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Protect large trees for climate mitigation, biodiversity, and forest resilience

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Abstract
Protecting the climate system requires urgently reducing carbon emissions to the atmosphere and increasing cumulative carbon stocks in natural systems. Recent studies confirm that large trees accumulate and store a disproportionate share of aboveground forest carbon. In the temperate forests of the western United States, a century of intensive logging drastically reduced large-trees and older forest, but some large trees remain. However, recent changes to large tree management policy on National Forest lands east of the Cascade Mountains crest in Oregon and southeastern Washington allows increased harvesting of large-diameter trees (≥53 cm or 21 inches) that account for just 3% of all stems, but hold 42% of total aboveground carbon. In this article, we describe synergies with protecting large trees for climate mitigation, biodiversity, and forest resilience goals to shift species composition, reduce fuel loads and stem density, and adapt to climatically driven increases in fire activity in eastern Oregon.

KEYWORDS
aboveground forest carbon, biodiversity, climate change, eastern Oregon, large trees

1 | INTRODUCTION

Society has a narrow window of opportunity left to avert catastrophic consequences from the intertwined climate and biodiversity crises (IPCC, 2022), and forests offer major solutions at the intersection of these urgent imperatives. Forests account for 92% of all terrestrial biomass globally (Pan et al., 2013), store about 45% of the total organic carbon on land in their biomass and soils (Bonan, 2008), and removed the equivalent of about 30% of fossil fuel emissions annually from 2009 to 2018, of which 44% was by temperate forests (Friedlingstein et al., 2019). Moreover, forests provide critical habitats to more than half of all known plant and animal species on Earth (Gibson et al., 2011; Vié et al., 2009). As climate change increases and accelerates amplifying feedbacks, preserving species- and carbon-rich forests becomes ever more important, alongside a rapid transition to net-zero fossil fuel CO_2 emissions (Matthews et al., 2022).

Forests of the western US contain large stocks of carbon and remove significant quantities of CO_2 from the atmosphere to help protect climate, biodiversity, and water security (Buotte et al., 2020; Law et al., 2021). But how we manage these forests will play a large role in determining future outcomes (Fargione et al., 2018; Hudiburg et al., 2009; Law et al., 2018). Oregon stands out with the most forested area in the western USA, yet the lowest proportion of its forests protected (Law et al., 2021), and significant opportunities to create strategic forest reserves (Law, Berner, et al., 2022). About 80% of tree mortality in Oregon and Washington is attributed to harvest (Berner et al., 2017). In this article we provide insights from a recent study that quantified large tree carbon stocks in diverse forests of eastern Oregon (Mildrexler et al., 2020), and describe synergies with protecting disproportionately valuable large trees for biodiversity and climate mitigation, and forest resilience goals.

2 | LARGE TREES DOMINATE ABOVEGROUND CARBON STORAGE

Trees capture and store massive amounts of carbon, thus forests are an essential component of limiting global warming to 1.5–2°C (IPCC, 2018). However, trees are not all equal in their capacity to slow climate change in the coming critical decades. Large trees play an inordinately large role in removing carbon from the atmosphere and storing it in long-lived tissues (Figure 1; Lutz et al., 2012; Leverett et al., 2021). Globally, studies have found that about half the aboveground carbon is concentrated in a small proportion of large trees (1%–5% of total stems) (Lutz et al., 2018; McNicol et al., 2018). Because most global forests are well below their potential carbon stocks due to past and current land management practices, they could store twice the carbon than now (Erb et al., 2018). As large trees grow larger, small increases in diameter add a relatively large amount of volume and biomass (Mildrexler et al., 2020; Stephenson et al., 2014). Protecting existing forests with large trees and letting more forests mature and develop additional large trees is crucial for preventing carbon emissions and for continued accumulation of carbon from the atmosphere in the coming decades (Birdsey et al., 2023; Law, Moomaw, et al., 2022; Moomaw et al., 2019).

