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Future exposure of forest ecosystems to multi-year drought in the United States

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Abstract

As the future climate becomes hotter or drier, forests may be exposed to more frequent or severe droughts. To inform efforts to ensure resilient forests, it is critical to know which forests may be most exposed to future drought and where. Longer duration droughts lasting 2–3 years or more are especially important to quantify because forests are likely to experience impacts. We summarized exposure to 36-month drought for forests across the conterminous United States using the Standardized Precipitation-Evapotranspiration Index (SPEI) overlaid on forest inventory plot locations. Exposure was quantified under 10 scenarios that combined five modeled climates and two Representative Concentration Pathways (RCPs, 4.5 and 8.5) through 2070. Future projections indicate a tripling of the monthly spatial extent of forests exposed to severe or extreme drought—38% of forests were exposed on average by mid-century as opposed to 11% during 1991–2020 (2041–2070). Increases in drought exposure were greatest under hotter (HadGEM2-ES), drier (IPSL-CM5A-MR), and middle (NorESM1-M) climate models, under either RCP. Projections agreed that forests in portions of the western United States, especially the southwestern United States, could face high levels of exposure. Forest types including pinyon/juniper, woodland hardwoods, and ponderosa pine were projected to be exposed to drought more than 50% of the time on average across all scenarios by mid-century, when no forest type was exposed more than 25% of the time under any scenario during the recent period. Projections agreed less for the eastern United States, but in some scenarios, particularly under RCP 8.5, large portions of the East could be exposed to drought nearly as often as parts of the West. Moreover, a substantial portion of oak/hickory forests occur in eastern regions, where projections agree on increased drought exposure. This study provides novel insights about the changing conditions forests face in both the eastern and western United States. Our results can be combined with information about the sensitivities and adaptive capacities of forest ecosystems to prioritize drought adaptation efforts.

KEYWORDS
climate change, drought exposure, forest ecosystems, long-term drought, model agreement, standardized precipitation-evapotranspiration index (SPEI)

INTRODUCTION

Drought is an important stressor affecting forests. Alone or in combination with other disturbances, such as fire or insects, and biophysical factors, drought can reduce forest productivity, cause vegetation shifts, and diminish the capacity of forests to provide ecosystem services (Anderegg et al., 2013, 2015; Desprez-Loustau et al., 2006; Jactel et al., 2012; Peters et al., 2015; Trouet et al., 2010; Vose et al., 2016; Williams et al., 2013). Prolonged drought stress can lead to tree hydraulic failure, crown death, and eventual mortality (Anderegg et al., 2012; Choat et al., 2018; Hammond et al., 2019). A warmer and drier climate will lead to more drought (Seidl et al., 2017), and specifically, droughts may become more frequent, severe, or longer in duration in the future (Dai, 2011, 2013; Prudhomme et al., 2014). Globally, forests are expected to undergo significant restructuring because of accelerating rates of drought-induced tree mortality (Choat et al., 2012; Etzold et al., 2019; McDowell & Allen, 2015). At the same time, there is increasing evidence that management actions such as forest thinning may play key roles in ameliorating the impacts of drought (Bottero et al., 2017; Bradford & Bell, 2017; Miralles et al., 2019; Restaino et al., 2019; van Mantgem et al., 2020) and therefore in improving the capacity of forests to adapt to changing climate. Thus, to ensure resilient forests in the future and inform management and conservation efforts, it will be important to know which forests are expected to face the greatest frequency and magnitude of drought (Glick et al., 2011; Turner et al., 2003). This paper uses one set of lenses based on the concept of meteorological drought to assess the exposure of forests across the conterminous United States to future drought compared to the recent past.

Generally, drought can be defined as a shortage of water resources. However, there is no universal definition of drought because the characteristics and impacts of a drought are context-specific: they depend on the location, ecosystem, climatic regime, or economic sector (e.g., agriculture) of interest (Orville, 1990; Wilhite et al., 2007; Wilhite & Glantz, 1985). Meteorological drought is defined as a deficit in precipitation relative to a long-term mean (Keyantash & Dracup, 2002; Orville, 1990), and thus quantifying meteorological drought requires only climate data. Current and historical gridded climate data, as well as global climate model (GCM)/Representative Concentration Pathway (RCP) model projections for climate variables, are readily available, which enables tracking and mapping precipitation deficits and surpluses through time. For forests, a meteorological drought is consequential if the period of precipitation deficit lasts long enough to deplete available soil water reserves, causing some impact on trees and other plants (Anderegg et al., 2012). The magnitude of these impacts at any forested location depends on the level of drought exposure as well as the sensitivities of the forest community or tree species to drought, landscape characteristics, including the types and mix of surrounding land uses, and nearby human responses to drought (Crausbay et al., 2017; Norman et al., 2016). However, such information is often lacking, as is a comprehensive picture of how these and related factors interact to affect ecosystem function and services (Crausbay et al., 2020). Thus, assessments of forest exposure to meteorological drought in the future compared with recent past exposure are important for prioritizing which forests need mitigation, increased adaptive capacity, and further research into potential future drought impacts (Anderson et al., 2018; Bolte et al., 2009; Halofsky & Peterson, 2016; Petr et al., 2014; Turner et al., 2003).

Forests across the United States support biodiversity and provide a number of ecosystem services, including water quality and carbon storage (Domke et al., 2021; Liu et al., 2022; USDA Forest Service, 2012). Therefore, knowledge about which forests may be more exposed to drought in the future is critical for informing national-level forest research and policy priorities. Projections of drought under future climate change point to potential for unprecedented drought in portions of the country such as the Southwest and California (Cook et al., 2015; Madakumbura et al., 2020). While we anticipate that drought conditions will become more common in the future, the occurrence of drought is also likely to vary over space and time, such that some forest ecosystems will be exposed more often in the future than others. Even within the range of some ecosystems, exposure will vary considerably. Several studies have assessed the potential for drought stress in forests across parts of the United States, including the Southwest (Thorne et al., 2018), California (Madakumbura et al., 2020), and across the western United States (Buotte et al., 2019). However, to our knowledge, no broadscale (national) characterization of future trends in multi-year drought for US forests has been done in a consistent way across forest ecosystems, including detailed information on which forest ecosystems will be most exposed, and in which portions of their ranges.

We use the Standardized Precipitation-Evapotranspiration Index (SPEI), a meteorological drought index, as our primary measure and basis for comparison with respect to exposure. The SPEI has been shown to be a useful metric for characterizing drought under climate change and comparing across ecosystems (Ault, 2020; Slette et al., 2019). Because it considers the effect of temperature (i.e., as a determinant of potential evapotranspiration [PET]), it is deemed more suitable for climate change research than precipitation-only drought metrics, most notably the Standardized Precipitation Index (SPI) (Ahmadalipour et al., 2017; Labudová et al., 2017; Vicente-Serrano et al., 2010). For example, the SPEI has been shown to capture the effects of future temperature increases on long-term drought events better than SPI (Jeong et al., 2014), and has also been useful in characterizing warm droughts, which are expected to have substantial impacts on forest ecosystems in the future (Gampe et al., 2021).

