	81.05	24.60	78.95
	Block plantation	79.24	21.84	120.09
Southern India (Karnataka, Andhra Pradesh, Tamil Nadu, and Kerala)	Agrisilviculture	37.37	11.87	35.96
	Plantation crop-based agroforestry	174.96	41.29	232.38
	Block plantation	170.9	69.49	239.8
	Coffee plantation	221.5	59.38	279.2

Source: Panwar et al., 2022

$$\text{Total CO}_2 \text{ equivalent} = \text{carbon content} \times 3.67$$

The biomass estimated under different agroforestry systems in different agroclimatic regions is given Table 10.1.

In an agricultural environment with larger net increases in carbon stocks, home gardens and block plantation agroforestry systems were observed to have higher carbon contents than other land uses. Agroforestry systems are now being adopted by developing nations as REDD+ strategic options to achieve climate change mitigation because they are financially viable, prevent deforestation, improve soil productivity, permanently sequester carbon in agricultural landscapes, and support growers.

As each agroforestry system differs based on site factors, tree species, the density and productivity of shade trees, as well as their longevity and subsequent use in processing systems, the production of litter, the rate of decomposition, and its incorporation in the soil matrix as soil carbon, nutrient cycling, and soil respiration, uncertainties in estimates of carbon stocks should be expected. Additionally, each system's management strategy plays a crucial role in determining how much carbon is added to and removed from each system. The system's resilience, or its capacity to tolerate climatic or other shocks and, so, retain carbon despite such disturbances may be more significant over the long run. The complexity and variety of the agroforestry management unit, as well as the characteristics of the landscape matrix in which agroforestry systems are located, influences all resilient mechanism in agroforestry systems. A functional landscape system must be viewed as an integrated landscape that includes flows of materials and services across system boundaries, from agroforests to natural forest patches, and more intensive land uses, such as plantations and annual crops. This is true from the perspectives of resilience and carbon storage. A detailed knowledge of the mechanisms and scales governing the allocation and partitioning of biomass in agroforestry plantings is necessary. Unfortunately, the exact nature of this driving force and its size are yet unknown. Due to a lack of data on changes in land use and land cover, there are also sizable uncertainties in the estimation of carbon fluxes into and out of systems.

10.7 Conclusion

Planting multipurpose tree species in non-forest land uses promotes biodiversity and carbon sequestration at the same time. When crops fail, trees provide an extra source of income. They also offer financial benefits from the non-carbon advantages. In order to produce valuable wood that is economically advantageous as well as wood for use as fuelwood and for construction purposes, it is useful to plant trees using a blend of fast- and slow-growing species. Agroforestry systems exhibit high soil and live biomass carbon accumulation, indicating their potential to provide the environmental service of carbon sequestration. Additionally, by preserving soil and preventing the burning of fuelwood derived from forests, agroforestry systems can aid in lowering CO_2 emissions. Agroforestry systems have the capacity to gather and store carbon, and they may develop into a technical alternative for reducing tropical deforestation rates while simultaneously providing rural populations with a wide range of goods and services.

Important knowledge gaps around C sequestration in AF include the following: (1) quantitative evaluation of carbon inputs and stocks in various AF systems, with special attention to deep soil carbon and its dependence on tree species and age; (2) optimization of the area allotted to trees and crops within each AF system to achieve maximum carbon sequestration, increase yield, maximize ecosystem services, and improve environmental conditions; (3) development of new remote sensing techniques to distinguish AF from the background of forests, plantations, and other agricultural areas.

It is important to note that the effectiveness of carbon sequestration in agroforestry systems can vary depending on factors such as site-specific conditions, management practices, and the longevity of the system. Additionally, carbon sequestration in trees and soil should be considered in the context of overall emissions reduction strategies and sustainable land management practices.

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