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Quantifying old-growth forest of United States Forest Service public lands

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A B S T R A C T

Old-growth forests are globally valued for their ecological attributes, cultural significance, and in many cases their rarity. Yet, defining and quantifying these forests has been a difficult task. This study developed an approach to consistently estimate extent of old-growth forest on United States Department of Agriculture (USDA) Forest Service National Forest System (NFS) lands, using NFS regional old-growth definitions applied to the US national forest inventory (conducted by the USDA Forest Service Forest Inventory and Analysis [FIA] program). This method was developed in response to a presidential order (EO#14072, April 22, 2022) and federal laws (e.g., Infrastructure Investment and Jobs Act, 2021; Inflation Reduction Act, 2022). We worked with NFS experts to obtain regionally approved criteria for establishing old growth status based on NFS definitions, assessments, and related documents. NFS regional old growth definitions focus on structural characteristics of forests with criteria for old growth status commonly including minimum abundance of large live trees (in eight of nine regions), tree or stand age (in eight of nine regions), and dead large tree density (in three of nine regions). Determining the regional criteria to use was straightforward for some NFS regions where old-growth forest definitions were specific, and in some cases, had already been applied to FIA data to quantify old-growth forest area. In other NFS regions, such as where definitions have never been applied in an operational manner, or where there were merely assessments of remnant old-growth forest conditions, determining exact criteria was more difficult. We estimate that there are approximately 10 million ha of old growth across NFS forests, as defined by NFS criteria, with the preponderance in the western US states. This study produces the first old-growth forest assessment at the national scale based on NFS definitions and FIA's statistically-rigorous national forest inventory of the US. These methods can be repeated with future inventories or modified when definitions change to produce updated estimates of old-growth forest attributes, and such work is already underway.

1. Introduction

Old-growth forests are globally valued for their ecological attributes, cultural significance, and in many cases their rarity. Yet, defining and quantifying these forests has proven to be a difficult task for decades. United States laws (Infrastructure Investment and Jobs Act, 2021; Inflation Reduction Act, 2022) and an executive order (Executive Order #14072, 2022) have directed federal agencies to define and estimate the extent of old-growth and mature forests because of the increasing interest in older forests and the ecosystem services they provide, especially in the context of global climate change. The classification of the old-growth stage in forest development has been a research topic for numerous decades and studies on definitions of old growth continue. The United States Department of Agriculture (USDA) Forest Service, National Forest System (NFS), is responsible for managing 78 million ha, 58 million of which is forested—or, 21% of all forested land in the country. This study proposes an initial quantification of old-growth forest extent on NFS lands with potential application on other federal lands (particularly Bureau of Land Management) as directed by EO#14072 using two primary data sources: 1) NFS old-growth

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definitions or assessments and regionally-approved criteria derived from these definitions; and, 2) data from the official national forest inventory of the US (Oswalt et al. 2019), conducted by the USDA Forest Service, Forest Inventory and Analysis (FIA) program.

Davis et al. (1996) argues that public perception of forests in the United States is shaped by two ends of a spectrum of forest conditions – 'natural' remnants of forest from before European settlement and forest recovering from near complete harvest in the previous century. This dichotomy is present on NFS lands: in the east, many NFS lands were purchased from private landowners, often after major cutting or other resource extraction, while in the western US, substantial portions of National Forests were formed from lands already in Federal ownership with little evidence of impact from colonization, despite the long presence of indigenous Americans (Shands 1992, Limerick 1992). This context has informed the studies that have sought to define old-growth forest in the US, where these exist, and how they will undoubtedly continue to evolve into the future. As reviewed by Wirth et al. (2009), attempts to define old-growth forest evolved from the 1940s (e.g., Andrews and Cowlin 1940), when the term 'virgin forest' was common, into the 1970s when published approaches to define these forests increased dramatically. However, definition development and acceptance are complex due to the wide variety of values associated with the old growth concept and emergent properties of forests that cannot be derived from tree measurement (e.g., Moore and Nelson 2023). Further, current understanding of the importance of non-equilibrium dynamics, disturbances to forest ecosystems and the significance of anthropogenic global change may lead to reconsideration of long-standing definitions of old-growth forests on NFS lands (e.g., Aplet and Cole 2010, Fraver et al. 2009, Kneeshaw et al. 2018, Woods 2000). See Gray et al. (2023) and Woodall et al. (2023) for companion discussion on the difficulty of defining and inventorying old-growth and mature forest related to this study.

The definition development approach of the USDA Forest Service NFS has focused on forest structure criteria as indicators of old growth. In 1989 the Chief of the Forest Service instructed each NFS region (Fig. 1) to establish definitions specific to local ecosystems that fit into this generic definition of old growth:

> Old-growth forests are ecosystems distinguished by old trees and related structural attributes. Old growth encompasses the later stages of stand development that typically differ from earlier stages in a variety of characteristics which may include tree size, accumulation of large wood material, number of canopy layers, species composition, and ecosystem function (USDA Forest Service 1989).

Each NFS region then jointly developed old-growth definitions or information documents (Table 1). Regions varied in the application of these definitions through Land Management Plans (LMPs) and regional guidance; in some cases, inventory systems were subsequently developed (such as for the NFS Northern Region and areas managed under the Northwest Forest Plan [Davis et al. 2022]). However, there has not been a national old-growth inventory on NFS lands based on these regional definitions.

