Mapping relative forest maturity and stand development for conservation in the conterminous USA

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Abstract

Context

Information on the maturity of forests is important for conservation planning. However, available information for the USA is inadequate to support national conservation assessment and planning.

Objectives

The main objective was to spatially model at a high resolution the relative level of maturity and stand development for forests across conterminous USA. A secondary objective was to explore which younger forests could be attributed to the impacts of severe natural disturbances.

Methods

We modelled the relative level of maturity for forests at a 30 m pixel resolution using spatial data for forest cover, height and biomass, stratified by forest types and ecoregions. National plot data were used to validate modelled results. The impact on Young forest from severe wildfire, insects and disease, and tornados was examined for the years 2000-2019.

Results

Of a total forest area of 248.9M ha, Young forest covered 52.9 M ha (22%); Intermediate 100.3 M ha (42%); and Mature 86.0 M ha (36%). Results suggest that the modelled data are tracking observed forest structure and stand development. 1.4 M ha (2.67%) of modelled Young forest was impacted by severe natural disturbances, with 51.5 (97.33%) M ha of Young forest unimpacted. The distribution of the disturbance factors varied geographically. The unimpacted Young plus Mature forest are where primary forests are most likely found.

Conclusions

The forest maturity data can assist forest decision makers in meeting environmental commitments regarding mitigating forest sector emissions, biodiversity conservation and water quality, including through prioritizing land for meeting protected area and ecosystem restoration targets.

Key words: forest maturity, conservation planning, primary forest, old growth, conterminous USA

Introduction

Information on the maturity of forests, including forest age, tree species, and stand structure, is critically important for conservation assessments and planning (Angelstam et al. 2018; Curtis and Gough 2018). More mature forests, including old growth, are important for biodiversity providing special habitat conditions and resources (Freund et al. 2015; Frey et al. 2016). Older forests have higher levels of biodiversity compared to logged forests in every region of the USA (Strittholt et al. 2006; Ducey et al. 2013). In addition, older forests at the stand level generally store more carbon (Moomaw et al. 2019) and are important for maintaining hydrological processes at the watershed scale (Perry and Jones 2017; Pypker et al. 2006; Crampe et al. 2021).

However, available information for the USA is inadequate to support national conservation assessment and planning as the relevant data sets are either at too coarse a spatial resolution or do not reflect recent forest condition (Pan et al. 2011). Conservation requires information about the condition of different forest ecosystems including distinguishing between those that are primary forests - largely undisturbed by modern land uses and dominated by ecological processes including successional stages arising from natural disturbance processes (Kormos C.F. et al. 2017) - and secondary and regrowth forest which are the result of human management including logging. We address this information gap by drawing upon available spatial data to provide a wall-to-wall high resolution (30m) spatial dataset of relative forest maturity and stand development for the conterminous USA.

Forest at the older end of the stand development continuum have become increasing rare due to land use impacts, mainly logging for commodity production that has shifted forest stand development to perpetual early re-growth phases (20-60 years depending on growth rates) (Foley et al. 2009). Severe wildfires also impact forest age and stand development (Pan et al. 2011), with consequences to structure and composition varying with burn severity (Reilly et al. 2018; Reilly et al. 2020). In the western USA, an increase in extreme fire weather conditions and area burned at high severity has now been attributed to in part to human influenced climate change (Abatzoglou and Williams 2016; Parks and Abatzoglou 2020).

Stand development is also impacted by insect and disease infestations (Fei et al. 2019) and tornados. Forest age and level of stand development are measured through tree ring analysis (e.g., core drill samples from living trees) or models based on measurements of forest structure – canopy height and density. Other forest characteristics indicative of stand age include vertical vegetation layering and coarse woody debris. Differences in the longevity, life history traits and niche requirements of tree species means that in many ecosystem types, the taxonomic composition of the dominant canopy species can reflect seral stages progressing from pioneer to late successional (Huston and Smith 1987). Gap-phase dynamics are diagnostic of older forests that result when some of the dominant trees die and provide opportunities for release of understory vegetation that fill those gaps overtime (for examples in the Pacific Northwest, see (Spies 2004); in eastern forests see (Davis et al. 1996). The lack of a large-scale disturbance over decades allows forest succession to proceed through mature stages. Furthermore, environmental factors that regulate plant growth, ecosystem processes rates and site productivity – thermal, moisture, radiation and nutrient regimes – also result in variation within the ecosystem type of forest structure in terms of canopy, height, canopy density, and above ground woody biomass, further confounding the use of structure to infer age (Shao et al. 2018).

Our main objective was to map the relative level of maturity and stand development for forests across conterminous USA, including both naturally regenerating forests and plantations. A secondary objective was to explore which younger forests could be attributed to the impacts of severe natural disturbances.

Methods

Overview

Our approach to mapping stand development was limited by the need to draw upon publicly available spatial data sets with wall-to-wall coverage for conterminous USA. This meant that suitable spatial data were available for only a subset of stand development characteristics. We mapped the relative level of forest maturity and stand development using three published spatial data sets for forest cover, height and biomass derived from modelled satellite data (Table 1). These data were stratified by USA Ecoregions Level III (n=28) (Omernik and Griffith 2014) and Forest Types Groups (n=85) (Ruefenacht et al. 2008) to account for the influences of variation in life history traits governing tree longevity and local environmental conditions on plant growth and ecosystem processes, as well as differing human and natural disturbance regimes. We used field measurements from the Forest Inventory and Analysis plot database (FIA 2022) to compare with our modelled forest maturity map as a form of validation. We used a time series of available spatial data to examine how modeled Young forests has been impacted by severe natural disturbances. An overview of the analytical workflow is given in Fig. 1. Further details on the methodology are provided below and in Supplementary Information - Methods.

