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EDITED BY
Alfredo Di Filippo,
University of Tuscia, Italy

REVIEWED BY
Roel Brienen,
University of Leeds, United Kingdom
Jeffrey Stenzel,
University of California, Merced,
United States

*CORRESPONDENCE
Richard A. Birdsey
✉ rbirdsey@woodwellclimate.org

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Assessing carbon stocks and accumulation potential of mature forests and larger trees in U.S. federal lands

Richard A. Birdsey[1]*, Dominick A. DellaSala[2], Wayne S. Walker[1], Seth R. Gorelik[1], Garett Rose[3] and Carolyn E. Ramírez[3]

[1]Woodwell Climate Research Center, Falmouth, MA, United States, [2]The Wild Heritage, A Project of Earth Island Institute, Berkeley, CA, United States, [3]Natural Resources Defense Council, Inc., Washington, DC, United States

Mature and old-growth forests (collectively "mature") and larger trees are important carbon sinks that are declining worldwide. Information on the carbon value of mature forests and larger trees in the United States has policy relevance for complying with President Joe Biden's Executive Order 14072 directing federal agencies to define and conduct an inventory of them for conservation purposes. Specific metrics related to maturity can help land managers define and maintain present and future carbon stocks at the tree and forest stand level, while making an important contribution to the nation's goal of net-zero greenhouse gas emissions by 2050. We present a systematic method to define and assess the status of mature forests and larger trees on federal lands in the United States that if protected from logging could maintain substantial carbon stocks and accumulation potential, along with myriad climate and ecological co-benefits. We based the onset of forest maturity on the age at which a forest stand achieves peak net primary productivity. We based our definition of larger trees on the median tree diameter associated with the tree age that defines the beginning of stand maturity to provide a practical way for managers to identify larger trees that could be protected in different forest ecosystems. The average age of peak net primary productivity ranged from 35 to 75 years, with some specific forest types extending this range. Typical diameter thresholds that separate smaller from larger trees ranged from 4 to 18 inches (10–46 cm) among individual forest types, with larger diameter thresholds found in the Western forests. In assessing these maturity metrics, we found that the unprotected carbon stock in larger trees in mature stands ranged from 36 to 68% of the total carbon in all trees in a representative selection of 11 National Forests. The unprotected annual carbon accumulation in live above-ground biomass of larger trees in mature stands ranged from 12 to 60% of the total accumulation in all trees. The potential impact of avoiding emissions from harvesting large trees in mature forests is thus significant and would require a policy shift to include protection of carbon stocks and future carbon accumulation as an additional land management objective on federal forest lands.

KEYWORDS

carbon stock, climate change, large trees, mature forests, national forest lands

1. Introduction

Nature-based climate solutions are needed to meet anticipated national targets associated with the Paris Climate Agreement which establishes a global framework to avoid dangerous climate change by limiting warming to less than 2°C (United Nations, 2015). In the United States, the Biden administration announced a "roadmap" for nature-based solutions during the COP27 climate summit (White House, 2022a). Reducing carbon dioxide (CO_2) emissions and increasing CO_2 removals from the atmosphere using forests are considered to be the most significant of terrestrial natural climate solutions globally and in the U.S. (Griscom et al., 2017; Fargione et al., 2018).

Protecting mature forests to achieve their potential to reduce greenhouse gases is controversial in part because it restricts logging (Law and Harmon, 2011; Moomaw et al., 2020). Forests in the later stages of seral development (mature and old-growth, DellaSala et al., 2022a) and the large trees within them (Stephenson et al., 2014; Mildrexler et al., 2020) play an outsized role in the accumulation and long-term storage of atmospheric carbon, and consequently enabling their protection where lacking has been recognized as an effective nature-based climate solution (Griscom et al., 2017). Notably, President Joe Biden issued an executive order (White House, 2022b) recognizing the climate value of mature and old-growth forests and directed federal officials to define and inventory them on Federal lands and develop policies for their conservation. Thus, providing techniques for defining when forests qualify as mature and quantifying their relative carbon content and storage potential has high policy relevance.

This undertaking supports the nation's goal of achieving net-zero greenhouse gas emissions by 2050 and to conserve 30% of the nation's land by 2030 (White House, 2021). Protecting older, larger trees and mature forests would also help reverse the global degradation of older forests that have diverse ecological values (Lindenmayer et al., 2012), and facilitate the continued growth of mid-sized trees toward maturity (Moomaw et al., 2019). Mature forests provide refugia for many imperiled species (Buotte et al., 2020; DellaSala et al., 2022a), store disproportionate amounts of above-ground carbon in forests (Stephenson et al., 2014; Lutz et al., 2018; Mildrexler et al., 2020), and historically constitute a large volume of valuable timber (Johnson and Swanson, 2009). These values often conflict with one another resulting in contentious policy debates about land management objectives and best practices, particularly on federal lands in the U.S. where much of the remaining mature forest area resides according to national forest inventory data (Bolsinger and Waddell, 1993; DellaSala et al., 2022a). Recent studies of land values reveal that the importance of mature forests for ecosystem integrity and non-timber ecosystem services far exceeds their value for timber products (Watson et al., 2018; Gilhen-Baker et al., 2022).

Some researchers argue that it is necessary to log larger trees in fire-suppressed forests in the western U.S. to restore fire regimes, reduce biomass, and minimize emissions from wildfires (Kirschbaum, 2003; Hessburg et al., 2020; Johnston et al., 2021). However, these assertions have been challenged (Stephenson et al., 2014; Lutz et al., 2018; Mildrexler et al., 2020; DellaSala et al., 2022b) in part because removing larger trees from forests having high carbon stocks creates a significant "carbon debt" that can take decades or centuries to repay (Moomaw et al., 2019; Law et al., 2022).