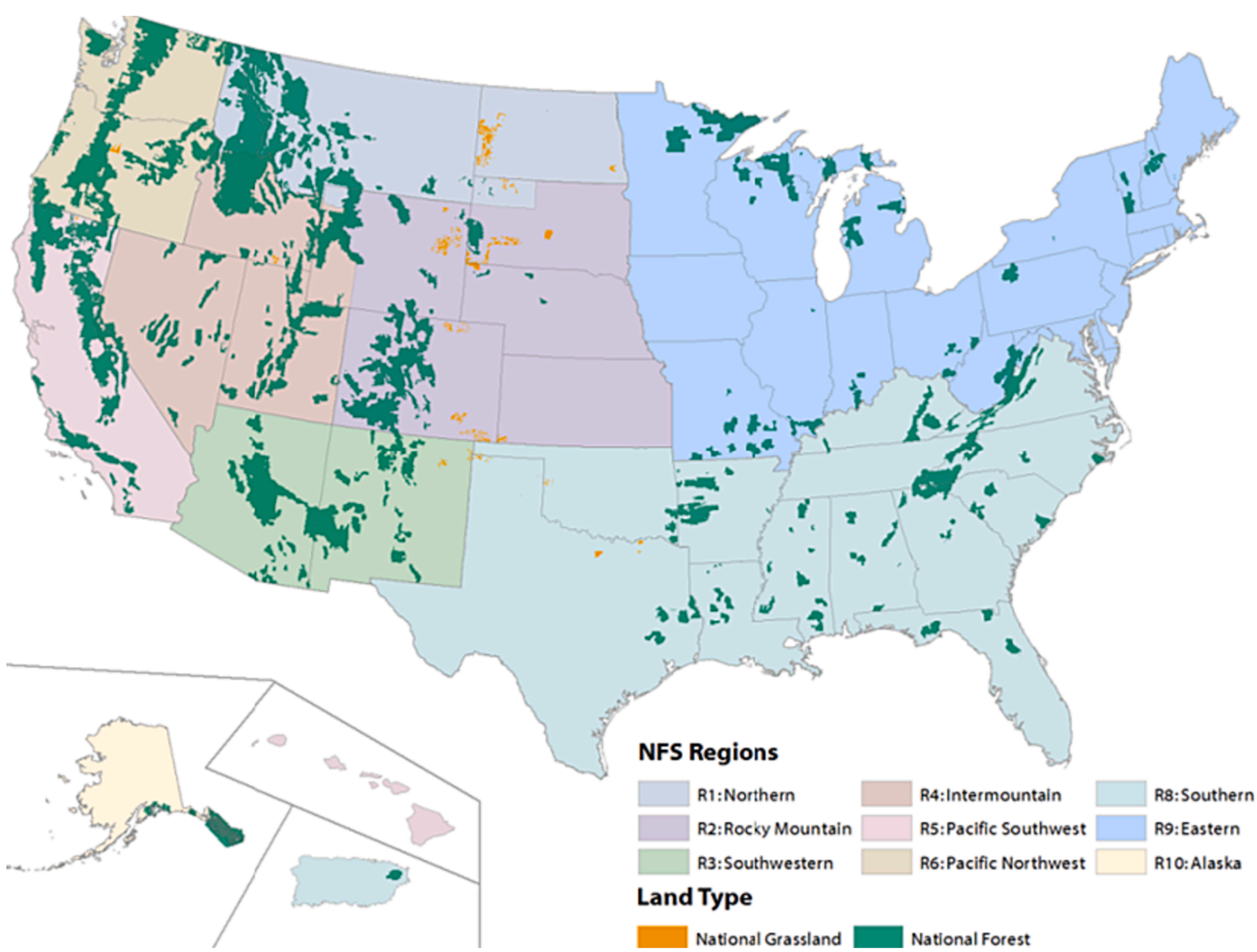

Fig. 1. Map of USDA Forest Service National Forest System (NFS) administrative boundaries and regions (map by Congressional Research Service (2016) from data available from Forest Service Geodata Clearinghouse, http://data.fs.usda.gov/geodata/). There is no NFS land in Hawaii.

Table 1
Regional USDA Forest Service National Forest System (NFS) documents used as basis for old-growth definitions, and derived criteria, in this study. Additional documents defining old-growth forest conditions exist in many regions (such as Popp [1992] for the NFS Southwestern Region). However, only the documents in this table were the primary sources modified by NFS regional experts working with FIA scientists to determine regionally approved old-growth forest criteria for this study.

NFS Region	Old-Growth forest documentation citation
1 - Northern Region	Green et al. (1992; errata 2011)
2 - Rocky Mountain Region	Mehl (1992)
3 - Southwestern Region	USDA Forest Service (2019)
4 - Intermountain Region	Hamilton (1993)
5 - Pacific Southwest Region	Beardsley and Warbington (1996)
6 - Pacific Northwest Region	USDA Forest Service (1993), Davis et al. (2022)
8 - Southern Region	Gaines et al. (1997)
9 - Eastern Region	Tyrrell et al. (1998)
10 - Alaska Region	Boughton et al. (1992a, 1992b)

The USDA Forest Service FIA program provides a sampling and estimation approach to produce statistically-rigorous estimates (with estimated uncertainty) of the extent of old-growth forest at NFS regional and national scales. FIA collects tree, stand, and site level variables associated with forests and their processes that can potentially be applied to NFS regional old growth definitions using forest attribute/structural criteria. In addition to providing a nationally-consistent approach for forest resource estimation (Bechtold and Patterson 2005, Westfall et al. 2022), the national FIA database is available to the public (Burrill et al. 2021). The FIA survey was developed as a strategic nationwide inventory for all forest conditions and ownerships, and therefore has potential limitations for identifying old-growth such as the size of field sampled plots, lack of individual tree ages (particularly in the eastern US), the forest attributes in existing data (e.g., continuous patch sizes are not available), and extent of the inventory (e.g., FIA is not complete in wilderness areas in Alaska).

