Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques

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Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques

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Definitions

Forest carbon stock	It is the amount of carbon sequestered from the atmosphere and stored in a forest ecosystem, mainly within living biomass and soil and, to a lesser extent, in deadwood and litter.
Forest carbon flux	It is the transfer of carbon (mass) to and from the per-unit forest area per unit time. Carbon efflux is the transfer of carbon out of the forest to another pool, and the influx is the transfer of carbon from other pools to the forest.
Forest carbon cycle	It is the constant movement of carbon between the atmosphere and forests. The biological part of this cycle involves carbon sequestration by plants from the atmosphere via photosynthesis and loss of carbon through respiration and decay.
Forest carbon balance	It is a dynamic process that can be calculated as the total carbon uptake by a forest minus the net carbon loss from the forest. The forest carbon balance is highly dependent on disturbances and environmental constraints.
Biomass	It is the mass of living organisms – any organic materials including plants, animals, fungi, and bacteria – in a forest both in above- and belowground at a given time. About 80% of the total biomass on Earth is comprised of plants (Bar-On et al. 2018). Organic materials consisting of or derived from dead plants and animals are called necromass.

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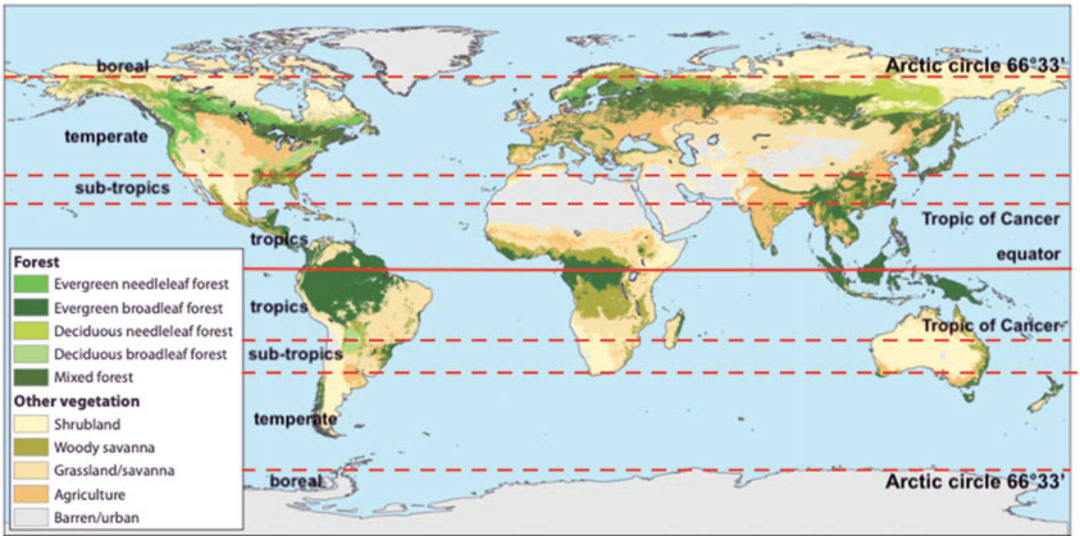
Soil carbon It is the amount of carbon stored in soil. It can be in two forms: organic and inorganic carbon. Organic carbon is the dominant form of soil carbon that is available in soil organic matters. Inorganic carbon, on the other hand, is the mineral form of carbon that is originated from Earth's parent materials primarily through weathering.

Introduction

Globally, forests cover more than 4 billion hectares, nearly 30% of Earth's land surface (FAO 2016a). Forests also account for 75% of terrestrial gross primary production (Beer et al. 2010) and contain more carbon in biomass and soils than is stored in the atmosphere (Pan et al. 2013). Forests also home to most of the species on Earth and provide valuable ecosystem goods and services, including food, fuel, timber, medicine, fiber, clean water, aesthetic and cultural values, and climate regulation primarily through carbon sequestration and storage (Landell-Mills and Porras 2002). Forests also are critical to about 1.6 billion people worldwide as a means of their livelihood and income (Chao 2012).

Forests are unevenly distributed across the globe (Fig. 1). Thirty-one percent of the total forest area is in Asia (including Russia), followed by 21% in South America, 16% in Africa, 19% in North and Central America, 9% in Europe, and 4% in Oceania (FAO 2016a). Forests sequester and store more carbon (C) than any other terrestrial ecosystem on Earth (Pan et al. 2011; Gibbs et al. 2007). Forest carbon is stored in five different pools: (i) aboveground biomass; (ii) belowground biomass; (iii) litter; (iv) deadwood/woody debris; and (v) soil (Mukul et al. 2016a). In forests, plants take up carbon dioxide (CO_2) and release oxygen (O_2) during photosynthesis, which transfers carbon to their stems, roots, and leaves as they grow (Kondo et al. 2018). When leaves fall and decompose or when plants die, the carbon that is stored in plants is released and transferred back to the atmosphere or the soil (Kayler et al. 2017).

Forests are also considered a major source of global anthropogenic carbon emissions to the atmosphere, the second largest after fossil fuel combustion, primarily through deforestation and forest degradation (van der Werf et al. 2009; Malhi and Grace 2000). Clearing forests destroys globally important carbon sinks that are currently sequestering stocks, emissions, and carbon dioxide from the atmosphere and are critical to future



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 1 Global forest cover map based on MODIS satellite data at 500 m resolution climate stabilization (Pugh et al. 2019). The most recent consolidated global forest cover data show a net loss of 129 million hectares of forest between 1990 and 2015 accounted for about 12–20% of global anthropogenic greenhouse gas (GHG) emissions (FAO 2016b; Saatchi et al. 2013). In tropical regions alone, deforestation and forest degradation are estimated to have released 1–2 billion tonnes of carbon per year during the 1990s, roughly 15–25% of annual global greenhouse gas emissions (Malhi and Grace 2000). Large uncertainties in emission estimates, however, persist from inadequate data on the carbon density of forests and the regional rates of deforestation (Baccini et al. 2017).