It follows that our objectives are to (1) present an approach to defining larger trees and mature forests on federal lands; (2) estimate the current carbon stock and annual carbon accumulation in larger trees in mature forests across a representative selection of national forests, and (3) estimate the carbon stock and accumulation left unprotected by current binding designations.

We do not identify the proportion of mature forest area and carbon stocks that could be classified more specifically as "old growth." Defining old-growth in a consistent way across the diversity of temperate forests is challenging since existing definitions are based on structural, successional, and biogeochemical factors that are unique for individual forest types and researcher's interests (Wirth et al., 2009). Our characterization of mature forests has ecological and policy relevance for restoring old-growth characteristics over time, pursuant to the presidential executive order as well (DellaSala et al., 2022a). Thus, we determined that this paper would be more broadly focused on mature forests rather than old-growth forests.

2. Materials and methods

2.1. Approach

Our approach requires addressing two components: (1) individual trees referred to as the "larger" trees in a forest; and (2) mature forest stand development represented by stand age. This method for identifying larger trees in mature stands—and the related assessment of above-ground live carbon stocks and annual carbon accumulation—is intended to be broadly applicable and readily implementable independent of how mature stands are defined. We settled on defining stand maturity with respect to the age of maximum Net Primary Productivity (NPP), which is estimated as the annual net quantity of carbon removed from the atmosphere and stored in biomass (see section 2.2 for definitions of key terms). NPP was calculated by combining 4 terms: Annual accumulation of live biomass, annual mortality of above-ground and below-ground biomass, foliage turnover to soil, and fine root turnover in soil (He et al., 2012). Live biomass and annual mortality were estimated from the Forest Inventory and Analysis (FIA) database. Foliage and fine root turnover were estimated using maps of leaf area index (LAI) and forest age to derive LAI-age relationships for different forest types. These relationships were then used to derive foliage and fine root turnover estimates using species-specific trait data (He et al., 2012).

This is a particularly appropriate approach to maturity in the context of how forests help temper climate change. Our integrating method of associating the median tree diameter with age is intended to be applicable to other definitions of stand maturity, including simple ones applied across the landscape without regard to specific stand characteristics, for example a uniform age cutoff.

2.2. Key definitions and data source

Net Primary Productivity (NPP)—The difference between the amount of carbon produced through photosynthesis and the amount of energy that is used for respiration. Estimate is based on the net increment of tree and understory biomass, leaf production, and fine root turnover (He et al., 2012).

Biomass—The carbon stored in live trees greater than 1 inch (2.54 cm) diameter at breast height (dbh), including stump, bole, bark, branches, and foliage.

Carbon stock—The carbon stored in live biomass at a point in time, unless otherwise defined to include additional ecosystem components, in units of megagrams (Mg) or teragrams (Tg) of carbon (C).

Carbon accumulation—The net change in carbon stock of live tree biomass over a period of time, in units of megagrams (Mg) or teragrams (Tg) of carbon (C), per hectare (ha^{-1}) and/or or per year (yr^{-1}).

Metric ton—In the literature, the term metric ton (Mt or tonne) is often used instead of megagram.

Definitions of other terms commonly used in this paper are included in the **supplementary material**.

To apply our method to each national forest, recent FIA data collected by the U.S. Forest Service were queried using the EVALIDator online query system (USDA Forest Service, 2022). The sampling approach and estimation methods of forest inventory variables in the FIA database follow documented procedures (**Supplementary material**; Bechtold and Patterson, 2005). Our analysis is focused on above-ground carbon in live-trees, though some representative data are also presented about all ecosystem C pools to show the full potential of protecting carbon stocks on selected national forests.

2.3. Study area

The study area includes 11 individual national forests or small groups of national forests in the conterminous U.S. (**Table 1** and **Figure 1**), selected to represent the geographic diversity of U.S. forests and to have at least one forest in each USFS region. Forests with similar characteristics within a region were grouped if preliminary analysis determined that there were insufficient sample data to develop the biomass distributions for a single forest by main forest types.

2.4. Defining larger trees and mature forests

We combine two key indicators—stand age and tree diameter—in a way that could be used by land managers to assess maturity for informing management practices, in contrast to basing maturity and management on either tree diameter or stand age alone as in some previous studies (Mildrexler et al., 2020; Johnston et al., 2021). Mature forests are defined as stands with ages exceeding that at which accumulation of carbon in biomass peaks as indicated by NPP. We considered FIA sample plots to represent stands of relatively uniform condition. The sampled areas and trees are partitioned into uniform domains during field sampling and data processing if more than one stand condition falls within the sampling area. For this study, a new term "Culmination of Net Primary Productivity" (CNPP) is used to describe the age at which NPP reaches a maximum carbon accumulation rate. Physiologically, peak productivity occurs approximately at the age when the growing space in the

TABLE 1 National Forests, sampling dates, and number of sample plots used in our study.