The goal of this study was to develop and employ an initial, nationally-consistent approach for quantifying old-growth forest extent across USDA Forest Service NFS lands. Our goal was to produce a transparent, rapid method to connect NFS regional old-growth definitions with the nationally-consistent FIA inventory, with expectations that these methods could be refined in the future and be applied elsewhere, such as on Bureau of Land Management (BLM) lands as directed by EO#14072. The objectives of this study were: 1) to work with NFS regional experts to identify regional old-growth forest criteria that could be applied to FIA data based on existing NFS old-growth definitions; 2) to develop approaches to consistently classify FIA inventory observations as old growth for all NFS regions; and, 3) to estimate the extent of old-growth forest on NFS land, by NFS region and nationally.

2. Methods

2.1. Study area

The USDA Forest Service NFS manages 58 million ha of forested public land that provide globally significant ecosystem services (Oswalt et al. 2019) such as carbon stocks (Smith et al. 2019). This study focused on NFS forested lands (Fig. 1). 'Forested lands' were defined as those that met the FIA definition: areas that currently or recently had $\geq$ 10% tree canopy cover extending $\geq$ 0.4 ha, were $\geq$ 36.6 m wide, and had a forest land use (e.g., a city park with sufficient tree cover is not considered forested because this is not a forest land use) (Burrill et al. 2021).

2.2. General old-growth forest inventory approach

NFS experts assessed multiple approaches to define and measure the extent of old-growth forest in the US before initiating this study. An acceptable method needed to complete an initial inventory by April 22, 2023, as stipulated by executive order (Executive Order 14072, 2022), include established regional NFS definitions where they existed and build on existing NFS documentation and concepts where definitions were unavailable, and use existing datasets and analysis techniques that could produce estimates of forest area (and uncertainty) at a national scale. NFS experts examined datasets currently in use on National Forests, including stand-scale data housed in the USDA Forest Service Field Sampled Vegetation database (https://www.fs.usda.gov/nrm/fsveg/index.shtml), spatially explicit models using field-sampled and/or GIS and remotely-sensed information (such as Wilson et al. 2018), and others, before choosing to use the USDA Forest Service FIA dataset and estimation techniques (Burrill et al. 2021, Bechtold and Patterson 2005, Westfall et al. 2022) with a transparent workflow to enable repeatability and statistical rigor (Fig. 2).

2.3. National forest System old growth definitions and related documentation

NFS experts compiled regional definitions of old-growth forest for all nine NFS regions, drawing from scientific and management publications (Table 1; Fig. 1). Many regions continue to use old-growth forest definitions and criteria developed in the 1990 s in response to Forest Service national direction (USDA Forest Service 1989), but the degree of formal use varies widely. For example, these definitions and subsequent refinement have been applied to monitor old-growth forest in the Northwest Forest Plan area (e.g., Davis et al. 2022) and in the Northern Region (R1). In contrast, information about eastern old growth summarized in Tyrrell et al. (1998) did not lead to specific old-growth definitions for the Eastern Region (R9). The Southwestern Region's (R3) initial documentation on old-growth definitions (Popp et al. 1992) was replaced by desired conditions to support forest restoration (USDA Forest Service 2019). We worked with NFS regional experts to determine the criteria that could be applied to existing FIA data. NFS regions provided their approved criteria that were ultimately used to estimate old-growth forest area on NFS lands.

2.4. National forest inventory of the United States – Forest inventory and Analysis data

The USDA Forest Service FIA program is the Congressionally authorized strategic inventory of forested area and forest structural attributes of the United States. In 1998, an annual inventory system was mandated by Congress (Gillespie 1999), which includes a systematic national sampling design consisting of one plot per approximately 2,428 ha, allowing for unbiased estimates of forest resources across all ownerships on the entire landscape (Smith 2002, Bechtold and Patterson 2005, Westfall et al. 2022). Since then, the program has been enhanced with spatially-intensified plots across portions of NFS lands, resulting in one plot per approximately 809 or 1214 ha on lands in areas of the NFS Pacific Northwest, Southern, and Northern Regions. There is a nationally-consistent plot configuration with four, fixed radius sub-plots (7.32 m radius; with 0.067 ha total sampling area) and annual measurement of a constant portion (1/cycle length) of plots, otherwise known as a subpanel. Each subpanel is spatially balanced across each US state. FIA data are generally remeasured on a 10-year cycle in the western United States and on a 5 to 7-year cycle in the eastern US (McRoberts et al. 2005). Field-collected data is recorded on plots with the plots delineated into 'conditions' if there are unique, homogenous portions of forested land within a plot (e.g., unique forest types; USDA Forest Service 2022a). There can be one or multiple FIA 'condition(s)' on each plot, and these are the units aggregated by FIA's estimation procedures (Bechtold and Patterson 2005). To improve the precision of estimates, samples in the population of interest are post-stratified – they are assigned to strata, such as those derived from remotely-sensed

