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Restoration of forest resilience to fire from old trees is possible across a large Colorado dry-forest landscape by 2060, but only under the Paris 1.5°C goal

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Abstract

Fire-prone dry forests often face increasing fires from climate change with low resistance and resilience due to logging of large, old fire-resistant trees. Their restoration across large landscapes is constrained by limited mature trees, physical settings, and protection. Active restoration has been costly and shown limited effectiveness, but lower cost passive restoration is less studied. I used GIS and machine learning to see whether passive restoration of old trees could overcome constraints in time, by 2060, across 667,000 ha of montane forests in the San Juan Mountains, Colorado, where temperatures are increasing faster than the global average. Random Forest models of physical locations of reconstructed historical old growth (OG) and relatively frequent fire (RFF) show historical OG with RFF was favored between 6.1 and 7.9°C annual mean temperatures. Random Forest models projected that similar temperature-suitable locations were moved into the current middle montane ca 2015, and would be extended to just below the upper limit of the montane if the Paris 1.5°C goal is reached, but beyond if not. US Forest Service common stand exam data, which covered ~15% of the study area and included 26,149 tree ages, show the highest potential for restoring resistance and resilience from old trees is a ≥120-year age class. This class could become a ≥160-year age class, which meets old-growth age criteria, over 81% of the area by ca 2060, nearly fully restoring historical old-growth levels. Half this age class is already protected, and much of the remainder could be retained using evidence-based diameter caps. Datasets thus are sufficient to show that passive restoration of old-tree resistance and resilience to fire is feasible by ca 2060 across a large montane landscape, although contingent on global success in achieving the Paris 1.5°C goal. Passive restoration may be viable elsewhere.

KEYWORDS
dry forests, fire, landscape, old growth, Paris goals, resilience, restoration

1 | INTRODUCTION

Potential effects of climate change for global forests appear dire (Albrich et al., 2020; Bradshaw et al., 2021; McDowell et al., 2020), but if Paris Agreement goals are reached and key landscape-scale restoration and protection occur in time, could better outcomes occur? Global forests face transition to shorter stature, younger stands, and altered composition, if not complete replacement by alternative stable vegetation after crossing tipping points as temperatures rise (Albrich et al., 2020; McDowell et al., 2020). Moreover, it is unclear whether forest resistance and resilience can be effectively enhanced or restored across large landscapes in time or in a manner that can reduce these transitions (e.g., Seidl et al., 2018). Indeed, 15 years of mechanical fuel treatments across large landscapes in the western USA had little effect on area burned by fires that are increasing from droughts and warming (Schoennagel et al., 2017). Fuel treatments last only 1–2 decades, are costly, and require field visitation. In contrast, little attention has been given to passive, landscape-scale restoration of resistance and resilience, which has lower cost, could persist much longer, and may need little field visitation. For example, if old, fire-resistant trees could be passively restored in a few decades, large land areas could simultaneously benefit from more adaptive resistance and resilience to fires (Schoennagel et al., 2017), carbon storage (Luyssaert et al., 2008), and other nature-based climate services (e.g., Seddon et al., 2021).

Here I analyze this possibility in a part of the western USA particularly vulnerable to climate change, in southwestern Colorado. This area is warming faster than the global average (Lukas et al., 2014), was identified as among the most vulnerable to increasing drought and fire (Buotte et al., 2018), and has been predicted to experience partial or complete loss of dry forests as their climate moves northward and upward, if emissions continue (Worrall et al., 2016).

Fire adaptations, that could be increased, are found in trees in fire-prone settings around the world (e.g., Fernandes et al., 2008; Schubert et al., 2016). Here, I focus on potential for landscape-scale restoration of resistance and resilience to fires in dry forests in the western USA. Dry forests include ponderosa pine (*Pinus ponderosa*) and mixed-conifer forests with ponderosa dominant. Fire-resistant old-growth ponderosa pines, that historically dominated dry forests of the western USA, were mostly removed by logging by the 1980s (Merschel et al., 2014; Romme et al., 2009), leaving forest resistance and resilience low. Resistance and resilience can be partly enhanced by restoring structure (e.g., tree density), but only fully by restoring these large trees.

Large ponderosa pine (Figure 1) have the most fire resistance and resilience. Resistance traits include (1) thick, heat-resistant bark (Stevens et al., 2020); (2) fire-resistant trunks with elevated canopies and few low branches (Baker, 2009; Stevens et al., 2020); (3) fast-flammable leaf litter that promotes rapid fire spread with less heat (Stevens et al., 2020); (4) capacity to regrow after high crown scorch (Hanson & North, 2009; Harrington, 1993); and (5) rapid juvenile growth that helps elevate canopies above low-severity fires, enabling more successful regeneration (Rodman et al., 2020). Surviving large trees also provide post-fire resiliency through seed. Cone and seed production in ponderosa are much higher and more frequent in larger trees, especially canopy dominants (Krannitz & Duralia, 2004). Seed from fire survivors within 100–250 m of severe burns is key to regeneration (e.g., Chambers et al., 2016; Rodman et al., 2019).

It is desirable, if the goal is to perpetuate dry forests in the face of increasing fire, to restore as much old-growth resistance and resilience to fire as possible by ca 2060. This is when climate change is likely to have raised temperatures to near maxima of 1.5–2.0°C as emissions reach net-zero, assuming goals of the Paris Agreement are reached (Baker, 2018a). It requires 160–200 years for ponderosa to grow from germination to old-growth age (e.g., Mehl, 1992; Popp et al., 1992), but only 40 years are available to 2060. The only feasible option is to put extant mature trees on a pathway to old growth (OG) while stand structure and fire are restored (Everett et al., 1994).

FIGURE 1 A typical old ponderosa pine forest [Colour figure can be viewed at wileyonlinelibrary.com]

Restoring old trees could also provide ancillary benefits for ecosystems and climate. Old trees are now considered a “keystone structure—a disproportionately important provider of resources crucial for other species” (Lindenmayer et al., 2014 p. 63). Old trees, for example, can strongly benefit wildlife (Carey, 1989). They also can mitigate warming effects at local scales (Frey et al., 2016), and they are major carbon sinks (Harmon et al., 1990; Luyssaert et al., 2008).

Effective old-growth restoration requires evidence about physical locations of historical OG and associated low-severity fire. Low-severity fire is often associated with old-growth dry forests dominated by ponderosa pine, as large fire-resistant trees better resist mortality (Baker, 2017). In dry forests of the western USA, OG has been reconstructed using tree-rings (e.g., Merschel et al., 2014; Sherriff et al., 2014), land surveys (Baker, 2015, 2020), and fire-history models (Lesica, 1996). Early inventories (e.g., Cowlin et al., 1942) can provide direct records. Evidence is often incomplete, but machine learning at known sites could possibly be used to train models to predict where restoration is most likely to succeed, as used here. For example, classification and regressions trees and physical predictors from 232 tree-ring samples were used to model fire severity across much of the Colorado Front Range (Sherriff et al., 2014).

Spatial data on modern forests are also needed, to focus old-tree restoration where potential is highest. US Forest Service stand-exam data and old-growth inventories are available. Are these data sufficient to identify locations likely to sustain or restore old trees in the 40-year transition?

Achieving old-tree restoration requires commitment, since little wood production can occur in restoration areas (Everett et al., 1994). The federal Collaborative Forest Landscape Restoration Program, created by the Omnibus Public Land Management Act of 2009, provides funding for ecological restoration that maximizes retention of large trees and fire-resilient forests. Other commitments have come from old-growth plans (e.g., Davis et al., 2015), protected areas (e.g., Research Natural Areas, Wilderness), policy designations, forest planning, and collaborative agreements (Spies & Duncan, 2009). Are old-tree protections adequate for restoration by 2060?

2 | MATERIALS AND METHODS

2.1 | Overview of analysis

In this study, I approached this problem several ways. I modeled, using Random Forests, potential historical and future physical settings of OG and low-severity fire across a large montane landscape in Colorado. I used physical predictors to model where there historically were both OG dominance and relatively frequent fire (RFF) at reconstruction points (Figure 2), a combination that favors old-growth stability (e.g., Baker, 2017). I then used the model to predict each of these across the study area, followed by analysis of contours of annual mean temperature that delimit their overlap area. I then projected physical old-growth suitability into the future using the same predictors, but substituting estimated future annual mean temperature, which is then overlain with temperature contours to project future overlap area. Finally, I used Forest Service data to determine potential old-tree restoration by ca 2060, given extant forest protection.

2.2 | Study area

The initial study area was the 773,366 ha montane part of the southwestern San Juan Mountains, Colorado (Figure 3) used to reconstruct historical vegetation from General Land Office (GLO) surveys ca 1881 (Baker, 2020). The montane includes (1) ponderosa pine forests with few other tree species; (2) dry mixed-conifer forests dominated by ponderosa but also with white fir (*Abies concolor*), blue spruce (*Picea pungens*), quaking aspen (*Populus tremuloides*), or Douglas-fir (*Pseudotsuga menziesii*); and (3) moist mixed-conifer forests with these same tree species, but little to no ponderosa (Romme et al., 2009). The montane is bounded at lower elevations by piñon-juniper (*Pinus edulis*-*Juniperus* sp.) woodlands and sagebrush (*Artemisia* sp.) and at higher elevations by subalpine forests dominated by subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and quaking aspen.

At this time of the GLO surveys (ca 1881), non-Indian settlers were few, and industrial land uses were just expanding. Land surveys created 1.609 km (1 mile) section lines, along which surveyors were required to record dominant overstory trees and also understory shrubs, trees, and other vegetation, in order of abundance (Williams & Baker, 2011). Each section line also required surveyors to monument a quarter corner halfway and a section corner at the end. Nearby bearing trees, to aid corner relocation, were marked, and their distance, azimuth, diameter at ~30 cm above the base, and identity were recorded. Two bearing trees were required at quarter corners and four at section corners. Bearing-tree data were the basis for reconstructing OG (Williams & Baker, 2011). To focus on relatively unaltered forests, I omitted area affected by fences, fields, roads, and other uses, leaving a net unaffected section-line analysis area (Figure 3) of 666,916 ha with 8422 km of section lines (Baker, 2020). A smaller section-corner analysis area of 235,884 ha with 2974 km of section lines also was used, as only here did surveyors adequately record required bearing trees at corners (Baker, 2020).

2.3 | Background on old-growth forests in the study area

On the San Juan National Forest (SJNF), which dominates the study area, likely 13–31 moss species are restricted to, or favored in OG, as are several fungi, five mammals, and several birds (Romme et al., 1992). Romme et al. (2009) found that most OG on the SJNF had been logged by about 1950. Remnant stumps, historical accounts, and records show where high-grade logging, particularly using railroads, occurred in the early 1900s (Baker, 2018b).