National Forest	FIA sampling dates	Number of sample plots
Gifford Pinchot, WA	2008–2019	626
Malheur, OR	2011–2019	758
Black Hills, SD	2013–2019	348
Chequamegon-Nicolet, WI	2013–2019	559
Green Mountain, VT and White Mountain, NH	2013–2019	580
Appalachian National Forests[1]	2013–2020	982
White River, CO	2010–2019	291
Flathead, MT	2010–2019	341
Arizona National Forests[2]	2010–2019	849
Central California National Forests[3]	2011–2019	410
Arkansas National Forests[4]	2017–2021	427

[1]Pisgah (NC), Nantahala (NC), Cherokee (TN), Monongahela (WV), Jefferson (VA), George Washington (VA).
[2]Coconino, Prescott, Tonto, Sitgreaves, AZ.
[3]Eldorado, Stanislaus, and Sierra, CA.
[4]Oachita, Ozark-St. Francis, AR.

ecosystem is fully covered by leaf area—i.e., tree canopy closure reaches 100%. After this age, NPP either stays constant or declines gradually, depending on tree species composition, and other environmental factors such as nutrient availability (Kutsch et al., 2009; He et al., 2012). Previous analyses of FIA data indicate that peak NPP occurs at a relatively young stage of stand succession, roughly 25—50 years following stand establishment (**Figure 2**; He et al., 2012; Dugan et al., 2017; Birdsey et al., 2019). Foresters have a similar metric, referred to as the "culmination of mean annual increment" (CMAI), that is based on estimated net volume increment (i.e., volume growth minus mortality) as a function of age, rather than net productivity as a function of age, which is more relevant to assessing forests potential to reduce greenhouse gases. CMAI is calculated in the same way as CNPP, except that the mean annual increment variable is net volume increment instead of net primary productivity.

Larger trees are then defined as having a diameter at breast height (dbh) that is equal to or greater than the median diameter in forest stands at or near the age of stand-level CNPP. A range of ages around the age of CNPP, taken to be the CNPP age plus or minus one age class (30-year bin size), was used in order to have sufficient FIA sampling plots (generally 100 or more) to develop a tree diameter distribution for individual forest types. Then the median diameter of the distribution is used as the lower diameter threshold of maturity for the population of trees in the CNPP age class.

Our approach involves clustering (post-stratifying) sample plots by forest type and stand age class, and individual sample trees by tree diameter class, and then calculating estimates for the clusters (populations) as groups. Because most clusters include a wide distribution of tree diameters, there can be larger trees present in stands having ages below CNPP age, and *vice versa*, stands with ages above CNPP age can have trees with diameters below the lower diameter limit. The definitions of mature stands and associated larger trees in this study is conceptually consistent with stages of maturity derived from classifying FIA sample plots (Stanke et al., 2020; USDA Forest Service, 2022) and from an approach involving spatial data (DellaSala et al., 2022a). **Table 2** compares the terminology and approaches of each.

To estimate the area of mature stands based on sample plot characterization, we used the FIA stand-size variable coded as "large diameter" (column 2 of **Table 2**) because our method is not based on stand-scale variables alone but rather a crosswalk

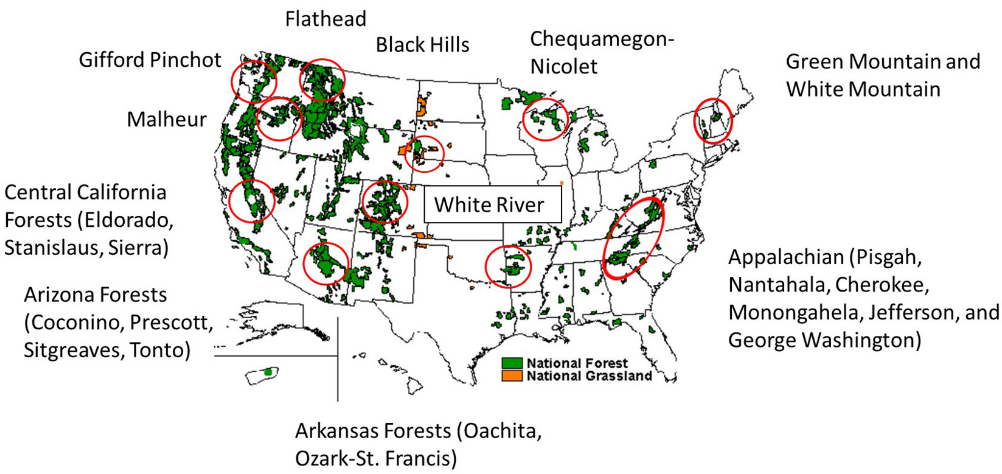

FIGURE 1
Approximate locations of 11 National Forests in our study area.

of stand and tree population variables. Large diameter stands are defined by FIA as those with more than 50 percent of the stocking in medium and large diameter trees, and with the stocking of large diameter trees equal to or greater than the stocking of medium and small diameter trees.

2.5. Estimation of carbon stock and accumulation in living biomass

We used the age-to-diameter crosswalk to estimate live above-ground carbon stocks and annual carbon accumulation for larger trees in forests above the CNPP threshold. We focused on live above-ground biomass since it is typically the largest of the C pools (except for soil in some cases) and is the most dynamic in terms of how carbon stocks and accumulation change with age or tree size (Domke et al., 2021). The estimated carbon in biomass of trees or stands is taken directly from the FIA database and is based on measurements of dbh and height. The current standard FIA approach to estimating biomass from tree measurements uses the component ratio method (Woodall et al., 2011). Unless stated otherwise, we use the term "carbon" to refer to carbon in live-tree biomass, not the carbon in all ecosystem carbon pools. Live-tree biomass includes the main stem or bole of the tree, rough or rotten sections of the bole, tree bark, branches, and leaves.