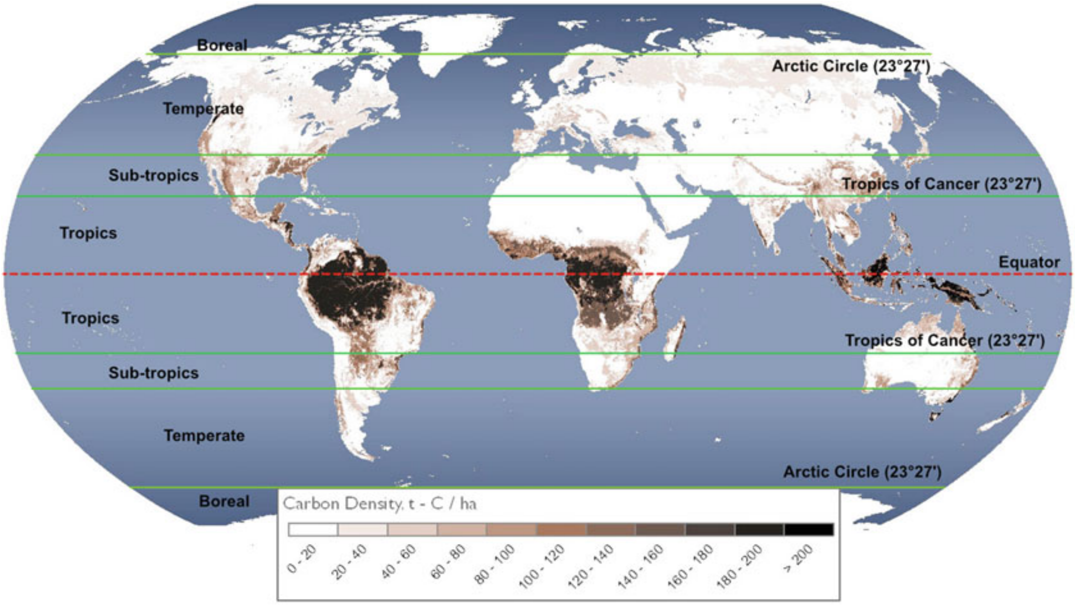
Forests can reduce greenhouse gases from the atmosphere in two ways: (i) by avoiding emissions from deforestation and degradation, and (ii) by letting them grow to sequester more carbon from the atmosphere (Houghton 2013). Since forests play a crucial role in the global carbon cycle, increasing emphasis is now given on forestry activities, including forest and landscape restoration as an effective tool for global climate change mitigation as well as to offset carbon emission (Mitchard 2018; Saatchi et al. 2013). Net emissions from forests occur mostly in the southern hemisphere, in tropical developing countries, while boreal forests act as carbon sinks (FAO 2016b). With the global carbon credits valued at over USD100 billion/year, there is now an emerging global market for forest carbon under different schemes, such as Clean Development Mechanism (CDM), payments for ecosystem services (PES), and reducing emissions from deforestation and forest degradation (REDD+) (Mukul et al. 2016b; Petrokofsky et al. 2011).

Distribution of Carbon Across Global Forests

With the advancement of global observation systems and analysis techniques, knowledge of the biomass and carbon distribution in the world's forests is advancing rapidly (Pan et al. 2013). New satellite and airborne observation facilities, improved land-based inventory methods, and ecosystem models are now providing forest maps with unprecedented resolution (Chave et al. 2019; Hansen et al. 2013). Three-dimensional remote sensing allows researchers to map the world's forests and estimate forest biomass and carbon stocks in greater precision (Saatchi et al. 2013). Figure 2 below shows the above- and belowground living carbon distribution in the world's forests. Tropical forests, including both regrowth and intact forests, constitute the largest component of the terrestrial carbon sink, representing nearly 45% of the total carbon stored in terrestrial ecosystems (Table 1; Anderson-Teixeira et al. 2016). Interestingly, world's highest known biomass carbon density (1867 t C/ha) is recorded from temperate moist Eucalyptus forests in Australia (Keith et al. 2009).

There is, however, a difference between the carbon carrying capacity of a forest and its current carbon stock. The carbon carrying capacity is the mass of carbon a forest ecosystem can store under prevailing environmental conditions. The difference between carbon carrying capacity and carbon stock allows an estimate of the carbon sequestration potential of a forest ecosystem (Keith et al. 2009). Tropical forests contain approximately as much carbon in living plant biomass as boreal forests contain underground, indicating a large difference in carbon dynamics between major biomes and ecosystems (Price et al. 2013; Fig. 3). They also play a crucial role in global carbon cycle by acting both as a source and sink of carbon (Pan et al. 2011). The Amazon forest, for instance, alone releases an estimated 1.3 Pg C/year due to natural disturbances, which is higher than the carbon dioxide compensated by sequestration through tree growth in forests in the same region (Espırito-Santo et al. 2014). In recent years, forest regrowth on abandoned agricultural land in the tropical region, however, created a sink of 1.4–1.7 Pg C/year – accounting approximately 20% of annual fossil fuel emissions (Lewis et al. 2015).

