Forest Carbon Modeling Resource Guide

Topic 1: Forest Inventory Data and Complementary Data Sources for Carbon Calculations

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Measuring Forest Carbon

The management of natural ecosystems relies on robust information informed by data and modeling tools developed to understand forests. Specifically, measuring the forest for carbon and other structural and health metrics, called a forest inventory, allows us to understand our natural surroundings with greater confidence. These measurements inform decisions for managing ecosystems under a changing climate and for continuously adapting management practices to create healthy and resilient forests to meet current and future demands.

Standardized, transparent, and consistent methodologies have been developed to measure and characterize forest attributes with a high level of accuracy using techniques that are repeatable and replicable. The measurement method defines how the measurement is taken where each method has some potential sources of error, leading to imprecision or bias in the measurements. However, there is no ‘correct’ method as each methodology has advantages and disadvantages depending on context. Cost and practical issues are also important considerations, so measurement efficiency can be thought of in terms of costs and benefits. It is important to consider tradeoffs between accuracy, time, and financial investment when selecting an appropriate measurement method.

When collecting forest measurements, lack of knowledge of the true value of a variable creates what is called uncertainty. Uncertainty can be expressed as a probability function, based on the range and likelihood of possible values. Use of Intergovernmental Panel on Climate Change (IPCC) guidance to quantify emissions and removals requires quantification of uncertainties consistent with a good practice principle of neither over- nor under-estimating so far as can be judged and reducing uncertainties as far as practicable (Espejo et al. 2020). Estimated uncertainty can be used to guide future development and continuous improvement of the system and its estimates. The IPCC provides additional guidance on good practices for forest measurements (Todorova et al. 2003) that are important to consider when choosing an appropriate method. These are outlined in Table 1.

Table 1. IPCC general principles for good practice

Principles	Definition
Transparency	Documentation sufficient to assess the extent to which good practice requirements have been met includes a clear description of input data, methods, and assumptions
Completeness	All relevant categories of emissions and removals are estimated and reported across the entire national territory and across time series
Consistency	Differences between years reflect differences in emissions or removals and are not artefacts of changes in methodology or data availability
Comparability	Inventory estimates reported within common formats
Accuracy	Delivered using methods designed to produce estimates systematically neither under- nor over-the true value and that reduce uncertainties so far as practicable. This addresses both accuracy and precision

There are several challenges associated with forest carbon measurements. These may include a lack of suitable data for regularly estimating changes in forest area or forest carbon stocks. Furthermore, lack of appropriate modeling tools can exacerbate data challenges. In some cases, challenges arise from a lack of experience in applying best practices or from having limited information on sources of error and uncertainty within estimates. However, the application of reviewed and consistent methods will aid in overcoming various challenges associated with forest measurements.

Components

There are multiple ways in which forests and forest changes can be measured. Carbon can be measured in terms of total stocks found in trees, the atmosphere, or other carbon pools, and in terms of fluxes of carbon between pools. Land use, land use change, and forestry activities can be quantified in terms of total spatial extent, total emissions, or emissions per spatial unit. Each metric requires different measurement approaches and methods, utilizes unique measurement units, and the valuation of each can align with different goals for monitoring, reporting, policy development, and communication. Measurable forest components are outlined in Table 2.

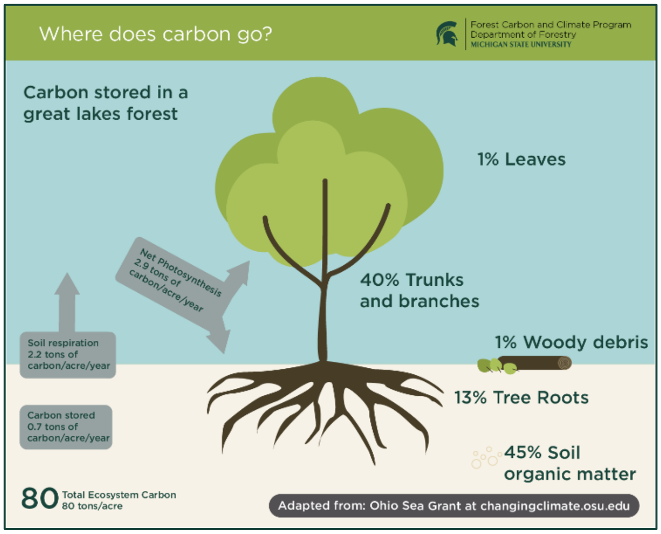
Table 2. Example forest components that can be measured for climate-related purposes