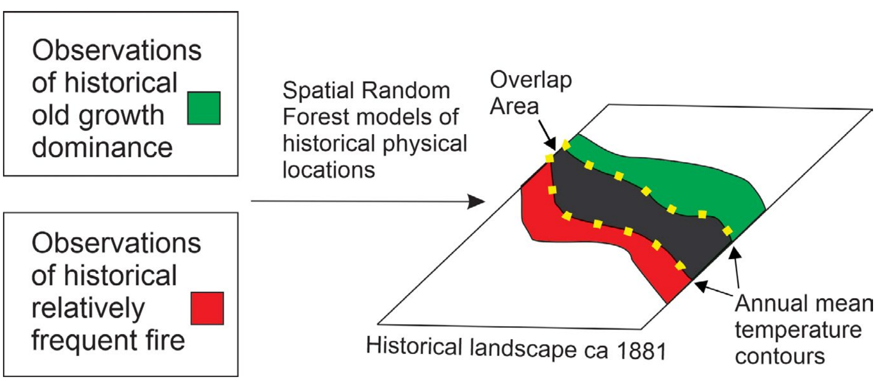

FIGURE 2 Overview of the historical analysis framework that is the basis for projecting where old-growth dominance and relatively frequent fire may similarly enable old-growth perpetuation currently and in the future as temperatures increase [Colour figure can be viewed at wileyonlinelibrary.com]

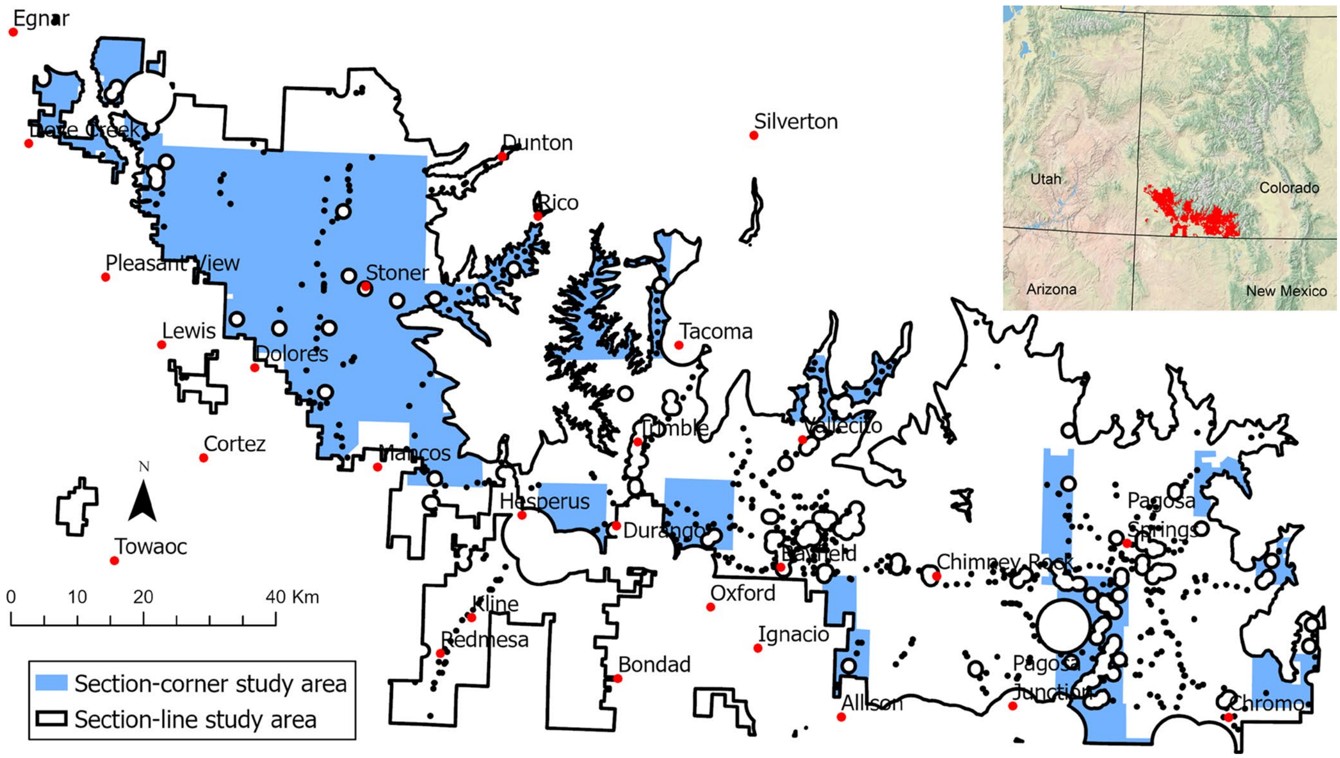

FIGURE 3 Section-line and section-corner study areas [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Reconstructed historical old growth in the section-corner training area, analyzed by Baker (2020), but re-analyzed here using San Juan National Forest old-growth definitions

Historical zone	Total area in zone (ha)[a]	Old growth analysis area (ha)[b]	Old growth: Area (ha)	Old growth: Area (%)
Pine and piñon-juniper	13,192	7349	4508	61.3
Pine	104,059	45,916[c]	37,988	82.7
Dry mixed conifer	46,522	24,537[d]	17,469	71.2
Moist mixed conifer	38,823	23,846	5550	23.3
Dry forests[e]	163,773	77,802	59,965	77.1
Forests—unknown zone	14,192	0	0	0.0
Non-forests—unknown zone	18,999	0	0	0.0
Whole montane	235,787	101,648	65,515	64.5

[a]The section-corner training area contained non-forest that could be associated with each zone, but other non-forest not assignable to a zone. All non-forest, and area only identified as forest, were excluded from the analysis area, which included only the usable forest with adequate bearing-tree data. This could only be 47% of total area of the montane. Forested area is only 79% of the montane, thus old-growth analysis area is 55% of total forest area in the montane.

[b]The old-growth analysis area is less than the total area in each zone, because some was non-forested, and, in the forested parts, the pooled Voronoi polygons, needed to reconstruct old growth from both tree diameters and tree density, could be created and intersected over only the part of the forests where bearing-tree data were adequate.

[c]This area was reported in Baker (2020) as 45,986 ha, due to a calculation error.

[d]This area was reported in Baker (2020) as 24,467 ha, due to a calculation error.

[e]Dry forests consist of Pine and piñon-juniper, Pine, and Dry mixed conifer.

Baker (2020) reconstructed historical montane OG using land surveys in the section-corner study area (Figure 3; Table 1). Baker used the diameter and density components of the Mehl (1992) old-growth definition for interior ponderosa pine in Southwest Colorado, and the Popp et al. (1992) definition for the mixed-species group in the Southwest. Here, however, I used diameter at breast height (dbh or 1.37 m) and density components of SJNF definitions (San Juan National Forest, 2007). OG ponderosa pine is defined by minima: (1) 200 years of age, (2) 40.64 cm (16″) dbh, (3) 24.7 trees/ha ≥40.64 cm dbh (10 trees/acre ≥16″ dbh); and (4) 2.47 dead or broken-topped live trees and/or rotten live trees/ha ≥40.64 cm dbh (one tree/acre ≥16″ dbh). These also apply to mixed-conifer forests, with one addition: (5) 4.94 dead trees/snags ≥25.4 cm dbh and 3.05 m tall per ha (two trees ≥10″ dbh and 10 feet tall per acre). To reconstruct OG from GLO data, only criteria (2) and (3) can be used, but since these were historical forests, other criteria likely were met. Because GLO diameters were in English units, (3) was rounded to 25 trees/ha ≥40 cm dbh. I applied these criteria to GLO reconstructions of tree density and diameters (Baker, 2020) that I analyzed in ArcGIS 10.8 (ESRI). After intersection, a new attribute was classified as OG or not old growth (NOG).

Old-growth protection exists on the SJNF in protected areas, as explained in the SJNF Land and Resource Management Plan Update of March 2021 (San Juan National Forest, 2021). Protected areas include parts of four Wilderness Areas, 20 Roadless Areas, eight Research Natural Areas, Chimney Rock National Monument, the Dolores River and the HD Mountains Unique Landscapes, and Boggy and Smoothing Iron Old Growth Areas. Most relevant, timber production is prohibited in all of these areas. Minor harvesting is allowed as a tool in Roadless Areas, Old Growth Areas, and Unique Landscapes. Mechanical fuel treatments are prohibited in Wilderness Areas and Research Natural Areas, but allowed in Roadless Areas and Old Growth Areas to meet desired conditions. Mechanical restoration and fuels treatments are allowed in limited cases in Chimney Rock National Monument and Unique Landscapes. Livestock Grazing is permitted in all areas, but in Research Natural Areas only to meet desired conditions. Prescribed burning, which may include low and some moderate severity, is allowed in all areas, but only to meet desired conditions in Research Natural Areas and Old Growth Areas. Managed fires for resource benefit are allowed in specific areas. San Juan National Forest (2021) reported 17.0% of moist mixed-conifer, 13.1% of dry mixed-conifer, and 4.3% of ponderosa pine forest area in the montane are formal old growth. Montane desired conditions were 20%–30% of moist mixed-conifer, 20%–30% of dry mixed-conifer, and 10%–15% of ponderosa pine area in old growth.

2.4 | Modeling the physical setting of historical old growth and relatively frequent fire

I modeled the physical setting of historical old growth to understand that setting and estimate locations across the full section-line study area that may also have been physically suitable for old growth. I trained a Random Forest model using 18 physical predictors (Table 2)

TABLE 2 Potential predictors of old growth and relatively frequent fire. Each predictor was projected to UTM Zone 13 NAD 1983 and clipped by the study area boundary

Source type/name	Source[a]	Short name	Range of values
Topography			
Area solar (WH/m^2) April–October	DEM-ArcGIS	areasolar	0.40–1.28 million
Aspect (azimuth in degrees)	DEM-ArcGIS	aspect	0.02–359.97°
Curvature (*z*-units)	DEM-ArcGIS	curvature	−1.3 to 2.6 million
Elevation	USGS DEM	elevation	1969–3070 m
Slope	DEM-ArcGIS	slope	0.14–62.18°
Topographic position: 100 m	DEM-GRASS	topopos100	6 positions[b]
Topographic position: 500 m	DEM-GRASS	topopos500	6 positions[b]
Topographic position: 1000 m	DEM-GRASS	topopos1000	6 positions[b]
Topographic position: 1500 m	DEM-GRASS	topopos1500	6 positions[b]
Topographic position: 2000 m	DEM-GRASS	topopos2000	6 positions[b]
Terrain ruggedness index	DEM-GRASS	topotri	0.00–4.33
Topographic wetness index	DEM-GRASS	topowet	2.51–17.05
Geology and soils			
Geology formation	Colorado Geology	geolform	15 formations[b]
Geology-rock type	Colorado Geology	geolrock	17 rock types[b]
Soil depth to bedrock	SSURGO	bedrock	0–203 cm
Soil available water storage	SSURGO	aws	0–29.76 mm
Soil organic carbon	SSURGO	soc	0–115285 g/m^2
Annual climate: 1895–1904			
Mean temperature	PRISM	anntmn1895	2.98–7.96°C

[a]Sources include: Colorado Geology: https://mrdata.usgs.gov/geology/state/state.php?state=CO; DEM-ArcGIS: Digital Elevation Model used in ArcGIS 10.8, ESRI, Redlands, California; DEM-GRASS: Digital Elevation Model used in GRASS GIS 7.8.2, https://grass.osgeo.org/; PRISM (gridded climate data): http://www.prism.oregonstate.edu/; SSURGO: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx; USGS DEM (Digital Elevation Model-10m): https://viewer.nationalmap.gov/.

[b]A list of the meaning of each category or type is in Appendix S2.

based on topography, geology and soils, and climate. Predictors were developed as rasters in ArcGIS and GRASS (https://grass.osgeo.org). I used a 10 m resolution digital elevation model (DEM), clipped by the study area boundary, as the base map (see Appendix S1 for processing details). From the DEM, I created maps of aspect, curvature, slope, and area solar. Curvature is the second derivative of the surface; negative is concave, zero is flat, and positive is convex. Area solar estimates incoming radiation (direct, diffuse, and reflected) in the growing season, April 1 to October 1. Topographic positions are classified over specified distances as planar, pit, channel, pass or saddle, ridge, and peak. Terrain ruggedness index measures sum change in elevation between a cell and its neighbors (Riley et al., 1999). The topographic wetness index measures area of the hillslope, per unit contour length, that drains through a pixel (Cho, 2000). To meet machine-learning limits with categorical variables, I merged 40 geologic formations in the Colorado geology map into 15 (see Appendix S2 for details). PRISM data (www.prism.oregonstate) for 1895–1904 annual temperature, which provide the best available spatial estimate of historical temperatures, are coarse resolution (~800 m). I limited analysis to temperature, the key climate-change variable of interest in this analysis.