Another practical feature of the SPEI is that it can be computed straightforwardly at multiple timescales, including timescales of 2–3 years or longer. Typically, forests can tolerate short-term droughts, despite differing levels of drought tolerance among constituent tree species (Archaux & Wolters, 2006; Berdanier & Clark, 2016; Peters et al., 2015). Multiple consecutive years of drought are more likely to lead to ecological impacts than short-term droughts (Bigler et al., 2006; Guarín & Taylor, 2005; Jenkins & Pallardy, 1995; Millar et al., 2007; Norman et al., 2016). For example, drought metrics calculated across multiple years were better at predicting patterns of recent widespread forest mortality in California than those calculated across shorter timescales (Goulden & Bales, 2019; Madakumbura et al., 2020).

Therefore, we sought to quantify the exposure of forests to meteorological drought characterized over multiple years (36 months) in order to support large-scale assessments of ecological impacts of drought across forest ecosystems in the conterminous United States. We leveraged recent forest inventory data for the United States and combined them with calculations of 36-month SPEI from 1950 to 2070 under 10 future scenarios spanning the range of projected future climate conditions for the United States. We sought to answer the following questions:

1. In future scenarios, how much exposure to drought is projected for forest land across the United States by the middle of the 21st century?
2. Under these scenarios, which forest ecosystems are expected to be most exposed to drought by the middle of the 21st century?

We addressed question 2 in two main ways. We examined which forests are expected to have the greatest exposure to drought across their current ranges as a whole, as well as which forests currently occur within regions that are expected to be highly exposed to drought in the future. The potential for wide-ranging impacts when forests are exposed to multi-year droughts means that our results will be useful for informing management, conservation, and research efforts. We discuss the implications of our exposure assessment for some forest types in light of their known sensitivities and adaptive capacities.

METHODS

Climate data

To analyze future drought trends across the conterminous United States, we obtained downscaled monthly time series of precipitation (P) and PET at a spatial resolution of 2.5 arcmin (approximately 4 km) for 1950–2070 for two RCPs, 4.5 and 8.5, from the Multivariate Adaptive Constructed Analogs (MACAv2-METDATA) dataset (Abatzoglou, 2013; Abatzoglou & Brown, 2012; Joyce et al., 2018). The entire MACAv2-METDATA dataset contains downscaled data for 20 GCMs. From these and for each RCP, we selected a subset of five GCMs that represented the hottest ("hot"; HadGEM2-ES365), least warm ("warm"; MRI-CGCM3), wettest ("wet"; CNRM-CM5), and driest ("dry"; IPSL-CM5A-MR) future conditions by 2070 for the conterminous United States, as well as one GCM that represented a midpoint in temperature and precipitation change ("middle"; NorESM1-M) (Joyce & Coulson, 2020b). These are the five GCMs and two RCPs that are used for the USDA Forest Service's 2020 Resources Planning Act (RPA) Assessment (https://www.fs.usda.gov/research/inventory/rpaa). The RPA Assessment projects forest conditions and drivers of change 50 years into the future under a range of possible future scenarios. For more details on GCM selection for RPA and future temperature and precipitation conditions under these models, see Joyce and Coulson (2020a). Importantly, the projected climate from those models is variable over space and time, such that, for example, the driest overall model in terms of precipitation is not necessarily the driest in every future month and in every region. Furthermore, the projected SPEI values for each GCM will not necessarily mirror the general precipitation trends in each GCM since SPEI is based on P and PET.

Combining the five GCMs and two RCPs produced a total of 10 scenarios used here. In the MACAv2 data, the period 1950–2005 in each scenario represents the modeled historical period. During that period, there is no difference in monthly values between the two RCPs for a given GCM. The period 2006–2070 is the modeled future period under each RCP.

SPEI calculations

The SPEI is a meteorological drought index that summarizes the departure of the climatic water balance from normal conditions, akin to a *z*-score. Negative SPEI values indicate drier than normal conditions for a given location, while positive values are wetter than normal. To define the water balance of a specific pixel for a target month in the climate data, SPEI uses the cumulative difference between P and PET over a lag period of months prior to the target month. The series of monthly values for water balance over a user-defined reference period are used to calibrate SPEI for each pixel. The result is a set of continuous SPEI values for the reference period for a single pixel, which are normally distributed with a mean of 0 and a standard deviation of 1. Based on the reference period distribution for a given pixel, SPEI values can then be calculated for every month outside the reference period and compared to the normal distribution.

We calculated the monthly water balance (P − PET) for all months in each of the 10 scenarios at all gridded locations in the MACAv2-METDATA. The SPEI has been shown to be sensitive to the PET estimation method (Beguería et al., 2014). Therefore, we took care to ensure the PET values we used were appropriate. The monthly MACAv2-METDATA dataset included PET values that had been estimated using the Penman–Monteith method with an FAO grass reference surface (Abatzoglou, 2013). Penman-Monteith is the recommended PET estimation method for SPEI calculations (Beguería et al., 2014).

An important assumption regarding SPEI relates to the underlying theoretical distribution used to calculate the index. The SPEI analysis fits a time series of differences (P − PET) to a probability distribution, which makes it possible to express those differences as standard normal scores with a mean of 0 and a standard deviation of 1 (Beguería et al., 2014; Vicente-Serrano et al., 2016). The default probability distribution is the log-logistic distribution (Beguería & Vicente-Serrano, 2017), but some have suggested the generalized extreme value distribution provides a better fit of the tails of the distribution, that is, for high and low values in the time series of differences (Stagge et al., 2015, 2016; Vicente-Serrano et al., 2016). Because we focused our analysis and summaries of drought exposure (see below) on places where SPEI ≤ −1.5 and did not make further distinctions among specific values of SPEI, we chose to use the default log-logistic probability distribution.

For each scenario at all gridded locations in the MACAv2 data, we used the values in the modeled historical period (1950–2005) as the reference period to calibrate SPEI and to assign monthly SPEI values to the entire time period, including the future through 2070. Hence, the SPEI values for the entire period 1950–2070 in each scenario represent wetter or drier conditions compared to the distribution of modeled values for 1950–2005 in that scenario. We used a 36-month lag to calculate the cumulative water balance for input into SPEI because forests generally respond to longer term drought exposure (Archaux & Wolters, 2006; Berdanier & Clark, 2016; Bunting et al., 2017; Koch et al., 2013; Peters et al., 2015; Xu et al., 2018). Because of this lag, the first month to have a value for SPEI in our time series is January 1953. We used the spei function in the R package SPEI 1.7 (Beguería & Vicente-Serrano, 2017) to calculate SPEI from the monthly water balance data, with all default parameters except the reference period start and end dates, which were set to January 1950 and December 2005, respectively. We set the scale parameter to 36 months.

Forest inventory data

From the SPEI grids, we extracted monthly values at forested locations across the United States using geographic coordinates of plots in the USDA Forest Service Forest Inventory and Analysis (FIA) database (FIADB version 8.0; Burrill et al., 2018). The FIA program applies a nationally consistent sampling design, with one permanent plot established for every ~2428 ha of land (Bechtold & Patterson, 2005). FIA plots consist of 7.2-m fixed-radius subplots (0.067 ha each), with three subplots spaced 36.6 m apart in a triangular arrangement and one subplot in the center (Burrill et al., 2018). Data collected by FIA field crews include the diameter and species of every tree in each plot. Plots are later classified into forest types by USDA Forest Service personnel using a decision-tree approach based on the combination of species that comprises the highest stocking values, which are primarily a function of basal area (Arner et al., 2003). Related forest types are aggregated into forest type groups (Eyre, 1980; see Appendix S1: Figure S2). To protect sensitive plot information, especially on privately owned lands, the publicly available FIA database contains plot coordinate information that has been slightly altered from the true coordinates. We used true plot coordinates here to extract SPEI values.