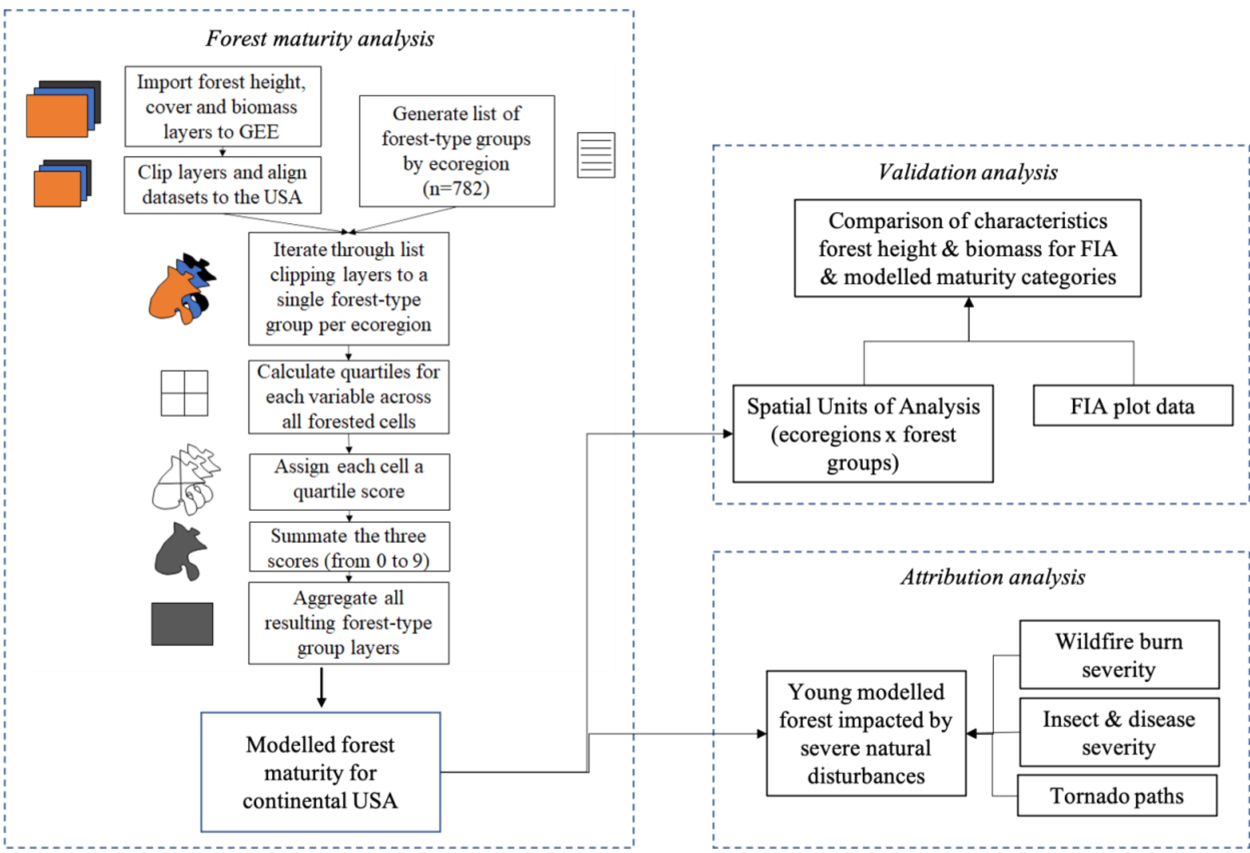


Fig. 1 Workflow showing main steps in the calculation of the forest maturity model for conterminous USA, the validation analysis and the wildfire attribution analysis. The three 30m resolution spatial data sets for forest cover,

height and biomass were analyzed within 872 spatial units of analysis (SUA) defined by the intersection of ecoregions and major forest types. FIA plot data were used for a validation analysis. A time series data set was assembled to identify which areas of modelled Young forest had been severely impacted by wildfire, insects and disease, and tornado paths. Further details in Supplementary Information – Methods

Expert workshops

A series of regional workshops were held via zoom to consult with ecological and conservation forest experts. The workshops were conducted between September and November 2021. In total over 40 experts attended the workshops with each focused on a major forested regions within the conterminous USA. Key objectives were to obtain expert advice on: (a) the most appropriate level of ecoregion and forest ecosystem classification to use for a continental analysis; (b) potential sources of error and limitation in these data; (c) the suitability of available forest data sets for modelling and analysis; (c)and (d) to provide feedback on preliminary modelling results. Further details on the workshop methods and outcomes are provided in Supplementary Information – Methods.

Forest maturity model

The three spatial data layers of forest cover, height and aboveground living biomass were available for the conterminous USA (Table 1). Spatial analyses were undertaken using Google Earth Engine (Gorelick et al. 2017). As the three data layers were generated using the Global Land Analysis and Discovery's (GLAD) Landsat Analysis Ready Data (ARD), they shared the same 30m pixel resolution.

Table 1. Details for the spatial data layers used in the forest maturity modelling and the attribution and validation analyses.

Layer	Description	Data type and scale / resolution	Calibration data / validation approach	Source
Forest cover	Percent tree cover stratum (e.g. >50% crown cover to ~0% crown cover)	Raster (30m)	High resolution imagery	(Hansen et al., 2013) (Hansen et al. 2013) updated to 2010 (GLAD)

Forest height	Forest canopy height	Raster (30m)	Vegetation structure data collected using airborne lidar instruments (ALS) and GEDI field plots	(Potapov et al., 2021)
Forest biomass	Modelled estimates of aboveground living biomass	Raster (30m)	Based on machine learning of satellite band ratios, plot measurements of biomass, environmental variables	(Harris et al., 2021)
Ecoregions (Levels III)	Areas of similar ecosystems	vector data layer (at or above 1:24,000 scale)	Field verification trips across 30 US states.	(Omernik and Griffith, 2014)
Forest Type Groups	Aggregation of forest types into 28 categories	Raster (250m)	FIA inventory plot data; spatial environmental data layers	(Ruefenacht et al., 2008)
Burn severity	Fire severity using variants of the normalized burn ratio (NBR, dNBR and RdNBR)	Raster (30m)	Calibrated per fire using high resolution imagery for both pre and post fire	(Eidenshink et al., 2007)
Insect and disease	Areas of forest with insect and disease outbreaks	Polygonised from 240 m resolution raster	Aerial and ground surveys	(USFS, 2022)(Frank J.K. Jr. et al. 2014)
Tornados	Tornado paths	Spatial vector data layer (scale not reported)	Tornado reports later field validated by local National Weather Service forecast offices	(NOAA 2020)