Estimation of the carbon accumulation rate is based on remeasurement of the same grid of sample points and trees at intervals ranging from 5 to 10 years depending on the state, with generally shorter remeasurement cycles in the eastern U.S. compared with the western U.S. (**Table 1**). Carbon in live-tree biomass was estimated at the beginning and end of the time period, and carbon accumulation was calculated as change in carbon over the period divided by the number of years.

The uncertainty of estimates of carbon stock and carbon accumulation was taken directly from the FIA data retrieval system that reports sampling error with 67% confidence, which we multiplied by 1.96 to report estimates with 95% confidence. These uncertainty estimates do not include the uncertainty of using biomass equations to estimate

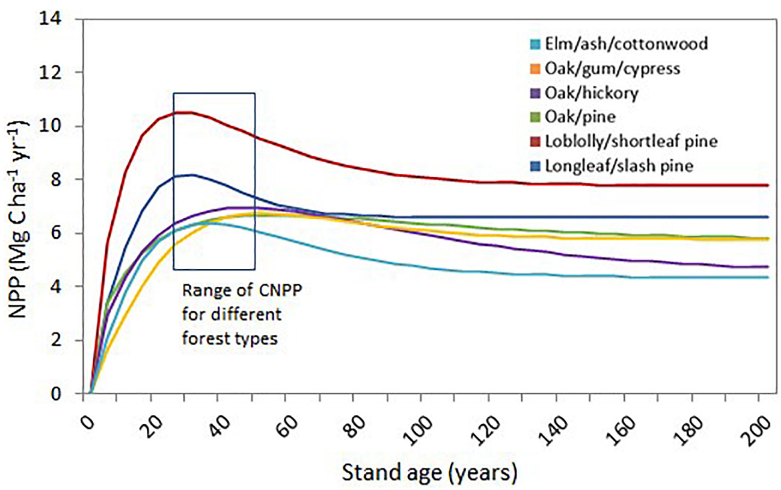

FIGURE 2
Net primary productivity (NPP) for selected forest types in the South (He et al., 2012). Culmination of NPP (CNPP) occurs at the stand age having the greatest annual increment rate, typically at or just after the tree canopy closes. Younger stands are those with ages less than CNPP. Older stands have ages greater than CNPP. CNPP is highly variable among forest types and geographic regions—in this example, from ages 23 to 45. The He et al. (2012) paper includes detailed uncertainty analyses of these and other NPP curves.

TABLE 2 Successional stages of forest maturity or stand structure as defined by several studies.

Maturity or structural stage	FIA stand-size[1]	Stanke et al. (2020)[1]	DellaSala et al. (2022a)[2]	This study[3]
1	Small diameter	Pole	Young	Young
2	Medium diameter	Mature	Intermediate	Mature
3	Large diameter	Late	Mature/Old-growth	

Classifications across the rows are similar but not identical.
[1] Stand structural stage is classified based on the relative basal area of canopy stems in various size classes.
[2] Forest maturity model based on three spatial data layers of forest cover, height, and above-ground living biomass for all landownerships.
[3] Based on culmination of net primary productivity (CNPP) and median stand diameter at CNPP. Late succession or old-growth not distinguished from mature.

tree carbon from diameter and height measurements or from wood density.

2.6. Domains and filters

We filtered the data to include only sample plots that were classified in the database as belonging to the national forest or group of forests being analyzed. For estimating CNPP, we screened out sample plots if they showed evidence of logging or natural disturbance. The remaining "undisturbed" stands, however, could still include some tree mortality and loss of live biomass associated with aging and succession, or small-scale disturbances. All plots including those disturbed or harvested were included in final estimates of the carbon stock and accumulation for the whole forest or for reserved and unreserved areas within the National Forest. Reserved and unreserved areas were defined by the FIA database variable "reserved class." The classification of reserved is not the same as land defined as "protected" by the USGS GAP analysis project (USGS, 2019). Reserved land is withdrawn by law(s) prohibiting the management of land for the production of wood products, though tree harvesting may occur to support other management objectives. We use the classification "unreserved" as a proxy for forest areas that are lacking protection from timber harvest, while acknowledging that this definition of unreserved land may not be consistent with other definitions of unprotected land.

2.7. Model outputs

Estimates of carbon stock and accumulation are presented separately for reserved and unreserved forest areas since the target for future management policies may focus on carbon stocks of older forests in areas that could be logged in the future. Some additional details regarding definitions and calculation protocols are available in the **Supplementary material**.

3. Results

3.1. National forest characteristics

Individual forests and groups of forests range in forest area from about 0.4 to 2.0 million hectares (M ha), and the total area of all forests analyzed is about 8.9 M ha (**Table 3**). The carbon stock in above-ground biomass ranges from 9 to 113 million megagrams (Mg). There is a wide range of average C density, with the lowest amount of 21 Mg ha^{-1} in Arizona National Forests, and the highest amount of 166 Mg ha^{-1} in the Gifford Pinchot National Forest in Washington. The total carbon in the forest ecosystems, which includes above- and below-ground biomass, dead wood, litter, and soil, is from 2 to 5 times the amount of carbon in above-ground biomass alone (Domke et al., 2021). All but one of the national forests studied (the Black Hills National Forest in South Dakota) experienced an increase in above-ground carbon over the

TABLE 3 Biomass carbon stock and accumulation for all live-trees greater than 1 inch (2.54 cm), for each National Forest or group of forests studied.