Type	Approach	Unit	Example
Carbon	**Pools:** tree and non-tree	C or CO_2-e	Aboveground tree biomass
	Fluxes: carbon and non-carbon GHGs	CO_2-e	CO2-e flux from decomposition
Land Use, Land Use Change and Forestry (LULUCF)	**Land Use:** by categories	Hectares	Total mature dry highland forest
	Land Use Change: e.g., forest loss, restoration planting	Hectares, emissions factors (CO_2-e)	Hectares of permanent forest loss to agriculture
	Forestry Activity Data	Emissions per hectare (CO_2-e)	Total CO2-e flux from commercial timber harvest

Because a forested ecosystem is composed of many smaller parts, the carbon it contains cannot be measured all at once. Instead, the forest is broken down into its major components and each individual pool is measured separately. It can also be useful and practical to estimate the carbon stocks and fluxes between these components separately, as they relate to unique forest functions and are impacted differently by management and natural ecosystem dynamics (i.e., environmental stressors, disturbance) (Figure 1).

Carbon is stored in pools above and below the ground. Above-ground components of forest carbon include trees, shrubs, other woody plants, and litter. Litter is the material on top of the soil and below the forest canopy that includes forest leaves, twigs, logs, and other dead plant tissues. Below-ground components include tree roots, smaller biomaterials, and soil. Figure 1 illustrates an example of carbon storage and fluxes of various between forest components in a forest ecosystem in the Great Lakes region of the US.

Figure 1. Aboveground and belowground forest carbon



Pools and Fluxes

A carbon pool is a reservoir of carbon which has the capacity to accumulate or release carbon, and is measured in units of mass (i.e., Pg, Tg, Mg). A few examples of forest carbon pools include trees and tree tissues, dead woody debris, forest soil, and the atmosphere. A carbon flux is a transfer of carbon from one carbon pool to another over a specified period and is measured in units of mass per unit area over time (i.e., Pg yr^{-1}, Mg ha^{-1} yr^{-1}, g m^{-2} sec^{-1}). Examples of forest carbon fluxes include the release of carbon from litter and tree tissues to the atmosphere (such as in the event of a wildfire) or the transfer of carbon from dead leaves into the soil via decomposition. Table 3 provides a brief description of each of these pools.

Table 3. Forest carbon pools

Carbon Pool	Description
Aboveground Biomass	All living biomass above the soil. Stems, branches, bark, seeds, and foliage.
Belowground Biomass	All living biomass below the soil. Live roots.
Deadwood	All non-living woody biomass not contained in the litter layer. Standing dead trees, downed logs, and course dead roots in the soil.
Litter	All non-living biomass contained in the litter layer. Leaves, needles, twigs, bark, flower, fruit, and other organic debris on the forest floor.
Soil Organic Matter	Carbon in mineral and organic soils

Techniques

In the section, we will briefly discuss some common methods employed in forest inventorying to assess structural metrics of trees for carbon and biomass estimation. Before someone can estimate the amount of carbon or biomass in a tree or plot, they must first learn appropriate techniques for measuring a tree. For those familiar with traditional forest measurements, carbon and biomass can be estimated using very similar techniques.

Diameter at Breast Heigh (DBH) Equation

Equations for tree carbon and biomass are important to forest inventorying, as physically weighing out all parts of every tree in a plot is not feasible. The most common approach to estimating the quantity of carbon stored in a tree is to use an allometric equation that estimates tree carbon as a function of tree diameter (Equation 1).

Equation 1. Basic formula to estimate tree carbon from diameter

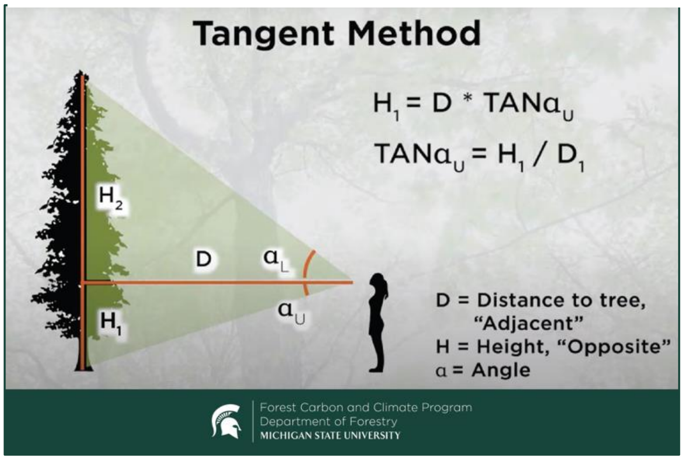
$$tree\ carbon = 0.5a(DBH)^b$$

In Equation 1, *a* and *b* are constants determined by the species present, stand density, and site condition. 0.5 is the typical ratio of carbon to dry tree mass, and DBH is the tree's diameter at breast height. Using this equation will provide a general estimate of the total carbon in a tree; however, more specific equations for species, region, and ecosystems generally do exist.

