



## Guidance on Use and Application of the National Forest Carbon Monitoring System Dataset

### Overview

Our U.S. forests store 30 years' worth of U.S. emissions and each year these forests capture or sequester an additional 11-13% of annual U.S. emissions. Forests are an essential aspect of state, federal and global climate solutions. Up-to-date forest carbon data is essential to supporting conservation organizations and government agencies in understanding the importance of forests as part of emissions reduction strategies and in directing conservation to places where work can be most effective. To support these goals, Open Space Institute and its partners have funded an update to the National Forest Carbon Monitoring System (NFCMS) dataset developed by Drs Natalia Hasler and Christopher Williams at Clark University. This guidance document provides useful background and context to support accurate and effective use of the data. The document briefly covers the following topics:

- Dataset Description
- Applicable Use Cases
- How to View and Download the Data
- Which Carbon Stocks are Included?
- Clarifying Carbon Stocks and Carbon Sequestration
- Units and Carbon Calculations
- Explaining Variation in Forest Carbon Content
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- Assumptions and Limitations
- Data Accuracy, Uncertainty, and Errors
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### Dataset Description

The U.S. NFCMS - version 3.0 is a conterminous U.S., 30m resolution dataset of forest extent, forest carbon stocks, historical forest conversion (1990-2020) and potential future forest carbon stocks under a grow-only scenario. It is based on a methodology similar to that used in the original version of the NFCMS (on ORNL DAAC (Williams et al., 2021)(<https://doi.org/10.3334/ORNLDAAC/1829>) but with significant updates to inventory-derived carbon curves, forest extent, and forest disturbance history.

### Applicable Use Cases

The NFCMS dataset may be useful for providing quantitative assessments of forest carbon as needed to inform climate policy and the land protection priorities of land trusts, public agencies, and other conservation organizations. Potential use cases include:

- Conservation planning with carbon and climate mitigation as a goal
- Project evaluation for current storage and potential sequestration
- Assessing the carbon benefit of sustained future growth
- Communicating the value of forest protection through the lens of carbon benefits
- Local to regional assessment of sequestration expected with sustained growth
- Policy, planning and implementation of state carbon or climate accounting
- Placement of renewable energy to reduce forest carbon emissions

### How to View and Download the Data

There are four ways the data is currently or will soon be available:

1. [Total ecosystem carbon for 2020](#) and [estimated sequestration from 2020 to 2050](#) is available for viewing on ArcGIS Online. The data can be brought into desktop or online ArcGIS maps. Access requires an ArcGIS Online account.
2. The data is also being added to the National Geospatial Data Asset (NGDA) [Land Use and Land Cover Theme \(arcgis.com\)](#). This platform will allow users to download total ecosystem and soil carbon stocks by Forest Service region. The NGDA helps to coordinate access to most efficiently support national priorities and government missions.
3. An avoided conversion tool will be released this fall. This Guidance Document will be updated when that tool is available.
4. Updated 2020 and 2050 data will also be uploaded to The Nature Conservancy's [Resilient Land Mapping Tool](#) in early 2025. The tool currently hosts the 2010 forest carbon data.

### Which Carbon Stocks are Included?

The NFCMS tracks forest carbon in a suite of live and dead pools, including aboveground in the wood and leaves of living trees, coarse woody debris, snags, litter, and belowground in living root systems, organic and mineral soil, and the microbial community. Total ecosystem carbon includes the carbon in all pools while live aboveground carbon includes only the carbon stored in aboveground woody biomass. Quantifying carbon in all pools is made possible with an inventory-constrained carbon cycle model that estimates the dead leaves, branches, roots, and stems typical for different kinds of forests and as their biomass increases. Comparison to forest inventory data shows generally good agreement across carbon pools.