Because FIA plots have fixed locations, a plot can straddle multiple forest type groups. To track those differences, multiple "conditions" can be identified within a plot, each with a unique forest type group. Each plot condition is associated with an area expansion factor, indicating the area of forest it represents. We used these expansion factors for all conditions to summarize the areas and proportions of forest area exposed to drought over time (see *Analysis and summaries of drought exposure* for more details). Hereafter, we refer to plot conditions simply as "plots." To ensure that we included the full set of plots for each state in the conterminous United States, we selected a set of plots for each state that was used by FIA to produce an evaluation of forest conditions circa 2016 (Appendix S1: Table S1). The resulting FIA plot database consisted of 163,283 plots across the conterminous United States, representing a total forest area of 277,147,000 ha (2,771,470 km^2).

Analysis and summaries of drought exposure

The results of the SPEI calculations were continuous positive and negative values. Those values are often grouped into categories, ranging from extreme wetness to extreme drought (see Appendix S1: Table S2; Hui-Mean et al., 2018; Yu et al., 2014). We focused on the combined categories of severe ($-2 < \text{SPEI} \leq -1.5$) and extreme drought ($\text{SPEI} \leq -2$) as our metric of drought exposure, so that we considered SPEI values ≤ -1.5 to be "exposed to drought." As discussed above, more extreme SPEI values are recognized as highly uncertain. We followed recommendations (Stagge et al., 2015, 2016) to limit the SPEI by setting any values outside [−3.0, 3.0] to whichever of those bounding values was appropriate. Consequently, the effective range for determining drought exposure was $-3 \leq \text{SPEI} \leq -1.5$.

As one geographical unit for analyzing exposure, we identified the ecological section (Cleland et al., 2007) that contained each FIA plot location. Ecological sections represent a moderate level of ecoregional classification, and there are 190 ecological sections across the United States. For forest land across the United States, by forest type group, and by ecological section, we calculated the monthly proportion of forest with $\text{SPEI} \leq -1.5$ in each of the 10 scenarios using the plot area expansion factors in the FIA database. This focus on $\text{SPEI} \leq -1.5$ is supported by other studies that have suggested a tipping point for forests near that value. For example, in pinyon pine (*Pinus edulis*) and ponderosa pine (*Pinus ponderosa*) forests in the southwestern United States, at $\text{SPEI} \leq -1.64$, forest mortality and rapid forest decline occur (Huang et al., 2015; Wion et al., 2022).

We calculated 30-year summaries of monthly data because global climate models do not necessarily reproduce the exact monthly timing, duration, or extent of meteorological conditions, including drought (Cook et al., 2016). We calculated the proportion of forest exposed to drought over a recent period (1991–2020, "recent") and a future 30-year period (2041–2070, "mid-century") in each of the 10 scenarios. The recent period was a means of comparison with the mid-century period. Computed metrics like change in exposure are consistent for periods within a given scenario for the same dataset but are not necessarily comparable across scenarios or with the SPEI based on other climate datasets. Within the two 30-year periods, we summarized the average monthly proportion of forest land that was exposed to drought (i.e., exhibited values of $\text{SPEI} \leq -1.5$) in each of the 10 scenarios for all forest land, by FIA forest type group, and within each ecological section. For each scenario, we also calculated the percent change in average monthly proportion of forest land exposed to drought between the recent and future periods. As a result, we had summaries of proportion exposed to drought and percent change in exposure for forests across the United States, by FIA forest type group, and by ecological section for all 10 scenarios.

Because the 10 scenarios were selected to span the large range of all projections in the MACAv2 dataset, we considered regions where most scenarios agreed in terms of projected values to be places where future drought exposure would be expected. Therefore, we summarized, for this diverse set of projected climates, which forested regions and which forest type groups were expected to have the greatest exposure to drought under all or nearly all scenarios. For each ecological section, we tallied the number of scenarios (0–10) for which the projected proportion of forest exposed to drought in mid-century was greater than the mean value across all forests and all 10 scenarios. We did the same by ecological section for the percent change in exposure between the recent and mid-century periods. We considered ecological sections with at least 8 of the 10 scenarios projecting greater than average exposure or change in exposure by mid-century to be regions of high agreement regarding future drought exposure—that is, where exposure or change in exposure is expected. In turn, we summarized the composition of forest type groups as well as the proportion of each forest type group that fell within those ecological sections.

For analysis of drought for all forests across the United States and within ecological sections, we included all plots in the FIA database. In summaries that characterized exposure for individual forest type groups, we excluded plots labeled as "nonstocked," which represent places with few, if any, trees. We also excluded two exotic type groups and three type groups that were restricted in geographic extent. Excluded type groups accounted for

3.9% of forest land area in the FIA database, with nonstocked plots accounting for the majority (85%) of that excluded land. See Appendix S1: Figure S1 for a list of forest type groups, their total areas, and proportions of their areas by region of the country.

In addition to the software already mentioned, for this analysis, we used R version 4.1.2 (R Core Team, 2021) within RStudio 22.02.0 Build 443 and contributed packages data.table 1.14.2 (Dowle & Srinivasan, 2021), patchwork 1.1.1 (Pedersen, 2020), raster 3.5.15 (Hijmans, 2022), RColorBrewer 1.1.2 (Neuwirth, 2014), sf 1.0.6 (Pebesma, 2018), tidyverse 1.3.1 (Wickham et al., 2019), and viridis 0.6.2 (Garnier et al., 2021).

RESULTS

Generally, the scenarios indicate larger monthly proportions of US forest exposed to drought in the mid-century period, 2041–2070, compared to the recent period, 1991–2020 (Figure 1; Appendix S1: Figure S2). Across all 10 scenarios, a mean of 11.0% of US forest area was exposed to severe or extreme drought (SPEI ≤ -1.5) monthly in the recent period, while 37.8% was exposed at mid-century, representing a 238% increase between the two periods (Figure 1). On average for the mid-century period, the NorESM1-M, IPSL-CM5A-MR, and HadGEM-ES365 models (middle, dry, and hot models, respectively) under RCP 8.5 projected the greatest monthly proportion of forest exposed to drought, with values of 49.4%, 59.3%, and 62.7%, respectively. The NorESM1-M and IPSL-CM5A-MR models under RCP 4.5 also generally projected greater than average exposure. Projected monthly exposure in the HadGEM2-ES365 model under RCP 4.5 was closest to the overall mid-century mean across all scenarios (37.8%), although slightly lower at 35.3%. Mid-century exposure in the MRI-CGCM3 (least warm) model under both RCPs was lowest at 18.7% but still greater than the recent period average (11.0%) for the 10 scenarios. Within each of the 10 scenarios and across all of them, the range of monthly drought exposure values increased over time from the recent period to the mid-century period (Figure 1; Appendix S1: Figure S3).