Fig. 1 gives an overview of the workflow to create a seamless conterminous-USA wide forest maturity spatial data layer. We created a spatial vector file of each major forest group for each Level III Ecoregions (Omernik and Griffith 2014). Spatial data layers were generated based on spatial coverage for the Major Forest Groups found in each ecoregion, resulting in a total of 782 unique forest group-ecoregion combinations. Quartile values for the three forest variables (canopy cover, height and biomass) were calculated for each pixel within each of the 782 combinations. A score was then calculated for each pixel as follows: (a) the lowest quartile value for each metric was given a score of 0 and the highest a score of 4; then (b) the four metric scores were summed giving a range in possible values from 0 (lowest quartile for the three variables) to 9 (highest quartile for the three variables), representing 10 ordinal forest maturity classes. Based on expert feedback from the workshops, we then produced a simplified maturity map by classifying pixels with a score of 0 as “indeterminant, those with scores of 1-3 as

"Young", scores 4-6 "Intermediate" and scores of 7-9 as "Mature". Using a global spatial data set (WRI 2016), we analyzed the modelled forest maturity map to identify how much of each maturity class was plantation rather than naturally regenerating forest. For further see Supplementary Information – Methods.

Natural disturbance attribution analysis

We assembled a 20-year time series for the period 2000-2019 from available spatial data sets for the conterminous USA to examine the extent to which modelled young forest have been subject to severe impacts from natural disturbances: high fire severity (Finco M. et al. 2012); very severe insect and disease outbreaks (USFS 2022) ; and high winds within tornado paths (Harris et al. 2016; NOAA 2022). The total area of modelled Young forest impacted by each severe disturbance factor was calculated. Further details are provided in Supplementary Information - Methods

Validation analysis

We used FIA plot data as an independent data source for validating the modelled forest maturity map. For this validation analysis, the spatial units of analysis (SUA) for comparison with the FIA plot data were generated from the intersection of the map of 85 USA Ecoregion Level III with the maps of the 28 Forest Type Groups. Those SUAs were analyzed for which there were at least 10 FIA plots for each of the three FIA Structural Stage Classification levels (Pole, Mature, Late) (n=41). For each of these 41 SUAs, we calculated aggregate statistics from the quartiles and median values for canopy height and biomass from a random sample of pixels within each of the three modelled maturity levels (Young, Intermediate, Mature) with 1.5-5% of pixels sampled (Table 2). We assumed that the FIA maturity levels (Pole, Mature, Late) were sufficiently equivalent with the modelled Young, Intermediate and Mature categories, respectively, to support comparisons among them. Further details are provided in Supplementary Information - Methods.

Table 2. Characteristics of the sampled FIA plot and modelled forest maturity pixel data used in the validation analysis. Details are provided here for the six SUA with largest forest cover.

			Modelled forest data	**FIA plot data**	
Spatial Unit of Analysis (Major Forest Group x Ecoregion Level III)	*total forest area*	*plantations (% of total forest area*	*total area of forest sampled (ha); forest area sampled (%)*	*no. biomass plots*	*total area sampled by biomass plots (ha); forest area sampled (%)*
Northeastern Highlands-Maple/Beech/Birch Group	10,262,450	0.01	513,122 (5)	1,480	100 (0.0010)
Southeastern Plains-Loblolly/Shortleaf Pine Group	8,704,181	49.1	435,209 (1.5)	146	10 (0.0001)
Ridge and Valley-Oak/Hickory Group	5,624,025	2.16	281,201 (5)	668	45 (0.0008)
Northern Rockies-Douglas-fir Group	4,717,516	8.64	235,876 (5)	425	29 (0.0006)
Southern Coastal Plain-Longleaf/Slash Pine Group	3,813,097	42.04	190,655 (5)	440	30 (0.0008)
Coast Range-Douglas-fir Group	3,284,700	27.8	164,235 (5)	558	38 (0.0011)

Results

The forest maturity map comprised 10 ordinal classes (Fig. 2). These were grouped into Indeterminant (class 0), Young (classes 1-3), Intermediate (classes 4-6) and Mature (classes 7-9). Total forested area was 248.9M ha categorized by Young (52.9M ha; 22%); Intermediate (100.3M ha; 42%); and Mature (86.0M ha; 36%). Maturity levels varied among ecoregions as expected with most regions showing Mature forests in a matrix of Young and Intermediate. Only two ecoregions had more Mature forest, including the most forested ecoregion (Western Cordilla). However, all forested ecoregions still retain substantial areas of Mature forest (Fig. 3). The total area of plantation in the conterminous USA is 24.10M ha of which most was Intermediate (11 M ha, 46%) followed by Mature (7 M ha, 29%), and Young (6 M ha, 25%). Note that we used Ecoregions Level II (rather then Level III) in Fig. 3 simply to provide a high-level overview of these results.