To derive training samples, I extracted data from the old-growth map and 18 predictors using systematic point samples, one at the midpoint of each 100 m pixel along section lines. Since bearing-tree data are from corners along section lines, and the old-growth reconstruction is thus best there, I constrained training to section lines. The initial sample was 11,190 points, but points had to be omitted near borders, where the topopos2000 predictor, extending over 2 km, was necessarily null, and also points with nulls in other predictors that had to be omitted. I extracted the resulting final 8296 point samples for the 18 predictors and old growth, then ran a "predict to raster" model of old growth across the section-line study area in ArcGIS Pro 2.6, using the Forest-based Classification and Regression tool, based on Random Forests (Breiman, 2001). I ran 200 trees, selected compensation for sparse categories, excluded 10% for validation, and accepted other defaults. I examined variable importance to interpret the model, and also compared distributions of the predictors, across the points, that distinguish OG from NOG, in Minitab (Minitab LLC). I also calculated contours of some predictors in ArcGIS and overlaid them on the map of OG versus NOG.

I modeled the physical location of historically RFF that likely helped perpetuate old growth. There were few fire rotations ≤25 years, considered frequent (Baker, 2017), in the study area (Baker, 2018b); thus, I used ≤30 years as RFF. I used published fire histories in the study area, but had to estimate fire rotation (see Appendix S3 for details). The dataset had 14 predictors at 28 sites with fire rotations of 15–112 years. I used Forest-based Classification and Regression in ArcGIS to predict rotations ≤30 years versus >30 years (Table 2). I selected 100 trees, excluded 10% for validation, accepted other defaults, and used the model to "predict to raster" across the section-line study area.

2.5 | Evaluating the potential of current forests to restore old growth and scattered old trees

Evidence about modern forests was from SJNF common stand exam data (CSE; pers. comm., Mark Roper, Forest GIS Coordinator, SJNF, December 22, 2020). I started with forest-wide "active" CSE data (not replaced by a new sample, not harvested or otherwise altered). I included all montane forests, not just dry forests, as climate change may force expansion into other montane forests. I clipped CSE data with the montane section-line boundary (Figure 3), and initially found 3776 active stands, each associated with a polygon interpreted from remote sensing or field survey. Stands, inventoried from 1971 to 2020, had records for trees sampled in variable-radius or fixed plots, which I processed for analysis in ArcGIS (see Appendix S4 for details). The final dataset included 3751 stands, 22,065 plots, and 111,090 tree records, 26,149 with tree ages, for stands covering 101,677 ha.

I assumed survival of trees from the inventory year to 2020 to provide an upper-limit estimate of current old trees. There is no accurate way to predict how many trees, sampled between 1971 and 2020, are alive in 2020 or will be in 2060. These estimates provide best-available estimates that need to be confirmed in the field if more reliable data are needed. To estimate 2020 age, I added years, between the inventory year and 2020, to basal age at the time of the inventory. I classified trees as old or not old in 2020, using age classes of ≥120, ≥140, ≥160, ≥180, and ≥200 years, which span ages that, by 2060, could meet regional old-growth definitions (Mehl, 1992; San Juan National Forest, 2007; Popp et al., 1992). I then calculated stand-level mean tree density, for each of these age classes in each stand (see Appendix S5 for details). Stands had a small tree-age sample, averaging ~8.5 trees, but there were 3072 stands with ages.

Where stands may not have the density or other attributes to qualify as old growth, they may still contribute resilience to fire. Tree regeneration is facilitated by surviving large trees within 100–250 m of severely burned area (Baker, 2018b; Rodman et al., 2019). I estimated the density of old trees needed to, on average, provide resilience to moderate- to high-severity fires, typically defined as killing 20%–100% of basal area (Agee, 1993), or roughly 20%–100% of trees (~60% on average). If trees are equally spaced, their density at 100 m spacing is 4.00 trees/ha, and at 250 m spacing is 0.64 trees/ha. Assuming 40% mean survival of large trees after average moderate- to high-severity fires, it would require a minimum of 1.6 large trees/ha or a more adequate 10.0 large trees/ha before fire to have at least one live post-fire large tree every 100–250 m to facilitate tree regeneration. This resistance/resilience function thus can be provided without the higher densities required by formal old-growth definitions. I used CSE data to analyze where minimum to adequate densities occur for trees of the five main old age classes across the study area.

Also, I separately analyzed tree diameter as a proxy for identifying potential old trees, as it is infeasible to age trees as their fate is determined. To see whether old trees could be mostly protected by a size limit, I analyzed the diameter (dbh) of trees that would include 90% or 80% of trees of an age class. I extracted into separate datasets all trees ≥120, ≥140, ≥160, ≥180, and ≥200 years of age in the inventory year. In each, I sorted trees by diameter, largest to smallest, identified the trees at 90th and 80th percentiles, and recorded their diameter. I also did this by each Local Type.

I analyzed the extent to which old age classes of trees are within protected areas on the SJNF. I intersected locations of age classes with locations of protection, using a geodatabase of SJNF management areas (Pers. comm., Mark Roper, SJNF, January 9, 2021).

2.6 | Old-tree restoration sensitive to climate change

Southwestern Colorado, based on weather-station records, has the strongest warming trend in Colorado; annual mean temperature increased by 1.6°C (2.8°F) between 1983 and 2012, mostly after ca 1995, with a rapid recent warming rate of about 1.0°C/decade (Lukas et al., 2014). Increases in annual mean temperature in the San Juan Mountains were reported to be slightly more than 1.0°C from 1895 to 2005 (Rangwala & Miller, 2010). Both studies found ~2.0°C of total warming from 1895 to 2015, the year of the Paris Agreement, based on 0.4°C to extrapolate Lukas et al. and 1.0°C to extrapolate Rangwala and Miller to 2015. This is much higher than mean global warming of just over 1.0°C since the pre-industrial period, which led to the Paris Agreement goal of total warming <1.5–2.0°C (Sanderson et al., 2016). Regional climate models, assuming ongoing high emissions, predicted >2.0°C of warming between 1971–2000 and 2041–2070 (Rangwala et al., 2012). This would be >3.0°C of warming after 1895, above the 2.5–3.0°C extrapolated here from station records and the Paris Agreement. With continued emissions, warming is projected to lead largely to a threatened or lost ponderosa pine zone and similar adverse changes in mixed conifer in the study area (Worrall et al., 2016).

I analyzed potential constraints of warming temperatures on old-growth restoration across the study area. I first estimated annual mean temperatures ca 1881, ca 2015 (the year of the Paris Agreement), and the unknown year that Paris Agreement goals are reached. I used 30-year annual mean temperature spatial PRISM estimates for the study area, which could differ from station estimates over southwestern Colorado. PRISM data for 1895–1904 are the closest available proxy for ca 1881 annual mean temperatures. To make the Paris estimates, I extrapolated from the most recent PRISM data, which are for 1981–2010 (Table 2), thus centered ca 1995 (see Appendix S5 for details). Then, to estimate potential future constraints on old-tree restoration as warming ensues, I overlaid contours for 1895–1904 annual mean temperature in 0.1°C increments to find contours that best match warmer and cooler constraints where OG historically dominated NOG and RFF occurred. I next used the Random Forest models of historical OG and RFF to predict to raster, but for the ca 1995, 2015, and Paris annual mean temperatures. Finally, I overlaid the historical annual temperature contours for OG and RFF on these new rasters, and evaluated potential for OG dominance with RFF, assuming historical physical constraints are likely to similarly constrain future OG and RFF, but in new locations.

3 | RESULTS

3.1 | Random forest model of historical old growth and relatively frequent fire

The trained Random Forest model of OG and NOG had out-of-bag errors of 1.3% for OG and 12.3% for NOG, thus high accuracy. Accuracy in the training dataset was 0.95 for both, but accuracy in the 10% validation dataset was 0.83 for both, suggesting some overfitting. I reduced depth of trees from near 100 down to 50 and 25 and made other adjustments, but could not obtain an outcome that had similar accuracy in both, thus I retained this model as the final model.

Overall, 64.5% of sampled montane forest in the training area historically had OG structure (Table 1). Pine (83%) and dry mixed conifer (72%) had highest percentages and moist mixed conifer (23%) lowest. The prediction raster (Figure 4) also had 64.5% OG and 35.5% NOG. This is just OG potential; not all was necessarily OG historically. Lack of historical OG likely occurred because of natural disturbances and physical constraints. Training data were lacking in places (e.g., border area) due to missing topographic predictors (Figure 4). The prediction thus covers 542,527 ha (81.3%) of the 666,916 ha unaffected section-line study area.

Variable importance (Table 3) showed that topographic predictors accounted for 60% of variation in the prediction, soil and geology predictors 29%, and the climate predictor 9%. Elevation and annual mean temperature were most important, but soil predictors were three of six top predictors. Geology had a minor role. The most important topographic predictors, besides elevation, were finer scale measures of topographic variation, including the topographic wetness index, curvature, aspect, slope, and topographic ruggedness index, which together accounted for 35% of variation in the model. Topographic position, accounting for only 8% of variation, was also important at finer scales (100–500 m). OG was favored at lower elevations on warmer sites, but with more moisture (see Appendix S6 for more details).

The Random Forest classification model of all-severity fire rotations ≤30 years versus >30 years had no out-of-bag errors for either class, and was fully accurate in the 90% training and 10% validation data. These are small tests, since the full dataset had only 28 sites. The prediction area (Figure 5a) was 600,680 ha, 90% of the 666,916 ha study area. Area was often not predicted on borders, due to missing topographic predictors or in other areas due to missing data in other predictors. Predicted area for all-severity rotations ≤30 years was 245,510 ha, 41% of prediction area, but is only for potential areas with physical characteristics that support RFF.