Tangent Method

Tree height, which is defined as the distance from the ground to the highest living point on the tree, can be measured in several ways. The tangent method involves measuring a horizontal distance to the tree and angles from horizontal to the top and base of the tree. Figure 2 demonstrates this process. The distance to the tree is measured and the angles between an individual's eye and the point on the ground and the highest point on the tree are collected. Note that it's possible to measure such angles from an electronic tilt sensor built into a laser, or with a mechanical clinometer. These measurements can then be utilized to estimate the height of the tree.

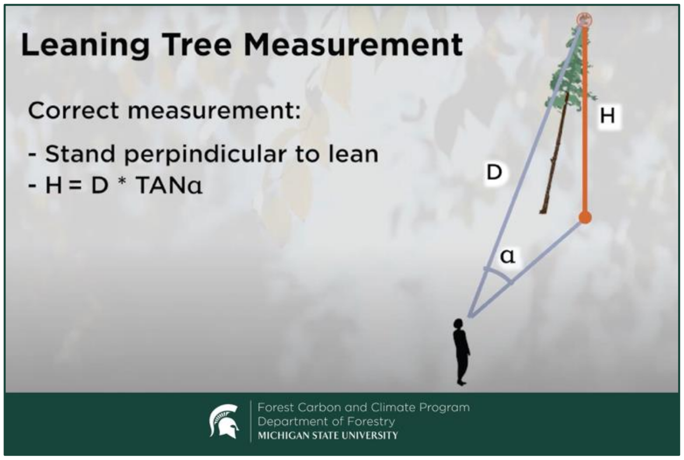
Figure 2. Tangent method



However, the tangent method does not work in all situations. When a tree is leaning, the top of the tree is not positioned directly over the base, which can cause a biased estimate when implementing the standard tangent method. One way to correct for this bias is to stand perpendicular to the tree's lean so that it is viewed from the side. It's important to identify the point on the ground below the highest point on the tree.

The distance from this point to our eye is the correct baseline distance to use when measuring a leaning tree's height. Figure 3 details the leaning tree correction for the tangent method. To measure the necessary angles, an individual must look down at the ground toward the point marked directly below the tree's highest point instead of the tree's base. The individual will then look to the top of the tree, as is performed in the traditional tangent method–looking at the tree from the side of its lean for better perspective. Then, the same calculations that are used for the tangent method are carried out to estimate the leaning tree's total height.

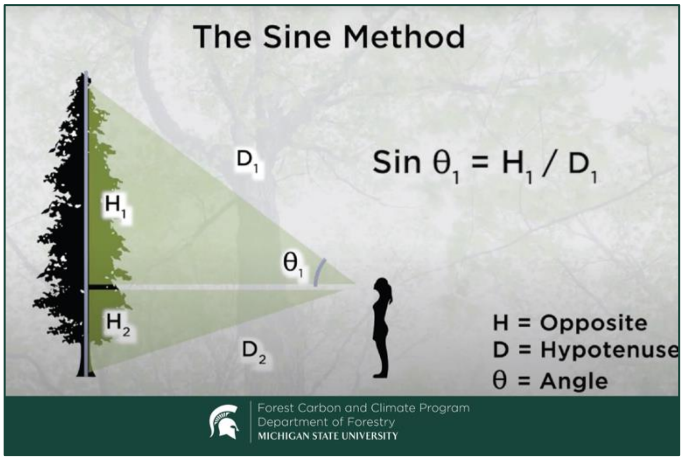
Figure 3. Leaning tree measurement technique



Sine Method

Specialized measurement tools, such as laser rangefinders, allow foresters to measure the distance to the top of the tree directly, thus enabling measurements of tree height using the sine method. By utilizing the sine method, a tree's total height can be calculated by adding together the opposite sides of two right triangles. As Figure 4 demonstrates, the sine of an angle is equal to its opposite divided by the hypotenuse. In this case, the hypotenuse is the straight-line distance from an individual's eye to the top of the tree, which is measured using the laser rangefinder.

Figure 4. Sine method



Crown Measures

Another important measurement of a tree is its crown, which is defined as the sum of all the branches and leaves. The crown is a biologically important component of the tree: it captures light from the sun and converts it to energy and carbon-storing tissues. Depending on the tree's structure, its crown can hold a significant proportion of total tree carbon. Foresters measure crown length and the height to the base of the crown. To obtain the crown length, the height to the base of the crown (height to the lowest live branch or lowest hanging foliage) must be collected first. This is calculated by measuring the angle and distance to the base of the crown, as well as to the base of the tree. After the height to the base of the crown has been measured, it is subtracted from total height to get the crown length. and Error! Reference source not found. illustrate how vertical crown dimensions are measured.