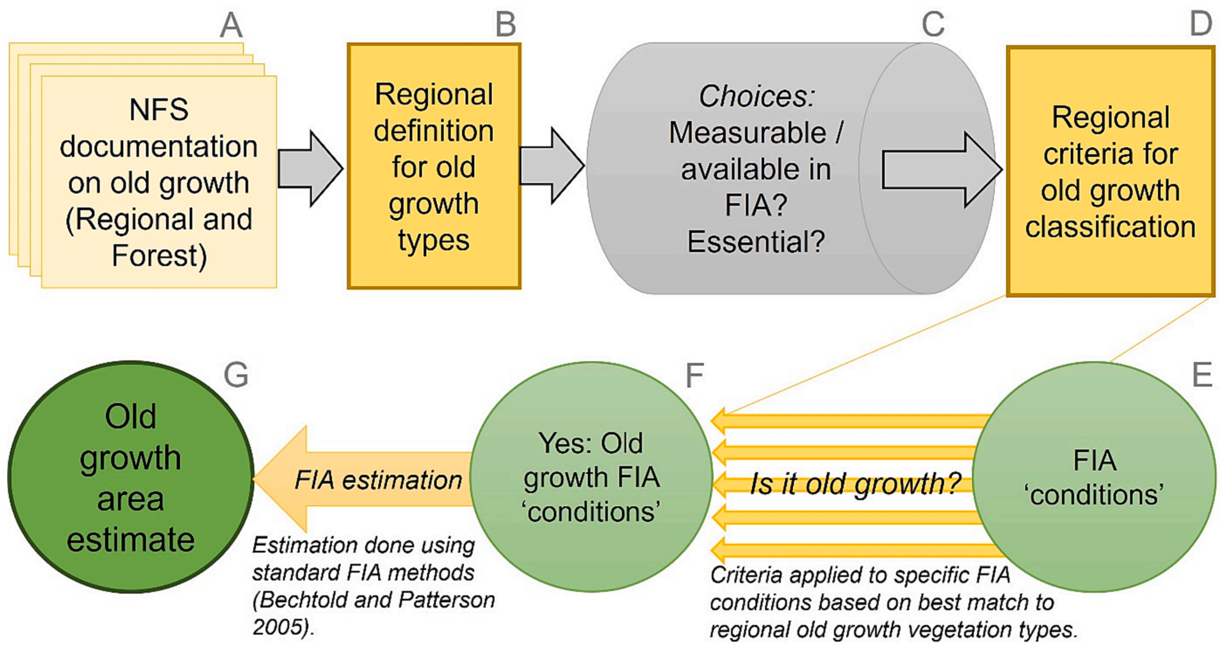

Fig. 2. Overview of process to get from USDA Forest Service National Forest System (NFS) old growth documentation (including regional and unit-level definitions and/or assessments), to old-growth forest criteria, to an estimate of old-growth forest area. This figure generalizes the approach but there was variation among NFS regions.

canopy cover classes – and given weights based on their representation compared to the known area of their strata to improve the precision of estimates (Westfall et al. 2022). Full FIA estimation procedures are beyond the scope of this study but widely documented (Bechtold and Patterson 2005, Pugh et al. 2018, Lister et al. 2020, Westfall et al. 2022).

In forested areas, field crews collect data for all live and dead standing trees ≥ 12.5 cm diameter at breast height (1.37 m above ground; dbh) on all subplots, including a variety of tree characteristics including species, status, crown characteristics, and damages. Seedlings (≥15 cm tall and 0–2.5 cm dbh) are counted by species and live and dead saplings (≥2.5 and <12.7 cm dbh) are measured on 2.07 m radius nested microplots. In west coast states (California, Oregon, and Washington) a larger, 18 m radius microplot (0.4 ha total sampling area per plot) is used for large trees (>76 or 60 cm dbh, depending on location). Dozens of additional attributes are collected and documented in field guides. There is a national field guide (USDA Forest Service 2022a, Burrill et al. 2021) and additional attributes are collected in FIA regions using field guides with regional protocols tiered to the national field guide (see USDA Forest Service 2022a–e for full data collection methods in each region). There is variation in data collection regionally related to local conditions and user interests. For example, in western states individual tree and stand ages are also available whereas only stand ages are reported in the eastern US. Habitat types (i.e., plant associations) used to classify potential natural climax vegetation are only collected in some areas of the western US. Additionally, down woody materials are inventoried on all western US plots while only measured on a portion (1/8th at minimum) of plots in the eastern US. Data for this study were the most recent complete state inventories available as of July 2023.

2.5. *Linking forest inventory data to specific NFS old-growth forest criteria*

Using NFS definitions and the FIA inventory, we estimated the extent of old-growth forest on NFS lands in the US. We worked with regional NFS experts to translate existing old growth definitions or assessments to old growth criteria applicable to FIA data. Across all regions, criteria included measures of density and size of living and standing dead trees, decay measures on living and dead trees, tree or stand age, downed woody material, or diameter variation (Table 2). We calculated attributes at the sampling unit scale, known as a 'condition'. FIA field crews sample forest on plots consisting of four subplots, but divides these into 'conditions', or, heterogeneous forested areas, when field crews determine clear boundaries exist (see USDA Forest Service 2022a). We used these regional criteria to determine if a given FIA 'condition' met a given NFS region's old growth definition, based on the appropriate criteria for a given vegetation type. We then used standard FIA estimation procedures (Bechtold and Patterson 2005, Pugh et al. 2018, Lister et al. 2020, Westfall et al. 2022) to estimate the extent of old growth by NFS region and nationally.