### Clarifying Carbon Stocks and Carbon Sequestration

Forest carbon stocks refer to the amount of carbon in a forest ecosystem at a moment in time and are often defined separately for different reservoirs such as live woody biomass, soil carbon, or coarse woody debris. Carbon [sequestration](#) is the process of capturing and storing atmospheric carbon dioxide, and forest carbon sequestration is the process of a forest having a net uptake of atmospheric carbon, accounting for primary productivity exceeding losses from respiration and fire, leading to a positive increment (a gain or growth) in forest carbon stocks. Forest carbon stocks range from 40 to 1,200 metric tons of CO<sub>2</sub>e per acre, while annual carbon sequestration ranges from 0 to 7 metric tons of CO<sub>2</sub>e per acre per year. See the U.S. Forest Service (USFS) [website](#) on forest carbon, carbon stewardship, management, sustainability and climate for helpful illustrations and discussions of these topics.

### Units and Carbon Calculations

The dataset provides carbon stocks and carbon fluxes in carbon dioxide equivalents with units of metric tons of CO<sub>2</sub>e per acre [Mg CO<sub>2</sub>e per acre] or metric tons of CO<sub>2</sub>e per acre per year. In the past the data was available in tons of carbon per acre. We have shifted the units to CO<sub>2</sub>e to support understanding forest carbon in the context of climate mitigation. To calculate the tons of carbon in tons of CO<sub>2</sub>e, multiply the carbon values by 3.67.

While the data is displayed in metric tons of CO<sub>2</sub>e per acre, the area of each individual pixel is only 900 square meters (from 30m\*30m pixels), which is only 22.2% of an acre (one acre equals 4,046.86 square meters). To get the total mass of carbon in a given pixel, multiply the pixel's value by the pixel's fraction of an acre, meaning multiply by 0.222 (from 900/4,046.8). Similarly, to calculate the total mass of carbon summed over a polygon or region, multiply the sum of pixel values by 0.222. Lastly, to convert from metric tons of carbon dioxide per acre to metric tons of carbon per acre, divide a pixel's value by 3.667 from the ratio of molecular masses for carbon to carbon dioxide (12/44).

### Explaining Variation in Forest Carbon Content

Many factors can cause forest carbon to be higher or lower in one area compared to another, including whether a recent disturbance (harvest, wildfire, windthrow) has reduced live carbon stocks, whether the climate and soils support a highly productive forest or not, and whether the forest type supports a lot of biomass at maturity, or less. Partial forest cover, such as at a forest edge, can also lead to lower biomass in some pixels compared to others. Taken together, these factors lead to large-scale geographic patterns in forest carbon at the continental scale, with hotspots of high or low carbon areas principally due to climate. It may be appropriate for some applications to identify high carbon forests within a local or regional context rather than at the national or continental scale.

### Methods, Data Sources, Novelty, and Evaluation

The essence of the NFCMS methodology involves mapping forest extent, forest type, stand age, and productivity class, and then assigning carbon stocks and fluxes to pixels as a function of those attributes.

We map forest extent at a 30m resolution for 2020 and forest conversions for the 1990-2020 period using a combination of the Land Change Monitoring, Assessment, and Projection (LCMAP) dataset (Pengra et al., 2020), the National Land Cover Database (NLCD), the CropScape - Cropland Data Layer (CDL) (Boryan et al., 2011), the North American Forest Dynamics dataset (NAFD), (Goward et al., 2015), (Zhao et al., 2018)), and the USFS Landscape Change Monitoring System (LCMS) (USDA Forest Service, 2023) dataset, following a stepwise method described in the dataset readme file. We map stand-altering disturbances with the Monitoring Trends in Burn Severity (MTBS) dataset (Eidenshink et al., 2007) to identify any forest fires that occurred between 1984-2020, as well as time-series analysis in LCMAP to detect when a forested pixel changes to a grass/shrub class. We map forest gain/recovery when a grass/shrub pixel changes to forested. We assign forest type to pixels with a USFS dataset (Ruefenacht et al. 2008).