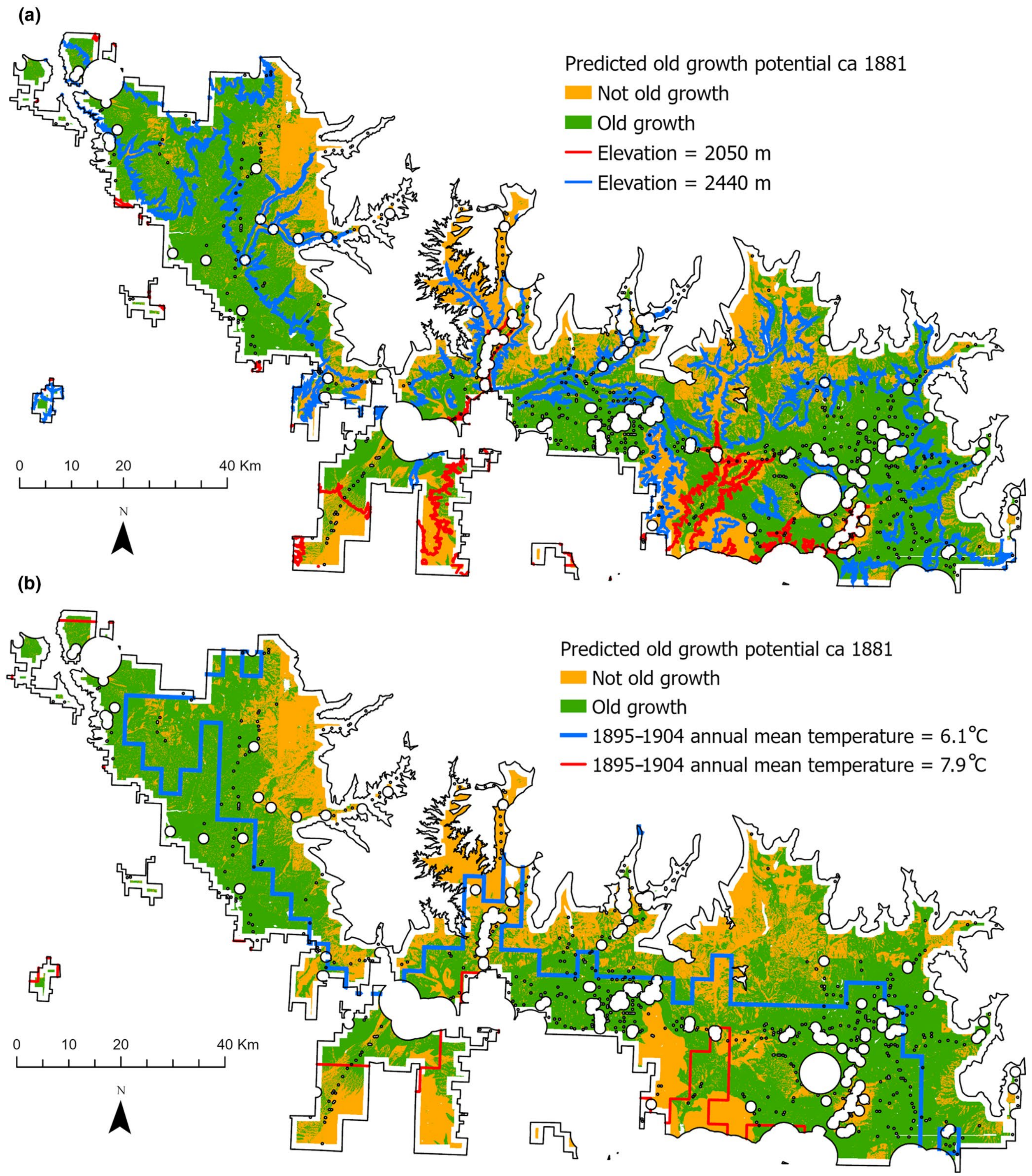

FIGURE 4 (a) Predicted old growth and not old growth, and the contour for 2440 m elevation, below which old growth dominated not old growth down to 2050 m elevation, (b) old growth and not old growth and the contour for 1895–1904 annual mean temperature of 6.1°C, below which old growth also dominated not old growth to as warm as 7.9°C [Colour figure can be viewed at wileyonlinelibrary.com]

Topographic predictors again were most important, accounting for 64% of variation in RFF, with geology and soils 26%, and the climate predictor 8% (Table 4). Geology and soils were three of five top predictors, including soil organic carbon (10%), depth to bedrock (8%), and available water storage (8%). Among topographic predictors, terrain ruggedness index was most important (9%), followed by elevation (9%), area solar (8%), slope (8%), and aspect (7%), with topographic position indices, mostly at finer

TABLE 3 Variable importance for the 18 predictors, in the Random Forest model of old growth, which together account for 98% of the model's ability to distinguish old growth from not old growth

Predictor	Importance	Percentage
Elevation	25.43	9
Annual mean temperature	24.41	9
Soil depth to bedrock	22.95	8
Area solar	22.06	8
Soil organic carbon	22.03	8
Soil available water storage	21.89	8
Topographic wetness index	20.71	7
Curvature	20.54	7
Aspect	20.43	7
Slope	19.79	7
Terrain ruggedness index	19.74	7
Geology formation	7.95	3
Topographic position: 500 m	6.51	2
Topographic position: 100 m	6.41	2
Geology-rock type	5.94	2
Topographic position: 1000 m	4.69	2
Topographic position: 1500 m	3.71	1
Topographic position: 2000 m	3.54	1

100–500 m scales, also contributing. Annual mean temperature accounted for 8%. RFF was favored on more carbon-rich soils with greater depth to bedrock and available soil water on warm, shallow, southerly facing slopes at lower elevations (see Appendix S7 for more details).

3.2 | Potential of current forests to restore old growth, scattered old trees, and historical forests

Age classes of old trees show it is likely possible to restore old trees, old growth, and their contribution to resistance and resilience to fire over much of the montane by 2060 (Table 5; Figure 6). The 2020 area of moderate+ old-tree resilience in the ≥200 year age class is limited, only 14.9% of CSE area overall (Table 5), except from Bayfield to Pagosa Springs (Figure 6a). However, if trees in the ≥160 year age class in 2020 mostly survive, then by 2060 the area of ≥200 year forests could expand to as much as 38.7% of the analysis area overall (Table 5), with substantial increases in all but the westernmost area (compare 2020 Figure 6a to 2060 Figure 6b). For the ≥160-year class, gains from 2020 to 2060 are much more substantial, increasing overall from 38.7% of area in moderate+ resilience in 2020 to 80.7% in 2060 overall (Table 5), with gains across all areas (compare 2020 Figure 6b and 2060 Figure 6c), even the west. But, overall estimates include aspen stands that do not increase in resistance and resilience to fire as they age and that seldom reach the ≥200-year age class.

More relevant individual Local Types show that, from 2020 to 2060, moderate+ resilience in ≥200 year old stands would increase from 6% to 20% in Ponderosa Pine, 18% to 50% in dry mixed conifer, and 39% to 72% in moist mixed conifer (Table 5). Again, much greater increases would occur for the ≥160-year age class, where moderate+ resilience would increase from 20% to 61% in Ponderosa Pine, 50% to 89% in dry mixed conifer, and 72% to 96% in moist mixed conifer. I left out Aspen and Aspen with Softwood, as these are uncertain forest types, but likely more like moist mixed conifer (Baker, 2018b), which are not the focus. More details on density of trees in old age classes overall and by Local Type are in Appendix S8. Note there that a median ponderosa stand has no trees ≥160 years old in 2020, but could have ≥35 trees/ha ≥160 years old by 2060, indicating a major recovery of old trees.

Potential survivors of moderate- to high-severity fire, provided by pre-fire old trees at least every 100–250 m, are generally insufficient (0.0–1.59 trees/ha) in 2020, but could greatly increase by 2060. Survivors are more possible with large-tree density of 1.6–10.0 trees/ha and become more likely up to and beyond the 25 trees/ha in old-growth definitions (Figure 6). For the ≥200-year age class in 2020 overall, insufficiency is widespread in the southeast and west, but less so from Bayfield to Pagosa Springs (Figure 6a). For the ≥160-year age class, insufficiency is lower, since more area of moderate+ occurs, as from Mancos to Stoner and scattered north of Durango (Figure 6b). For the ≥120-year age class, areas from minimal to high density dominate and insufficiency is quite limited (Figure 6c). Most important, if extant trees mostly survive, insufficiency nearly disappears by 2060 as this age class reaches ≥160 years (Figure 6c).

Common stand exam data provide a large dataset for using tree diameters as a proxy for age (Figure 7; Table 6). At the 90th percentile, lower limits are moved in near the left edge of the thicker part of the point cloud (Figure 7), with trees left of vertical lines not included and trees to the right included. This graph and Table 6 both show that a 48.0 cm (18.9 inch) diameter limit would likely include 90% of trees ≥200 years old, part of the SJNF old-growth definition. Similarly, a 38.1 cm (15.0 inch) diameter limit would likely include 90% of trees ≥140 years old, trees that are remnants of the historical forest. Note also the 34.5 cm (13.6 inch) diameter limit for trees ≥120 years old, trees in 2020 that can produce trees ≥160 years old by 2060. To provide an alternative and more detail, these same data are shown for the 80th percentile and by Local Type (Table 6).

Remnant historical trees, that originated in or before ca 1880, when non-Indian settlement expanded, are still surprising abundant (Figure 8; Table 5). Overall, in 2020, ≥25 historical trees/ha may still exist across 55% of the montane, ≥50 historical trees/ha across 43%, and ≥100 historical trees/ha across 29% (Table 5). Large deficiencies in historical trees, relative to these densities, are in western and southeastern areas (Figure 8). Even in ponderosa pine forests, where large trees were most heavily logged, 30% have ≥25 historical trees/ha, and 13% have ≥50 historical trees/ha. In dry mixed conifer, fully 50% have ≥50 historical trees/ha and in moist mixed conifer an even higher 64% have ≥100 historical trees/ha (Table 5). This resource of

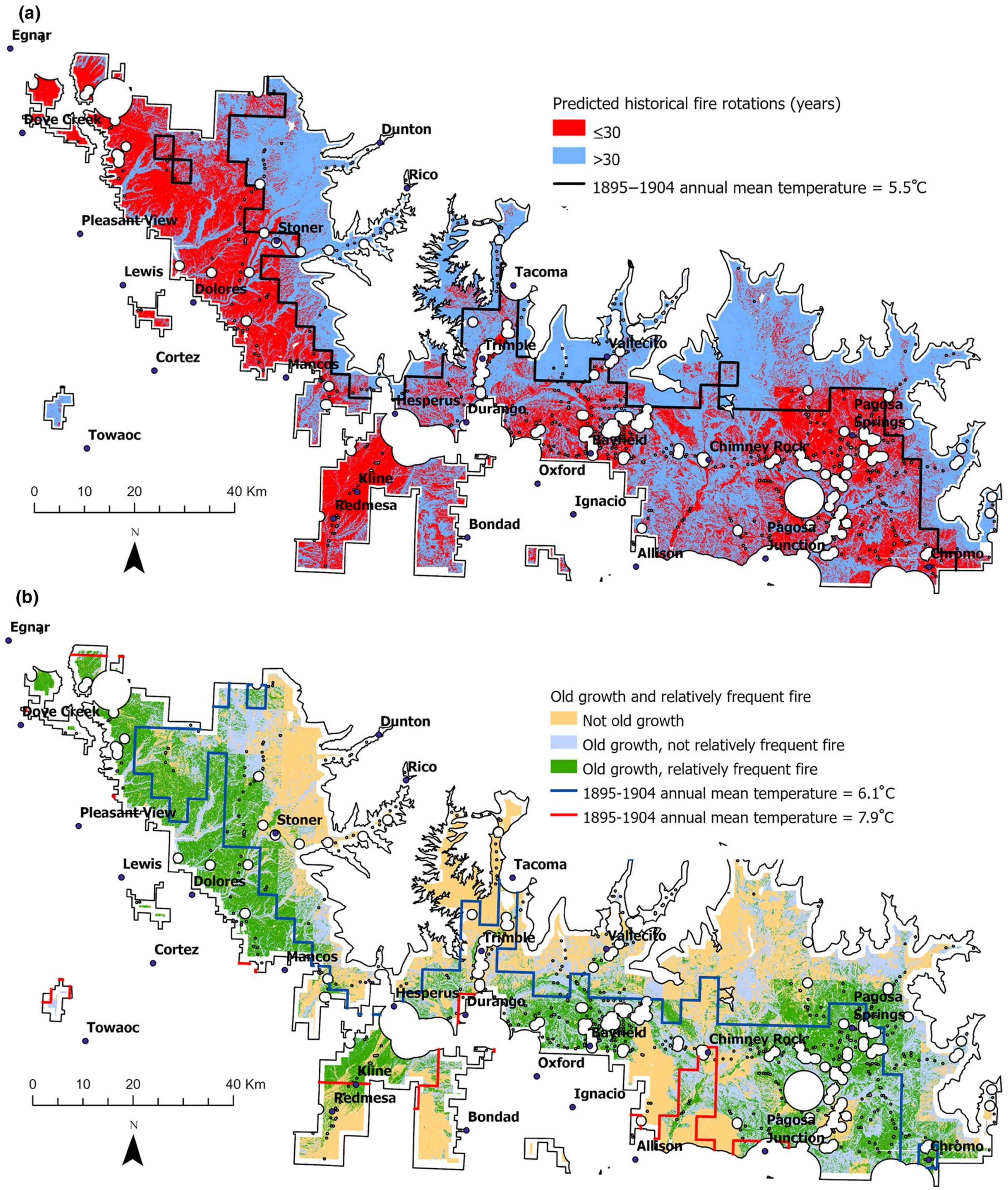

FIGURE 5 (a) Relatively frequent fire (all-severity fire rotations ≤30 years) versus longer-rotation fire in historical montane forests overlain by the contour for 5.5°C annual mean temperature between 1895 and 1904, which roughly corresponds with the upper limit of relatively frequent fire. (b) Old growth, relatively frequent fire, and longer-rotation fire in historical montane forests overlain by the contour for the approximate lower historical limit of dominant old growth with relatively frequent fire at 7.9°C annual mean temperature and the contour for 6.1°C annual mean temperature, below which old growth with relatively frequent fire dominated not old growth. These two contours delimit the temperature ranges of dominant historical old growth with relatively frequent fire [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Variable importance for the 14 predictors, in the Random Forest model of relatively frequent fire (RFF), which together account for 98% of the model's ability to distinguish RFF from longer-rotation fire