2.6. *Regional old growth criteria*

2.6.1. *NFS Northern Region (Region 1)*

The Northern Region has developed a system for quantifying forest as old growth with algorithms developed from minimum criteria for determining if a stand is potentially old growth, based on analysis of field data differentiated by forest type and habitat type group in three geographic zones (Green et al., 1992, errata 2011). The region's minimum criteria were used to define old growth status for this analysis: a minimum density of live trees meeting age and dbh thresholds, and a minimum basal area (m^2/ha; of live trees ≥12.7 cm dbh) (Table S1). When implemented by the Northern Region, old growth associated characteristics, such as variation in diameters, decay measures (dead/broken tops or bole decay), canopy layers, and standing and down dead wood are used as guidelines to further assess stands that meet minimum old-growth forest criteria. Because the presence and amount of these associated characteristics depends on forest type, biophysical setting, and disturbance regime(s), necessitating more targeted data collection and interpretation than available using FIA, these associated characteristics were not used for this study. Further details on the Northern Region's old growth criteria, including how old growth forest types and habitat type groups are determined, are available in Green et al. (1992, errata 2011).

2.6.2. *NFS Rocky Mountain Region (Region 2)*

The NFS Rocky Mountain Region provided current definitions for old

Table 2
Elements of USDA Forest Service National Forest System regional old growth criteria as applied to Forest Inventory and Analysis (FIA) data for this study. The Pacific Northwest Region has two sets of old growth definitions: one for the Northwest Forest Plan (NWFP) area and another for other lands. All elements shown are applied as minimum criteria. (Quadratic Mean Diameter = QMD; Stand Density Index = SDI.).

NFS Region	Old and large tree density	Large tree density	Tree or stand age	Stand basal area	Dead tree density (of a certain size)	Density of trees with decay	% total SDI from trees ≥ 45.7 cm diameter	QMD of trees ≥ 25.4 cm diameter	Down wood cover	Diameter diversity
Northern	X	X*	X*	X						
Rocky Mountain	X	X*	X*		X	X				
Southwestern							X	X		
Intermountain	X	X*	X*							
Pacific Southwest		X	X							
Pacific Northwest (NWFP)		X			X				X	X
Pacific Northwest (Other)		X	X							
Southern		X	X	X	X					
Eastern		X	X							
Alaska		X	X		X					

*As part of the 'density of trees that are old and large' element.

growth based on Mehl (1992). These definitions, with limited modification based on land management plans and vegetation classification programs, were used as the foundation for the Rocky Mountain Region's old growth criteria. Stands generally had to meet a required density of trees over a certain dbh and age, a required density of trees with cull, broken tops, or dead tops, and a required density of dead trees over 25.4 cm dbh and 3.05 m tall to qualify as old growth, though some forest types had no dead tree, cull, broken top, or dead top criteria (Table S2). Minimum density, dbh, and ages varied depending on forest type. In Colorado and Wyoming, tree age is sampled for one tree per species per diameter class, and then estimated for all trees based on this sample (USDA Forest Service 2022c). In Nebraska and South Dakota, stand age was used instead of tree age because tree ages are not collected by FIA in these states.

2.6.3. NFS Southwestern Region (Region 3)

The NFS Southwestern Region developed old growth definitions based on analysis conducted to support forest plan revision (USDA Forest Service 2019, Weisz and Vandendriesche 2013) (Table S3). The Southwestern Region classifies vegetation into 'ecological response units' (ERUs), so regional NFS scientists provided a translation between ERU and FIA habitat types (Table S4). Nine ERUs were assessed as to whether Zeide's Stand Density Index (SDI) (Zeide 1983) value for large (≥45.7 cm dbh) live trees met a required percentage relative to the SDI from all live trees. Twelve ERUs used a minimum quadratic mean diameter (QMD; of trees ≥ 25.4 cm dbh) criteria instead.

2.6.4. NFS Intermountain Region (Region 4)

For the NFS Intermountain Region, Hamilton (1993) defines old-growth forest characteristics, and subsequent communication from the Regional Forester clarified that only age, size, and density was to be used to determine old growth status. For a given forest type, as defined by composition, geography, and productivity (Table S5), stands had to have a minimum density of trees meeting dbh and age requirements to be considered old growth (Table S6). In the Intermountain Region, tree age is sampled on one tree per species per diameter class, and then calculated for all trees based on this sample (USDA Forest Service 2022c).

2.6.5. NFS Pacific Southwest Region (Region 5)

The Pacific Southwest Region developed a series of white papers defining old-growth forest summarized in Beardsley and Warbington (1996). These were modified by regional NFS experts to reflect their professional perspectives and reduce the number of productivity classes (Table S7). Vegetation types, based on dominant tree species, were grouped by productivity class (based on Dunning's site index, with index < 45 assigned to 'low', otherwise 'high'). Old growth criteria consisted of a minimum stand age and a minimum density of large diameter live trees. We created translations from the defined vegetation types to FIA forest types; oak and pinyon-juniper forest types did not have applicable old growth criteria and therefore had no potential to be classified as old growth. Criteria for some Pacific Southwest Region forest types were distinguished by ecoregion. Because most old growth definitions use stand ages based on the oldest trees in a stand and not the average age of overstory trees, we used either the age of the oldest increment-cored tree within the FIA 'conditions' observed on the plot. If no increment-cored ages were available then FIA's estimated stand age was used to determine whether the age criterion was met. FIA 'conditions' that met the minimum density of large trees (determined by dbh) and the age criteria were classified as old growth.