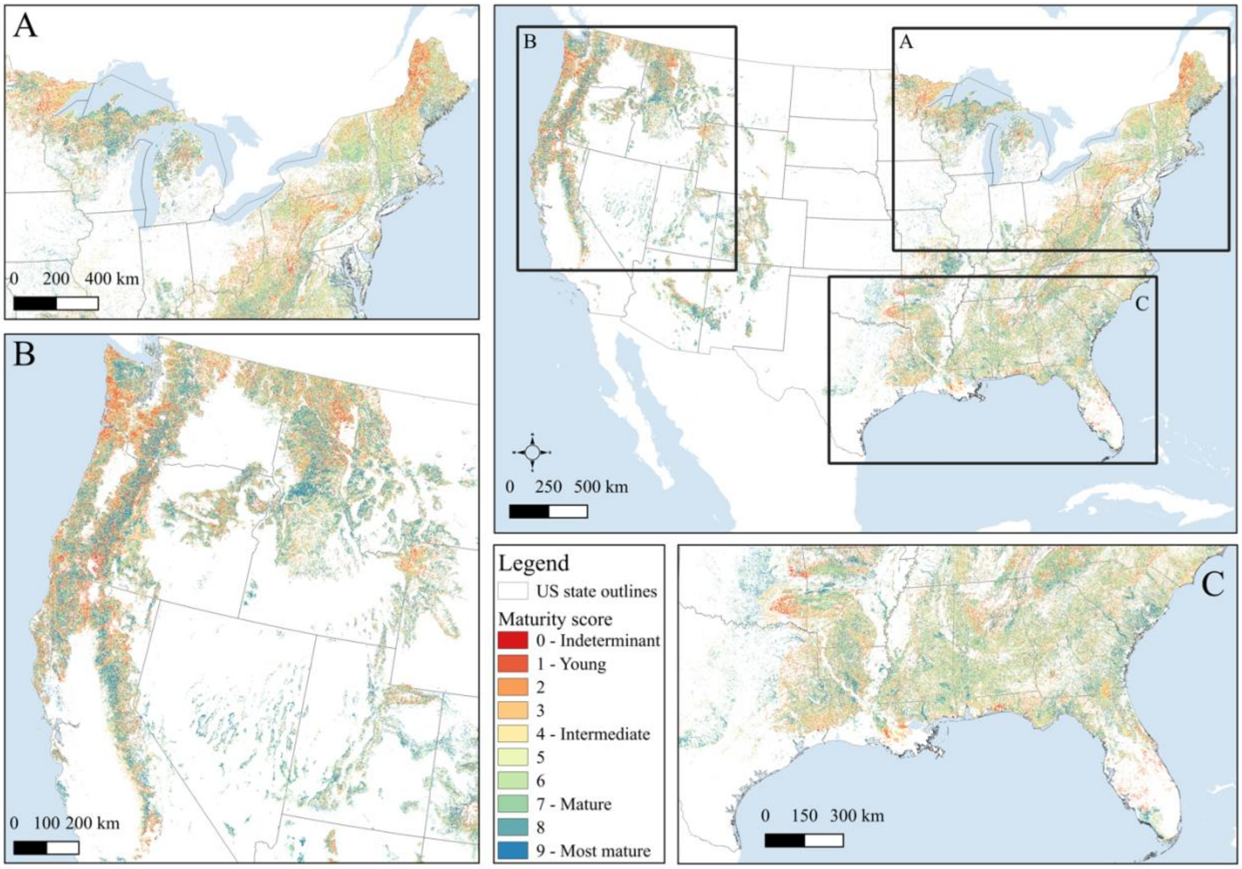


Fig. 2 Forest maturity ranking. High maturity ranking score means a pixel has denser forest cover, a taller canopy and larger biomass compared to a younger forest. Note that this is a relative index