2.1 | The 21-inch rule and carbon stocks

Forests in eastern Oregon and southeastern Washington are recovering from a century of intensive logging that eliminated much of the region's large trees by selective harvest of the largest, most robust trees including clearcutting older forests. Nevertheless, the United States Forest Service (USFS) recently weakened protection for trees 21 inches diameter at breast height (DBH) and larger ("21-inch rule") across six national forests in this region. The 21-inch rule specifically applied to large-diameter trees on millions of acres of federal public lands. To assess the consequences of the loss of these trees it is essential to quantify large tree carbon stocks prior to changes in management actions. Mildrexler et al. (2020) evaluated carbon storage in large-diameter trees across the six national forests located east of the Cascade Crest in Oregon and Washington ("eastside forests") (Figure 2). Specifically, we quantified the relative contribution of large trees (≥21 inches DBH) to aboveground carbon (AGC) storage based on analysis of 636,520 trees on 3335 USFS Forest Inventory & Analysis (FIA) plots, and also assessed the carbon implications of relaxing the 21-inch rule. In these forests, large trees compose a small fraction of total stems (2.0% to 3.7% of all stems among five dominant tree species) yet hold 33% to 46% of total AGC stored by each species (Figure 3). The very largest trees, >30 inches DBH, held an even greater proportion of carbon (16.6%) relative to their small numbers (0.6%) demonstrating the importance of letting large trees grow larger and accumulate more carbon. Our research contributes to growing recognition that forests with large trees play a

FIGURE 1 Large-diameter grand fir (*Abies grandis*) in a mesic, mixed-conifer forest of northeast Oregon. These carbon-rich forests have a large cooling effect on maximum temperatures, provide thermal refugia for biodiversity including sensitive species, and are a high priority for protection. Large grand fir form the best hollow trees for wildlife (Rose et al., 2001).

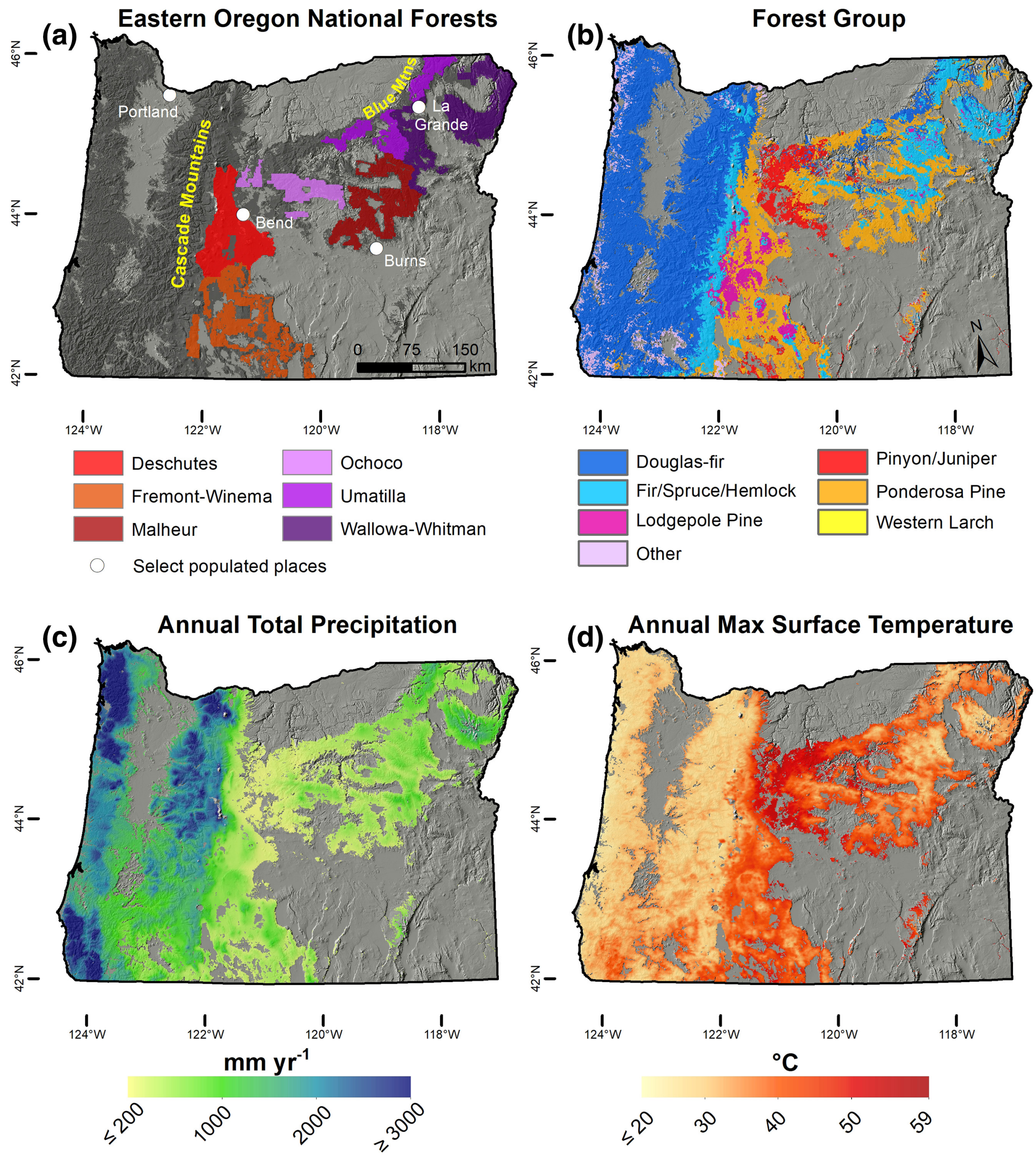
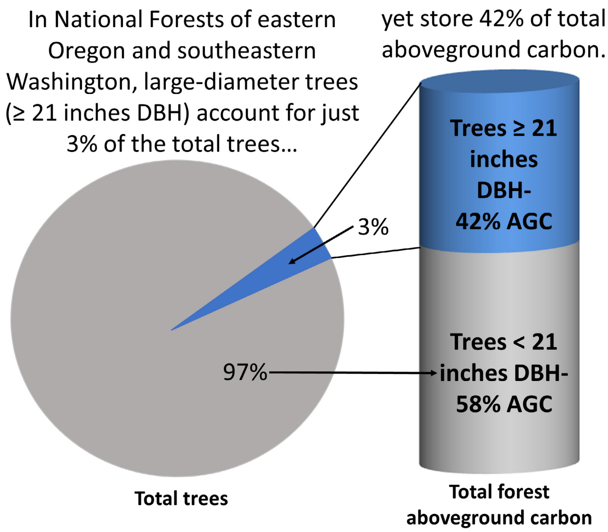