Soils in equilibrium with forest ecosystems also have high carbon density (Table 1; Köchy et al. 2015). Soil organic carbon (SOC) stored and



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 2 Global map of biomass carbon distribution across different forest biomes and ecosystems. (Source: https://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html)

Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Table 1 Carbon stock in world's forests

Biome/ecosystem	Area (M ha)	Terrestrial carbon stock (Pg C)[a]			Carbon density (Mg C/ha)[b]	
		Plants	Soil	Total	Plants	Soil
Tropical forests	1.76	340	213	553	157	122
Temperate forests	1.04	139	153	292	96	122
Boreal forests	1.37	57	338	395	53	296
Total	4.17	536	704	1240	–	–

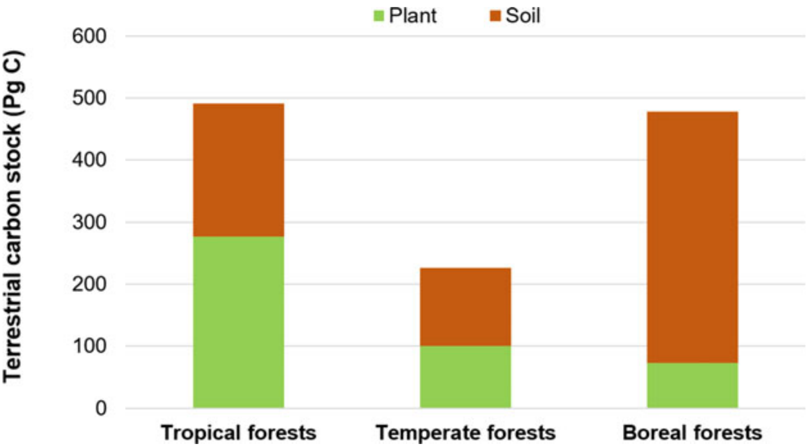
Source: Prentice et al. 2001
[a] Petagram (Pg), equivalent to 10^{15} g or 1 billion tonnes
[b] Megagram (Mg), equivalent to 10^{6} g or 1 t

cycled under forests is a significant portion of the global total carbon stock but remains poorly understood due to its complexity in mechanisms of storage and inaccessibility at depths (Lal 2005). There is also inconsistency within the biomes and forest ecosystems in their capacity to carbon storage and sequestration above- and belowground (Fig. 4). Tropical mangroves, for example, have higher carbon density than in tropical rainforests, where they are also highly regarded for their capacity to sequester carbon faster (~40×) than any other terrestrial ecosystem (Donato et al. 2011).

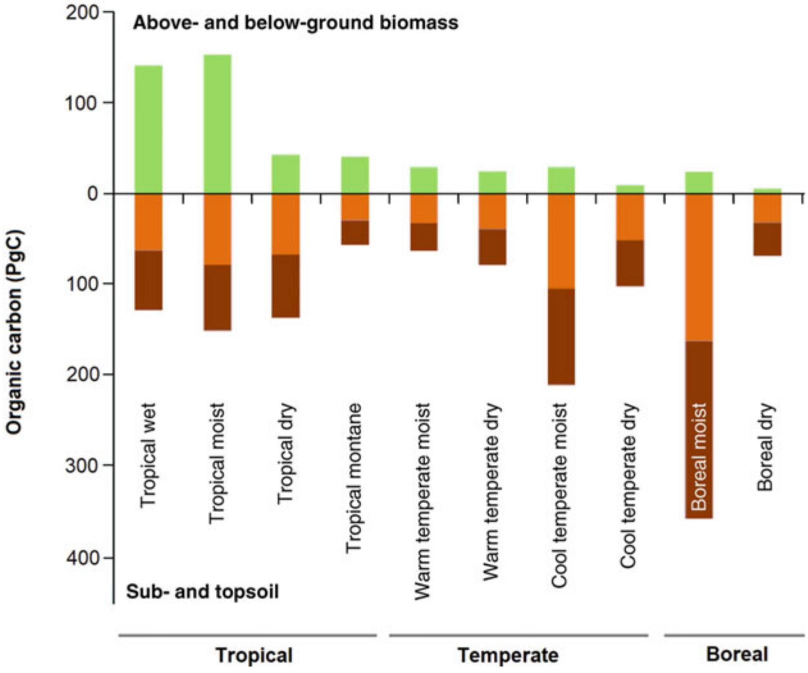
Biogeochemical Cycles Associated with Forest Carbon Stock and Fluxes

In the global carbon cycle, the amount of carbon in the environment always remains the same, although there is a constant movement of carbon between the forest and other ecosystems and atmosphere (Prentice et al. 2001). The two main

Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 3 Global forest carbon stock by major biomes



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 4 Carbon storage capacity of different forest biomes and ecosystems. (Source: Modified after Scharlemann et al. (2014))