Geographic patterns of exposure differed not only between the recent and mid-century periods in each scenario but also among the 10 scenarios in each period (Figure 2). Despite this variation, there are some places of agreement, both in the extent of future drought exposure as well as increase in drought exposure between the periods (Figure 3). A total of 22 ecological sections in portions of the western United States had high agreement among scenarios (at least 8 scenarios agreed) that forest exposure to drought during mid-century will be greater than the average mid-century exposure rate across all forests in all scenarios (>37.8%, Figure 3a). Those ecological sections fell into three main groups—one group centered in New Mexico and stretching into Arizona, Colorado, western Texas, Utah, and southern Wyoming; a second mainly in Nevada and eastern portions of California; and a third in eastern Oregon. Scenarios in a total of 12 ecological sections were in high agreement that the increase in exposure compared with the recent period would be greater than the average increase (>238% increase, Figure 3b). Those ecological sections were largely a subset of those where scenarios agreed on high exposure, including all of the same ecological sections in eastern Oregon and some of those in New Mexico, Colorado, and western Texas. The only ecological sections where scenarios agreed on a greater than average increase in exposure but not on greater than average exposure were two sections in central Texas. By contrast, in almost all the coastal ecological sections of California, Oregon, and Washington, as well as one section in central Florida, no more than one modeled scenario projected exposure or an increase in exposure exceeding the overall average (Figure 3a,b).

The exposure to drought for an entire forest type group is a function of the geographic distribution of the type group combined with the geography of drought. Monthly proportions of forest exposed to drought by type group for the recent period ranged from a median of 7.1% across all 10 scenarios (min. 6.3% and max. 19.7%) for alder/maple to 14.9% (min. 3.6% and max. 24.6%) for pinyon/juniper (Figure 4). The pinyon/juniper type group was projected to have the highest monthly exposure at mid-century, with a median of 66.9% (min. 36.9% and max. 90.9%) of forest exposed across the scenarios (Figure 4). For the pinyon/juniper type group, relatively high exposure was projected throughout its full geographic distribution in most scenarios (Figure 5a shows exposure under the HadGEM2-ES365 model in RCP 4.5, which had exposure values closest to the overall mean in the future period; see Appendix S2 for maps in all scenarios). Similarly, the woodland hardwoods type group had high exposure projected across its range in most scenarios (see Appendix S2). The tanoak/laurel type group had the lowest median exposure at mid-century of 11.6% (min. 4.8% and max. 29.1%). That forest type group showed a uniform pattern of comparatively low future exposure projected across its current geographic distribution (Figure 5b). Other forest type groups with distributions confined to California, Oregon, or Washington, including alder/maple, hemlock/Sitka spruce, and western oak, also had uniformly low future exposure projected for all scenarios (Figure 4; Appendix S2).

Several forest type groups with relatively wide geographic distributions were projected to have a range of drought exposure rates for different portions of their

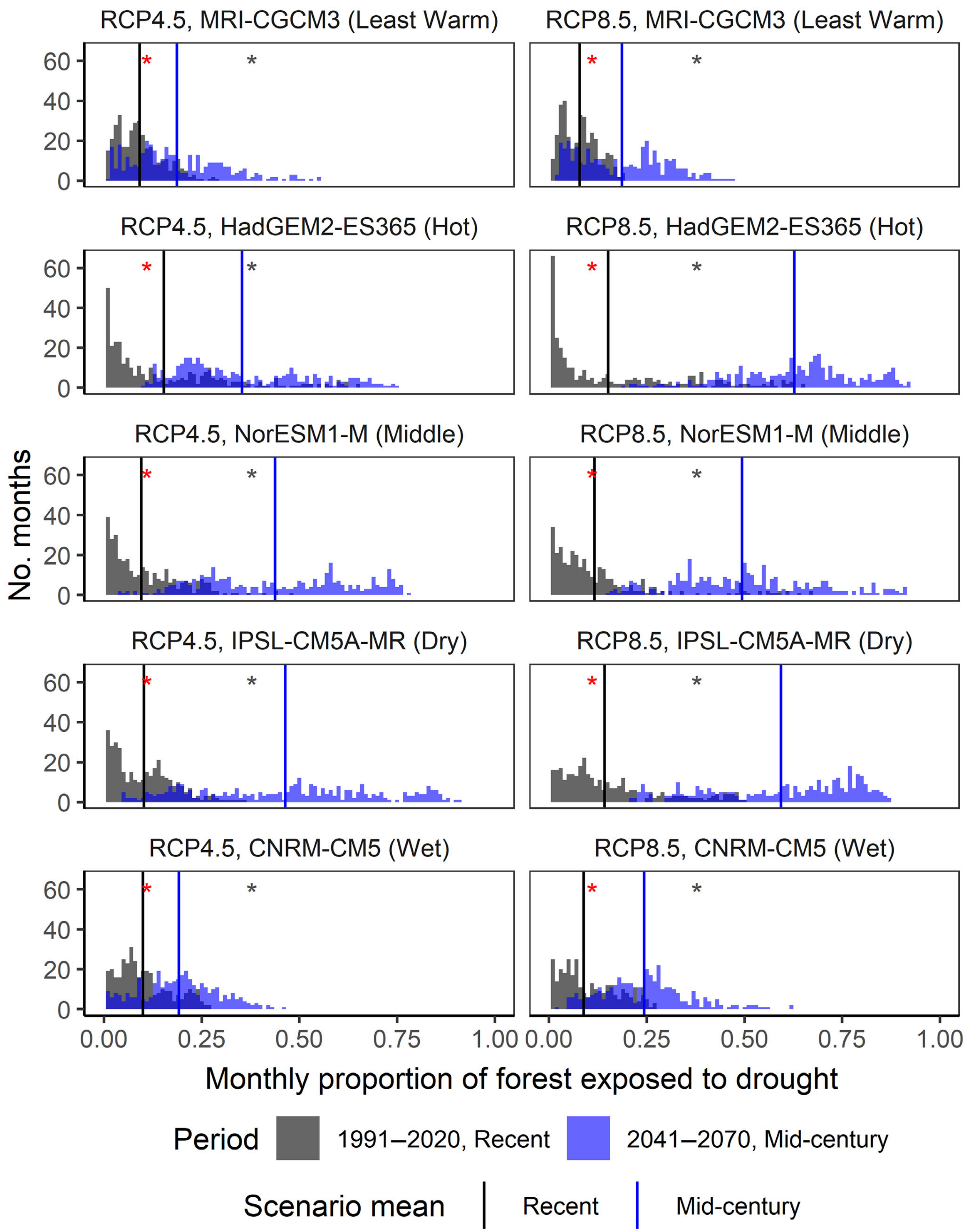

FIGURE 1 Histograms of proportion of US forest exposed to drought (Standardized Precipitation-Evapotranspiration Index ≤−1.5) in the recent and mid-century time periods. Solid lines indicate mean proportion for each time period for individual scenarios. Red and gray asterisks indicate overall means across the 10 scenarios for the recent and mid-century time periods, respectively, and do not change across the panels. RCP, Representative Concentration Pathway.