2.6.6. NFS Pacific Northwest Region (Region 6)

Parts of the NFS Pacific Northwest Region are managed under the Northwest Forest Plan (NWFP). In these areas, an old growth structure index score for stand age 200 (OGSI 200) identified old-growth forest and is consistent with NWFP monitoring (Davis et al. 2022; Table S8). The NWFP OGSI200 is based on density of large live trees, density of large snags, cover of down dead wood, and a diameter diversity index based on density of trees in different size classes (Davis et al. 2022). For the remaining Pacific Northwest Region forests in eastern Oregon and Washington, the 1993 'interim definitions' were used (https://ecoshare.info/2009/12/16/r6-old-growth-interim-definitions/). For both sets of criteria, tree and understory species on FIA plots were classified to plant association zone (PAZ) by regional NFS ecologists (Simpson et al., in review) and matched to the old-growth criteria, which vary by PAZ. For the east-side classifications, FIA site classes 1 and 2 were assigned to 'high', 3 and 4 to 'medium', and > 4 to 'low'. Central Oregon was defined as being in the east Cascades ecoregion (M242C) and not in Hood River or Wasco counties, with the remaining areas assigned to the Blue Mountains and eastern Washington grouping. Any FIA 'condition' with more than the minimum density of large trees and at least one old tree was classified as old growth. In the absence of increment-cored trees, stand ages were used.

2.6.7. NFS Southern Region (Region 8)

Definitions for characteristics of old growth in the NFS Southern Region are listed by old growth community type in Gaines et al. (1997), necessitating a crosswalk to FIA forest types; FIA forest types were often matched to more than one potential old growth community type (Table S9). To be considered old growth, each FIA 'condition' had to meet or exceed minimum values of live basal area (of trees ≥ 12.7 cm dbh), stand age, dead tree (≥12.7 in dbh) density, and have ≥ 14.8 trees ha^{-1} meeting a minimum diameter for a given old growth community type (Table S10). If the thresholds were met for any of the FIA forest type's potential old growth community types, the stand was considered old growth. The Southern Region's forest in Puerto Rico was considered old growth if in a wilderness area, as these forests had native ecosystems that were largely intact and not cleared for agriculture in the previous century. Throughout the Southern Region, forest types dominated by commonly planted pine species were only considered old growth if they met the appropriate thresholds and were located in a county where the species is known to be native (Table S11).

2.6.8. NFS Eastern Region (Region 9)

Characteristics of old-growth forests derived from extensive field surveys by major vegetation types in the northeastern US (Tyrrell et al. 1998) were used as the primary basis for old growth criteria for this study in the NFS Eastern Region. These field surveys of sites deemed by regional botanists or ecologists to most likely be old growth were conducted decades ago in a non-systematic manner using vegetation types that differ from FIA forest types. As such, the Eastern Region classified Tyrrell et al. (1998) vegetation types into the old growth types (ten types, including an "other" category) deemed most appropriate and translated to with FIA forest types. For each given old growth type to be considered old growth, FIA plot measurements had to meet thresholds for stand age (100–160 years) and density (12.3–49.4 trees ha^{-1}) of large trees at least 30.5–50.8 cm dbh (Table S12).

2.6.9. Alaska Region (Region 10)

The NFS Alaska Region used old-growth forest definitions from Boughton et al. (1992a, 1992b) as the basis for their old growth criteria. We developed a translation from the described community types to available data on FIA plots using forest type, elevation, slope, topographic code, and understory vegetation composition. FIA plots were identified as old growth if, for the appropriate old growth community type, it met either a minimum density of large, live trees; a minimum density of large, dead trees; a minimum stand age; or a minimum-aged tree on the FIA 'condition' (Table S13). While original definitions required meeting all four criteria, NFS experts decided that relaxing the definition to classify a FIA 'condition' as old growth when any of four criteria were met was more appropriate because results agreed more closely with the independent, map-based classification of old growth used by the Tongass National Forest in the Alaska Region. The current FIA inventory of coastal Alaska does not sample designated and candidate wilderness areas because field access to plots data by FIA crews has been restricted due to access concerns. Based on partial wilderness data collection by FIA in 2005, we estimate 3.0 million ha of total wilderness land, 1.38 million ha of which being forested, that was not included in this study.

3. Results

3.1. Common elements of NFS regional old-growth forest criteria

The old growth criteria used to make these estimates varied widely across NFS regions, but most had common elements (Table 2). The most common criteria were a minimum number of large trees (in eight of nine regions). In the NFS Northern, Rocky Mountain, and Intermountain Regions, these trees had to be both large and meet minimum age thresholds. Seven NFS regions had tree or stand age requirements. Other elements included minimum numbers of dead trees of a certain size (four regions). The Rocky Mountain Region was the only to require a certain number of live trees with rotten or dead portions, though several regions had similar characteristics described in foundational definition documents or as optional metrics for assessing old growth status. The Southwestern Region had unique criteria for old-growth forest based either on QMD of larger trees in forest types with typically longer fire return intervals, or percentage of total stand density index contributed by larger trees for forest types with typically shorter fire return intervals. Finally, many NFS regions purposefully disallow certain forest, such as planted forests or those identified as being characteristically in earlier stages of stand development, from being able to be considered old growth.

3.2. National and regional extent of old-growth forest on NFS lands, according to NFS definitions

We estimate that 9.8 to 10.2 million hectares of old-growth forest are in the NFS (Table 3), or approximately 17% of all forested NFS lands, according to NFS regional old growth criteria. The absolute extent of old growth is greatest in western NFS regions, with over two million hectares in each of the Pacific Northwest and Alaska Regions, and between approximately 0.9 and 1.1 million hectares in each of the Northern, Rocky Mountain, Southwestern, and Intermountain Regions. The Eastern and Southern Regions contain only approximately 0.6 million hectares of old-growth forest, mostly in the southeastern US. The NFS regions with the greatest extents of old growth also had the greatest proportion of NFS land classified as old growth – approximately 76% of the Alaska Region's surveyed forested land and 27% of Pacific Northwest Region surveyed forested land was old growth.