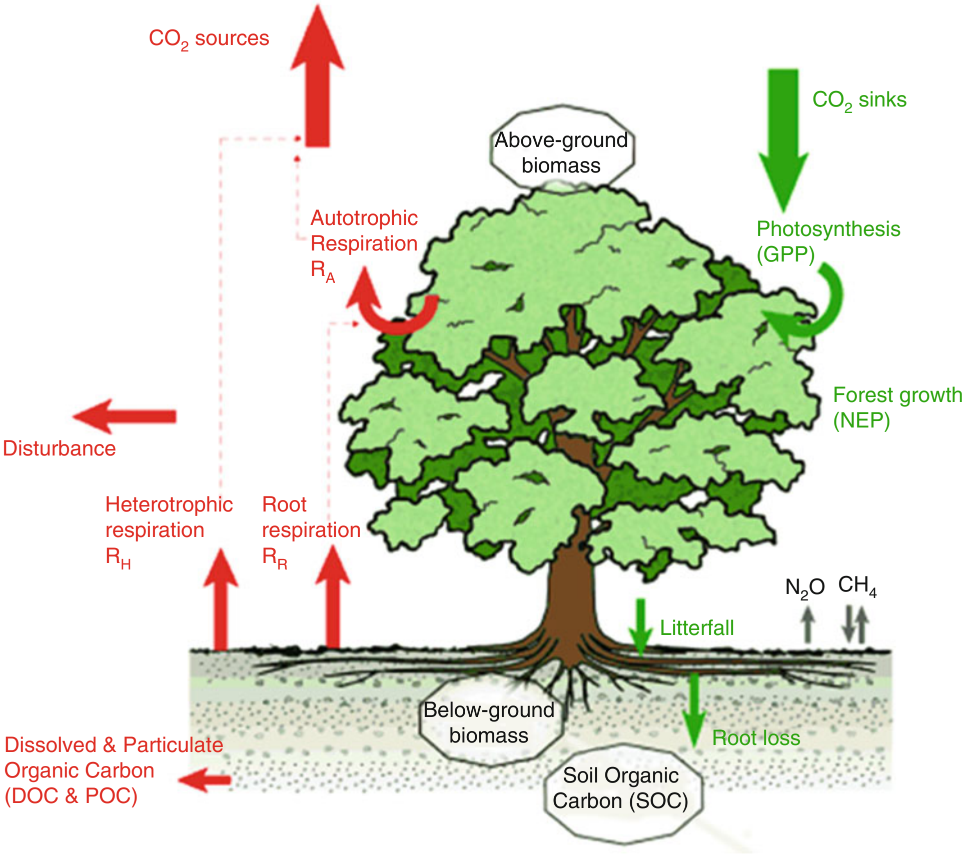


physiological and chemical processes that control the forest carbon stock and flux are photosynthesis and respiration. Photosynthesis (Eq. 1) is responsible for carbon assimilation, resulting in carbon influx. Respiration (Eq. 2), on the other hand, is responsible for the release of carbon to the atmosphere, a major pathway of carbon efflux (Schulze et al. 2019). Photosynthesis primarily occurs during the daylight in the mesophyll layer of leaves and stems where chlorophyll is present and creates carbohydrates ($C_6H_{12}O_6$) necessary for plant growth and reproduction. Respiration is the oxidation of carbohydrates that produces energy and releases carbon dioxide; it can be autotrophic (R_a, occurs in plants) or heterotrophic (R_h, occurs in microbes).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad (1)$$

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O + \text{energy} \qquad (2)$$

In forest ecosystems, most carbon is stored in intermediate pools consisting of wood, litter, or partially decomposed organic matter that range in their degree of chemical reduction (Schulze et al.

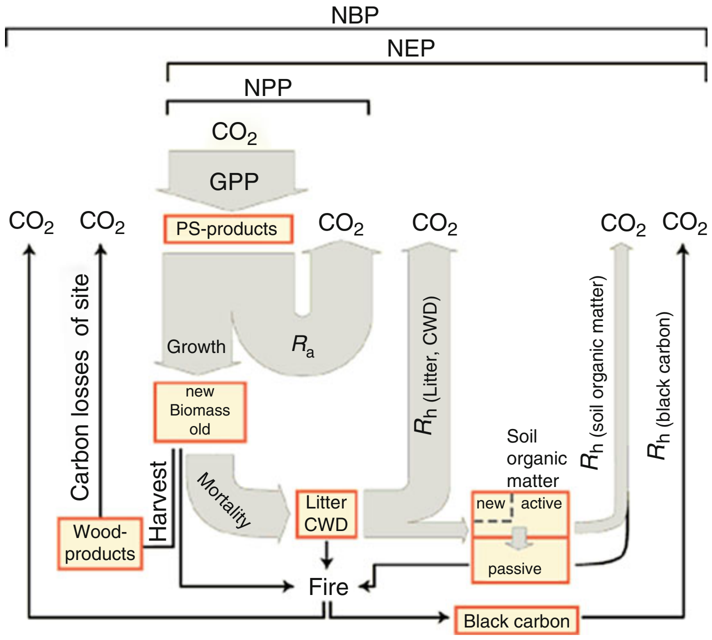


Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 5 Carbon cycle at the plot level. The size of each arrow indicates the relative rate of fluxes; red arrows indicate effluxes, and green arrows indicate influxes

2000). The three major carbon "stock" or "pools" in forest ecosystems are: (i) aboveground biomass; (ii) belowground biomass; and (iii) soil organic carbon (Fig. 5). The rate of carbon sequestration and the magnitude and quality of carbon stock, however, depend on the complex interaction between climate, soils, tree species, and management, as well as the chemical composition of the forest floor as determined by factors such as dominant tree species, soil type, and litter (Steidinger et al. 2019; Lal 2005).

The biological part of the carbon cycle involves carbon sequestration by plants from the atmosphere via photosynthesis and losses of carbon through respiration and decay. The nonbiological part of the carbon cycle includes geological processes, such as volcanic eruption and weathering of parent material through which soil forms. The nonbiological part of the cycle is not as pronounced as the biological part of the cycle, though it may enhance carbon stock in the forest (Battin et al. 2009). Leaching and runoff are also the nonbiological parts of the carbon cycle through which carbon is lost from the forest, particularly from the soil. Forest fire, anthropogenic and climate-driven disturbances, and insect and pest attacks can also release forest carbon to the atmosphere (Schulze et al. 2019).