National Forest	Total forest area (ha)	Total biomass C stock (Mg)	Total biomass C accumulation[1] (Mg yr^{-1})	Average C density (Mg ha^{-1})	Average C accumulation[2] (Mg $ha^{-1}yr^{-1}$)
Gifford Pinchot	508,502	84,233,113	878,348	166	1.73
Malheur	584,951	23,566,550	234,124	40	0.40
Black Hills	394,508	9,130,825	−32,622	23	−0.08
Chequamegon-Nicolet	583,050	30,777,312	607,023	53	1.04
Green and White Mountains	478,285	35,572,874	299,164	74	0.63
Appalachian Forests	1,216,520	112,798,380	1,122,302	93	0.92
White River	685,869	30,887,524	N/D	45	N/D
Flathead	906,902	39,688,676	N/D	44	N/D
Arizona Forests	2,083,049	43,194,094	N/D	21	N/D
Central California Forests	996,197	86,238,281	125,730	87	0.13
Arkansas Forests	454,986	64,714,071	1,498,668	142	3.29
Total	8,892,819	560,801,700	4,732,737	63	0.91

[1]Change in carbon stock over approximately the last 10 years.
[2]Average of national forests with available growth data from FIA database.
"N/D" means data were not available.

remeasurement period, ranging from 0.13 (Central California) to 3.29 (Arkansas) Mg $ha^{-1}yr^{-1}$. All of the national forests were affected by disturbances—the most common being fire, insects and logging—though the areas and mix of disturbance types that occurred and the areas undisturbed are highly variable among the forests (**Supplementary Table 1**). Natural disturbances can result in significant tree mortality and transfer of carbon from live to dead trees, and gradual net emissions over several decades especially if the disturbances are of high severity (Birdsey et al., 2019). In the case of logging disturbances, emissions are significant both in the near term and over time, even when accounting for the amount of carbon in the harvested live trees that is initially transferred to the long-term harvested wood product pool (Hudiburg et al., 2019).

3.2. Culmination of net primary productivity and diameter limits

The estimated CNPP ages range from 35 to 75 years among the 11 National Forests with an average age of 50 years (**Table 4**) and are highly variable by forest type within each forest (**Supplementary Table 2**). Productivity at CNPP ranges from <1.0 to about 4.0 MgC $ha^{-1}yr^{-1}$, which is higher than the average productivity among all age classes since it represents the peak value. Typically, the productivity values after CNPP age decline at a variable rate by region and forest type (**Figure 2**). The estimates of CNPP age may be affected by sparse data points for some age classes, different stand disturbance histories, and other factors that influence tree growth rates over time such as climate and topography. In this study, the age at CNPP is used to define the lower age threshold for mature forests.

Determining the age threshold associated with CNPP involves examining the distribution of biomass by diameter (dbh) class for the stand-age class window around the age of CNPP. In most cases, there is a clearly defined peak of biomass at the median diameter of the distribution (**Supplementary Figure 1**). Because of the diversity of stand conditions associated with CNPP across the landscape, as well as uneven aged stand conditions, there are rather wide distributions of tree sizes associated with any particular CNPP (**Supplementary Figure 1**). Since the FIA stand-age data we used were compiled into diameter classes of 2 inches (5 cm), we used the upper end of the range to define the diameter threshold. Typically, there is more carbon stored in the population of trees with diameters at and near the diameter at CNPP, though these trees can grow to much larger sizes as indicated by the upper end of the diameter distributions. For the national forests in this study, the diameter limits ranged from a low of 4 inches (10 cm) for Douglas-fir in the Flathead National Forest to a high of 18 inches (46 cm) for two forest types in the Central California National Forests (**Supplementary Table 2**). Combining CNPP with median diameter in a cross-tabulation results in identifying the carbon stocks in larger trees in mature forests for each national forest, highlighted in yellow in the example table (**Supplementary Table 3**).

TABLE 4 Average age and tree diameter at culmination of net primary production (CNPP), all forest types combined on 11 National Forests in our study area.

National Forest	Average CNPP age (Years)	Diameter threshold (Inches/cm)
Gifford Pinchot	45	13/33
Malheur	45	12/30
Black Hills	75	14/36
Chequamegon-Nicolet	45	9/23
Green and White Mountains	35	12/30
Appalachian Forests	35	11/28
White River	55	6/15
Flathead	45	8/20
Arizona Forests	75	12/30
Central California Forests	50	16/41
Arkansas Forests	40	10/25
Average of all Forests	50	11/28

Tree diameters represent the lower age bound of mature forests (i.e., age at CNPP). Detailed ages and tree diameters by forest type are shown in supplementary Table 2.

3.3. Comparison of CNPP and CMAI

Evaluation of forest inventory data indicated that CNPP and CMAI occur at about the same age (**Supplementary Figure 2**). Some older studies based on different data, mainly from volume growth and yield studies, associate CMAI with a greater age (e.g., McArdle, 1930). This difference is likely caused by several factors such as management intensity, temporal changes in productivity from environmental changes, and sampling protocols.

3.4. Carbon stocks and accumulation of larger trees in mature stands

The total C stock and C accumulation of larger trees in stands older than age at CNPP compared with all trees and stands is highly variable among the different forests analyzed (**Table 5**). Likewise, sampling errors are highly variable, reflecting the total areas classified as mature and therefore the number of FIA sample plots therein. Sampling errors for C accumulation estimates are significantly higher than for C stocks, mainly because the variability of accumulation rates among sample plots is higher than the variability of stock estimates.

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TABLE 5 Estimated area, carbon stock, carbon accumulation, and sampling errors for larger trees in mature stands within individual National Forests based on most recent forest inventory data (Table 1).