Figure 5. Vertical crown dimension measurement technique (source: MSU FCCP 2022)

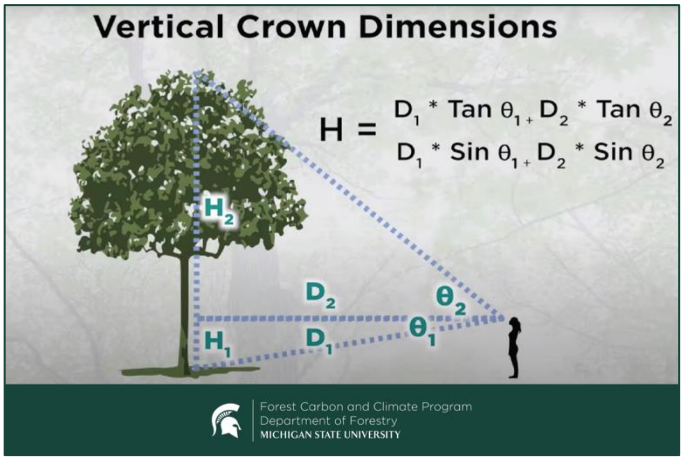
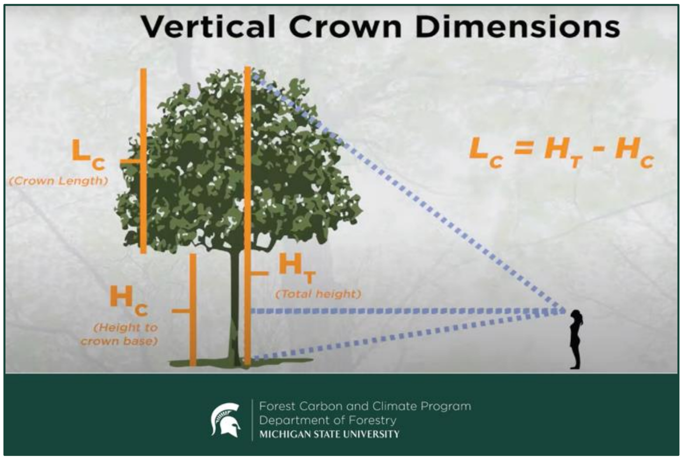


Figure 6. Vertical crown dimension calculation (source: MSU FCCP 2022)



The **crown spread** is the width of the crown from drip line to drip line in a particular direction. A tree's **drip line** is the area directly located under the outer circumference of the tree branches. To obtain this measurement, an individual on the ground must first find a point directly under the edge of the drip line. That point is then marked on the ground with a stake or pin to ensure that the person taking measurements is looking straight up at the edge of the crown. A clinometer or similar device is used to measure a 90-degree angle from the eye to the edge of the crown. Next, a partner will find and mark a similar point opposite of the first person using the same procedure. Once each person is marked the location of the two opposite edges on the ground, a tape measure or other measuring device can be used to measure the distance between the edges to estimate the crown width.

Note that tree crowns are generally irregular in shape– so the crown spread will be different in different directions (e.g., north to south vs east to west). There are several ways to deal with this issue, but the most common is to measure the spread in two perpendicular directions measuring the direction from person to person with a compass. For example, measuring the crown spread on a north-south axis, then east-west, and then averaging the two measurements.

Using Measurements to Estimate Forest Carbon

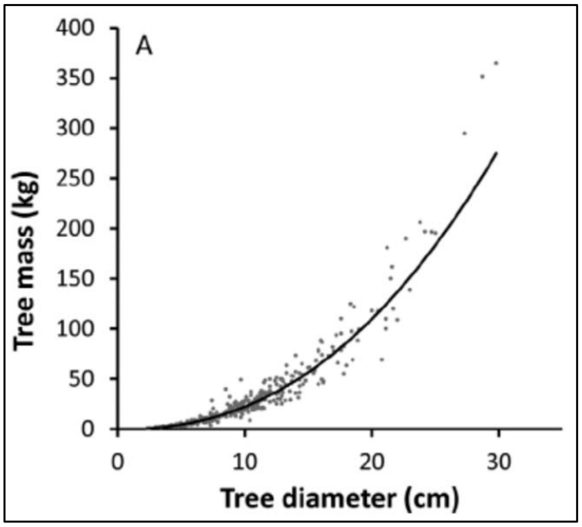
This section will explain how the values obtained from measurement methods described above can be applied in calculations to estimate the biomass and carbon in trees, plots, and forests.