The significant fluxes in the forest carbon cycle are: (i) gross primary production (GPP, carbon assimilation through photosynthesis); (ii) net primary production (NPP, the fraction of GPP resulting in growth when plant respiration is taken into account); (iii) net ecosystem production



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, **Fig. 6** Schematic representation of the forest carbon cycle, where: PS, photosynthesis; CWD, coarse woody debris; arrows indicate fluxes; boxes indicate pools; the size of each arrow indicates the relative rate of fluxes. (Source: Schulze et al. 2000)

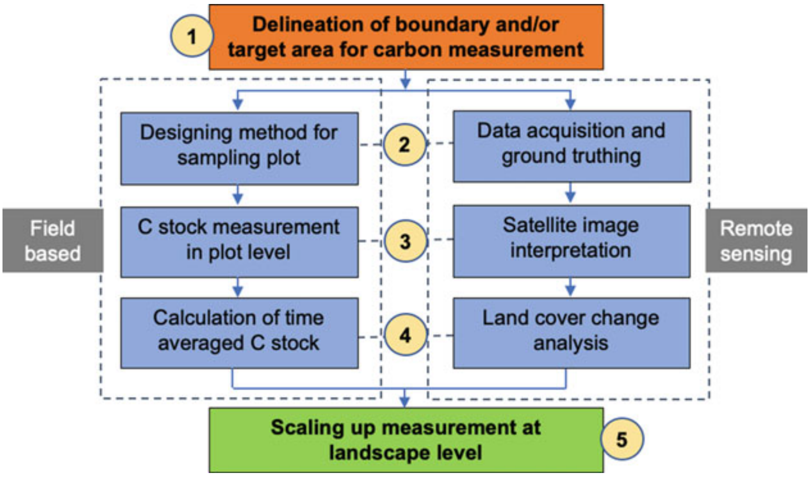
(NEP, taking the annual budget of heterotrophic respiration of soil organisms into account); and (iv) net biome production (NBP, taking non-respiratory losses such as fire and harvest into account) (Fig. 6; Schulze et al. 2000). In a forest stand, NPP is equivalent to gross annual increment (GAI), NEP is equivalent to the net annual increment (NAI), and NBP is equivalent to the net change in standing volume. Global total GPP is estimated to be about 120 Gt C/year, where NPP is about half of this GPP (Hairiah et al. 2011). The NBP can be measured only at the decadal or longer time frame, as the disturbances that are to be considered for the measurement of NBP do not occur every year. In the exchange of carbon dioxide between terrestrial vegetation and the atmosphere, with net accumulation followed by carbon release, the net balance between sequestration and release shifts from minute-to-minute to a day-night pattern, across a seasonal cycle of the dominance of growth and decomposition (Schulze et al. 2019; Battin et al. 2009).

Measuring Forest Carbon Stock and Fluxes

The recent development of global carbon market and trading has led to an increasing interest in accurate estimates of forest carbon stock and fluxes (Roxburgh et al. 2015). Established methods for measuring carbon in forests exist and can be based on both field measurements and remote sensing techniques (Table 2). Estimates of biomass are needed for tracking changes in forest carbon, which can be the outcome of decadal patterns of a build-up of woody vegetation or century-scale build-up of soil carbon (Martin and Thomas 2011; Battin et al. 2009). The timescale selected, therefore, is critical for the measurement and interpretation of carbon stock and fluxes in a forest where carbon flux regularly influences the stock of carbon in that forest. The spatial consideration is another important aspect while measuring carbon stock in the forest. The four different levels of measurements based on spatial coverage are: (i) tree level (assessing carbon stock of an individual tree); (ii) plot level (assessing carbon stock in a plot representing a particular land-use or forest ecosystem); (iii) land-use system (calculating time-averaged carbon

Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Table 2 Examples of techniques available for carbon stock estimation in forest biomass

Category	Methods	Data used	Characteristics	Reference(s)
Field measurement methods	Conversion from volume to biomass expansion factor	Volume from sample trees or stands	Individual trees or forest stands	Wang et al. 2007; Woodbury et al. 2007; Fang et al. 2001
	Allometric equations	Sample trees	Individual trees	Qie et al. 2017; Mukul et al. 2016a; Sullivan et al. 2016; Phillips et al. 1998
Remote sensing methods	Methods based on fine to coarse spatial resolution data	Aerial photographs, IKONOS, Landsat, SPOT, AVHRR	Pixel level	Muukkonen and Heiskanen 2007; Lu and Batistella 2005; Dong et al. 2003; Laporte et al. 1995
	Methods based on radar data	Radar	Pixel level	Levesque and King 2003; Sun et al. 2002
	Methods based on LiDAR data	LiDAR (Light Detection and Ranging)	Pixel level	Hughes et al. 2018; Drake et al. 2003



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 7 Steps in carbon stock measurement in forest

stock of a land-use or forest ecosystem from plots of various ages within the same land-use system); and (iv) landscape level (extrapolating the time-averaged carbon stock of all land-use systems to the whole landscape by integrating them with the area of land-use/cover and change). Figure 7 presents the basic steps for carbon stock measurement using field measurement and remote sensing techniques at the forest and landscape level.

Remote sensing is a novel revolutionary technology for forest carbon estimation, with the unprecedented capability of spatial, temporal, and spectral resolution and potential coverage of remote forest areas (Hansen et al. 2013; Lu 2006). Their reliability, however, largely depends on field validation and ground data (Chave et al. 2019). They can be divided into passive sensing (e.g., satellite images, aerial photographs that are characterized by reflected light) and active sensing (radar, LiDAR that emit and receive microwaves or light, respectively).

Long-term forest inventories remain central for the estimation of carbon stock and fluxes in the forest (Chave et al. 2005; Phillips et al. 1998).