We define each pixel's biomass in the year 2000 with the National Biomass Carbon Dataset (NBCD) of Kellndorfer et al. (2013) and infer the associated stand age from Forest Inventory and Analysis (FIA) yield curves. We then increment age forward and backward in time while also taking account of forest conversions and new disturbance events. We apply forest carbon values to each 30m forest pixel based on each pixel's attributes, most importantly forest type and stand age, with carbon curves defined regionally for a complex suite of strata.

We define carbon curves by training a forest disturbance version of the Carnegie-Ames-Stanford Approach ecosystem carbon cycle model to match forest biomass yield curves sampled from the FIA

database. This produced a suite of curves characterizing forest carbon stocks and fluxes with stand age that are uniquely defined for a wide range of forest type group, post-disturbance, and site productivity conditions. In addition to estimating carbon stocks and fluxes in the year 2020, we estimate the carbon sequestration by 2050 and 2070 that is expected with sustained forest growth and maturation consistent with the FIA yield curves. This “grow-only” scenario represents forest maturation in the absence of a stand-replacing disturbance during the 30-year timeframe, thus being free of forest harvest, forest conversion, or a major natural disturbance from severe pest or pathogen attack.

The original NFCMS framework has been developed over many years and used for diverse applications (e.g., Williams et al. 2012, Williams et al. 2014, Gu et al. 2016, Gu et al. 2019a, Gu et al. 2019b, Williams et al. 2021, Zhou et al. 2021). Several of those studies provide detailed comparison and evaluation to state- and regional-scale USFS reports of forest carbon stocks and fluxes, as well as regional forest biomass carbon maps of similar resolution, all showing very favorable agreement. The NFCMS is relatively unique in its national coverage, training on stratified sampling of FIA yield curves, data outputs at a spatial resolution reaching the scale of management units and land ownership (note the 30m resolution of the NFCMS is 1,000 times higher resolution than a 1km grid, and 11 times higher resolution than a 1 ha dataset), explicit incorporation of disturbance history and associated legacies, inclusion of all forest carbon pools spanning live, dead and soil components, and offering a forecast mode that estimates a grow-only scenario of ongoing carbon sequestration potential.

### **Assumptions and Limitations**

The NFCMS dataset relies on a biomass map and inherits any errors in that map, particularly for those forest tracts that have not experienced a stand-resetting disturbance since 1985. The NFCMS approach assumes that forests experiencing a stand-resetting disturbance remain forestland and recover with the same forest type unless an area is mapped as having been converted to cropland or development. The NFCMS’s forecast of potential forest carbon stocks in the future represents what is expected with a grow-only scenario in which forests experience only low to moderate disturbance at a background rate but remain free of stand-resetting, high-severity disturbance. With hundreds of trajectories describing carbon stock changes over time in different forest settings, we then can map to pixels, producing wall-to-wall characterization of forest carbon today and expected in the future. This captures carbon dynamics at the average rate for a forest of a given stand age, forest type and productivity class combination, averaged across forests within the corresponding region, with nine regions across the conterminous US. Some forest plots might be higher yielding than that average, and would have a higher baseline than the average, while others will be lower.

Thus, the framework captures dominant sources of variation but not all of the real-world variation in current stocks and stock growth. Also, sharp spatial discontinuities in carbon stocks and/or sequestration potential may be detected at state borders and are an artifact of regional boundaries. Those areas are likely to have larger errors in estimates, with real-world patterns showing smoother geographic variation. Future stock accumulation is represented with an average for a given forest type group and site class within a broad region. Again, these forecasts represent a grow-only scenario, and future disturbance risks are not represented in the current NFCMS.