Individual Tree Mass

The first step in determining how much carbon is in a forest plot or stand is to estimate the total amount, or total mass, of carbon that exists within individual trees of that plot or stand. In order do this, one must first estimate the total biomass of individual trees. Biomass refers to the mass of a living thing- in this case, a tree. To do this, biomass equations are employed to provide reasonable estimates of tree mass. Biomass equations take a measurable attribute of a tree and convert it into a mass value for the whole tree.

In most cases, a tree's stem diameter is used as the measured input value for these equations, as tree stems are the simplest and most efficient part of a tree to measure that relates to the total mass of a tree. More specifically, stem diameter at breast height (denoted as DBH) is used, which specifies that the stem diameter should be measured at a consistent height of 1.37 m (4.5 ft) from the ground. Generally, the more massive a tree is, the more massive its trunk is and, in most cases, tree mass increases exponentially with DBH (Figure 7).

Figure 7. Exponential relationship between tree mass and tree diameter. Source: Roxburgh et al. 2015



Biomass equations also utilize pre-specified values, called conversion factors, that are unique to each tree species. These conversion factors allow biomass estimates to account for variable wood densities (wood mass per unit volume) across trees of different species. For example, a sugar maple with a DBH of 20 cm may weigh about 145 kg, while a white pine of the same diameter might weigh only 85 kg because it has a lower wood density. By adjusting the conversion factor for each measured tree's species, the accuracy of biomass estimations is improved.

Plot-Level Carbon

Once the total mass of each tree within a plot has been estimated, they can be summed to find the total mass of all trees in that plot. This value can then be converted to total carbon mass by using the following rule of thumb conversion: carbon mass = ½ of total tree biomass. Thus, to estimate the total carbon in a plot, one can simply divide the total plot mass by 2. For example, if the summed mass of all trees within a plot is 3.4 metric tons, it means there are roughly 1.7 metric tons of carbon in that plot.

Stand-Level Carbon

To extrapolate plot-level data to the stand-level, one must first collect measurements from multiple plots in a stand. If these plots are uniform in size, the total carbon mass of each plot can be summed and then divided by the total number of plots to find the average carbon mass per plot. Average carbon per plot can then be transformed to estimate the average amount of carbon per specified unit of area (Equation 2).

Equation 2. Estimating carbon per unit area from plot-level data

$$\frac{avg.\,C\ mass}{plot} \times \frac{\#\ plots}{hectare} = avg.\,C\ mass/hectare$$

For example, if the average carbon per plot is 1.7 metric tons (t), and the plot size is 0.1 hectares (ha), then the average amount of carbon per hectare would be 17 t (Equation 3).

Equation 3. Example calculation of C per unit area using plot-level data (plot size = 0.1 ha)

$$\frac{1.7\ tC}{plot} \times \frac{10\ plots}{ha} = 17\ tC/ha$$

By taking this one step further, one can estimate the total C stock of an entire forest stand. Say the total extent of the example forest used in Equation 3 is 100 ha. Since carbon mass per hectare is estimated to be 17 t, 100 hectares should contain roughly 1700 tC, which is the estimated total carbon stock of trees in that forest.

Landscape-Level Carbon

The basis of all carbon estimation starts with ground-based observations of individual trees on sample plots that represent larger forested areas. Typically, basic dimensional measurements of sample trees are taken, namely DBH, total height and crown dimensions (described in the previous section) and fed into models (see above) which predict carbon mass. This is necessary because standing trees cannot be weighed to determine mass, but mass is roughly proportional to tree volume which can be predicted accurately from dimensional measurements. From tree volume, the bulk density (mass per unit volume) of tree tissues and the carbon content of mass are assumed to vary by species, such that a tree's carbon stocks can be computed from knowledge of its species and dimensions. Trees on plots can be scaled up to represent all trees in a forest at larger spatial extents, such as a stand, county, landscape, or region. Plot level measurements are oftentimes combined with remotely-sensed data (see below), such as satellite imagery, to provide spatially explicit estimation of forest characteristics, which may allow for continual monitoring of ecosystems without the need for frequent remeasurement of plots.