FIGURE 2 Forest and climatic diversity across the state of Oregon. (a) Extent of National Forests in Eastern Oregon. (Note a small portion of southeastern Washington included in our original study is not shown in this figure). (b) Distribution of forest groups. (c) Mean annual total precipitation from 1981 to 2010. (d) Mean annual maximum land surface temperature [LSTmax] from 2003 to 2020. Data sources include forest groups from Ruefenacht et al. (2008), precipitation climatology from Daly et al. (2008), and annual LSTmax derived using MODIS Aqua satellite data from Wan (2014).

very important role in climate mitigation now and in the near future (Lutz et al., 2018; Stephenson et al., 2014).

2.2 | A wildlife protection measure with a crucial carbon co-benefit

The 21-inch rule was implemented in the early 1990s as a habitat and species protection measure to recover large tree structure and to protect remaining late successional and old-growth forest and associated species (e.g., American Marten, Northern Goshawk) (Bull et al., 2005; Bull & Hohmann, 1994; Henjum et al., 1994), similar to the Northwest Forest Plan (NWFP) that was implemented to ensure persistence of old-growth forest species and their habitat in the western portion of the region (FEMAT, 1993). The NWFP resulted in a strong carbon benefit for climate mitigation, in addition to protecting sensitive species and riparian



Species common name	% of total species trees ≥ 21 inches	% of total species AGC in trees ≥ 21 inches
Douglas-fir	3.7	37.5
Engelmann spruce	2.4	34.7
Grand fir	2.0	38.4
Ponderosa pine	3.7	45.8
Western larch	2.8	33.3
Overall	**3.1**	**42.2**

FIGURE 3 Percentage of all tree stems above and below the 21-inch DBH threshold and their total aboveground carbon (AGC) stores overall, and for five dominant tree species, evaluated based on measurements from USFS inventory plots located in the six eastside national forests.

systems (Turner et al., 2011). Mildrexler et al. (2020) showed that carbon storage associated with the 21-inch rule on the six eastside national forests is a significant co-benefit of this protective measure (Pörtner et al., 2021).