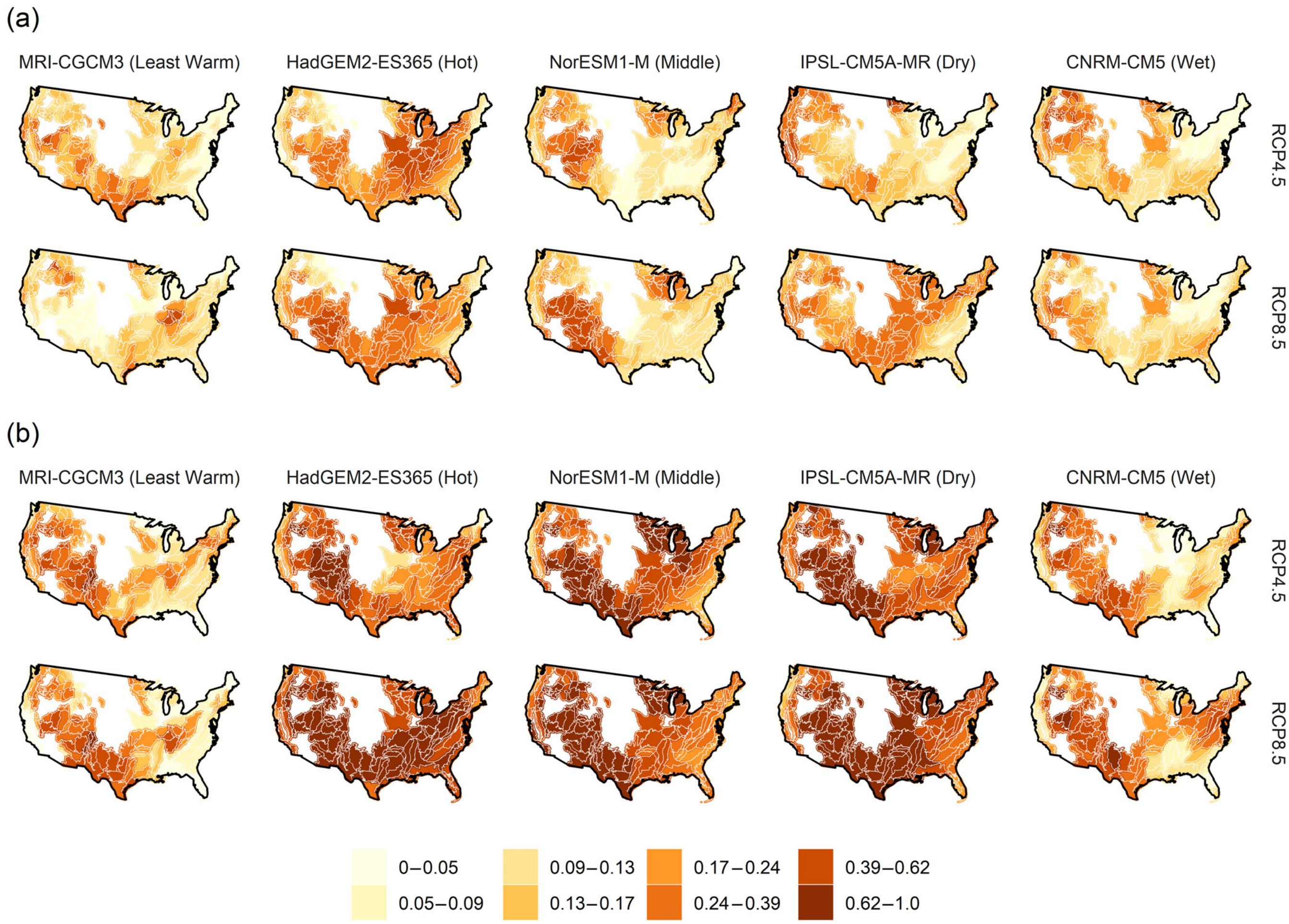

FIGURE 2 Average monthly proportion of forest exposed to drought (Standardized Precipitation-Evapotranspiration Index ≤−1.5) by ecological section in the (a) recent (1991–2020) and (b) mid-century (2041–2070) periods, symbolized by quantile (equal frequency) classification. Ecological sections containing less than 10% forest land use are not symbolized here. RCP, Representative Concentration Pathway.

ranges, depending on the scenario. Some of those type groups still had relatively high future exposure projected overall. Aspen/birch is an example of this: its overall exposure at mid-century across all scenarios is relatively high (Figure 4), and high exposure is projected for much of its geographic distribution, but lower exposure is also projected for some parts of its distribution, such as in Maine for the HadGEM2-ES365 model (Figure 5c) and in other portions of its range under other scenarios (Appendix S2). Exposure for the ponderosa pine type group showed a similar pattern (Appendix S2). Some forest type groups that are widely distributed, especially in the East, were projected to have more moderate drought exposure rates on average, albeit with a sizeable range of values across scenarios (Figure 4). Those included elm/ash/cottonwood (Figure 5d), as well as maple/beech/birch (Appendix S2).

Ecological sections where high exposure to drought at mid-century is expected (i.e., at least eight of the modeled scenarios agreed) and where a large increase in average monthly exposure is expected were similar in terms of forest type group composition (Figure 6a,b) because the two groups of ecological sections overlapped geographically (Figure 3). In each case, two forest type groups—pinyon/juniper and woodland hardwoods—comprised at least half of the forest area (65.6% where high exposure is expected; 50.0% where a large increase is expected). The forest type groups making up the remainder of the forest were similar as well, with some differences in actual proportions. Those type groups included fir/spruce/mountain hemlock, ponderosa pine, other western softwoods, aspen/birch, Douglas-fir, and lodgepole pine. However, oak/hickory forests composed a substantial portion (11.6%) of forests within ecological sections where a large increase in exposure is expected, but were only a small portion of forests where high exposure itself is expected (0.9%, included in the "other" category in Figure 6a).

The woodland hardwoods, other western softwoods, and pinyon/juniper type groups had the largest proportions