National Forest	Area (ha)	C Stock (Mg)	C stock sampling error[1] (%)	Net C accumulation (Mg yr^{-1})	Net C accumulation sampling error[1] (%)	C stock[2] (% of total NF)	Net C accumulation[2] (% of total NF)
Gifford Pinchot	440,005	68,148,420	5.5	380,998	22.7	80.9	43.4
Malheur	471,439	16,886,265	7.1	165,949	19.1	71.7	70.9
Black Hills	215,379	3,711,144	14.6	−15,167	82.2	40.6	−46.5
Chequamegon-Nicolet	303,176	20,625,499	6.9	281,034	11.9	67.0	46.3
Green and White Mountains	301,884	15,786,690	7.9	60,593	141.7	44.4	20.3
Appalachian	1,033,833	83,571,980	6.2	675,970	15.3	74.1	60.2
White River	390,370	26,038,059	13.1	N/D	N/D	84.3	N/D
Flathead	507,053	27,841,625	13.6	N/D	N/D	70.2	N/D
Arizona National Forests	1,738,672	36,254,717	11.2	N/D	N/D	83.9	N/D
Central California National Forests	821,991	65,973,313	8.8	−66,370	52.2	76.5	−52.8
Arkansas National Forests	384,972	41,808,132	6.3	619,759	13.5	64.6	41.4
Total/mean	6,608,774	406,645,844	[redacted]	2,102,766	[redacted]	72.5	44.4

[1]With 95% confidence.
[2]Calculated by dividing values by those in Table 3. The percentages of carbon stocks and accumulation of larger trees in mature stands compared with all forests are also shown (last 2 columns). Larger trees in mature stands are the subset of the forest population composed of trees greater than the median dbh associated with CNPP in stands greater than CNPP age (Figure 2). Areas of mature forests estimated by a proxy variable "stand-size class" from FIA (see methods).
"N/D" means data were not available.

Of the 11 forests, the C stock of larger trees in mature stands ranged from 41 to 84 percent of the total C stock of the forests, whereas C accumulation ranged from −53 to 71 percent of the total C accumulation. This difference between changes in C stock and C accumulation reflects several underlying causes: (1) younger forests can have higher NPP rates than mature forests as illustrated in **Figure 2**; (2) increasing mortality as forests grow older because some trees die from overcrowding or insects and diseases; and (3) disturbances such as severe wildfire that kill significant numbers of trees can reduce NPP, in some cases to a negative number.

3.5. Carbon stocks and accumulation in mature stands and larger trees in unreserved forest areas

The methodology described above can be further refined to separate out unreserved areas that could be designated for protection of carbon stocks and accumulation on national forest lands. In the 11 forests analyzed, unreserved C stocks of larger trees from all tree species in mature stands ranged from 36 to 69 percent of total C stocks (**Table 6** and **Supplementary Table 4**). Unreserved C accumulation of such trees in mature forests ranged from 12 to 60 percent of total C accumulation, not including the Black Hills national forest where the unreserved C accumulation was negative because of logging and natural disturbances (primarily insects). Typically, one or a few species comprise the main part of unprotected stocks and accumulation. Generally, the percentage of unreserved C accumulation is less than the percentage of unreserved C stock because the growth rates of mature forests are somewhat lower than younger forests.

3.6. Potential protected carbon stocks with variable diameter and age limits

The final stage of the analysis estimated the amount of C in unreserved areas above variable diameter and age limits for logging (**Supplementary Table 5**). These data further illustrate the functionality and flexibility of the age to diameter association that we developed for policy makers and land managers. The impact of selecting either the diameter limit or the age limit, or both, is highly dependent on the distribution of the estimated C stocks by these factors. For example, the diameter limit for Gifford Pinchot at a stand age of 80 years (20 inches; 51 cm dbh) would protect 57% of the total above-ground C, and the age limit of 80 years would protect 79% of the total above-ground C. In contrast, the diameter limit for Chequamegon–Nicolet at a stand age of 80 years (13 inches; 33 cm dbh) would protect only 27% of the total above-ground C, and the age limit of 80 years would protect only 48% of the total above-ground C. Each of the studied forests has a unique pattern of unreserved C based on diameter or age limits.

4. Discussion

4.1. Summary of results

The average age of maximum carbon accumulation (CNPP) ranged from 35 to 75 years for all forest types combined (**Table 4**), and the ranges were wider for individual forest types (**Supplementary Table 2**). Many factors contribute to determining the CNPP age (e.g., tree species, competition, site productivity, and climate). The lowest CNPP ages were estimated for the eastern forests in the southern and northern Appalachian regions, while the highest CNPP ages were found in the West. Typical diameter thresholds that separate smaller from larger trees (based on CNPP age) ranged from 6 to 16 inches (15–41 cm), with larger diameter thresholds found in the Western forests. The unprotected carbon stock of larger trees in mature stands ranged from 4 to 74 million MgC (**Table 6**), representing between 36.0 and 68.3 percent of the total carbon in the forest biomass. Forests with the highest percentage of unprotected carbon stock in larger trees in mature forest stands included Gifford Pinchot, Malheur, Chequamegon–Nicolet, and Appalachian National Forests. The unprotected carbon accumulation of larger trees in mature stands ranged widely from 11.5 to 60.2 percent of the total carbon accumulation in biomass, with one forest (Black Hills) showing a reduction in biomass.