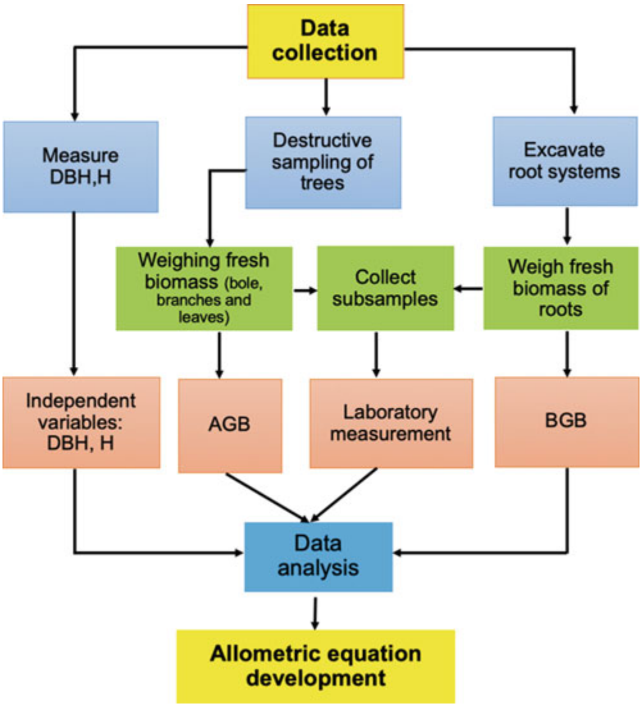
Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Table 3 Field measurements and methods for estimating forest carbon stock in major pools

Carbon pool	Measurement	Method
Aboveground biomass (live)	Aboveground live tree biomass	Mostly non-destructive, using allometric equation
	Understory/herbaceous	Destructive sampling
Aboveground biomass (dead)	Dead standing trees	Non-destructive, using equation for volume of cylinder (or allometric equation)
	Dead felled trees	
	Stump (trunk) remains on forest	
	Litter	Destructive sampling
Belowground biomass	Coarse roots	Non-destructive, using default value
	Fine roots	Destructive sampling followed by laboratory analysis
	Coarse woody debris	Destructive sampling
Soil organic carbon	Soil organic matter	Destructive sampling followed by laboratory analysis

Tree biomass in the forest can be estimated using both destructive and non-destructive method. Litter and woody debris are directly measured as dry weight, while soil organic carbon stocks are estimated from samples taken at various depths (Table 3). Allometric equations are widely used for the estimation of tree biomass in the forest, which relates biomass of individual trees to easily obtainable non-destructive measurements, such as diameter and height (Roxburgh et al. 2015). Allometric equations, however, based on destructive sampling undertaken at a limited scale in permanent sample plots laid out in representative forest ecosystems and biomes across the world (Fig. 8; Chave et al. 2005; Brown 1997). Figure 8 illustrates the steps involved in the development of allometric regression equations using a destructive sampling approach, and Table 4 lists some widely used allometric equations developed for different forest biomes and ecosystems.

Accurate knowledge of carbon content in biomass is essential for quantifying forest carbon stocks. Carbon content usually assumed to be 50% by biomass (Martin and Thomas 2011). Tree biomass differs among different plant parts, with the majority of the biomass found in logs of mature trees (Fig. 9). Species-specific wood density is a major prerequisite for estimating biomass at tree level, which can be derived from direct measurement or secondary sources including, the World Agroforestry Centre Wood Density Database (available at http://db.worldagroforestry.org/wd). The belowground coarse root biomass usually measured using the default value or conversion factor (Cairns et al. 1997). Organic carbon in soil (SOC) is measured in the laboratory using Walkley-Black or Heanes method (see Mukul 2016 and Saner et al. 2012 for details).

Unlike biomass estimation, measurements of carbon flux during photosynthesis, autotrophic respiration (in plants), and heterotrophic respiration (in soil microbes) usually require sophisticated instruments (e.g., IRGA-based portable photosynthesis system, cavity-enhanced absorption gas analyzer). Eddy covariance is the most widely used technique to measure the exchange of carbon dioxide (CO_2 flux) at a landscape scale. This method samples three-dimensional wind speed and carbon dioxide concentration over a forest canopy at a high frequency (10–20 Hz) and determines the carbon dioxide flux by the covariance of the vertical wind velocity and concentration of carbon dioxide (Bosveld and Beljaars 2001). This method, however, is computationally intensive, still limited by systematic biases, and has limited observation sites around the world. Inverse methods are another family of techniques usually used at continental or global scales. This method calculates the total sources and sinks, including both anthropogenic and natural, using available atmospheric carbon dioxide



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 8 Flowchart showing steps of allometric equation development using destructive sampling, where: AGB, aboveground tree biomass; BGB, belowground tree biomass; DBH, diameter at breast height; H, tree height

concentration data and transportation models (Ashton et al. 2012).

Drivers of Changes in Global Forest Carbon Stock and Fluxes

Various natural and human-induced disturbances exert profound impacts on the global forest carbon cycle (Houghton 2013). More than 60% of the world's forest area is recovering from some past disturbances, and 3% of the world's forests are disturbed annually by logging, fire, pests, or weather (Pan et al. 2013). The drivers of changes in forest carbon stock and flux could broadly be categorized into the following:

Biotic Drivers of Change

The biotic drivers of carbon stock and fluxes in the forest are photosynthesis, autotrophic reparation, heterotrophic respiration, and decomposition. If the carbon uptake by photosynthesis exceeds the carbon efflux by respiration, intact forests are thought to remain as a carbon sink (Lewis et al. 2006). About one-fifth of the carbon dioxide currently produced globally by land conversion and industrial emissions is absorbed by the tropical forest regions through increased productivity (Houghton 2013). However, the increase in productivity cannot continue indefinitely. If the increased atmospheric level of carbon dioxide is the cause of this increased productivity, trees will eventually reach a saturation point and become limited by some other resources (Kondo et al. 2018). Many studies also predict soil drying as a major cause of reduced capacity of the forest to take up carbon due to lack of water (Lewis et al. 2006). Water stress in forest is important because it affects stomatal feedback in the plant, which could affect photosynthesis. As tropical forest soils become drier, litter decomposition and release of carbon dioxide from soil may slow in response to water deficiency (Schulze et al. 2000). Moisture or oxygen limitation inhibits aerobic respiration on the forest floor. When oxygen stress limits aerobic respiration, microbes and fungi responsible for decomposition rely on anaerobic respiration – a less efficient method of respiration in which methane is often a byproduct (Steidinger et al. 2019). The activity and outbreak of insects

Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Table 4 Example allometric equations for biomass estimation in different biomes

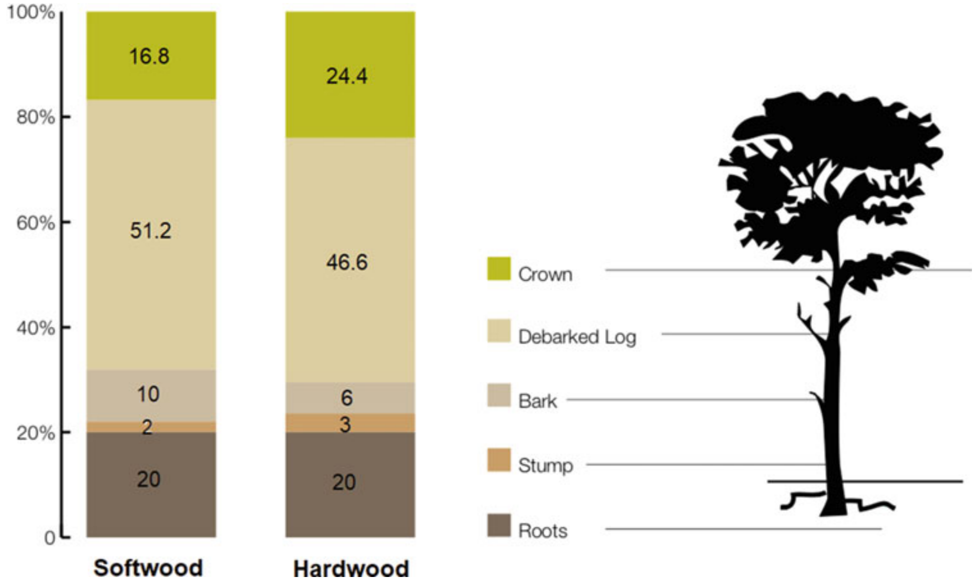
Biome/ ecosystem	Species group/other classification	Allometric equation[a]	Reference
Tropical forests	General	$AGB = 0.0673 \times (\rho DBH^2 H)^{0.976}$	Chave et al. 2014
	Dry tropics (rainfall <1500 mm/year)	$AGB = 0.112(rDBH^2 H)^{0.916}$	Chave et al. 2005
		$AGB = \rho \times \exp.(-0.667 + 1.784 \ln(DBH) + 0.207 (\ln(DBH))^2 - 0.0281 (\ln(DBH))^3)$	Chave et al. 2005
		$AGB = 10(-0.535 + \log_{10} BA)$	Brown 1997
	Humid tropics (rainfall 1500–4000 mm/year)	$AGB = 0.0509 \times \rho DBH^2 H$	Chave et al. 2005
		$AGB = \rho \times \exp.(-1.499 + 2.148 \ln(DBH) + 0.207(\ln(DBH))^2 - 0.0281 (\ln(DBH))^3)$	Chave et al. 2005
		$AGB = \exp.(-2.289 + 2.649 \times \ln DBH - 0.021 \times \ln DBH^2)$	Brown 1997
	Wet tropics (rainfall >4000 mm/year)	$AGB = 0.0776 \times (\rho DBH^2 H)^{0.94}$	Chave et al. 2005
		$AGB = \rho \times \exp.(-1.239 + 1.980 \ln(DBH) + 0.207 (\ln(DBH))^2 - 0.0281 (\ln(DBH))^3)$	Chave et al. 2005
		$AGB = 21.297 - 6.953 \times DBH + 0.740 \times DBH^2$	Brown 1997
Temperate forests	Hardwood (general)	$AGB = 0.5 + ((25{,}000 \times DBH^{2.5})/(DBH^{2.5} + 246{,}872))$	Schroeder et al. 1997
	Hardwood (general)	$AGB = \exp.(-2.2094 + 2.3867 \times \ln DBH)$	Jenkins et al. 2003
	Softwood (cedar/larch)	$AGB = \exp.(-2.0336 + 2.2592 \times \ln DBH)$	Jenkins et al. 2003
	Softwood (Douglas fir)	$AGB = \exp.(-2.2304 + 2.4435 \times \ln DBH)$	Jenkins et al. 2003
	Softwood (pine)	$AGB = \exp.(-2.5356 + 2.4349 \times \ln DBH)$	Jenkins et al. 2003

[a] Where: AGB, aboveground tree biomass, kg/tree; DBH, diameter at breast height, cm; H, tree height, m; BA, basal area, m^2; r, wood density, g/cm^3; ρ, wood specific gravity, Mg/m^3

and pests in forest stands also influence the release of carbon dioxide and methane into the atmosphere (Stephenson and van Mantgem 2005).