Some, but not all, aspects of forest management are captured by the NFCMS approach. The average effects of management that are embedded in inventory yield curves are included in the dataset, and describe business-as-usual, contemporary management effects on forest yields. However, the NFCMS is not currently designed to capture the effects of unique management treatments either in the past or potentially in the future. Grid cells that can support only a partial forest cover because of a persisting non-forested area, such as with a residential lot or park property that has lawn backing up to forest, will have an overestimated carbon stock potential in the current NFCMS. Maps of forest type group and

productivity class are not readily available on a regular basis. The NFCMS approach has adopted the most recent national mapping of forest type group provided by the USFS circa 2008. The NFCMS produced its own mapping of site productivity class based on a statistical spatialization of USFS county-level proportions.

### **Data Accuracy, Uncertainty, and Errors**

Several of our studies have provided detailed comparisons to state- and regional-scale USFS reports of forest carbon stocks and fluxes, and all these comparisons show very favorable agreement at this coarse scale. Our studies have also compared forest biomass carbon maps of similar resolution, finding very good agreement across datasets at a scale of 1 km or greater, but disagreement growing at higher resolutions.

One independent, plot-level evaluation of the dataset's aboveground biomass estimates found a 6% error rate on 12 forest carbon projects in the mid-Atlantic, with a lower error rate than NCX (formerly SilviaTerra) data. Another independent evaluation reported a 2% error rate for carbon projects in the central Appalachians. Additional analysis of data uncertainties at pixel to regional scales is underway, with propagation of uncertainties from multiple sources (pixel assignments of stand age and productivity class, as well as within-stratum spread in FIA yield curves). Additional testing of the 2020 update would be useful to assess accuracy at pixel to parcel levels, including evaluation with field-based measurement plot data and remote-sensed forest carbon estimates.

### **Opportunities for Extension and Improvement**

There are several opportunities for extending and improving the framework. Management scenarios could be embedded in the framework with an interface that allows users to select from a range of typical treatments to biomass and biomass yields, ideally with graphical display that allows users to compare baseline and alternate outcomes. Future disturbance risks could be taken into account with maps estimating the probability of biomass loss from harvesting, wildfires, and other disturbances. The NFCMS dataset could be directly embedded within, or otherwise linked to, a range of tools and platforms reporting forest carbon and climate resilience.

### **Where To Learn More**

The Forest Carbon Data Partnership is a group of NGO, government and academic institutions working to ensure the conservation field has the data and tools to optimize forest carbon through land protection as part of meeting state and federal climate goals. The Partnership has conducted multiple webinars and produced a variety of fact sheets and tools, which can be found here:

[Tools to Quantify the Carbon Value of Forest Protection](#)

### **Attribution**

This update to the U.S. National Forest Carbon Monitoring System was developed by Dr. Natalia Hasler and Dr. Christopher Alan Williams of the Biogeosciences Research Group at Clark University for the Open Space Institute with additional support from the U.S. Forest Service Forest Legacy Program, Trust for Public Land, and The Nature Conservancy.

### **Citations**

Boryan, C., Yang, Z., Mueller, R., & Craig, M. (2011). Monitoring US agriculture: the US Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer Program. *Geocarto International*, 26(5), 341-358. <https://doi.org/10.1080/10106049.2011.562309>

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.-L., Quayle, B., & Howard, S. (2007). A project for monitoring trends in burn severity. *Fire Ecology*, 3, 3-21.