Forest Inventorying and Analysis (FIA): An Introduction

Collecting data for biomass and carbon quantification is a timely and costly endeavor. However, widely available data and model tools to inform forest carbon science and decision-making already exist and are regularly used in forest carbon quantification and modeling exercises. The United States Department of Agriculture Forest Service's Forest Inventory and Analysis (FIA) Program is one of the largest ecological datasets in the world in terms of spatial and temporal extents for forests (Tomppo et al. 2010). This program provides scientifically credible data about the status and trends of America's forests providing information to resource managers, policy makers, investors, and the public. Records dating back to the 1930s provide periodic information about the extent, condition, volume, growth, and use of trees (Smith 2002). Beginning in 1999, the FIA program implemented a nationwide systematic grid of permanent ground plots measured on a continuous cycle providing spatially unbiased estimates through time of forest attributes (Tinkham et al. 2018). The continual expansion of the FIA program tracks multivariable plot attributes such as species composition, tree size, and biophysical features eventually expanding to include soil chemistry, downed woody material, and understory plant composition (Pugh et al. 2018).

The FIA program provides the necessary data and tools to quantify and estimate forest carbon stocks and change across the US with direct applications to understanding the interaction between forests and the atmosphere (Bechtold & Patterson et al. 2005). Quantification of carbon pools, sequestration rates, and other system fluxes rely on converting modeled biomass estimations derived from tree structural characteristics such as DBH, tree height, and crown base height. FIA data have direct applications to carbon cycle science including: 1) estimation of carbon and carbon change; 2) calibration of models or model parameterization; 3) validation and accuracy assessment of model outputs; or 4) some combination of calibration and validation of models (Tinkham et al. 2018).

Beyond basic forest inventory and forest health indicators, the FIA program collects additional information on timber products and forest landowners through the Timber Products Output (TPO) studies and the National Woodland Owner Survey (NWOS). The TPO studies estimate both industrial and non-industrial uses of roundwood across the US by surveying mills processing primary materials to determine the location, size, and types of mills as well as the volume of product received, species composition, and geographic origin. The program also determines volume, type, and disposition of wood residues generated during primary processing. Furthermore, logging utilization studies are used to related volume estimates from both the TPO studies and FIA inventory by surveying logging operations to characterize the logging site, trees harvested, volume removed, products taken, and residues left behind.

Remote Sensing Data: An Introduction

Remote Sensing (RS) is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (United States Geological Survey [USGS]. This type of data is collected using satellites, airplanes, drones, or other types of platforms and can be linked to ground-based measurements recorded in a forest inventory plot to extrapolate those findings across larger spatial extents. RS data can be helpful in the quantification of land-use change, estimation of biomass, and the mapping of forest cover types to better inform carbon quantification. In conjunction with ground-based observations, RS data is used to calibrate and develop models to understand changes in forest characteristics across space and time in addition to other types of datasets.

Combining traditional forest inventory measurements with RS data has moved the paradigm of research from individual and periodic studies of forests to continual observation and monitoring of forest ecosystems. As data availability increases, statistical methods and models are rapidly being adapted to better incorporate data to increase inference from expanded temporal bases. RS models and tools will only continue to advance the ability to monitor on a continual basis, providing wall-to-wall estimates of forest carbon stocks and change.

References Cited

Bechtold, William A.; Patterson, Paul L.; [Editors] 2005. The enhanced forest inventory and analysis program - national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

- *Sampling design and population estimation methods*

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., & Wagner, F. (2003*). Intergovernmental Panel on Climate Change Good Practice Guidance for Land Use, Land-Use Change and Forestry*. IPCC National Greenhouse Gas Inventories Programme.

- *Provides supplementary methods and good practice guidance for estimating, measuring, monitoring and reporting on carbon stock changes and greenhouse gas emissions from LULUCF activities under Article 3, paragraphs 3 and 4, and Articles 6 and 12 of the Kyoto Protocol*

Pugh, Scott A.; Turner, Jeffery A.; Burrill, Elizabeth A.; David, Winnie. 2018. The Forest Inventory and Analysis Database: population estimation user guide (Edition: November, 2018). U.S. Department of Agriculture, Forest Service. 166 p. [Online].

- *This guide presents procedures that can be used to obtain population estimates (and associated sampling errors) for standard FIA attributes from the measurement data stored in the FIAD.*

Smith, W., 2002. Forest inventory and analysis: a national inventory and monitoring program. *Environ. Pollut.* 116, S233–S242.

- *Paper provides a brief history and a look at new directions for the enhanced FIA Program*

Tinkham W.T., Mahoney, P.R., Hudak A.T., Domke, G.M., Falkowski M.J., Woodall C.W., Smith A.M.S. (2018). Applications of the United States Forest Inventory and Analysis dataset: a review and future directions. *Can. J. For. Res.* 48: 1251-1268.