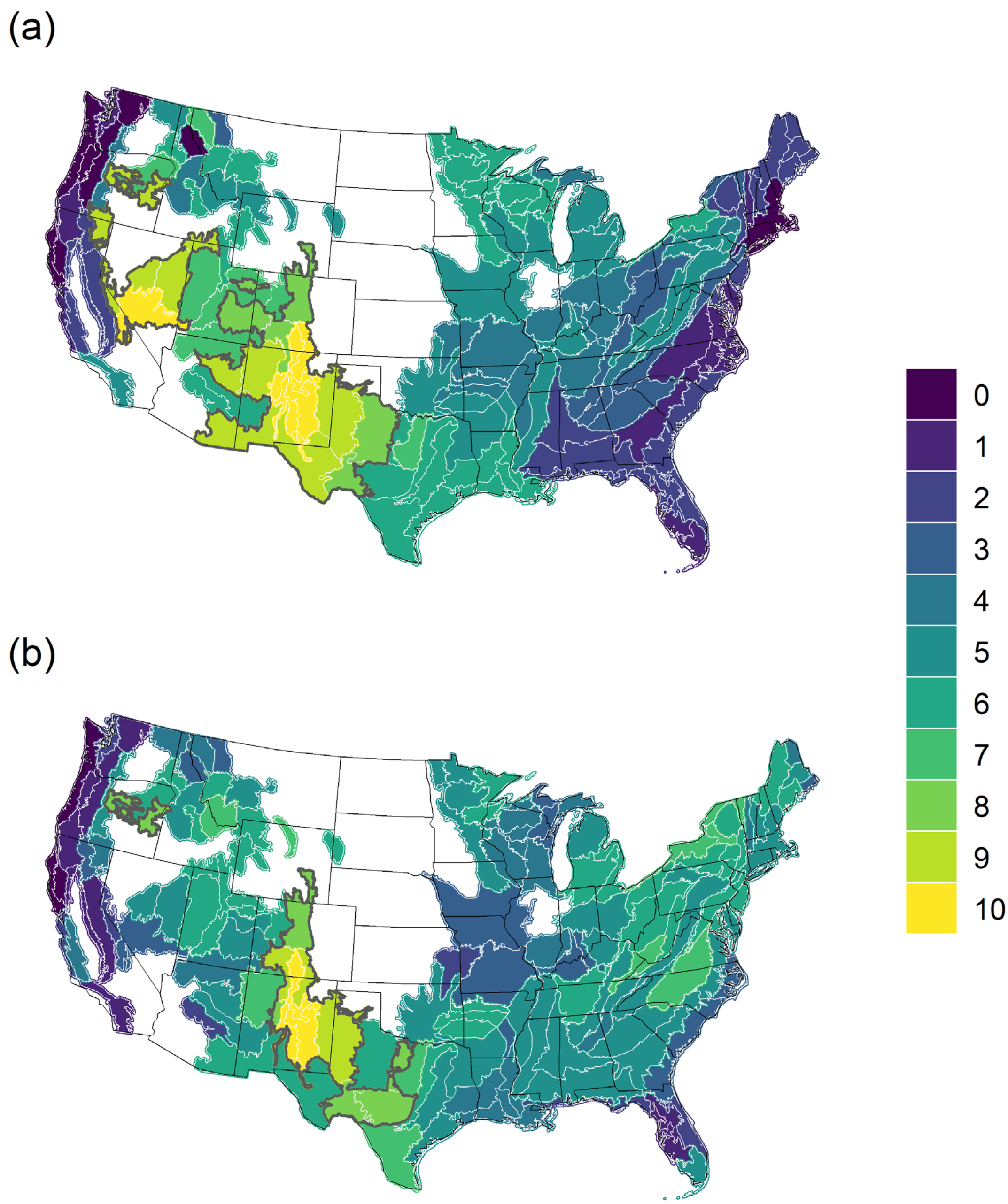

FIGURE 3 Number of scenarios projecting (a) greater than the US average of 37.8% of forest exposed to drought for mid-century and (b) greater than the US average of 238% increase in proportion of forest exposed to drought. Ecological sections that are less than 10% forested are not shown. Ecological sections labeled 8, 9, or 10 on each of these maps were considered places of high agreement and are outlined in black.

(≥20% each) of their total areas occurring in ecological sections where high exposure to drought at mid-century is expected, as well as where a large increase in exposure by mid-century is expected (Figure 7). Other forest type groups with greater than 10% of their areas in high-agreement sections included ponderosa pine, lodgepole pine, fir/spruce/mountain hemlock, and aspen/birch. For most forest type groups, and especially those with the largest areas in high-agreement ecological sections, a larger proportion occurred within ecological sections where high exposure is expected than in sections where a large increase in exposure is expected. However, a few, including the oak/hickory and other hardwoods groups, showed the reverse pattern, with a greater proportion occurring where a large increase is expected.

DISCUSSION

Increases in the frequency and extent of exposure to drought may be an important way in which forest ecosystems are affected by climate change in the future

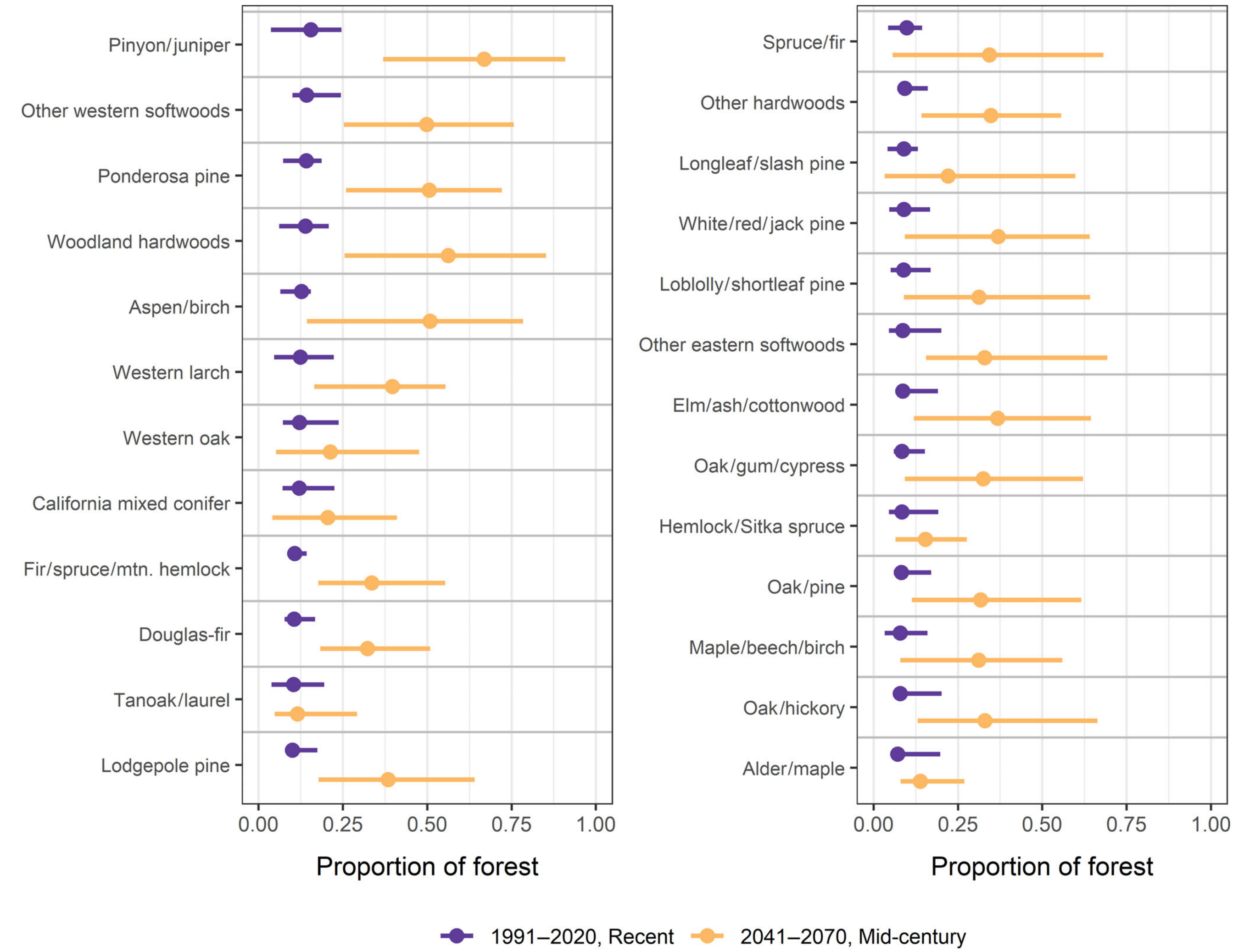

FIGURE 4 Comparison of 30-year average monthly proportion of forest type groups exposed to drought (Standardized Precipitation-Evapotranspiration Index ≤−1.5) for the recent and mid-century periods. Dots represent the median of the projections from the 10 scenarios for the given time period, and horizontal bars indicate the range of values across those projections. Forest type groups are listed here in decreasing order of median proportion exposed in the recent period.