3.3. Discussion

We estimate that approximately 10 million hectares of old-growth forest exist on NFS lands in the United States equivalent to 17% of total NFS acreage. This is a national-scale estimate based on the application of minimum, regionally-defined criteria for old-growth forest applied to FIA plot data, providing a strategic starting place for quantifying the extent and distribution of old growth on NFS lands. We expect that field-verified inventories of old growth using more locally-calibrated definitions, or criteria unavailable in FIA, will modify these estimates. At this time, we have no reason to expect that the national estimate following these definitions is biased. Regional criteria differed from one another based on local forest types and local understanding of old growth, and expectations as to whether estimates are high or low likely differ among regions. For example, in the Southwestern Region, it was known that criteria tied to large tree diameters might include forests with relatively large but not very old trees. Similarly, stand age criteria used by the Eastern Region are young compared to the potential lifespan of many tree species and the presumed ages of forests prior to colonization (e.g., Tyrrell et al. 1998). In contrast, the fact that elements of old

Table 3
Estimated extent, in hectares, of old-growth forest on USDA Forest Service National Forest System (NFS) lands in the United States. Total forested lands were estimated using Forest Inventory and Analysis's US definition of forest land. The NFS Alaska Region estimate excludes wilderness and wilderness study areas.

NFS Region	Hectares of old-growth forest			% forested NFS land
	Estimate	95% Confidence Interval		
		Min	*Max*	
Northern	1,010,000	919,000	1,101,000	11%
Rocky Mountain	1,010,000	921,000	1,100,000	17%
Southwestern	853,000	768,000	938,000	14%
Intermountain	1,076,000	981,000	1,171,000	12%
Pacific Southwest	688,000	614,000	763,000	11%
Pacific Northwest	2,443,000	2,357,000	2,529,000	27%
Southern	472,000	426,000	519,000	9%
Eastern	123,000	102,000	144,000	3%
Alaska*	2,335,000	2,252,000	2,417,000	76%
Total	10,011,000	9,777,000	10,245,000	17%

*Excludes wilderness or wilderness study areas.

growth often manifest themselves over a large area of forests— or the small extent of many 'old-growth forest' patches, particularly in the Eastern and Southern Regions— may result in under sampling old growth using the relatively-small footprint and spatial dispersion of plots in the FIA sample, designed to serve as the strategic national forest inventory of the US (e.g., Woods 2000, Fraver et al. 2009, Kaufmann et al. 2007, Azuma and Monleon 2011, Gray et al. 2023).

This inventory is based on definitions of old growth indicated by forest structure, while alternative old growth indicators perhaps based on forest function or non-ecological values might lead to different results (e.g., Tyrell et al. 1996, Wirth et al. 2009, Kaufmann et al. 2007). Two other recent studies (DellaSala et al. 2022; Barnett et al. 2023) estimated roughly four million hectares of old growth on NFS lands in the conterminous US, about half of our estimate. However, each study uses definitions of old growth that are based on different attributes than regional NFS definitions. Consequently, we expect differences in estimated extent of old growth among investigations. Further, both recent publications developed methods applicable to all lands, not limited to NFS lands with neither including Alaska. We estimated 2.3 million hectares of old growth occurs on NFS land in the Alaska Region, though due to incomplete data our estimates for Alaska did not consider designated wilderness, which includes approximately 1.4 ha of forested land. Barnett et al. (2023) use FIA data, separated by forest types and productivity classes, to estimate the age at which the 90th percentile of biomass accumulation was achieved for that type and productivity class. They then use this age as a threshold to determine old growth status. DellaSala et al. (2022) define old growth based on the highest sum of scores of quantile ranks (score of zero for lowest quantile, score of three for highest quantile) for canopy cover, canopy height, and biomass derived from 30 m resolution remotely-sensed geospatial products. Given these fundamental differences in approaches, it would be surprising if estimates did not differ substantially among investigations.

Tree ages and stand ages can be difficult to determine and were considered imperfect but useful criteria for determining old growth status for most regions. Though tree sizes are often used to estimate tree ages, and the two can be strongly related in certain growing conditions (e.g., managed even-aged stands), they can also be poorly correlated particularly in resource-limited environments and situations with complex stand dynamics (Helms 2004, Di Filippo et al. 2016). FIA data provide information about approximate tree and stand ages but do not attempt to provide exact age information. In the eastern US, FIA determines stand ages through a combination of ages from cores of site index trees and expert opinion of local, field foresters. In the western US, FIA crews core trees across diameter classes and determine tree age on each field visit but there is still uncertainty about exact tree age (USDA Forest Service 2022c, 2022d, 2022e). For example, most trees are cored at 1.37 m above ground and age to coring height is approximated by FIA by species and location but varies widely depending on site productivity and forest conditions during tree recruitment (e.g., Brown et al. 2019). Accurately identifying tree ages, particularly for older trees, may be difficult due to indiscernible tree rings and require sophisticated dendroecological techniques such as cross-dating. Even with these techniques, rotten tree centers or other issues can make it impossible to be certain of ages for many trees. In some cases, morphological characteristics, informed by local research, can be more reliable to identify the oldest trees than breast height ages (Brown et al. 2019). Even with accurate tree age information, determining stand age can be complex, and stand age may not be appropriate for multi-cohort or uneven-aged stands and would likely vary depending on the intended use of the information (Stevens et al. 2016, Di Filippo et al. 2016).