Predictor	Importance	Percentage
Soil organic carbon	0.08	10
Terrain ruggedness index	0.08	9
Elevation	0.08	9
Soil depth to bedrock	0.07	8
Soil available water storage	0.07	8
Annual mean temperature	0.07	8
Area solar April–October	0.07	8
Slope	0.07	8
Aspect	0.06	7
Topographic position: 100 m	0.05	5
Curvature	0.05	5
Topographic position: 500 m	0.04	5
Topographic wetness index	0.04	5
Topographic position: 1000 m	0.03	3

historical trees, important in ecological restoration, is high generally, especially in mixed conifer.

More than half of old age classes in 2020 with moderate+ tree density (≥25 trees/ha), known from CSE data, is protected on the SJNF, but substantial area is unprotected (Table 7, Figure 9). Roughly 3/4 of protection is from designation as "Natural Landscapes with Limited Management," which includes many Roadless Areas. Other significant protection is in the Piedra Wilderness, Hidden Mesa RNA, Hermosa Creek Special Management Area, and the HDs Unique Landscape (Table 7). Since CSE data cover only 37,707 ha (14%) of the total 264,712 ha of protected areas, it is unknown how much in total is protected. However, protected areas have relatively abundant old trees; in the 37,707 ha of CSE area inside protected areas, 85% has the ≥120-year age class, 65% has ≥140 year, 47% has ≥160 year, and 21% has ≥200 year. Also, 51% of the ≥120-year age class and 67% of the ≥200-year age class inside CSE areas are also inside protected areas. Yet, protected areas cover only ~34% of the study area; thus, they play oversized roles, reflecting extensive logging of old trees outside. However, protection is concentrated in the central to eastern part of the study area; only part is protected in the Chimney Rock to Pagosa Springs area, and very little of the western third of the study area has protection for old age classes (Figure 9).

3.3 | Old-growth restoration constraints historically and under warming

Useful limits for focusing restoration historically, from the standpoint of OG abundance and viability with fire, would have been between the lower limit of OG up to where OG still dominated over NOG and RFF also occurred. However, OG in the historical montane was only about half maintained by RFF; about 52% of predicted OG had predicted fire rotations ≤30 years and 48% had rotations >30 years (Figure 5b). The part of predicted OG dominance with RFF, where OG also dominated over NOG, was below about the historical 6.1°C annual mean temperature contour and above the 7.9°C contour (Figure 5b), in the lower to middle montane.

However, these temperature constraints, which likely still constrain OG and RFF, are no longer in the same locations, due to warming in the study area since ca 1881 (Figure 10). Warming in the study area, from comparing ca 1881 and ca 1995 PRISM data, was not as high as expected from weather-station data (Lukas et al., 2014; Rangwala & Miller, 2010). Subtraction of 1895–1904 annual mean temperatures from ca 1995 (1981–2010) temperatures had a mean/median of only 0.34°C. Thus, addition of 1.25°C to estimate ca 2015 temperatures led to a mean/median of only 1.58–1.59°C of warming in 2015 relative to pre-industrial temperatures, less than the 2.00°C of warming from weather stations. Also, annual mean temperatures by the time the Paris goal of 1.5°C of global warming is reached would lead to mean/median of 2.1°C of warming in the study area, less than the 2.5°C expected from weather-station data.

Using the Random Forest predict-to-raster models for the area of OG dominance with RFF for ca 1995, 2015, and under the Paris Agreement goal of 1.5°C, the possibility remains for restoring old growth, but in different areas than historically (Figure 10). In ca 1995, with 0.34°C of warming in the study area, before rapid warming after ca 1995 (Lukas et al., 2014), the annual mean temperature constraints of 6.1–7.9°C for OG dominance over NOG left abundant area of potential OG with RFF (Figure 10a), only slightly reduced from the historical (Figure 5b). By ca 2015, however, the 7.9°C warm constraint for OG dominance moved substantially up in elevation and to the north, almost halving ca 1995 areas of potential OG dominance with RFF (compare Figure 10b with Figure 10a). Under the Paris Agreement goal of limiting global warming to 1.5°C, the area of potential OG dominance with RFF is predicted to further expand, but only slightly relative to 2015 (Figure 10b,c). No formal analysis of the Paris goal of limiting warming to 2.0°C was completed here, as further warming would clearly push the cold, upper limit of old-growth dominance beyond the current extent of the montane (Figure 10c).

There are significant constraints and opportunities for restoration of OG by 2060, assuming the goal of the Paris agreement is reached to limit warming to 1.5°C. These include (1) the location and extent of forest age classes with the highest potential for restoration (Figure 9); (2) whether they are or are not protected (Figure 9); (3) the location of physically suitable sites for OG and RFF (Figure 10c); and (4) the expected location of old-growth temperature constraints by ca 2060 when 1.5°C of warming may be reached (Figure 10c). Figure 9 has the full section-line analysis area, to show all potential protection, but calculations had to be done in the unaffected section-line study area (666,916 ha) in Figure 10. In this area, 320,700 ha (48%) would be above the 7.9°C lower limit for old-growth dominance and 346,216 ha (52%) would be below. Above, 53,508 ha (17%) of the 320,700 ha are predicted suitable for OG with RFF, and 72,903 ha (23%) suitable for OG with longer-rotation fire for a total

TABLE 5 Area and percentage of common stand exam stand-age analysis area in five classes of density of old trees, increasing in resistance and resilience, in 2020 and 2060

Resilience class[a]	Density (trees/ha)	Old age classes in 2020 and 2060: 2020 ≥120 years / 2060 ≥160 years ha	%	2020 ≥140 years / 2060 ≥180 years ha	%	2020 ≥160 years / 2060 ≥200 years ha	%	2020 ≥200 years / 2060 ≥240 years ha	%
Overall (*n* = 3072 stands, 78,105 ha; includes 1323 Aspen stands)[b]									
Insufficient	0.00–1.59	5765	7.4	18,386	23.5	30,064	38.5	48,259	61.8
Minimal	1.60–24.99	9333	11.9	16,504	21.1	17,808	22.8	18,213	23.3
Moderate+	25.00+	63,007	80.7	43,214	55.3	30,233	38.7	11,633	14.9
High+	50.00+	54,849	70.2	33,645	43.1	19,783	25.3	5560	7.1
Very high+	100.00+	43,192	55.3	22,461	28.8	10,518	13.5	1736	2.2
Ponderosa pine (n = 917 stands, 29,726 ha)									
Insufficient	0.00–1.59	3416	11.5	9738	32.8	14,551	49.0	21,012	70.7
Minimal	1.60–24.99	8092	27.2	11,202	37.7	9303	31.3	6815	22.9
Moderate+	25.00+	18,218	61.3	8786	29.5	5871	19.7	1899	6.4
High+	50.00+	11,977	40.3	3976	13.4	2285	7.7	576	1.9
Very high+	100.00+	5891	19.8	1575	5.3	590	2.0	92	0.3
Mixed conifer: warm dry (*n* = 474 stands, 10,977 ha)									
Insufficient	0.00–1.59	571	5.2	1635	14.9	2254	20.5	4570	41.6
Minimal	1.60–24.99	597	5.4	2244	20.4	3216	29.3	4393	40.0
Moderate+	25.00+	9810	89.4	7099	64.7	5507	50.2	2014	18.4
High+	50.00+	8983	81.8	5479	49.9	3204	29.2	827	7.5
Very high+	100.00+	6117	55.7	2597	23.7	1130	10.3	271	2.5
Mixed conifer: cool, moist (*n* = 358 stands, 8349 ha)[b]									
Insufficient	0.00–1.59	222	2.7	639	7.7	1466	17.6	2573	30.8
Minimal	1.60–24.99	92	1.1	476	5.7	907	10.9	2513	30.1
Moderate+	25.00+	8035	96.2	7234	86.6	5976	71.6	3263	39.1
High+	50.00+	7809	93.5	6513	78.0	4875	58.4	1908	22.9
Very high+	100.00+	7119	85.3	5349	64.1	2950	35.3	586	7.0

[a]The first three resilience classes have areas and percentages that sum to the total area in the type, but the high+ and very high+ classes represent higher density subsets of moderate+ with the remainder of the area left in moderate, but not given in the table.

[b]Cool, moist mixed conifer and most aspen stands do not currently have much, if any, ponderosa pine, and until this species invades into these forests under the influence of warming temperatures, resilience to fire will certainly be incomplete. However, other species in cool, moist mixed-conifer forests (e.g., Douglas-fir, *Pseudotsuga menziesii*) do already have some fire resistance and resilience capabilities. Thus, here I included cool, moist mixed conifer, but omitted all the aspen stands, except in the Overall case, where all forest types, including aspen, were included to provide perspective.

of 126,411 ha (39%) suitable for OG. Of this 126,411 ha, 37,788 ha (30%) are protected. CSE data provide only partial information, as they cover only 46,281 ha (14%) of the 320,700 ha above the limit. However, 40,913 ha (88%) of the 46,281 ha with CSE data were in the ≥120-year age class with ≥25 trees/ha, thus considerable potential OG in this area. Also, 20% of the 46,281 ha was ponderosa pine and 11% dry mixed conifer, key forests that would not have to undergo a more difficult transition from moist mixed conifer. The percentage of dry forests is likely larger, since 42% of the area is Aspen with Softwoods, some of which is dry mixed conifer. Below the 7.9°C lower limit, 206,487 ha (60%) of 346,217 ha are predicted suitable for OG, ~23% is protected, and the area is 91% dry forests.