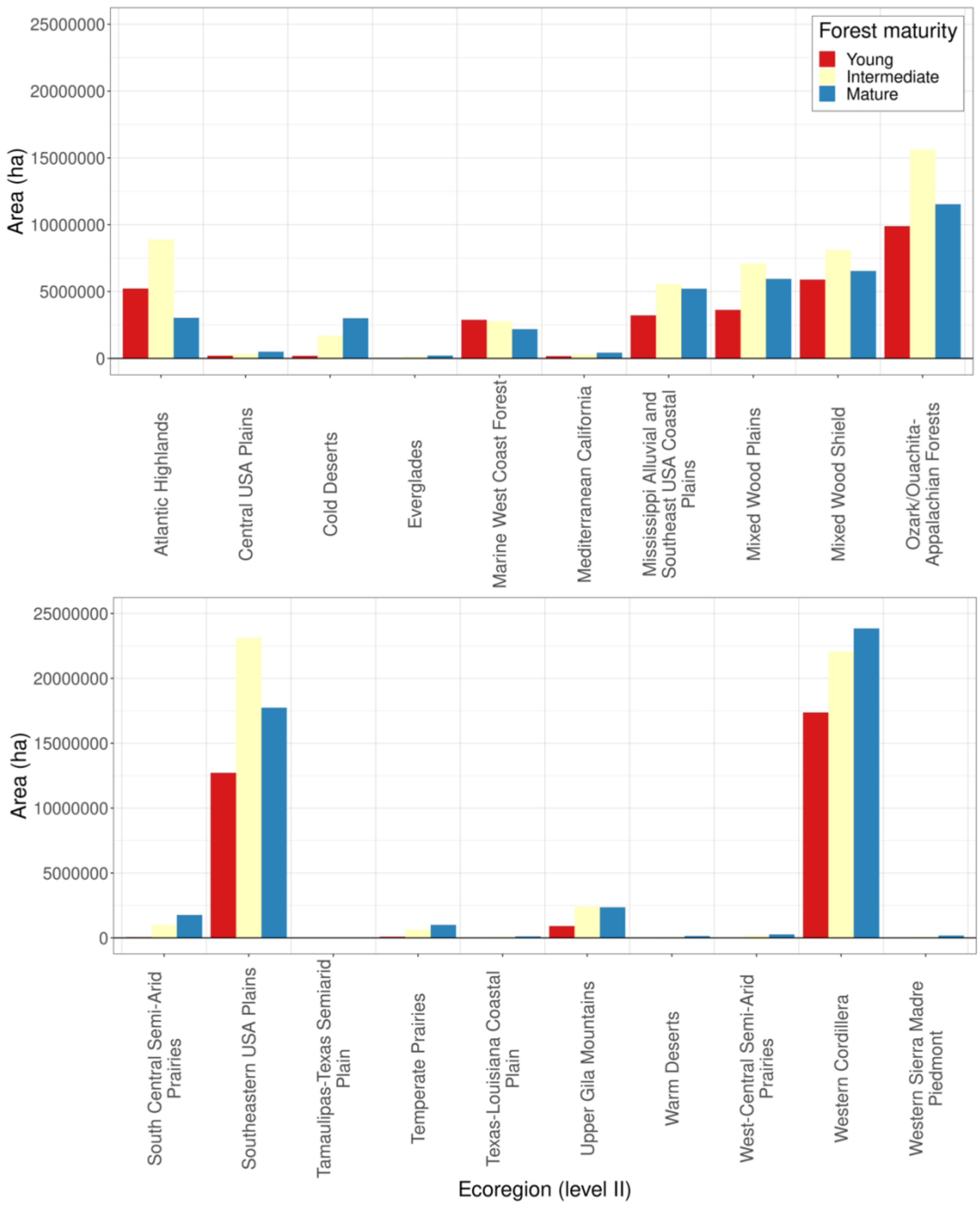
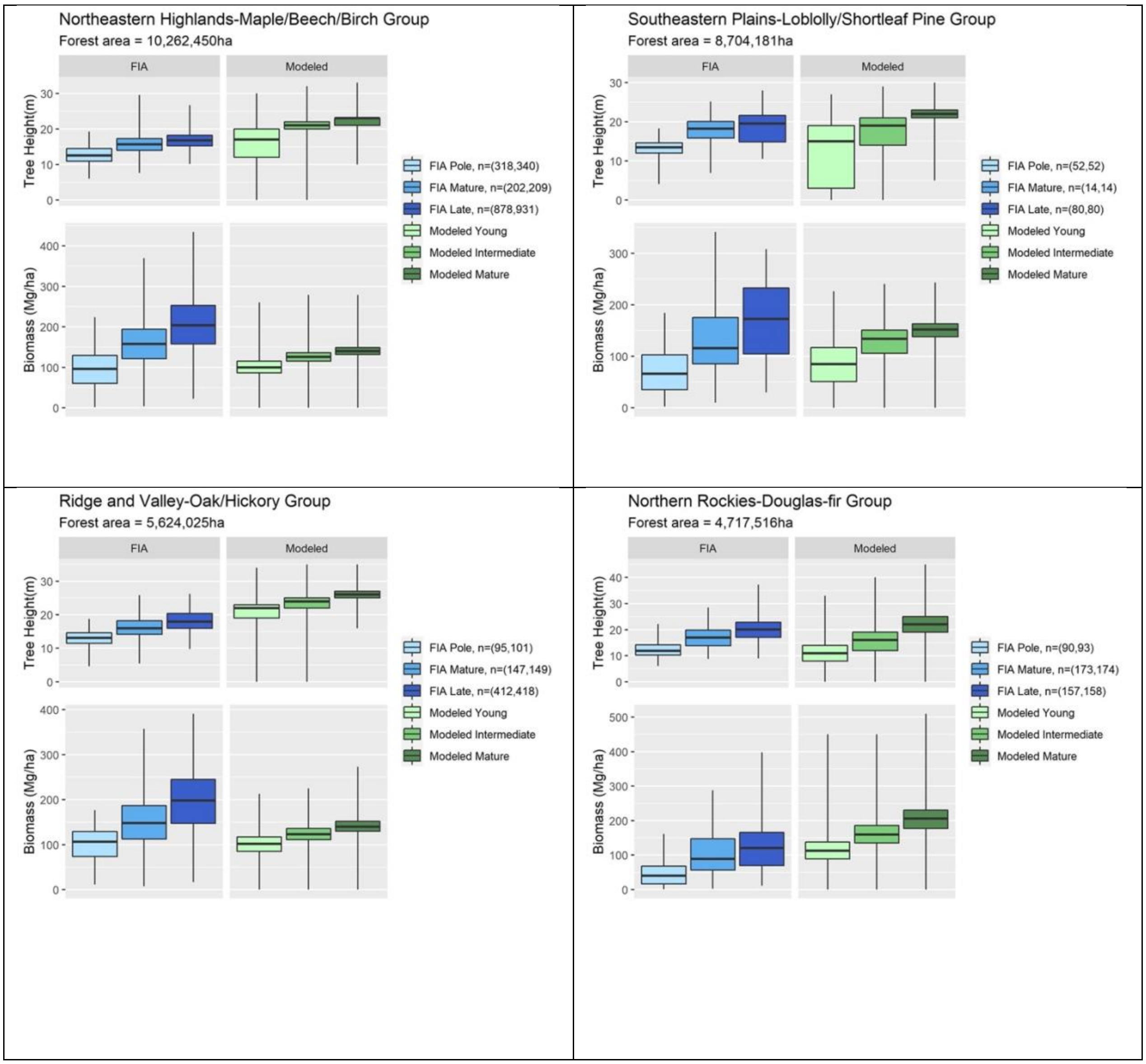


Fig. 3 The area (ha) of young, intermediate and mature forest maturity within USA Ecoregions Level II. The three categories of maturity are based on the 10 ranked forest maturity classes (Fig. 2): Young 1-3; Intermediate 4-6; Mature 7-9. A percent area version of the figure can be found in the Supplementary Information Fig. SI1)

Visual inspection of the box plots for the six SUA with the largest forest area show that the canopy height and biomass increase with forest maturity level in both the plot and modelled data. It is also evident that there is considerable agreement between the FIA plot data and modeled forest maturity as the values for the modelled data largely fall within the range of the plot data, and the median values are reasonably aligned (Fig. 4). However, in some cases the ranges differ considerably between them (plots for all 41 SUA are provided in Supplementary Information – Figures, Fig. SI3).