Detailed analysis of stand structure and carbon impacts is essential for science-based decision-making about large-tree forest management policies because such policies affect many different values and services provided by forests (Davis et al., 2019; Teich et al., 2022), including consequences on greenhouse gas emissions and for increasing atmospheric carbon removal and accumulation in forests (Fargione et al., 2018; Griscom et al., 2017). Moreover, large live trees eventually create large-diameter snags and downed wood that continue to store carbon for decades and contribute directly to biodiversity by providing unique specialized habitats such as hollow trees and logs, and micro-environments (Lutz et al., 2021; Rose et al., 2001). However, the USFS General Technical Report on the 21-inch rule did not assess large tree carbon stocks (Hessburg et al., 2020), even though storage and accumulation of carbon in forests is an increasing priority in National Forests (Depro et al., 2008; Dilling et al., 2013; Dugan et al., 2017). Consequently, quantitative assessments of management effects on both forest carbon and biodiversity are important, including assessment of the effects of long-standing rules before they are eliminated or weakened (Mildrexler et al., 2020).

The 21-inch rule has since been amended. Grand fir (DBH ≥53 cm and <150 years) has lost protections in stands not designated as Late and Old Structure, and protections for all tree species have been significantly weakened from a standard to a guideline (USDA, 2021). This represents a major shift in management of large trees across the region, highlighting escalating tradeoffs between goals for carbon sequestration to mitigate climate change, and efforts to increase the pace, scale, and intensity of cutting across national forest lands. The potential impacts of removal of large grand fir on wildfire are unclear, although a trait-based approach to assess fire resistance found that the grand fir forest type had the second highest fire resistance score, and one of the lowest fire severity values among forest types of the Inland Northwest USA (Moris et al., 2022).

3 | ARE LARGE GRAND FIR OUTCOMPETING LARGE PONDEROSA PINE AND LARCH?

The key rationale for amending the 21-inch rule is that increased cutting of large-diameter fir trees (≥53 cm DBH and <150 years) is needed to facilitate the conservation and recruitment of early-seral, shade-intolerant old ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) by reducing competition from shade-tolerant large grand fir (*Abies grandis*) (USDA, 2021). Previous studies have looked at tree age-size relationships (Merschel et al., 2019; Perry et al., 2004), large tree numbers, and changes in basal area (Hessburg et al., 2022), but there has been no spatial analysis of close-range co-mingling of large-diameter tree species across the six national forests covered by the 21-inch rule. This is an important consideration because the competitive interaction among large-diameter trees, and their protection under the 21-inch rule, should not be conflated with small tree dynamics and common dry forest restoration strategies to reduce small tree density and favor retention of early-seral species.

We therefore examined how often large trees (≥53 cm DBH) of these species co-mingle on USFS FIA plots (~1 acre) across the same six eastside national forests where we previously examined carbon storage by large trees (Mildrexler et al., 2020). Drawing on the same USFS FIA measurements as our prior study, we found that large ponderosa pine, grand fir, and western larch were present

TABLE 1 Coverage, mean annual precipitation from 1981 to 2010, and mean annual maximum land surface temperature from 2003 to 2020 for the major FTG's within the six national forests, standard deviations in parenthesis (excludes lands in Washington and Idaho).

		Mean annual precipitation		Mean annual maximum LST	
Forest type group	**Area (km^2)**	**mm**	**in**	**°C**	**°F**
Douglas-fir	2372	679.9 (187.3)	26.8 (7.4)	37.8 (3.5)	100.1 (6.3)
Fir/Spruce/Hemlock	12,224	974.3 (369.5)	38.4 (14.5)	33.2 (2.8)	91.8 (5.0)
Lodgepole pine	3573	822.0 (274.6)	32.4 (10.8)	37.2 (3.8)	99.0 (6.8)
Pinyon/Juniper	634	329.5 (96.0)	13.0 (3.8)	50.4 (3.7)	122.7 (6.6)
Ponderosa pine	18,514	548.3 (139.2)	21.6 (5.5)	39.8 (3.5)	103.6 (6.3)
Western larch	47	746.9 (78.9)	29.4 (3.1)	31.5 (2.4)	88.7 (4.3)

on 56%, 18%, and 7% of all plots ($n = 3335$). Large ponderosa pine co-mingle with large grand fir about 14% of the time (259 plots), leaving 86% of plots with large ponderosa pine without large grand fir (1616 plots). Similarly, large western larch co-mingle with large grand fir about 56% of the time. Large ponderosa pine and grand fir are found together on only 8% of all plots in the region, while large larch and grand fir are found together on only 4% of all plots in the region. In other words, large ponderosa pine are by far the most common tree species found in these six National Forests and infrequently co-mingle with large grand fir at the FIA plot scale, whereas large western larch are far less common and co-mingle with large grand fir about half the time, which is expected since these species occupy similar environmental settings that receive more moisture (Table 1, Johnson & Clausnitzer, 1992).