4 | DISCUSSION

The largest potential to achieve widespread restoration of old trees by 2060 is from retaining trees ≥120 years old in 2020, which has the potential to nearly fully restore the historical extent of old growth (Table 1) by 2060. No other age class has this potential, and this is likely primarily a natural age class. CSE data show that moderate+ density (≥25 trees/ha) in the ≥120-year age class occurs in 2020 in 61% of ponderosa pine, 89% of warm, dry mixed conifer, and 96% of cool, moist mixed conifer (Table 5). This age class is well distributed across the SJNF, except in the west and southeast (Figure 6c). Also, montane trees ≥120 years old, initiated before ca 1900, are

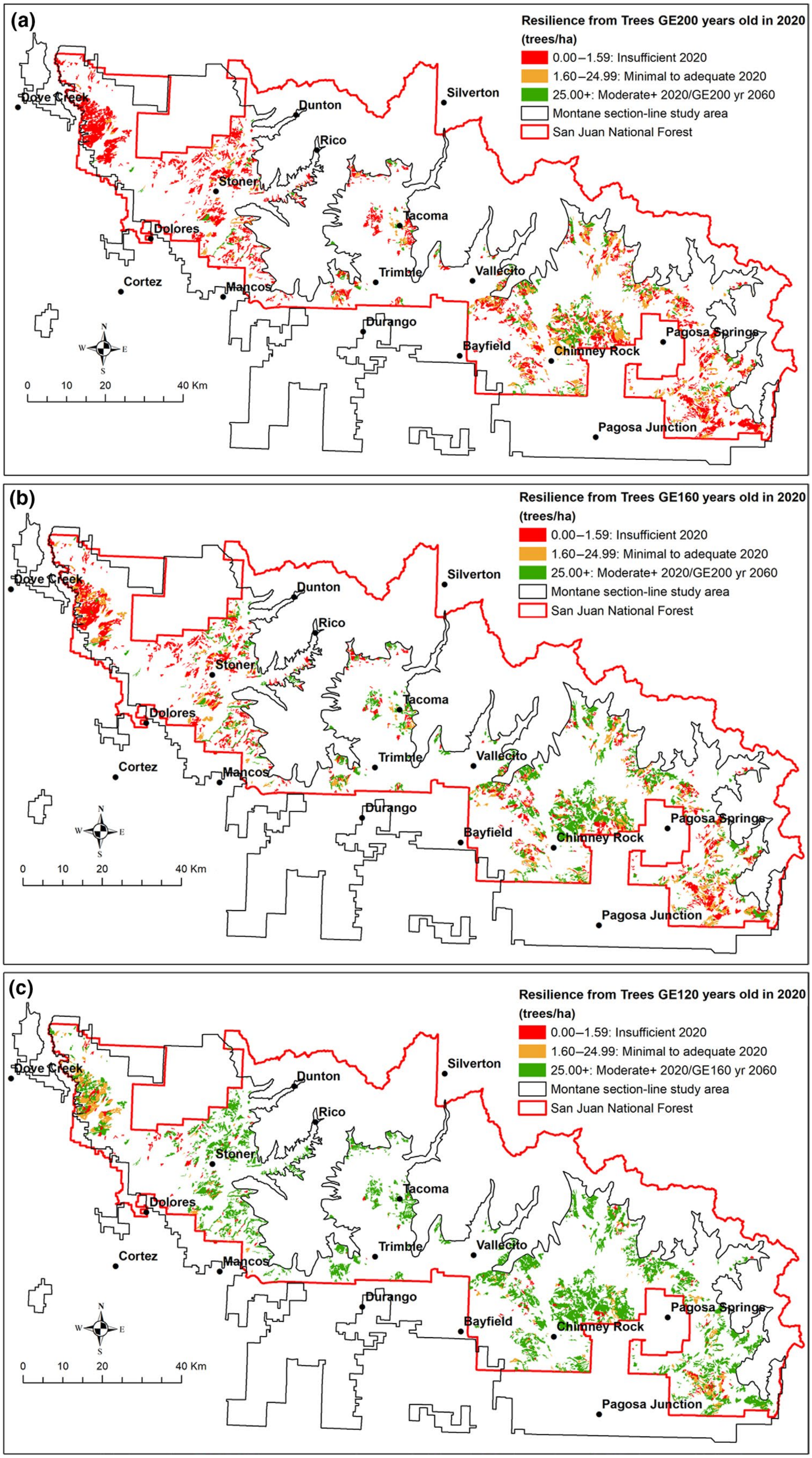

FIGURE 6 Tree density of age classes of trees in the 3072 stands with ages in the full montane section-line study area of the San Juan National Forest part of the study area: (a) the GE200 year age class in 2020, (b) the GE160 year age class in 2020 and corresponding GE200 year age class in 2060, and (c) the GE120 year age class in 2020 and corresponding GE160 year age class in 2060 [Colour figure can be viewed at wileyonlinelibrary.com]

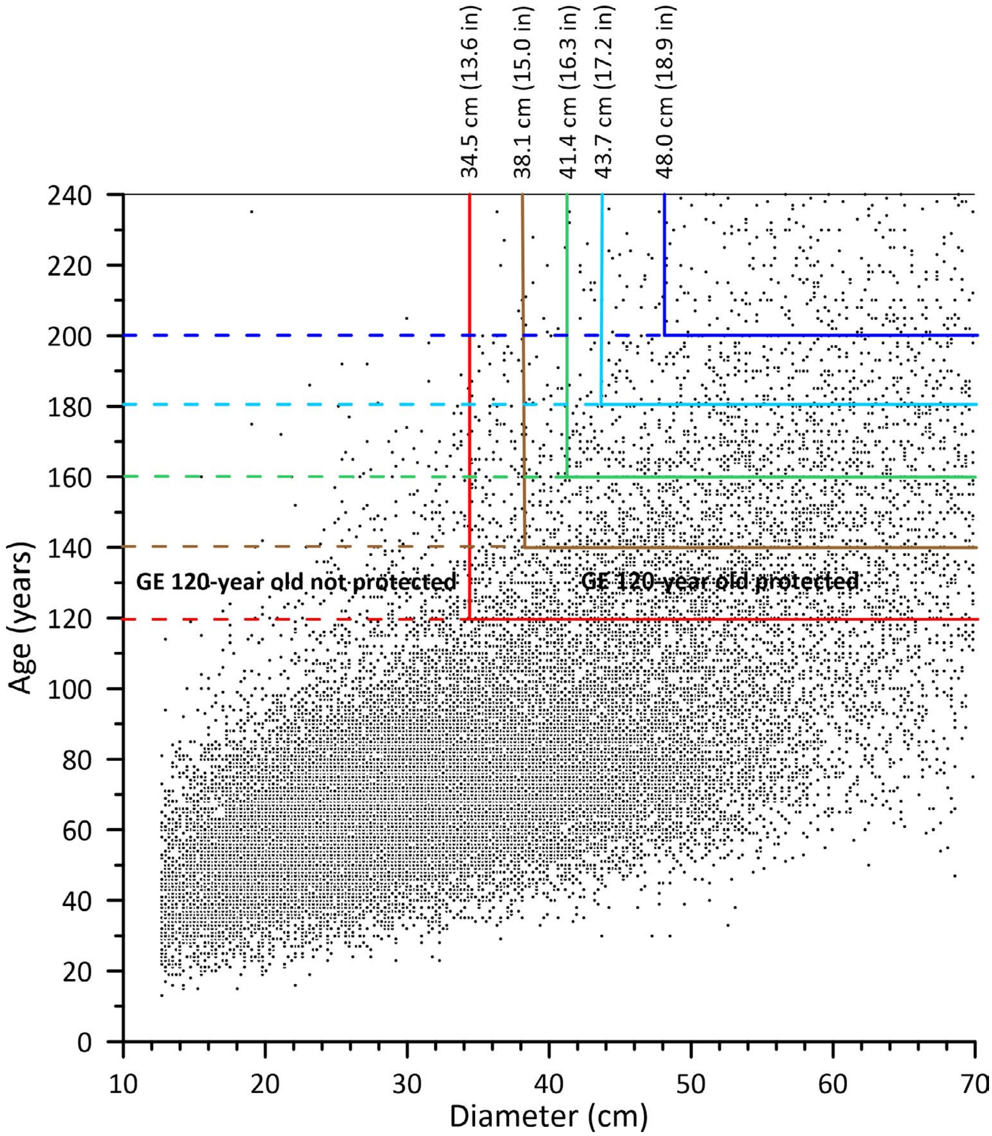

FIGURE 7 Age versus diameter and 90% diameter-protection breakpoints for old trees in the full common stand exam dataset of 26,251 trees ≥12.7 cm dbh with ages in the study area. The large variability in age at any particular diameter makes it infeasible to protect every tree of a particular age. However, it is feasible to identify a breakpoint that protects most trees, and also to identify compromise breakpoints for use in some areas. To see a compromise 90% breakpoint for a particular age on the *Y*-axis (e.g., 120 years), follow the dashed line right to the solid vertical line of the same color. At the top of this line is the centimeter and inch breakpoint with 90% of the trees ≥120 years to the right of the vertical line and the unprotected 10% to the left of this vertical line. Breakpoints other than 90% could be chosen, but 90% moves the breakpoint onto the thicker edge of the distribution. The figure truncates the *X*-axis at 70 cm and *Y*-axis at 240 years to enable a closer view [Colour figure can be viewed at wileyonlinelibrary.com]

likely not primarily the result of intentional fire suppression, which was ineffective that early (Baker, 2009), or recovery after early logging, which was not extensive until after ca 1900 (Baker, 2018b). The ≥120-year age class most likely is primarily from natural regeneration after pre-1900 natural disturbances and other favorable natural conditions.

Most of the restoration value is in areas of the ≥120-year age class with moderate+ density (Figure 9), but areas with old trees of minimal to adequate density (1.60–24.99 trees/ha) also have a reasonable chance of providing post-fire resilience from survivors (Figure 6c). This density class is most important in ponderosa pine forests, where it covers 27% of forest area in 2020 (Table 5). Since that density is at most just adequate, if the goal is to enhance resilience, then it would make sense to protect all extant scattered old trees and increase them.

Also of restoration importance are trees ≥140 years old (Figure 8), which are historical trees, present at or before non-Indian settlement expanded after ca 1880 in the study area (Baker, 2020). Retaining historical trees is widely accepted in ecological restoration: "There is also agreement that, regardless of their size, old trees that were established before Euro-American settlement ('presettlement') in the late 1800s generally should be conserved" (Abella et al., 2006, p. 407). It is fortunate there are likely ≥25 historical trees/ha across 55% of the montane, ≥50 historical trees/ha across 43%, and even

TABLE 6 Minimum tree diameters (dbh) that likely will include 90% or 80% of trees of a particular age class of old trees, based on 6702 aged trees ≥120 years old at the time of each inventory, from 3776 stands in the initial San Juan National Forest common stand exam dataset across the study area

Age class	Trees	90th percentile		80th percentile		Trees	90th percentile		80th percentile	
Years[a]	*n*	cm	in	cm	in	*n*	cm	in	cm	in
	Overall: All trees					Ponderosa pine				
≥120	6702	34.5	13.6	40.1	15.8	1732	40.4	15.9	45.7	18.0
≥140	4592	38.1	15.0	44.5	17.5	1180	44.2	17.4	48.5	19.1
≥160	3119	41.4	16.3	47.8	18.8	840	45.0	17.7	50.0	19.7
≥180	2053	43.7	17.2	51.3	20.2	542	47.0	18.5	52.6	20.7
≥200	1337	48.0	18.9	53.8	21.2	343	51.0	20.1	55.4	21.8
	Mixed conifer: Warm dry					Mixed conifer: Cool moist				
≥120	1176	36.3	14.3	42.4	16.7	1498	31.8	12.5	37.3	14.7
≥140	857	39.4	15.5	46.5	18.3	1097	35.3	13.9	40.6	16.0
≥160	608	43.4	17.1	49.5	19.5	750	37.8	14.9	44.5	17.5
≥180	410	46.7	18.4	52.6	20.7	509	39.6	15.6	48.3	19.0
≥200	256	49.3	19.4	53.8	21.2	348	43.4	17.1	51.3	20.2
	Aspen					Aspen with softwoods				
≥120	117	29.0	11.4	32.8	12.9	2179	33.0	13.0	38.1	15.0
≥140	36	30.2	11.9	36.6	14.4	1422	36.8	14.5	42.9	16.9
≥160	–	–	–	–	–	911	40.1	15.8	46.7	18.4
≥180	–	–	–	–	–	587	42.4	16.7	49.5	19.5
≥200	–	–	–	–	–	386	47.5	18.7	54.6	21.5

[a]Ages include the addition of 15 years for the period to reach coring height (dbh).