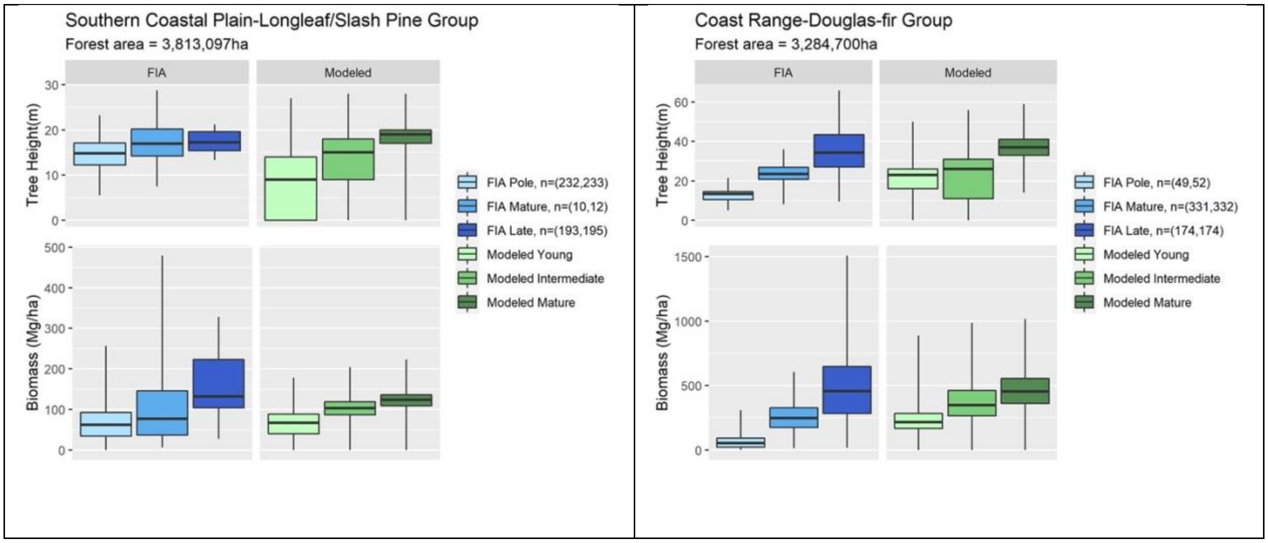


Fig. 4 Comparison of characteristic canopy height and biomass from modelled forest maturity with estimates from FIA plot data. The spatial units of analysis (SUA) were the intersection of USA Ecoregions Level III with modelled geographic distributions of major forest groups. SUA were analyzed that contained at least 10 FIA plots for each of the four FIA maturity levels. The SUA are labelled according to their major forest group name. Box plots defined by interquartile range (first quartile, median, third quartile) with whiskers being minimum and maximum based on the most recent values from all available FIA plots within each of the three stand structure categories (Pole, Mature, Late), for each SUA

The spatial distribution of the three natural disturbance factors (wildfire, insects and disease, tornado paths) varied geographically with wildfires most prevalent in the Northwest and tornados in the Southeast (Fig. 5). It follows that the correlation between these factors and Young forest varied among Forest Type Groups (Fig. 6): California Mixed Conifer and Western White Pine Groups have been most impacted by wildfire; Loblolly/Shortleaf Pine and Oak Pine Groups most by tornados; and Fir/Spruce/Mountain Hemlock and California Mixed Conifer Groups by insects and disease.

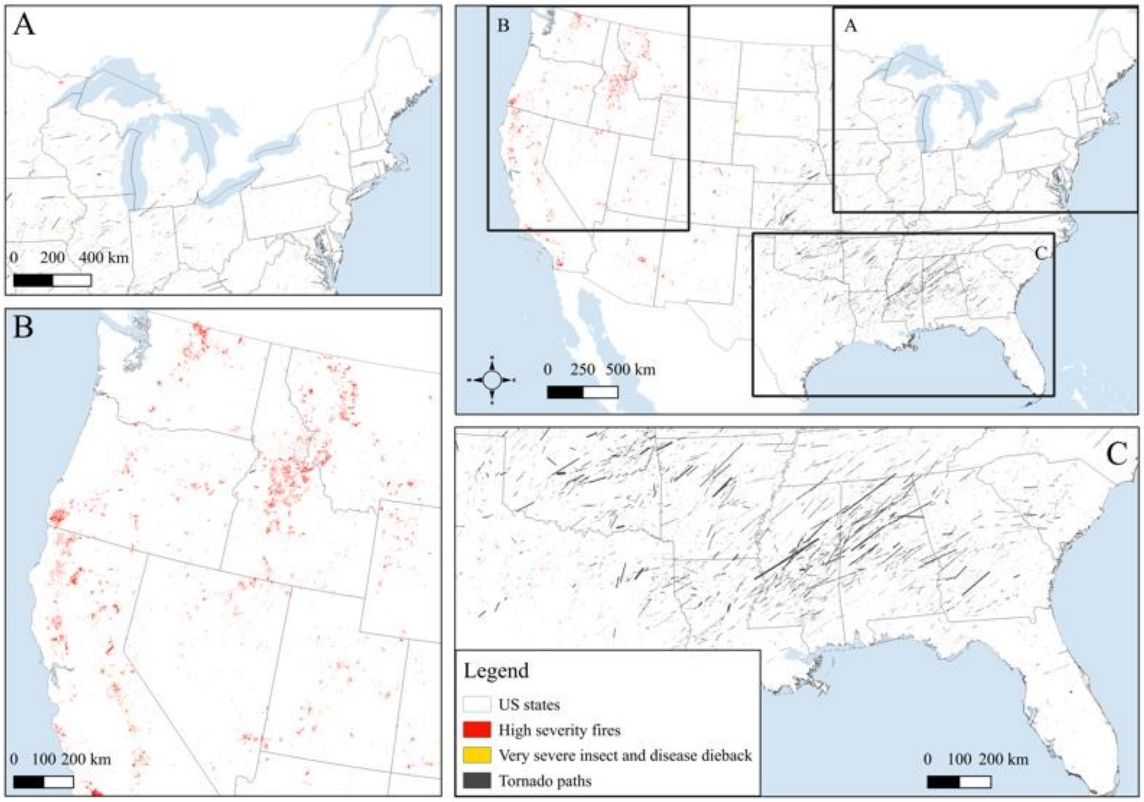


Fig. 5 Spatial distribution of the three natural disturbance factors (wildfire, insect and disease, tornado paths)