- *Review of over 180 publications that directly utilize FIA data, broken down into broad categories of application and further organized by methodologies and niche research areas*

Todorova, S., Lichte, R., Olsson, A., & Breidenich, C. (2003). National greenhouse gas inventories: application of the principles of transparency, consistency, comparability, completeness and accuracy. In *UNFCCC Secretariat.*

- *Describes improvements in national GHG inventories in adhering to the principles of transparency, consistency, comparability, completeness and accuracy achieved during the period 2000-2002*

Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., Gabler, K., Schadauer, K., Vidal, C., Lanz, A., Ståhl, G., Cienciala, E., 2010. National forest inventories, pathways for common reporting. *Eur. Sci. Found.* 541–553.

- *Book containing large collection of National Forest Inventory (NFI) data and reports from 38 countries*

United States Geological Survey. *"What is remote sensing and what is it used for?" www.usgs.gov/faqs/what-remote-sensing-and-what-it-used*. Accessed August 11, 2022.

- *USGS FAQ page that provides concise overview of remote sensing basics*

Additional Resources

Webinars/videos

Domke, G. (2021, June 23). *Greenhouse Gas Inventory Update: Estimates at the National level & Finer Spatial Scales* [Conference presentation]. 2021 FIA National Users Group Meeting, Virtual Meeting.

- *Presentation discussing how carbon stocks are changing, using maps and graphs showing national and state level information, as well as advancements in carbon science and accounting (starts at 2:30 in the video)*

Stanke, H. & Finley, A. (2022, March 23). *Creating the "Next Generation" Carbon On-Line Estimator (COLE) Model* [Conference presentation]. 2022 Forest Carbon Decision Support, FIA National Users Group Focus Session, Virtual Event.

- *Presentation discussing improvements being made to the COLE interface, including improving the user experience, integrating expanded plot data and carbon allometrics, and new methods of combining FIA data (starts at 2:12 in the video)*

Westfall, J. (2021, June 22). *Implementation of the New National Volume/Biomass/Carbon Modeling System for FIA* [Conference presentation]. 2021 FIA National Users Group Meeting, Virtual Meeting.

- Presentation discussing new approach to national forest biomass and carbon estimation and modeling (starts at 4:45 in the video)

Peer reviewed resources

Bond-Lamberty, B., Christianson, D. S., Malhotra, A., Pennington, S. C., Sihi, D., AghaKouchak, A., … & Zou, J. (2020). COSORE: A community database for continuous soil respiration and other soil-atmosphere greenhouse gas flux data. *Global change biology*, 26(12), 7268-7283.

- *Study describing the lightweight, open-source COSORE (COntinuous SOil REspiration) database and software, that focuses on automated, continuous*

and long-term GHG flux datasets, and is intended to serve as a community resource for earth sciences, climate change syntheses and model evaluation

Brand, G. J., Nelson, M. D., Wendt, D. G., & Nimerfro, K. K. (2000). The hexagon/panel system for selecting FIA plots under an annual inventory.

- *Paper describing the sampling grid used to distribute FIA plots across the landscape and to allocate them to a particular measurement year, as well as the integration of the FIA and Forest Health Monitoring (FHM) plot networks*

Chojnacky, D. C., Mickler, R. A., Heath, L. S., & Woodall, C. W. (2004). Estimates of down woody materials in eastern US forests. *Environmental Management*, 33(1), S44-S55.

- *Study examined data on Down Woody Materials (DWMs) from 778 plots to develop regression equations predicting DWM components for extension to FIA's more intensive plot network*

Chojnacky, David C.; Heath, Linda S.; Jenkins, Jennifer C. 2014. Updated generalized biomass equations for North American tree species. Forestry. 87: 129-151.

- *Update to previously published equation database, equations were developed based on allometric scaling theory, using taxonomic groupings and wood specific gravity as surrogates for scaling parameters that could not be estimated, resulting in 35 theoretically based generalized equations (13 conifer, 18 hardwood, 4 woodland)*

Espejo, Andres; Federici, Sandro; Green, Carly; Amuchastegui, Naikoa; d'Annunzio, Remi; Balzter, Heiko; Bholanath, Pradeepa; Brack, Cris; Brewer, Charles; Birigazzi, Luca; Cabrera, Edersson; Carter, Sarah; Chand, Narendra; Donoghue, Danny; Eggleston, Simon; Fitzgerald, Nikki; Foody, Giles; Galindo, Gustavo; Goeking, Sara; Grassi, Giacomo; Held, Alex; Herold, Martin; Kleinn, Christoph; Kurz, Werner; Lindquist, Erik; McRoberts, Ronald; Mitchell, Anthea; Næsset, Erik; Notman, Evan; Quegan, Shaun; Rosenqvist, Ake; Roxburgh, Stephen; Sannier, Christophe; Scott, Charles; Stahl, Goran; Stehman, Stephen; Tupua, Viliame; Watt, Pete; Wilson, Sylvia; Woodcock, Curtis; Wulder, Mike. 2020. Integration of remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and guidance from the Global Forest Observations Initiative, Edition 3.0. Rome, Italy: U.N. Food and Agriculture Organization. 300 p.