(Allen et al., 2010; McDowell & Allen, 2015). We summarized trends in exposure to 36-month drought based on SPEI for forests across the United States under 10 scenarios spanning a range of modeled climates and two RCPs through 2070. On average, future projections indicate a tripling of the monthly spatial extent of forests exposed to drought: from 11.0% of forests exposed monthly in the recent period to 37.8% by mid-century. Increases in drought exposure are expected to be greatest if climate tends toward the hotter, drier, or middle climate models used here (HadGEM2-ES, NorESM1-M, IPSL-CM5A-MR) under either RCP. While all forest ecosystems have some potential to experience greater drought exposure by mid-century than in the recent period, nearly all scenarios suggest that forests in the southwestern United States and a few other areas of the western United States will have high levels of exposure.

Our results for the southwestern United States agree with other assessments that showed the potential for unprecedented drought during the latter half of this century (Cook et al., 2015) and that forest mortality from drought in that region is likely to be substantial in the future (McDowell et al., 2016; Williams et al., 2013). Indeed, recent and ongoing droughts in the southwestern United States have already led to considerable tree mortality (Flake & Weisberg, 2019; Kannenberg et al., 2021; Shriver et al., 2022; Wion et al., 2022). According to our analysis, many forest type groups in that region are projected to have high future exposure to drought (Figures 3 and 7). Those type groups include pinyon/juniper, other western softwoods, ponderosa pine, woodland hardwoods, and aspen/birch. Other studies in western US forests have also found relatively high drought vulnerability for similar forest types (Buotte et al., 2019; Thorne et al., 2018).

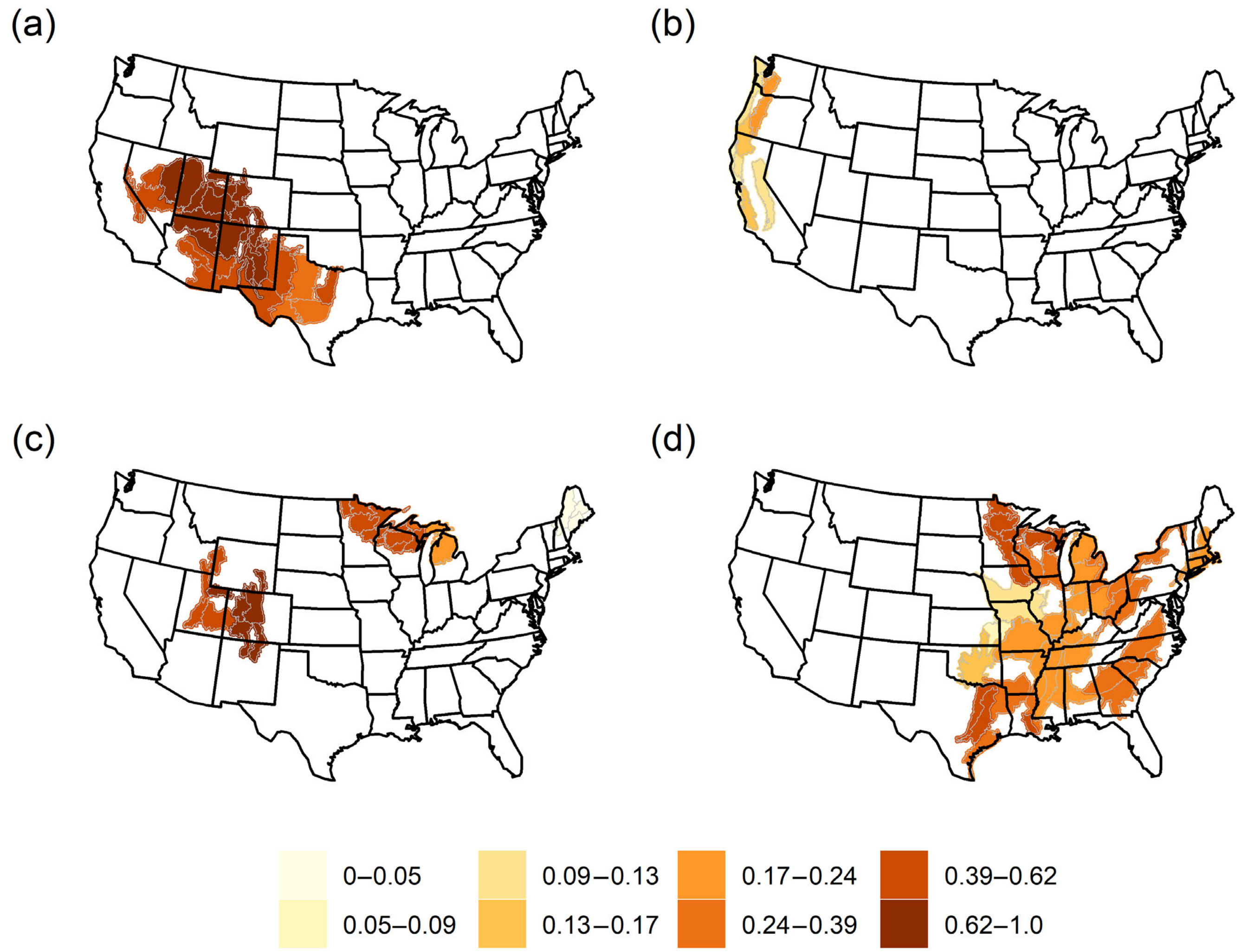

FIGURE 5 Proportion of forest type group's area within each ecological section that was projected to be exposed to drought (Standardized Precipitation-Evapotranspiration Index ≤−1.5) in the HadGEM2-ES365, Representative Concentration Pathway 4.5 scenario for the mid-century period. This scenario had exposure values that were closest to the overall mean for the mid-century period. Maps show (a) pinyon/juniper, (b) tanoak/laurel, (c) aspen/birch, and (d) maple/beech/birch forest type groups. Ecological sections that are less than 10% forested as well as those that contain less than 1% of the forest type group's area were included in analyses but are not shown on the maps. Classes displayed here are the same as in Figure 2 and were determined by quantile (equal frequency) classification across all forest type groups and scenarios. See Appendix S2 for maps of all forest type groups under each of the 10 scenarios.

Our results showing that many of the forests along the Pacific Coast are not expected to have high exposure to drought seem to contradict some recent studies that suggest potential for large increases in drought in California (Madakumbura et al., 2020; Ullrich et al., 2018). This contradiction may be related to the large extent of our assessment with comparisons among forested regions across the United States, versus others that assess future drought at the scale of California alone. While we projected some increase in drought exposure for forest type groups in California, those forests are not projected under most climate scenarios to have the levels of exposure projected for the Southwest and other parts of the western United States. Furthermore, our results are consistent with another study that assessed forest vulnerability to drought across the western United States and projected relatively low values of exposure along much of the Pacific Coast (Buotte et al., 2019).