The relative prevalence of large ponderosa pine in eastside forests is good for climate resilience given that large-diameter pines are exceptionally drought and fire-resistant trees (Irvine et al., 2004; Irvine et al., 2007). In the drought-prone region of central Oregon, mature and old ponderosa pine forests had 60% to 85% higher seasonal gross photosynthesis than a young forest (Irvine et al., 2004). Large ponderosa pine trees experienced only 34% mortality in moderate severity fire, and accounted for 91% of post-fire stemwood production, while small trees experienced 82% mortality (Irvine et al., 2007).

Across the entirety of all six national forests large grand fir represent 2% of the total species population, a proportion slightly lower, but roughly on par with other dominant species (Figure 3, Mildrexler et al., 2020). It is not uncommon for grand fir to reach 250 to 300 years of age (Howard & Aleksoff, 2000). Thus, large grand fir ≥53 cm DBH and <150 years of age can continue growing and play an important role in storing and accumulating carbon from the atmosphere to help abate the climate crisis.

Synergy: Enhancing forest resilience does not necessitate widespread cutting of any large-diameter tree species. Favoring early-seral species can be achieved with a focus on smaller trees and restoring surface fire, while retaining the existing large tree population.

4 | LARGE TREES, VULNERABILITY, STAND DYNAMICS, AND THE CARBON COST OF THINNING

As eastside forests recover from a century of intensive logging, it is important to distinguish between the shift of AGC stocks into small-diameter, fire-sensitive trees and the retention of a small fraction of the largest more fire-resistant trees that store disproportionately massive amounts of carbon. Small tree carbon stores are relatively unstable and at risk of loss to fire and drought, whereas large tree carbon stores are relatively stable and resistant (Hurteau et al., 2019). Physiological-based studies in ponderosa pine forests of Oregon have found that small trees are most vulnerable during drought relative to mature trees that have reached full root, bark and canopy development and respond to climate variability better than smaller trees (Domec et al., 2004; Irvine et al., 2004; Vickers et al., 2012). Buotte et al. (2019, 2020) identified forests in the western U.S. with high potential carbon accumulation and low vulnerability to future drought and fire using the Community Land Model and two climate models with high CO_2 emissions (RCP8.5), and species-specific traits capturing sensitivity of different species to water limitations and to drought and fire. The Eastern Cascades and Blue Mountains contain substantial area with opportunity to enhance forest carbon in large trees (Buotte et al., 2020; Law et al., 2018).

In dry forests historically maintained by a frequent, low-severity fire regime, the priority ought to be restoring the process of periodic surface fire. Prescribed fires create landscape heterogeneity, reduce surface and ladder fuels, lower stand density, and confer drought resistance to surviving trees (Knapp & Keeley, 2006; van Mantgem et al., 2016). In these forests prescribed fire can modulate future fire activity (Schoennagel et al., 2017), and favor early-seral species such as ponderosa pine, western larch and Douglas-fir. Large trees of these species and grand fir are resilient to prescribed fire because they have attained the thick bark that provides resistance to low- and moderate-severity fire (Howard & Aleksoff, 2000; Pellegrini et al., 2017).

Thinning also has an inherent carbon cost that increases as larger trees are harvested, thereby putting thinning of larger trees in conflict with carbon goals because it takes so long to replace the harvested biomass (James et al., 2018; Law & Harmon, 2011). The underlying principle for these losses is the negative relationship between harvest intensity and forest carbon stocks whereby as harvest intensity increases, forest carbon stocks decrease and emissions increase (Hudiburg et al., 2009; Mitchell et al., 2009; Simard et al., 2020). Claims that carbon stores will be "stabilized" by increasing harvest of large-diameter trees that store and accumulate the most carbon (Johnston et al., 2021) are inconsistent with basic science on thinning (Zhou et al., 2013) and the carbon cycle (Campbell et al., 2012; Law et al., 2018). These claims ignore the large amounts of CO_2 rapidly released to the atmosphere following harvest (Hudiburg et al., 2019), and that large trees cannot be replaced in short timeframes. It can take centuries to reaccumulate forest carbon stocks reduced by harvest of large trees (Birdsey et al., 2006).