- *Provides practical advice related to the development of a National Forest Monitoring System to help meet national and international reporting requirements*

Hoover, Coeli M.; Bagdon, Ben; Gagnon, Aaron. 2021. Standard estimates of forest ecosystem carbon for forest types of the United States. Gen. Tech. Rep. NRS-202. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 158 p. https://doi.org/10.2737/NRS-GTR-202.

- *Document presenting forest ecosystem carbon yield tables, representing stand-level merchantable volume and carbon stocks as a function of stand age, for 53 forest types within 11 regions of the United States*

Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest science*, 49(1), 12-35.

- *Study compiled all available diameter-based allometric regression equations for estimating total aboveground and component biomass, defined in dry weight terms, for trees in the United States, then implemented a modified meta-analysis based on the published equations to develop a set of consistent, national-scale aboveground biomass regression equations for U.S. species*

Jenkins, Jennifer C.; Chojnacky, David C.; Heath, Linda S.; Birdsey, Richard A. 2004. Comprehensive database of diameter-based biomass regressions for North American tree species. Gen. Tech. Rep. NE-319. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 45 p. [1 CD-ROM].

- *A database consisting of 2,640 equations compiled from the literature for predicting the biomass of trees and tree components from diameter measurements of species found in North America*

Jucker, T., Fischer, F. J., Chave, J., Coomes, D. A., Caspersen, J., Ali, A., ... & Zavala, M. A. (2022). Tallo–a global tree allometry and crown architecture database. *Global Change Biology*.

- *Massive database that is highly relevant for carbon calculation, features a collection of 498,838 georeferenced and taxonomically standardized records of individual trees for which stem diameter, height and/or crown radius have been measured, collected at 61,856 globally distributed sites, spanning all major forested and non-forested biomes*

Malhotra, A., Todd-Brown, K., Nave, L. E., Batjes, N. H., Holmquist, J. R., Hoyt, A. M., ... & Harden, J. (2019). The landscape of soil carbon data: emerging questions, synergies and databases. *Progress in Physical Geography: Earth and Environment*, 43(5), 707-719.

- *Progress report describing recent advances in soil carbon data led by the International Soil Carbon Network and other networks the landscape of soil datasets currently available, highlighting their strengths, weaknesses and synergies*

Roxburgh, S. H., Paul, K. I., Clifford, D., England, J. R., & Raison, R. J. (2015). Guidelines for constructing allometric models for the prediction of woody biomass: how many individuals to harvest?. *Ecosphere*, 6(3), 1-27.

- *Study using computer resampling experiments and allometric models of the form B = aDb to assess the trade-off between increasing the sample size of*

individuals to construct an allometric model and the accuracy of the resulting biomass predictions

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Woodall, Christopher W.; Heath, Linda S.; Domke, Grant M.; Nichols, Michael C. 2011. Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

- *Documentation of relevant tree attribute models, needed individual tree gross volume, sound volume, biomass (including components), and carbon models for species in the United States are compiled and described in this publication*

Non- Peer reviewed resources

Computation of FIA Plot Expansion Factors. (n.d.). In FIA *Library Sampling and Estimation Documentation*. USDA Forest Service. Retrieved August 5, 2022, from https://www.fia.fs.fed.us/library/sampling/index.php

- *Documentation of how FIA expansion factors (the number of acres that a given plot represents) are calculated based on total area, stratum weight, and the number of plots in the stratum*

Examples of FIA Change-Component Estimation Procedures for Several Common Cases. (n.d.). In *FIA Library Sampling and Estimation Documentation*. USDA Forest Service. Retrieved August 5, 2022, from https://www.fia.fs.fed.us/library/sampling/index.php

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US Forest Service. (n.d.-a). *Biomass Volume Estimation*. Www.fs.fed.us.

- *USFS open-source libraries of volume and biomass models for cruising, planning, and stand exam software, made available as Excel functions, also includes links to training, tools, and software for model validation and development*

US Forest Service. (n.d.-b). *Forest Inventory and Analysis National Program - FIA Library*. Www.fia.fs.fed.us.

- *FIA resource hub featuring field guides, methods, and procedures*

USDA Forest Service. (2015). *Demonstration Plot Handouts*. Forest Inventory and Analysis National Program - FIA Library.

- *Documents describing how an FIA plot is located and measured, using the FIA demonstration plot as an example*