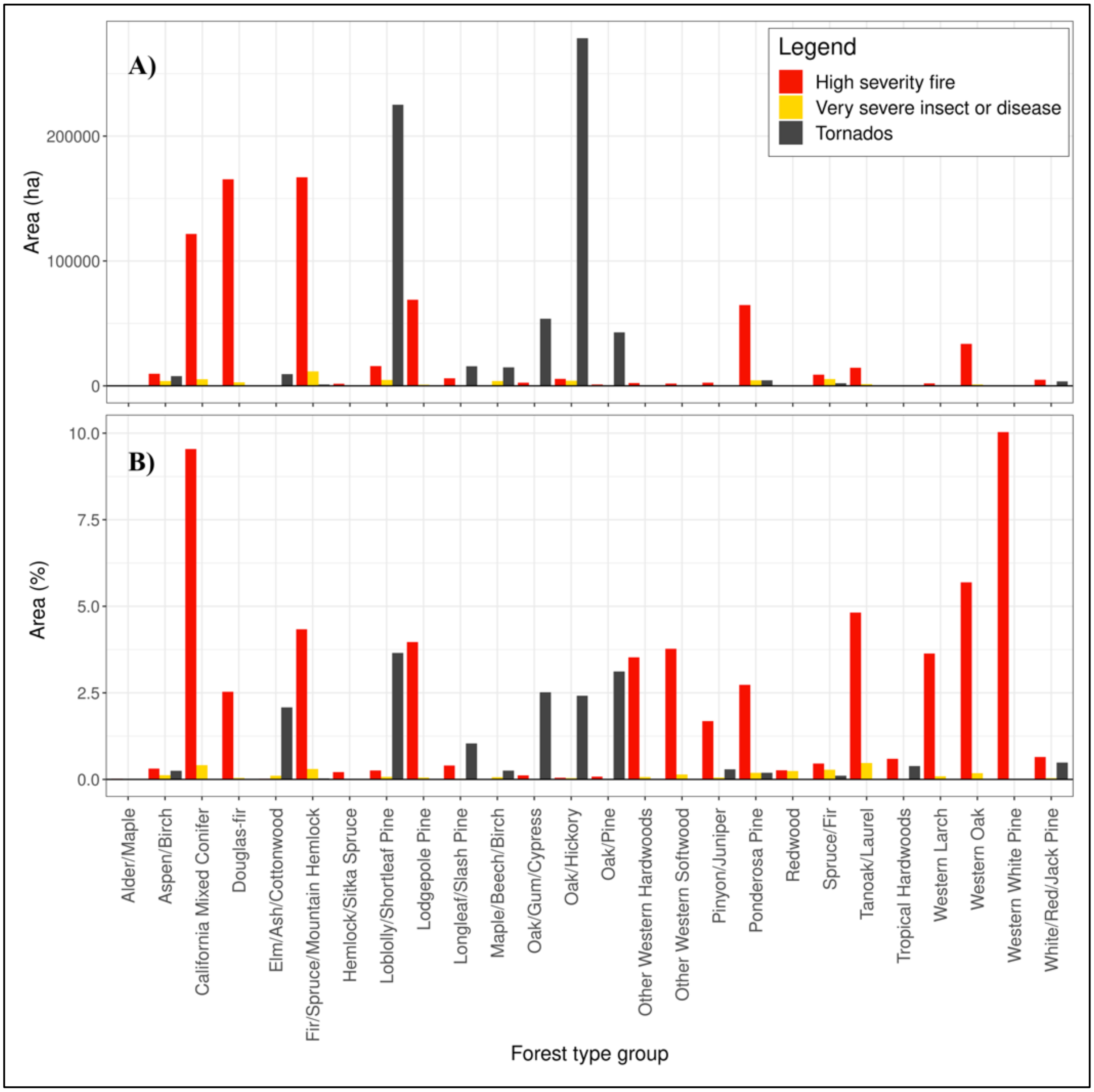


Fig. 6 The area (a) and percentage areas of modelled young forest in Forest Type Group that have experienced severe impacts from wildfire, insect and disease or tornados during the period 2000-2019

A total of ~1.4 M ha of modelled Young forest was impacted by high burn severity wildfires, severe insects and disease, or tornado paths, though this is only 2.67% of the total area (Table 3). This leaves ~51.5 M ha of Young forest which has not been impacted by these natural disturbance during the 20-year time period examined here.

Table 3. The area and percentage of modelled Young forest impacted by high burn severity wildfires, severe insects and disease, and tornado paths.

High severity fire		Very severe insect and disease		Tornado paths		Total impacted by natural disturbances		Unimpacted Young forest	
area (ha)	%	area (ha)	%	area (ha)	%	area (ha)	%	area (ha)	%
701,824	1.33	51,931	0.01	660,094	1.25	1,413,849	2.67	51,494,949	97.33

Discussion

To our knowledge, this is the first map of forest maturity classes at 30m resolution for the conterminous USA. Our results complement earlier studies that mapped forest aged distributions at a 1-10 km resolution (Besnard et al. 2021; Pan et al. 2011), recent studies examining the impact of natural disturbances on the net carbon exchange of forested lands (Harris et al. 2021), and the contribution of forested lands to meeting conservation targets (Law et al. 2021). With growing interest in the ecological and conservation values of older forests in natural climate solutions (DellaSala et al. 2020; Griscom et al. 2017; Law et al. 2021; Mackey et al. 2020; Moomaw et al. 2019). information on mature forests is relevant to conservation policy makers. However, it is important that the assumptions and limitations of the data and approach are understood for the forest maturity map to be applied appropriately.

We assumed that for a given Forest Type Group in a given ecoregion, the level of maturity would be monotonically related to increasing cover, height and biomass. An initial visual inspection of the modelled forest maturity map identified two landscape settings where the forest was likely erroneously assigned a younger forest maturity class. One was forests bordering the alpine zone that naturally have a sparer and shorter canopy and support smaller biomass stocks forests compared to a similar type at a lower elevation. Less obviously, are forests in climatically drier ecoregions on exposed topographic positions that naturally would be sparser, shorter and have less biomass than similar forest types nearby with higher site productivity (McKenney and Pedlar 2003). The Oak/Hickory Forest Type Group also had some anomalous results with lower-than-expected areas of Young forest. This is likely the result of substantial wildfire suppression in these fragmented forests across their range (Nowacki and Abrams 2008). In addition, closer inspection of the input data revealed differences in how non-forest land was mapped. The Landfire tree cover layer used to delineate Alpine vegetation has a stricter classification of forest than the other inputs. We also tacitly assumed that the quantile thresholds correspond to age classes. However, it could be that an ecoregion with a majority of mature forests could have some mature mapped as intermediate/young, while the opposite could occur in an ecoregion with a majority fraction of young forests. This could also explain why substantial areas of plantations were mapped as having mature forest even though they are managed to be harvested at a young age.