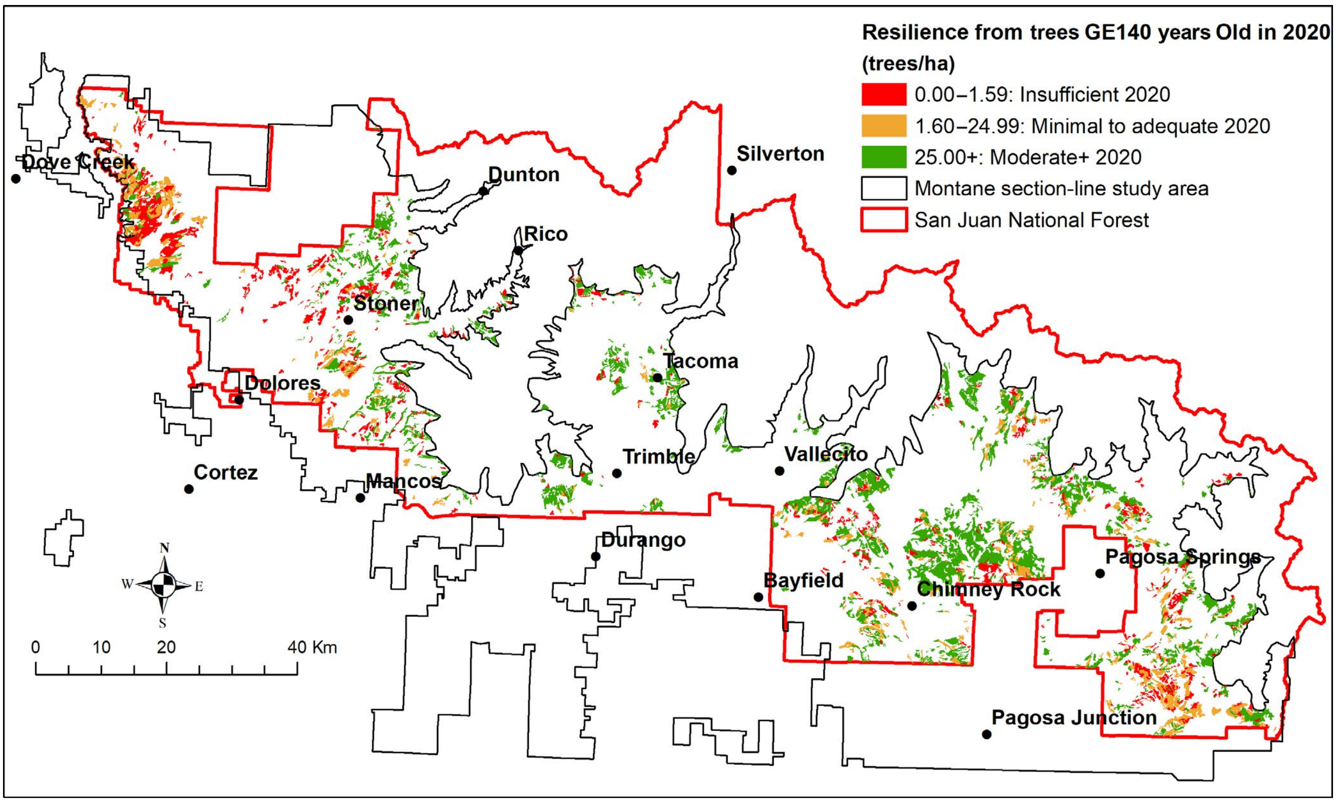

FIGURE 8 Tree density of historical trees (GE140 years old) in 2020 in the 3072 stands with ages in the full montane section-line study area of the San Juan National Forest [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 7 Area of old age classes in 2020 with moderate+ tree density (≥25 trees/ha) in protected areas on the San Juan National Forest. These are only areas with common stand exam (CSE) data in the 3072 stands with tree ages inside the full montane section-line study area

Management focus	Name	Type	Montane area (ha)	CSE area (ha)	Area of old age classes (≥25 trees/ha)			
					≥120 year (ha)	≥140 year (ha)	≥160 year (ha)	≥200 year (ha)
1. Natural processes	None	None	1143	133	133	133	125	122
1. Natural processes	Hermosa	None	1793	261	244	241	187	106
1. Natural processes	S. San Juan Adjacent	Roadless area	2965	287	245	99	93	62
1. Natural processes	Weminuche Adjacent	Proposed wilderness	195	27	15	15	15	15
1. Natural processes	Dolores River	Unique landscape	230	55	47	14	4	0
1. Natural processes	Hermosa Creek	Wilderness	3869	69	69	69	69	69
1. Natural processes	Piedra	Wilderness	19,332	1357	1344	1243	1099	641
1. Natural processes	South San Juan	Wilderness	4482	219	219	137	123	1
1. Natural processes	Weminuche	Wilderness	12,565	45	44	44	35	35
1. Natural processes	Hermosa Creek	Wilderness, RNA	3575	3	3	3	3	3
1. Natural processes	Piedra	Wilderness, RNA	1884	116	116	116	116	116
2. Special areas	Chimney Rock	National monument	1912	61	61	24	16	0
2. Special areas	Boggy	Old growth area	1026	846	23	23	14	0
2. Special areas	Smoothing Iron	Old growth area	1070	600	519	288	215	199
2. Special areas	Electra	RNA	994	98	98	98	98	29
2. Special areas	Hidden Mesas	RNA	1263	703	635	495	405	170
2. Special areas	Martinez Creek	RNA	113	84	84	76	16	13
2. Special areas	Narraguinnep	RNA	668	120	1	0	0	0
2. Special areas	Williams	RNA	196	1	1	1	1	1
2. Special areas	Hermosa Creek	Special mgmt. area	19,359	1928	1806	1352	988	114
2. Special areas	HDs	Unique landscape	18,873	2358	1998	1194	850	417
2. Special areas	McPhee	Unique landscape	2930	22	13	13	13	13
3. Natural landscapes with limited mgmt.	None	Includes Colorado roadless areas	164,275	28,314	24,228	18,791	13,269	5662
Total protected area, CSE area, and protected age-class area			264,712	37,707	31,944	24,441	17,754	7786
Total unprotected area, CSE area, and unprotected age-class area			217,996	40,398	31,062	18,773	12,479	3847

Abbreviations: CSE, common stand exam area, RNA, research natural area.

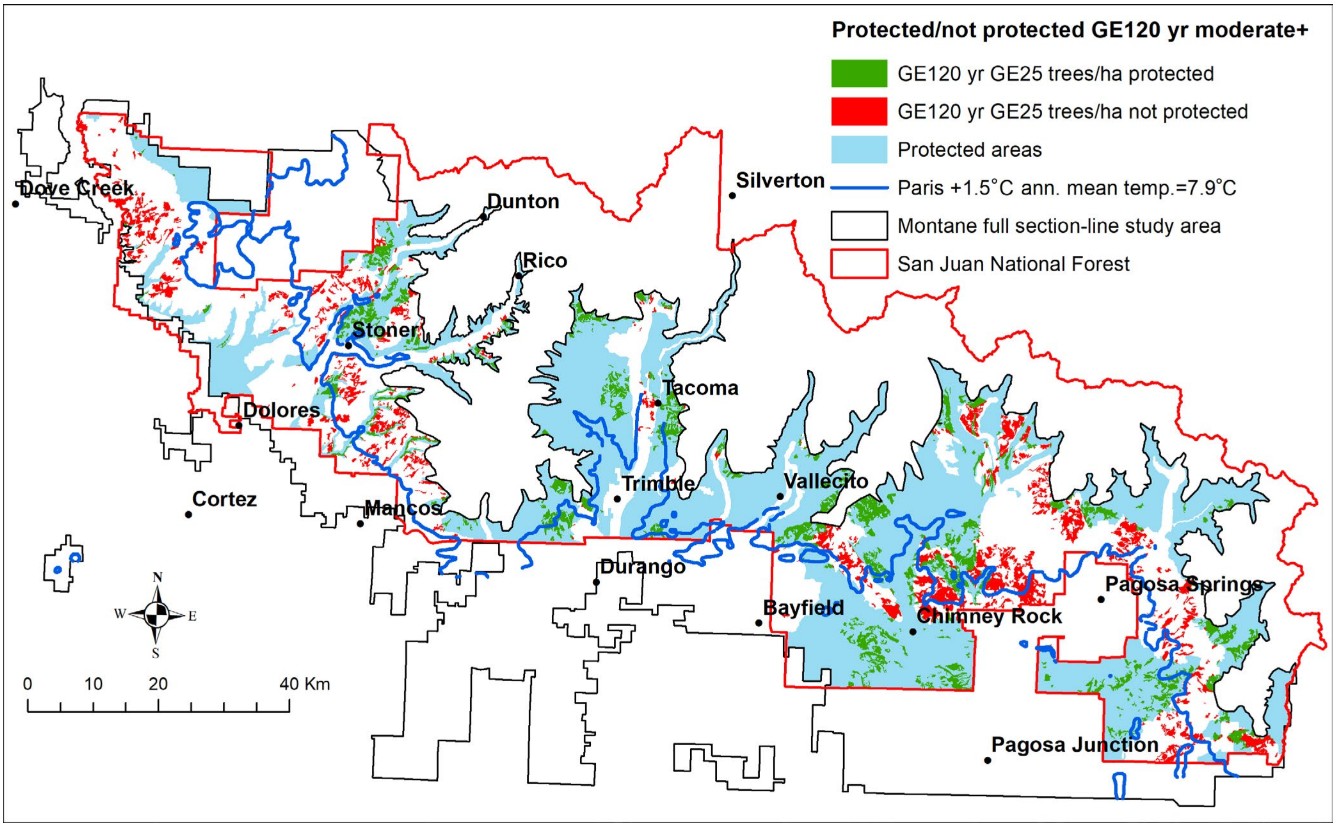

FIGURE 9 Protected and not protected ≥120-year age class with moderate+ density (≥25 trees/ha) on the San Juan National Forest within the full montane section-line study area. Shown is the 7.9°C annual mean temperature contour line expected to mark the lower limit for the area of old-growth dominance in the montane under the Paris Agreement's goal of limiting warming to 1.5°C over pre-industrial levels [Colour figure can be viewed at wileyonlinelibrary.com]

≥100 historical trees/ha across 29%. This large historical resource anchors restoration by providing baseline structure that can be complemented with younger trees, like the ≥120-year age class. A substantial part of restoration of median historical montane tree density of 150 trees/ha (Baker, 2020) can be from retaining all historical trees.

Diameter caps are a common means to ensure protection of most old trees during restoration in dry forests (e.g., Abella et al., 2006; Allen et al., 2002; Sánchez Meador et al., 2015). Here I use CSE data for 6702 aged trees in the study area (Table 6) to provide a more substantive basis than usually available for identifying limits. A 40.6 cm (16″) diameter cap is used to ensure protection of all historical trees in ponderosa pine in this region (Allen et al., 2002). This regional 40.6 cm diameter cap in ponderosa is also needed here over most of the restoration area to protect a large proportion of historical trees now ≥140 years old. And, 40.6 cm would also meet a 90% criterion for retaining the key ≥120-year age class of ponderosa pine, although a 36 cm (14″) cap is needed to accomplish this in dry mixed conifer (Table 6). However, compromises could be used to achieve restoration in certain areas, such as designated commercial timber areas, as long as most historical structure is still protected. It is possible to achieve substantial protection using a 90% criterion while leaving more flexibility with smaller trees (Figure 7). Using a 90% criterion for retention of historical trees ≥140 years old would also achieve the 80% criterion for trees ≥120 years old with a 43 cm (17″) limit in ponderosa pine and a 39 cm (15.5″) limit in dry mixed conifer (Table 6). Morphological distinctions, such as thick bark, flattened crowns, large lateral branches, and high crown base height could identify some old trees, but may not develop fully until trees are ≥150 years old (Brown et al., 2019; Huckaby et al., 2003). These criteria can be added to identify and protect small, but old trees that would be missed by diameter criteria.