Even thinning smaller trees involves substantial carbon tradeoffs in the short term, a 30%–40% reduction in live tree carbon stores in some forests (Krofcheck et al., 2017; North et al., 2009). To minimize reductions in carbon stocks and emissions, focus on removing smaller-sized trees, restoring surface fire, and managed wildfire in favorable weather conditions (Mitchell et al., 2009; Stenzel et al., 2021).

Synergy: Small trees are more relevant to drought and fire vulnerability and store less carbon, whereas large trees are more resilient to fire and drought and are the highest priority for keeping carbon in the forest.

5 | DIVERSE CLIMATE REGIMES AND FOREST TYPES REDUCE CLIMATIC EXTREMES

It is critical to accurately represent the diversity of climatic regimes and forest types in decisions affecting large tree management because large trees play unique roles in ecosystem water and energy cycles, and these biophysical effects can promote local climate stability by reducing extreme temperatures in all seasons and times of day (Lawrence et al., 2022). Forest modulation of summer maximum temperature is especially powerful (Mildrexler et al., 2018) and can partly offset the projected increases in temperature due to anthropogenic climate change (de Frenne et al., 2019). With heatwave frequency and severity projected to increase, the capacity of forests to buffer against temperature extremes and provide refugia is increasingly recognized as important to sustaining biodiversity in a warming world (Davis et al., 2019; de Frenne et al., 2019).

The six eastside national forests affected by the 21-inch rule cover a region of pronounced geographic and climatic variation and associated forest types (Figure 2; Johnson & Clausnitzer, 1992; Wyatt, 2017). Mean annual precipitation varied from 484 to 571 mm per year on the Ochoco and Malheur National Forests, to ~800 mm per year on the Deschutes, Umatilla and Wallowa Whitman National Forests (Mildrexler et al., 2020). We further examined the climatic regimes of the major forest types across the six national forests using satellite-based annual maximum land surface temperature (LST_{max}) and mean annual precipitation datasets (Figure 2D, Table 1). Our analysis shows that ponderosa pine and fir/spruce/hemlock types cover the largest area on the six national forests. The fir/spruce/hemlock type received the most total precipitation (~974 mm yr^{-1}) and had the second lowest annual LST_{max} (33.2°C). Average LST_{max} for the fir/spruce/hemlock type was 6.6°C (~12 °F) cooler than ponderosa pine (39.8°C), and 4.6°C (~8 °F) cooler than Douglas-fir (37.8°C). The pinyon juniper type had the lowest total precipitation (329 mm yr^{-1}) and highest annual LST_{max} (50.4°C) due to low canopy cover and heating of the dry surface during summer. These results show the region's pronounced variability in hydrologic and forest thermal regimes and highlight the thermal offsetting capacity of closed-canopied mesic forest systems. These valuable ecosystem services can be severely degraded by industrial logging (Lindenmayer et al., 2009).

Synergy: Mature and old mesic forests are a high priority for protection, provide crucial biophysical benefits on climate, including a large cooling effect on maximum temperatures regulating climate extremes and protecting biodiversity. Large grand fir is essential to this ecology.

6 | CONCLUSIONS

The 21-inch rule is an excellent example of a policy initiated for wildlife and habitat protection that has also provided significant climate mitigation values across extensive forests of the PNW Region. The rule resulted in a valuable resource of large-diameter trees in a landscape that remains below historical levels for large live trees and large snags due to historical logging (Bell et al., 2021). We have described synergies between protecting these disproportionately valuable large trees and forest resilience goals, providing common potential solutions for these urgent challenges.

Inland PNW forests can make a significant contribution to climate mitigation goals by protecting and enhancing carbon stores in large trees that accumulate and store the most carbon and are much more resistant to fire and drought than small trees, even when the current status of ecosystems has changed from historical baselines. Climate science makes clear that we do not have time to wait for regrowth after logging to accomplish these important ecosystem services (IPCC, 2022).

AUTHOR CONTRIBUTIONS

David J. Mildrexler led the writing. David J. Mildrexler and Logan T. Berner performed data analysis, investigation, and visualization. All authors commented on drafts, and assisted with writing, review and editing. All authors gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

This study relied on data from prior studies that are publicly available: Forest Inventory Data from the United States Forest Service (https://apps.fs.usda.gov/fia/datamart/datamart.html), MODIS Land Surface Temperature data from the Land Processes Distributed Active Archive Center accessed through Google Earth Engine, and gridded precipitation climatologies from Oregon State University PRISM Climate Group (https://prism.oregonstate.edu/normals/).

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