- Goward, S. N., Huang, C., Zhao, F., Schleeweis, K., Rishmawi, K., Lindsey, M., Dungan, J. L., & Michaelis, A. (2015). *NACP NAFD Project: Forest Disturbance History from Landsat, 1986-2010*. <https://doi.org/DOI:10.3334/ORNLDAAAC/1290>
- Gu, H., Williams, C. A., Ghimire, B., Zhao, F., & Huang, C. (2016). High-resolution mapping of time since disturbance and forest carbon flux from remote sensing and inventory data to assess harvest, fire, and beetle disturbance legacies in the Pacific Northwest. *Biogeosciences*, *13*, 6321-6337. <https://doi.org/doi:10.5194/bg-13-6321-2016>
- Gu, H., Williams, C. A., Hasler, N., & Zhou, Y. (2019). The Carbon Balance of the Southeastern U.S. Forest Sector as Driven by Recent Disturbance Trends. *Journal of Geophysical Research: Biogeosciences*, *124*(9), 2786-2803. <https://doi.org/10.1029/2018jg004841>
- Gu, H., Williams, C. A., Hasler, N., & Zhou, Y. (2019). Forest Carbon Stocks and Fluxes After Disturbance, Southeastern USA, 1990-2010. In: ORNL Distributed Active Archive Center.
- Kellendorfer, J., Walker, W., Kirsch, K., Fiske, G., Bishop, J., LaPoint, L., Hoppus, M., & Westfall, J. (2013). NACP Aboveground Biomass and Carbon Baseline Data, V. 2 (NBCD 2000), U.S.A., 2000. Dataset Available on-line [<http://daac.ornl.gov>] from ORNL DAAC, Oak Ridge, Tennessee, U.S.A. <http://dx.doi.org/10.3334/ORNLDAAAC/1161>.
- Pengra, B. W., Stehman, S. V., Horton, J. A., Auch, R. F., Kambly, S., Knuppe, M., Sorenson, D., Robison, C., & Taylor, J. L. (2023). *LCMAP CONUS Reference Data Product 1984-2021 land cover, land use and change process attributes: U.S. Geological Survey data release*, .
- Ruefenacht, B., Finco, M. V., Nelson, M. D., Czaplewski, R., Helmer, E. H., Blackard, J. A., Holden, G. R., Lister, A. J., Salajanu, D., Weyermann, D., & Winterberger, K. (2008). Conterminous U.S. and Alaska Forest Type Mapping Using Forest Inventory and Analysis Data. *Photogrammetric Engineering and Remote Sensing*, *74*(11), 1379-1388.
- USDA-Forest-Service. (2023). *USFS Landscape Change Monitoring System Conterminous United States version 2023-9*.
- Williams, C. A., Collatz, G. J., Masek, J. G., & Goward, S. (2012). Carbon consequences of forest disturbance and recovery across the conterminous United States. *Global Biogeochemical Cycles*, *26*, GB1005. <https://doi.org/doi:10.1029/2010GB003947>
- Williams, C. A., Collatz, G. J., Masek, J. G., Huang, C., & Goward, S. (2014). Impacts of disturbance history on forest carbon stocks and fluxes: merging satellite disturbance mapping with forest inventory data in a carbon cycle model framework. *Remote Sensing and the Environment*, *151*, 57-71.
- Williams, C. A., Gu, H., & Jiao, T. (2021). Climate impacts of U.S. forest loss span net warming to net cooling. *Science Advances*, *7*(7), eaax8859. <https://doi.org/10.1126/sciadv.aax8859>
- Williams, C. A., Hasler, N., Gu, H., & Zhou, Y. (2021). Forest Carbon Stocks and Fluxes from the NFCMS, Conterminous USA, 1990-2010. ORNL DAAC, Oak Ridge, Tennessee, USA. <https://doi.org/10.3334/ORNLDAAAC/1829>.
- Zhao, F., Huang, C., Goward, S. N., Schleeweis, K., Rishmawi, K., Lindsey, M. A., Denning, E., Keddell, L., Cohen, W. B., Yang, Z., Dungan, J. L., & Michaelis, A. (2018). Development of Landsat-based annual US forest disturbance history maps (1986–2010) in support of the North American Carbon Program (NACP). *Remote Sensing of Environment*, *209*, 312-326. <https://doi.org/https://doi.org/10.1016/j.rse.2018.02.035>
- Zhou, Y., Williams, C. A., Hasler, N., Gu, H., & Kennedy, R. (2021). Beyond biomass to carbon fluxes: application and evaluation of a comprehensive forest carbon monitoring system. *Environmental Research Letters*, *16*(5), 055026. <https://doi.org/10.1088/1748-9326/abf06d>