Where are the best locations for restoring old trees, given rising temperatures? There is likely a higher probability of old trees surviving warming in the cooler part of the present montane. Annual mean temperature is the second most important predictor of historical OG (Table 3) and sixth most important predictor of historical RFF (Table 4). It also remains uncertain how closely forests will track rising temperatures, since other aspects of climate also are changing. The expected Paris +1.5°C location of the 7.9°C contour (Figure 10c), which was correlated with the historical lower limit of OG dominance with RFF, is thus only an approximation. From a bet-hedging standpoint, it makes sense to prioritize restoration above this line, which is 48% of the current montane while also maintaining extant old trees below this line. There are uncertainties above the line. Only 39% is predicted physically suitable for OG, and only 14% has CSE data, although 88% of the CSE area has the ≥120-year age class.

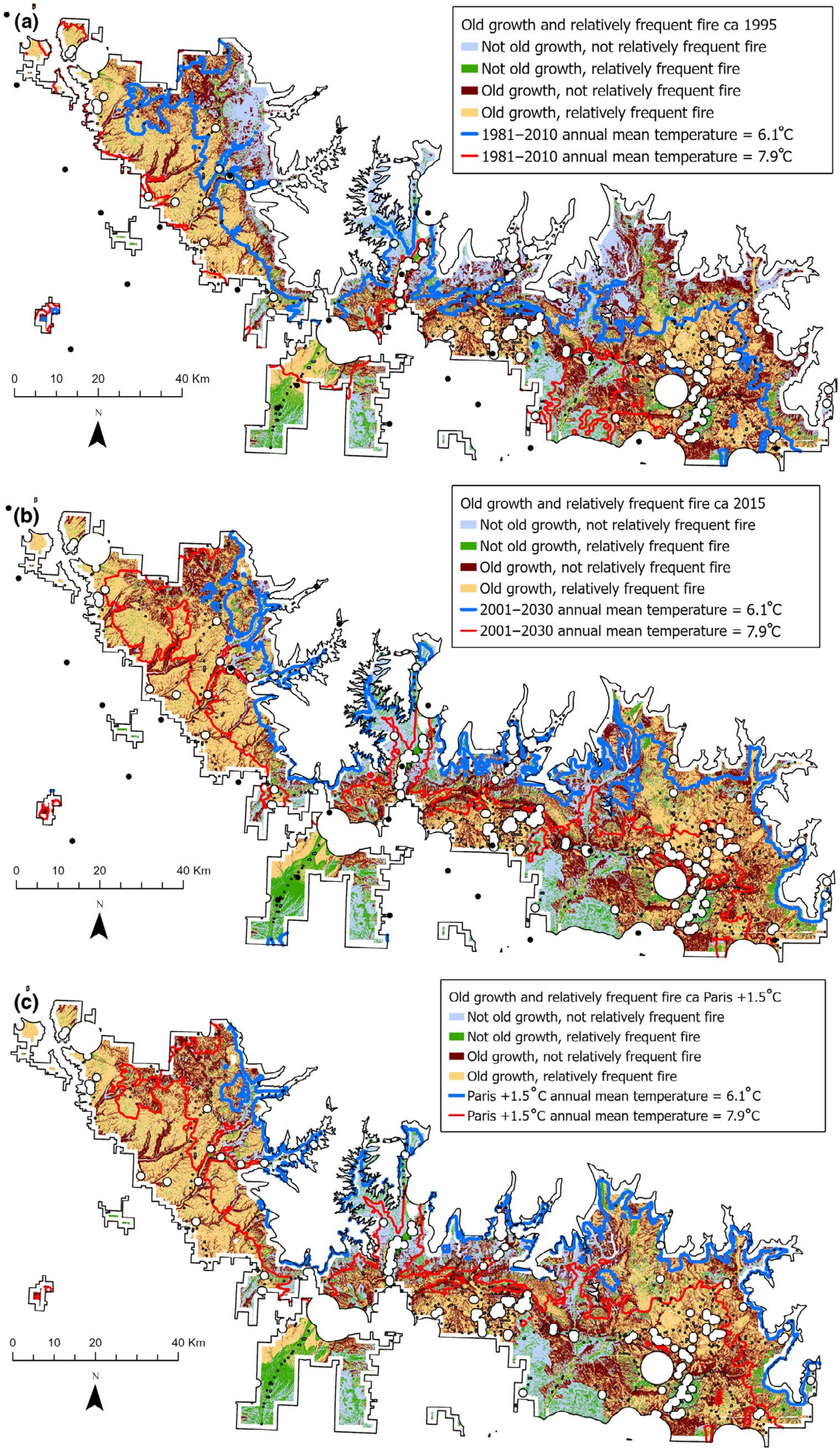

FIGURE 10 The relationship of predicted old growth and relatively frequent fire with historical warmer and cooler annual mean temperature limits where old growth with relatively frequent fire dominated not old growth in: (a) ca 1995, (b) ca 2015, the year of the Paris Agreement, and (c) the expected mid-century year when the Paris Agreement's <1.5°C goal is reached. Shown are corresponding historical warmer (7.9°C) and cooler (6.1°C) annual mean temperature constraints where predicted potential old growth, dominant over not old growth, is expected to occur with relatively frequent fire [Colour figure can be viewed at wileyonlinelibrary.com]

How much more is there? And, how much forest is in restorable ponderosa or dry mixed conifer, versus moist mixed conifer, which cannot be transitioned to ponderosa or dry mixed conifer without ponderosa establishment?

Below the line effectively is a future "trailing-edge" forest (Parks et al., 2019), since its historical climate may be gone by ca 2060. Below the line has more area of physically suitable old growth and more restorable dry forest is also available, but is it sensible to expend resources to restore these forests in this setting? Parks et al. think so, but based this on risk of loss to high-severity fire. However, more likely mortality agents in trailing-edge forests are drought and beetles, which can spread mortality across large landscapes quickly (Baker, 2018a). Continued protection of extant old trees and old-growth stands is sensible below the line, as some or many of these could persist and provide ecosystem services for decades. More intentional restoration below the line is sensible where potential for persistence is higher and opportunity cost is lower, since some of these areas may tend to transition to piñon-juniper woodlands or sagebrush. It is sensible to identify and protect climate refugia below and especially near the line, where forests might better persist (e.g., Haight & Hammill, 2020), particularly where old age classes are known, protection is in place or achievable, and little must be done. Possibilities need further research.

Existing and potential future protection is important to consider, since forests now ≥120 years old would need to be protected until ca 2060 and later, if old-tree restoration is to be achieved. About half the area of the key ≥120-year age class with moderate+ density is already inside protected areas (Figure 9), particularly in central and eastern areas (Figure 9), and this age class is found over 85% of protected areas. The half of this age class outside protected areas is where increased protection attention would be needed, if the goal is to restore landscape-scale resistance and resilience by 2060. It could be that some of the protected area, that lacks CSE data, contains this key age class, suggesting some field inventory would be worthwhile. However, little protection of this age class exists in the western third of the study area (Figure 9); if restoration is to be ensured, protection is needed north of Mancos, northwest of Stoner, and east of Dove Creek (Figure 9). Also warranting protection are large areas of this age class north and east of Chimney Rock and north of Pagosa Springs (Figure 9). Other protection mechanisms, such as a forest-wide age-class screen that simply protects this age class in general, could achieve this.

Formal designation of old growth using current criteria is important, but additive rather than essential. On the SJNF, for example, stand age for old growth must reach 200 years, and usually be verified by dating upper canopy trees in the field. Only ~1/4 of the forest is surveyed, a significant, but incomplete dataset. The SJNF 200-year criterion for ponderosa pine is also more stringent than the best available published criteria for Southwest Colorado, which uses 160 years (Mehl, 1992), and regional science that considers old trees to be ≥150 years (Brown et al., 2019). This program is also not focused on resilience from old trees, thus with its current criteria is mainly additive to the focus here. However, it would be sensible to adopt a 160-year criterion.

Moreover, functional values of large trees for resistance and resilience to fire (e.g., bark thickness) typically increase continuously with tree size, and are not achieved at a particular age, although it makes sense to have age-related goals congruent with the historical fire regime. A historical mixed-to-high severity fire rotation of 135 years across ponderosa pine zones in the study area (Baker, 2020) suggests it is more feasible to restore and maintain widespread 160-year-old than 200-year-old forests. Mehl (1992) defines old-growth ponderosa in Southwestern Colorado as ≥25 trees/ha ≥160 years old and ≥46 cm dbh, with some ancillary criteria. This also provides a sensible functional age goal for mixed conifer, which had an even shorter historical mixed-to-high severity fire rotation of 94–130 years (Baker, 2020). For forest resistance and resilience, widespread restoration of ≥160-year-old ponderosa pines and mixed conifers is very important, congruent with historical fire, and complementary to current 200-year old growth.

To provide evidence relevant to other management issues, if the goal is to help restore old trees, more research is needed about the current structure of stands with extant old trees and the status of fire. However, from this study, we do know that mean tree density of the current ≥120-year age class could average up to as much as ~40% of mean historical overall tree density in ponderosa pine, ~66% in dry mixed conifer, and ~73% in moist mixed conifer (see Appendix S8 for current density and Baker, 2020; Table 6 for historical density). This suggests that, from a restoration perspective, there could be sufficient old trees ca 2060 in many stands, if they mostly survive, and possibly more small trees than historically. However, field research is also needed to confirm the extent of survival of old trees recorded in earlier CSE inventories, and estimate future survival. Both wildfires and prescribed fires have occurred since some CSE inventories, and more are planned that could reduce tree density further and change other aspects of forest structure, which also need specific research. Analysis of rates of modern fires is also needed to inform fire-restoration prescriptions.

This analysis has other limitations. The model of relatively frequent fire is based on a small dataset for a Random Forest model. The CSE dataset is large in terms of trees sampled, but only covers ~15% of the study area, leaving substantial uncertainty about modern forests, a not uncommon reality. The assumption, that CSE trees inventoried from 1971 to 2020 are present in 2020 and will be in 2060, explained as an upper-limit analysis, leaves a central part of the analysis more uncertain than is desirable. Analysis of the future location of annual mean temperature constraints is likely a reasonable first approximation, but warrants further refinement. I hope that some of these limitations can be overcome in the future. This research finds hope for old trees, but is insufficient to rule out a possibility of ecosystem collapse.

The region of the study area is facing higher rates of warming than the global average, with perhaps ≥2.1°C of warming by 2060 under the 1.5°C Paris Agreement goal, and these forests thus remain vulnerable. However, this study shows that an age class of moderately old trees (≥120 years old) is likely sufficiently widespread, to make it feasible to nearly fully restore historical resistance and resilience to fire from old trees by 2060. Existing CSE data also suggest about half this age class could be already protected. This research also shows that the climate-envelope projection, that montane forests may be lost or threatened in the study area by 2060, if emissions continue (Worrall et al., 2016), may not occur if the Paris Agreement 1.5°C goal is reached. However, the upper limit of the area where old-growth dominance is likely possible, and restoration of resistance and resilience to fire from old trees is feasible, is pushed to near the upper limit of the current montane under this Paris goal (Figure 10c). Above this upper limit are subalpine forests, where fire-resistant trees are absent, and restoration is precluded. This montane forest's fate for 40 years thus hinges on whether the world can reach the strictest Paris goal.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Dryad depository at: https://doi.org/10.5061/dryad.2z34tmppmj

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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