We compared the modelled forest maturity with FIA plot data. The validation results suggest that the modelled forest maturity map is realistically tracking forest structure and stand development. However, the categories of stand development (FIA – Pole, Mature, Late; Modelled – Young, Intermediate, Mature) were derived using different methods and therefore can only be considered indicatively equivalent. While overall the box plots frequently share overlapping inter-quartiles and medians, there are interesting difference, for instance in cases where the plot data samples a wider range of biomass than the modelled data. These differences warrant further investigation.

From a conservation perspective, primary forests in the temperate biome are an increasingly rare asset globally (FAO 2020; Mackey et al. 2015). Our attribution analysis revealed the areas of modelled Young forest that have been subjected to at least one of the severe natural disturbances examined (wildfire, insects and disease, tornado paths) between the years 2000-219. Regardless of their level of stand development, natural forests can be defined as "primary forest', so long as the impacts that have resulted in younger rather than older maturity levels are the result of natural disturbances rather than human land use (Kormos C.F. et al. 2017). It is reasonable to assume therefore that the (non-plantation) forest impacted by severe natural disturbances could be primary forest, so long as they have not also been impacted by logging prior to the year 2000. Similarly, primary forest is also likely to be found in the Mature forest category where it would be typically recognized as old-growth forest. However, confirming more accurately the location of the remaining primary forest in conterminous USA requires further attribution studies using logging and land use history data. Unfortunately, a consistent spatial logging data set is not currently available for the conterminous USA.

A limitation of our modelled forest maturity is that it does not directly provide a measure of forest stand age. However, as noted, our maturity levels (Young, Intermediate, Mature) are analogous with the FIA Structural Stage Classification levels (Pole, Mature, Late), and the validation analysis comparing the FIA plot data with our modelled data suggest they are indicative of age classes typically used in forest classifications. In any case, assigning an age to forest development is not straightforward except where field-based measurements are available or in the case of an even-aged forest area following a complete stand-altering natural disturbance or land use. Forest age and the level of stand development reflects the influence of multiple interacting factors, including the longevity of dominant canopy tree species, the physical environmental factors that regulate plant growth, land use including logging, and the impacts of natural disturbance regimes. As tree age reflects genetically determined life history traits, and phenotypic responses to site conditions, the characteristic range varies among and between forest ecosystem types, as well as physical environmental conditions. Some of the Major Forest Groups in the East and Southeast have forest cover that is either recovering from relatively recent clearing and logging or are plantations with a timber harvesting regime that maintains a young age structure. It follows that in these forests, the Mature class may indeed be the oldest forest but are still young relative to the age these trees would reach under natural conditions. This is probably also the case with the plantation results as they are managed to be harvested at a relatively young age and therefore the most mature stands will be young compared to a mature natural forest.

The Forest Type Groups, stratified by USA Ecoregions Level III, were used to represent the major differences in forest ecosystems. However, as these Groups are only intended to indicate broad distribution patterns of forest cover in the USA, they represent a highly generalized level of ecological organization within which resides a rich forest biodiversity. Furthermore, the spatial models (i.e., maps) of Forest Types Groups used here are based on statistical models correlating FIA plot data with environmental and remotely sensed variables, with an overall accuracy of 65% (Ruefenacht et al. 2008). Also, it should be noted that using these maps for spatial stratification purposes means there was a minor element of circularity in our validation analysis in that the FIA plot data were input data to the modelled potential distribution of the Forest Type Groups. These were used to stratify forest cover in calculating the aggregate statistics shown in the box plots (Fig. 4). Future research could investigate using the general approach presented here but applied to the next level of Forest Type mapping that provides maps for 141 forest types, or to other data sources with more finely defined forest ecosystem types and mapping for particular ecoregions.

Other than calculating aggregate statistics (see Table 2), we did not distinguish in this analysis between naturally regenerated forests and plantations. However, to apply the modelled forest maturity mapping for conservation assessment purposes, this distinction is critical. Plantations are a significant component of the USA forest cover. Three of the largest forested SUA support significant areas of plantations (Table 2) including the Southeastern Plains-Loblolly/Shortleaf Pine Group (49%) and the Coast Range-Douglas-fir Group (28%). Conservation applications of the modelled forest maturity map will also require further partitioning by land ownership and management categories.

Conclusion

Further research is needed to calibrate the relative forest maturity mapped here with actual forest age classes, undertake analyses at a finer level of forest ecosystem delineation, and to investigate the impact of logging on, and its interactions with, the natural disturbances impacting on forest stand development and the distribution of modelled Young forest. While recognizing the limitations of the methods and data used here, the modelled forest maturity map and related analyses can make a useful contribution to forest planning and management by providing information needed by decision makers to meet national and international environmental commitments regarding mitigating greenhouse gas emissions from the forest sector, biodiversity conservation and the provision of clean water. The new high resolution spatial data on the level of forest maturity can be used to prioritize land for conservation through, for example, government programs aiming at meeting protected area targets. Information on the likely causes of Young Forest can assist planning for ecosystem restoration, for example, by identifying areas where stand development is the result of human land use pressures and a change in forest management is required. However, these appplications will require further research to examine the intersection of forest maturity with spatial data related to the density of forest carbon stocks, water quality and flow, and the habitat suitability and presence of threatened and characteristic wildlife species.

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Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Brendan Mackey and Heather Keith. The first draft of the manuscript was written by Brendan Mackey and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Supplementary Information Files

Supplementary Information - Methods. This file contains additional details on the methods in relation to: data assembly and visualization; the expert workshops; forest maturity cluster analysis; as well as the validation and attribution analyses

Supplementary Information – Figures. This file contains three supplementary figures. Figure SI1is a screen shot of one of the interacting mapping apps developed for the expert workshops. Figure SI2 shows the percentage area of young, intermediate and mature forest within USA Ecoregions Level II. Figure SI3 presents the box plots for all the Spatial Units of Analysis (SUA) that compare the canopy height and biomass from the modelled forest maturity with estimates from the Forest Inventory and Analysis (FIA) plot data