4.2. Diameter and age thresholds

Our approach to establishing mature forest definitions and diameter thresholds for larger trees is rooted in a crosswalk of stand age and tree diameter that integrates two variables used to describe mature forests and trees. Both tree diameter and stand age have been used independently in the past to identify the lower bounds of maturity and provide guidance for on-the-ground tree and forest management decision rules (Mildrexler et al., 2020; Johnston et al., 2021). The two variables complement each other because although age is a good indicator of stand maturity, it can sometimes be difficult to determine a precise stand age in the field especially for stands of multi-aged trees, whereas tree diameter is an easily and accurately measured variable in any forestry operation. While our approach lacks complexity, it can form the foundation for more detailed analyses needed to guide on-the-ground management decisions.

Our approach is based on the application of FIA data, a standard source of detailed field inventory data for all forests of the U.S. that is readily available to the public and continuously updated. There are sufficient sample plots to evaluate most

TABLE 6 Carbon stocks and accumulation in larger trees in mature stands in unreserved forest areas, all forest types, within 11 National Forests in our study.

National Forest	Unreserved C stock		Unreserved C increment	
	Mg	% of total C[1]	Mg yr^{-1}	% of total C increment[1]
Gifford Pinchot	57,074,409	67.8	378,553	43.1
Malheur	16,103,923	68.3	108,878	53.7
Black Hills	3,625,966	39.7	−22,597	−69.3
Chequamegon-Nicolet	19,949,333	64.8	271,540	44.7
Green and White Mountains	12,794,081	36.0	60,821	20.3
Appalachian	74,359,965	65.9	675,969	60.2
White River	17,767,821	57.5	N/D	N/D
Flathead	18,383,736	46.3	N/D	N/D
Arizona National Forests	23,540,573	54.5	N/D	N/D
Central California National Forests	51,225,061	59.4	14,483	11.5
Arkansas National Forests	40,184,951	62.1	747,726	49.9
Total	335,009,819	59.7	2,235,373	47.2

[1]Calculated by dividing values by those in Table 3. Percentages of total forest C stock and accumulation are included. Detailed estimates by forest type are in supplementary Table 4.

National Forests individually or in groups, and different forests or regions can be compared or aggregated using consistent and high-quality data. Furthermore, FIA data have become a standard for many other forest analysis tools and greenhouse gas registries (Hoover et al., 2014), so consistency across platforms is also feasible. Finally, there are developments underway to integrate FIA-based ground data analysis with other approaches based on remote sensing and mapping to support policy and land management (Dugan et al., 2017; Harris et al., 2021; Hurtt et al., 2022), which is the objective of future research building directly on this study and related work (DellaSala et al., 2022a).

Moreover, using CNPP as the threshold for stand maturity is an extension of and a refinement on prior work. The concept of CNPP is closely related to CMAI, which has been used for many decades to describe the point at which tree volume increment is greatest in the maturation of a forest stand for assessing return on investment in forestry operations (e.g., Assmann, 1970; Curtis, 1994) but more recently has been proposed as a way to identify the minimum age of ecosystem maturity for protection efforts (Kerr, 2020). Published CMAI estimates are often derived from managed forests and plantations, which limits their applicability to low-intensity management regimes. Also, CNPP is more closely related than volume to the carbon variables of interest (C and CO_2) for analyses of climate mitigation potential by the forest sector to reduce emissions or remove atmospheric CO_2. Considering the uncertainties of establishing the exact age for forests that did not originate as tree plantations, CNPP and CMAI often occur at similar ages in the life of forests, that is, at or very near the age of crown closure and the onset of tree physiological maturity (Burns and Honkala, 1990; Groover, 2017).

4.3. Uncertainty and data limitations

Most forests or groups of forests studied had sufficient sample plots to keep uncertainty of carbon estimates (described in methods) within 15% of the estimated values (Tables 1, 5). In contrast, the uncertainties of carbon accumulation estimates were significantly larger and more variable, ranging from 13 to 142% of the estimated values (Table 5). Although the same number of sample plots were available for both estimates, the variability of C accumulation estimates was much higher in some cases, most likely because C accumulation has higher interannual variability if affected by natural disturbances, tree mortality, and tree growth rates that can vary from year to year. Although the reported uncertainty is related to sample size and variability of the tree populations studied, there is additional uncertainty associated with the biomass models used to estimate above-ground biomass carbon. The error of biomass models typically ranges from about 10–15% for large forest areas, with 95% confidence (US Environmental Protection Agency, 2021).

Our ecosystem C estimates only include above-ground live biomass in trees greater than one-inch (2.4 cm) dbh. C pools in standing and down dead wood, understory vegetation including tree seedlings, litter on the forest floor, and soil C account for significantly more C that could double or quadruple the amount of estimated C stock depending on the geographic location of the forest and other land characteristics such as physiography and soil depth (Domke et al., 2021; US Environmental Protection Agency, 2021). Above-ground live biomass is typically the most dynamic of the C pools in forests, though in some cases, particularly related to logging and natural

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disturbance, the dead wood and litter C pools may change significantly over short periods of time (Domke et al., 2021).

Forest age is an important variable used to estimate when NPP reaches a maximum value (CNPP) above which forests are considered mature. However, forest age (or time since disturbance) can be difficult to determine especially for uneven- or multi-aged forests and is based on coring trees and counting tree rings from just a few sample trees on a sample plot in the FIA sampling protocol. It is likely that the sample trees that are cored do not represent the population of larger and older trees on a sample plot, meaning that the assigned age could be biased to younger ages (Stevens et al., 2016). In some cases, the NPP curve is rather flat at and around the age of CNPP, making it difficult to identify the precise age associated with CNPP. Despite these issues, age is an easily understood metric that is closely related to forest maturity, and the approach of identifying the median diameter associated with CNPP using a 30-year window of age classes helps to mask the uncertainty of using age as a critical step in the methodology.