Anthropogenic and Abiotic Drivers of Change

Anthropogenic disturbances constitute the major disturbances responsible for forest carbon loss, particularly in the tropics (Baccini et al. 2017). In large-scale disturbances, such as deforestation and forest degradation, a considerable amount of carbon is lost from the forest (Houghton 2013). Deforestation and forest degradation in tropics are estimated to have released 1–2 Pg C/year during the 1990s, roughly 15–25% of global annual greenhouse gas emissions. Land-use conversion to non-forest uses, like agriculture and urban development, also releases carbon to the atmosphere, further altering the carbon cycle and fluxes in the forest (Foley et al. 2005). Forest regrowth via natural regeneration, afforestation, and reforestation programs, however, positively affects carbon budget in the forest (Pugh et al. 2019). Forest management and operations, such as logging, on the other hand, reduce carbon stored in woody biomass. Forest fire, natural or managed, is also an important perturbation that affects carbon storage in biomass and soil in addition to their impacts on the composition and age structure of forest (Mukul and Herbohn 2016). Defaunation or reduction of wildlife due to hunting and other human activities also has long-term impacts on the carbon storage in a forest, as wildlife is the



Forest Carbon Stock and Fluxes: Distribution, Biogeochemical Cycles, and Measurement Techniques, Fig. 9 The relative contribution of different plant parts in total tree biomass

primary agent for seed dispersal and pollination, which is vital for forest regeneration and productivity (Bello et al. 2015). Tree mortality is a natural phenomenon and abiotic drivers of forest carbon change. When trees die, they decompose and release carbon dioxide and nutrients to the soil and atmosphere. Nutrients may be taken up quickly by other plants, stored in the soil for some time, or leached from the system due to rain (Schulze et al. 2000).

Climate Change Impacts

Atmospheric carbon dioxide concentration today is higher than at any point in at least the past 800,000 years (Blunden and Arndt 2019). Increased carbon dioxide concentration in the atmosphere may benefit plant growth as it is a major constraint on photosynthetic efficiency (Schulze et al. 2000). However, this benefit is transient, minimal, and limited to certain biomes (Lo et al. 2019). Changing climate regimes will alter the distribution of biomes and shift in ecotones in the long run (Ashton et al. 2012). Boreal forests, for example, may decrease by 37% if there is a doubling of atmospheric carbon dioxide concentration with significant implications in the global carbon cycle (Emanuel et al. 1985). Moreover, the likely shift of boreal forests into the tundra could greatly increase fuel loads, bringing fire into a system where it is not common (Scheffera et al. 2012). Such transformation, however, will not be rapid; instead, the existing community will degrade at a faster rate than new vegetation types can invade, causing a substantial loss in the global forest carbon stock (Schulze et al. 2019). Changes in the snow cover in boreal forests due to global warming may expose permafrost (soil remaining frozen for long time), which currently holds a large pool of carbon (Kayler et al. 2017). Climate change may, however, stimulate forest growth by increased nitrogen deposition in soil, which may partially compensate for the release of carbon from the soil due to global warming (Schulze et al. 2019).

The seasonality pattern and length of the growing season likely be influenced by climate change, which may enhance primary productivity (and respiration) chiefly in the temperate forest zones (Stephenson and van Mantgem 2005). In response to the changing climate, extreme weather events, like drought, cyclone, and heavy rainfall, also predicted to occur more frequently. Such events drive the successional dynamics of forests and, therefore by implication, the above- and belowground carbon stock. In tropical regions, droughts are already more severe during strong El Niño years affecting the forest carbon stock and productivity (Lewis et al. 2006).

Forest Carbon Stock and Opportunities for Sustainable Development

Despite recent progress to halt deforestation and forest degradation (FAO 2016a), globally forests are still under anthropogenic pressure such as clearance for agriculture and settlement (Curtis et al. 2018; Lewis et al. 2015), shifting cultivation (Mukul and Herbohn 2016), and humanitarian use (Mukul et al. 2019a). Climate change and biodiversity loss exacerbate this situation in most forested regions (see Mukul et al. 2019b; Qie et al. 2017; Bello et al. 2015). Since it is well established that deforestation and forest degradation play a critical role in the global forest carbon cycle, reducing emissions from deforestation and forest degradation in tropical countries should be of crucial importance in efforts to reduce carbon emission from global forests (Houghton 2013; Gibbs et al. 2007).

The development of global carbon market to offset emissions from developed countries and mechanisms like REDD+ is now providing new avenues for sustainable development in tropical developing countries where population growth is most rapid, people are the poorest, and biodiversity is richest, and yet most threatened globally (Mukul et al. 2016b; Parrotta et al. 2012). The primary purpose of these mechanisms is to reduce emissions of carbon from deforestation and degradation by financially compensating forest owners and help stabilize the concentration of carbon dioxide in the atmosphere, thereby limiting the rate and amount of climatic disruption (Edwards et al. 2010; Gibbs et al. 2007). In contrast to such developments, future forest management in tropical regions should also emphasize the protection of regrowing forests and the reestablishment of forests on lands not intensively used now that were forests in the past (Chazdon 2014). Together, these measures have the potential to reduce carbon emission and increase uptake by forests by as much as 3–5 Pg C/year (Houghton 2013).

Carbon sequestration through forestry activities, such as forest and landscape restoration, is also among the most cost-effective strategies for global climate change mitigation (Busch et al. 2019; Chazdon and Guariguata 2016). They offer excellent prospects to offset carbon emission (Pugh et al. 2019), although entirely carbon-focused conservation may fail to protect tropical biodiversity. As global forests are limited by land, soil carbon sequestration through biochar and other strategies may be an important strategy to ameliorate changes in atmospheric carbon dioxide concentration (Thomas et al. 2019). Key scientific challenges must be addressed to prevent any policy roadblocks from converting forests as a carbon sink rather than a source of carbon. Much of the work on carbon storage and flux in forest ecosystems, particularly in the temperate and boreal zones, are based on modeling; there is, therefore, an urgency of field-based measurements from new regions and forest types. Quantifying the nation’s carbon emissions from deforestation and forest degradation with greater precision, and seeking new opportunities where forest restoration can take place is also crucial.

Cross-References

- ▶ Biomass
- ▶ Boreal Forests
- ▶ Carbon Sequestration
- ▶ Climate Change Mitigation
- ▶ Ecosystem
- ▶ Forests
- ▶ Land-Use
- ▶ Mangrove Forests
- ▶ Rainforests
- ▶ REDD+
- ▶ Temperate Forests
- ▶ Tropical Forests

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