We estimated area of forest that met minimum NFS criteria for old growth status. For field-application of old-growth classification approaches it will likely be necessary to change the scale of the inventory and/or incorporate additional metrics, likely necessitating surveys targeting potential old growth stands with locally-specific protocols. The foundational descriptions of old-growth forest in publications (e.g., Green et al. 1992, Tyrrell et al. 1998) discuss supplementary indicators that some regions use as guidelines in addition to minimum criteria for field identification of old growth conditions. Many of these indicators are not available in the current FIA inventory but if added through targeted data collection could reduce old growth classification errors made when applying regional criteria to the FIA inventory. For example, the oldest ponderosa pine trees are often identified by morphological characteristics including flattened crowns, large branches, and yellow bark color relative to neighbors which could not be extracted from existing FIA data (e.g., Morgan et al. 2002, Brown et al. 2019). Similarly, it is likely necessary to expand the sampled area beyond the FIA plots (0.067 ha sampling area nationally; 0.4 ha sampling area for larger trees in NFS Pacific Northwest, Pacific Southwest, and Alaska Region areas) to more reliably assess if old growth is present in some areas, due to small patch sizes or dispersed forest structure elements. Indeed, the importance of spatial scaling in ecology and land management has been recognized for years (e.g., Wiens 1989, Turner et al. 1993, Schneider, 2001) and has implications for determining if forest is considered old growth (Fraver et al., 2009, Kneeshaw et al., 2018, Woods, 2000). See Gray et al. (this issue) for more discussion of sampling issues related to old-growth forest inventories.

Old-growth estimates in this study use the most recent full set of FIA data on NFS lands by state, but plot characteristics may have changed since most recent measurement. State measurement end dates were between 2018 and 2021, measured over the previous five or seven years in the east or 10 years in the west. Major fire, hurricane, and other disturbances may have occurred since the last measurement. Though these disturbances are often large, they do tend to affect a small portion of the actual landscape (and FIA plots), while the remainder of the landscape continues to develop, potentially into old growth forest. Studies to identify the current status of plots using disturbance data are ongoing but will necessitate the use of modeled datasets with their own uncertainty, rather than reporting directly from field measurements.

Recent decades' research on the role of disturbance in forests, along with current and future stressors on old-growth ecosystems, challenge assumptions behind definitions, and the scale at which we consider them. Today, forests and all ecosystems are largely understood to be governed by nonequilibrium dynamics, whereas many definitions were built when equilibrium paradigms were widely accepted (e.g., Aplet and Cole 2010). Ongoing revision of definitions is likely justified, as is stated repeatedly in regional publications from the 1990s and beyond. For example, how might old growth definitions based on observations from the second half of the 20th century be viewed considering the reduction of western white pine (Kinloch 2003) and loss of American chestnut (Hepting 1974) due to invasive pathogens decades earlier? Should definitions be modified considering the current decimation of whitebark and other five-needle pines (Schoettle et al. 2022), eastern hemlock (Abella 2014), and native ashes (D'Amato et al. 2018) by non-native insects and diseases, fundamentally reshaping forests throughout the country (e.g., Gunn and Orwig 2018)? Similarly, to what extent might a different cultural lens suggest criteria informed by very different characteristics of forests? In systems where large-scale, severe disturbances are a primary driver, it may be more appropriate to create a new concept of old growth at the landscape scale than the classic, stand-scale concept (Kneeshaw et al. 2018). This may be true in systems shaped by disturbances of all sizes and severities (Mladenoff and Forrester, 2018; Davis et al. 2022; USDA Forest Service 2019). Increasing mortality due to native and non-native pests, as well as impacts of climate change, such as drought stress, or increased area of fires burning under extreme fire weather, create the need to reconsider how old growth concepts, and potential management and restoration of these forests might evolve to sustain these ecosystems into the future.

3.4. Conclusions

This is the first nationally-consistent quantification of old-growth forest of the United States National Forest System, based on NFS definitions using the statistically-rigorous US national forest inventory. We estimate an extent of 10 million ha of old-growth forest on NFS lands. Underlying this estimate is a repeatable method to quantify potential old growth that can be applied elsewhere, such as on federal BLM lands as directed by EO#14072. Furthermore, this method can be applied to emerging FIA data for monitoring old growth through time, and can be modified to include emerging research results, ancillary data such as remotely-sensed information, and altered definitions co-produced by managers, scientists, and/or the public as they evaluate this inventory across spatial scales and diversity of US forest ecosystems. Further examination of how these definitions align with FIA data, evaluation of how this national-scale inventory compares to field-verified old-growth stands, and refining definitions given global climate change is likely warranted, and work is already underway to refine old-growth inventory techniques to inform monitoring and conservation in many areas.

4. Authorship contributions

Kristen Pelz: conceptualization, criteria finalization, data manipulation/code writing and estimation, table creation, writing - original draft, writing – editing and final draft; Greg Hayward: conceptualization, definition development, writing – review and editing; Andy Gray: conceptualization, criteria finalization, data manipulation/code writing and estimation, writing – review and editing; Erin Berryman: data manipulation/coding and estimation; writing – review and editing; Christopher Woodall: criteria finalization, data manipulation/coding and estimation, writing – review and editing; Amy Nathanson: definition development, criteria finalization, table creation, writing – review and editing; Natalie Morgan: definition documentation, table creation (Renate Bush and others from NFS Northern Region conceptualized and developed the region's methods and old growth algorithms), writing – review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

See supplemental information for code and publically available data.

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Appendix A. Supplementary data

National Forest System Regional criteria, as supplementary data, are provided online at https://doi.org/10.1016/j.foreco.2023.121437. Public FIA data used for this work are available from the FIA database (FIADB) at https://apps.fs.usda.gov/fia/datamart/datamart.html. The code used to quantify FIA data as old growth, along with supplementary data and example FIA estimate calculation code, are posted at https://doi.org/10.6084/m9.figshare.24036387.v1.

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