4.4. Policy and management implications

Recent policy goals target "net zero" emissions for all sectors by 2050 to arrest the global climate emergency. Since net zero cannot be achieved by reducing fossil fuel emissions alone (United Nations, 2015; Griscom et al., 2017), the potential of nature-based climate solutions to contribute to this larger goal is the subject of legislation and executive orders in the U.S. The approach and methodology developed here are designed to inform policy makers about federally managed mature forests and their large and vulnerable C stocks and high rates of accumulation of carbon from the atmosphere. Some recent legislation and executive orders specifically call for increased analysis of the current and potential role of mature forests and large trees (White House, 2021, 2022b; U.S. Congress, 2022). The approach and methods presented here provide options for policy makers to consider as the specific land management rules are implemented by agencies for national forest lands.

Our study further corroborates that large areas of mature federal forests are significant carbon sinks that lack protection. Results indicate that 10 of the 11 forests analyzed were carbon sinks over the last decade or so, with the largest sinks occurring in the Eastern U.S. Forests with less disturbance and/or younger age-class distributions had greater increases in above-ground carbon per area than forests with higher rates of disturbance and/or older age-class distributions. These observations reflect multiple factors: the past history of management, trends in incidence and severity of recent natural disturbances and logging, and the inherent age at which the productivity of different forest types begins to level-off or decline. We also note an important distinction that rates of carbon accumulation tend to be higher in younger forests while the largest amounts of stored carbon are found in mature forests. Protecting these carbon sinks and avoiding losses of carbon from logging would require a policy shift to focus more on the potential role of federal forests in climate mitigation (DellaSala et al., 2022a). Such a shift requires considering how both natural disturbances (exacerbated by climate change) and harvesting are emitting carbon stored in larger trees across federal forest lands. In this context, it is notable that national and regional estimates of emissions from logging (direct plus lifecycle emissions) are 5–10 times greater than direct emissions from natural disturbances (wildfire, insects, and wind combined) (Harris et al., 2016; Law et al., 2018).

For operational land management practices, it is often easier to apply a diameter limit in timber operations by species than an age limit by forest type, because as noted previously it can be challenging to determine a precise stand age, whereas measuring tree diameter is simple and accurate [although see DellaSala et al. (2022a) for an alternate approach to stand maturity without age or dbh determinations]. The diameter limits derived here are based on stand age at CNPP and so have that element of maturity embedded in their determination. And, as noted, this approach can be used regardless of the age selected. For some forest types, stand level characterization is obscured by their frequent association with selective logging and/or natural disturbances like wildfire, making larger trees the more appropriate component for defining maturity.

The results presented here by region and forest type reveal that there is a wide variation in CNPP age and associated tree diameters reflecting variation in forest type/composition, climate, competition for resources and soil moisture, disturbance dynamics, site productivity, and geographic region. This variability needs to be considered in developing policies and management practices. It is also important to consider risks of loss to stored C from natural disturbances, and other values of forests that are tied to land management objectives, which may or may not be compatible with increasing C stocks and accumulation.

We developed an approach to assess mature forests and their current carbon stock and accumulation benefits, and applied the methods to 11 different case studies of individual or groups of National Forests that can inform implementing the president's executive order. This method can be applied regardless of how mature stands are defined (e.g., it is readily applicable to age thresholds above CNPP). And this ground-based estimation approach can be linked with remote sensing and mapping approaches (e.g., DellaSala et al., 2022a) to provide a geographic view of forest maturity as well as protected status beyond the reserved/unreserved designation available in the FIA database.

This work can also be extended to more clearly identify that subset of mature forests that are truly old-growth, and estimate the associated carbon stocks and accumulation. As forests get older, they tend to have very large and increasing carbon stocks, making them especially valuable as carbon reserves (DellaSala et al., 2022a; Law et al., 2022). Even when threatened by natural disturbances or climate change, there is substantial evidence that old-growth forests can continue to maintain or increase carbon stocks (Stephenson et al., 2014; Law et al., 2018; Lesmeister et al., 2021; Begović et al., 2022). Building upon our definition of mature forests, future research could further inform management decisions by more clearly and consistently identifying those mature forests that are truly old-growth or that potentially could become old-growth, and estimating their carbon stocks and accumulation.

5. Conclusion

Our study presents a framework for in-depth analysis and management of larger trees and mature forests on federal lands. The integration of basic data about stand age, tree diameter, biomass carbon dynamics, and reserved status comprises the main elements of the methodology. After applying the methods to 11 national forests, we found that the unprotected carbon stock in larger trees in mature stands ranged from 36 to 68% of the total carbon in tree biomass. The unprotected annual carbon accumulation in tree biomass of larger trees in mature stands ranged from 12 to 60% of the total accumulation in all trees. The potential climate impact of avoiding emissions from logging larger trees and mature forests is thus significant. Key discussion points focused on uncertainty, policy implications, and land management practices. This work is highly relevant to emerging policies regarding climate change, nature-based climate solutions, and mature forests including the role of larger trees.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.fia.fs.usda.gov/tools-data/.

Author contributions

RB led the research along with GR and DD. All authors contributed to the writing.

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Conflict of interest

GR and CR were employed by Natural Resources Defense Council, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.1074508/full#supplementary-material

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