While most assessments of drought in US forests have been conducted in local regions or landscapes in the western part of the country, our study assesses drought exposure for all forests in the conterminous United States. In quantifying drought exposure nationwide, our analysis has some advantages. First, it enabled us to evaluate exposure to drought across the entire range of forest type groups such as aspen/birch and woodland hardwoods, which span portions of the eastern and western United States, and for wide-ranging ecosystems like ponderosa pine, which

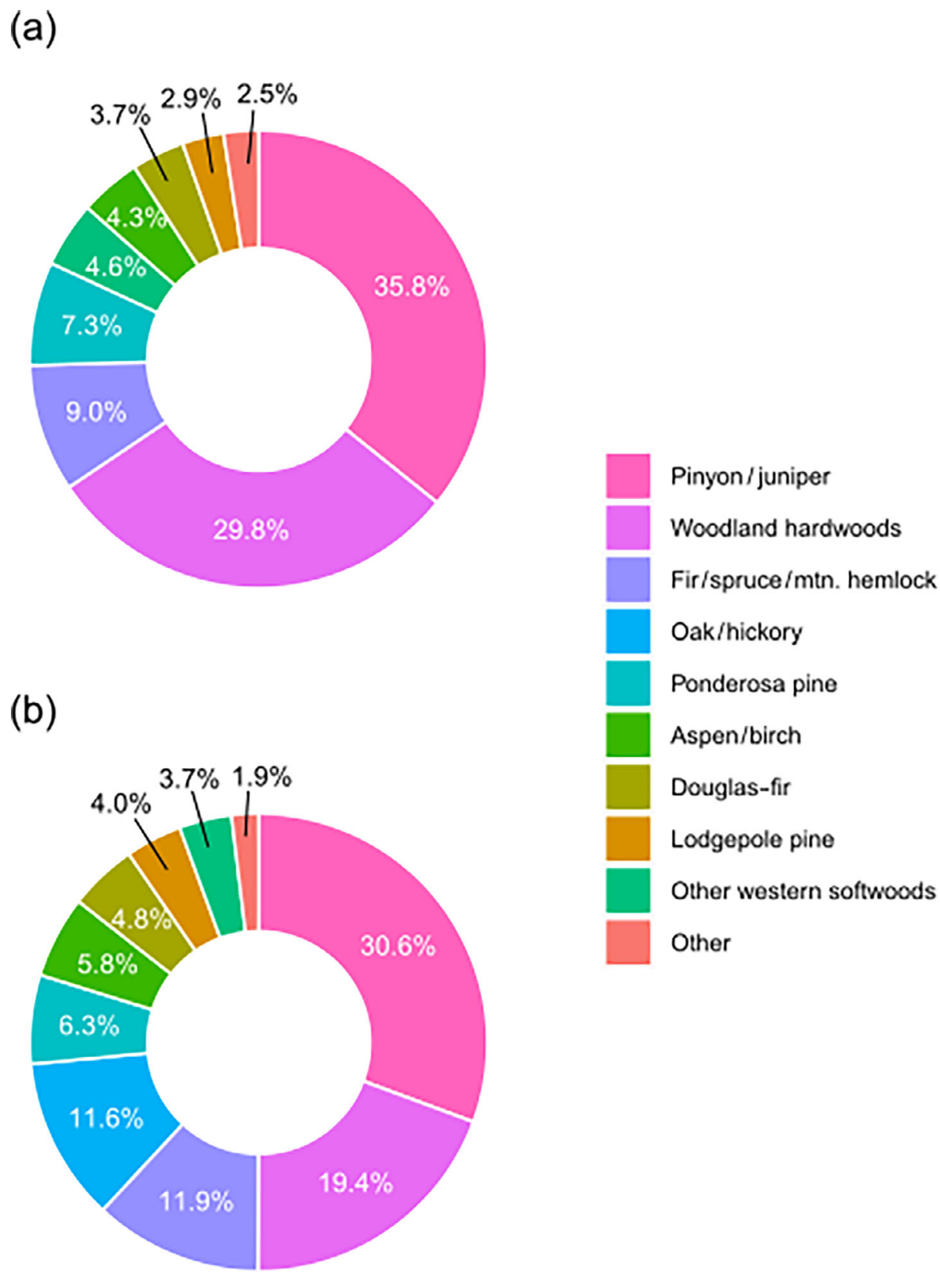

FIGURE 6 Composition of forest type groups in areas of high agreement among the modeled scenarios that (a) the average monthly proportion of forest exposed at mid-century will be greater than the overall average, and (b) the increase in average monthly exposure by mid-century will be greater than the overall average. Areas of high agreement are ecological sections where projections for at least 8 of the 10 scenarios are indicated in Figure 3a,b. Forest type groups that made up at least 1.5% of the forest in high-agreement areas are listed. The "other" category in both panels is composed of forest type groups that individually made up less than 1.5% of the forest.

occurs both in areas of higher and lower expected future exposure. This nationwide look provides insights such as which portions of those distributions may be more or less exposed. Second, we show that future drought exposure is less certain in much of the eastern United States as compared with the western United States. Unlike the western United States, where there are clear places of agreement among the scenarios included here, the scenarios agree less often in the eastern United States, especially in terms of increases in exposure (Figure 3). But in some scenarios, especially the hotter, drier, and middle climates (HadGEM2-ES365, IPSL-CM5A-MR, or NorESM1-M) projected under RCP 8.5, large portions of the eastern United States could be exposed to drought nearly as often as much of the western United States. Third, despite the lower agreement in the eastern United States, our analysis points to at least one predominantly eastern forest type group—oak/hickory—that makes up a substantial portion

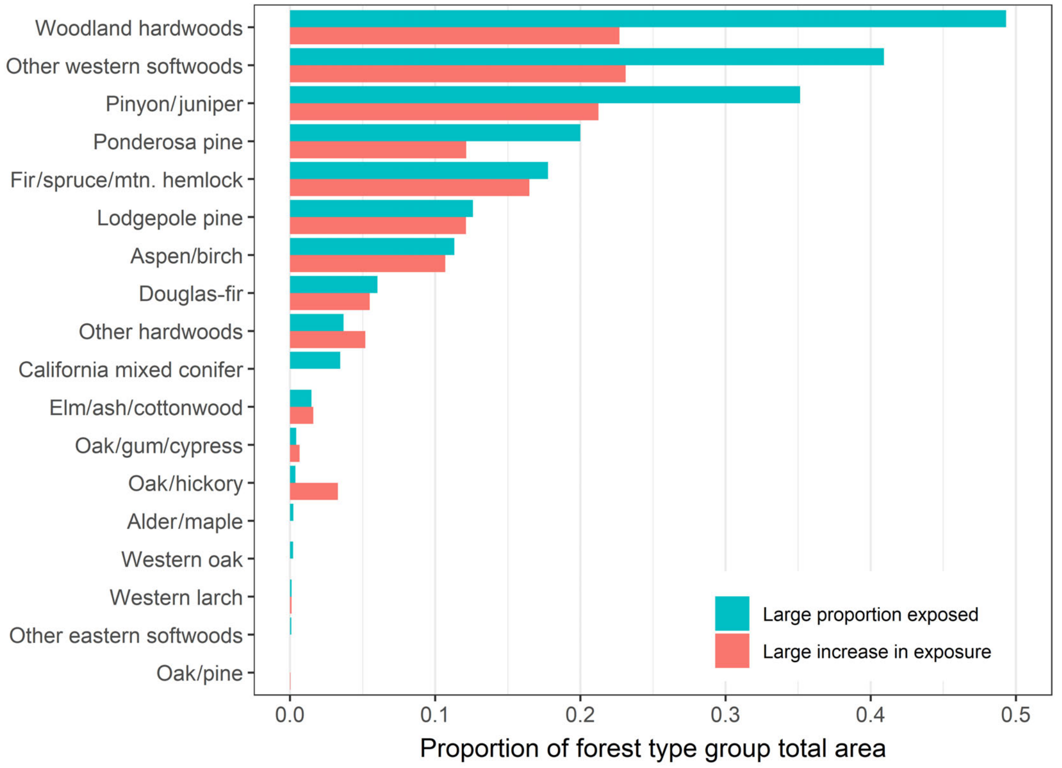

FIGURE 7 Proportion of the total areas of forest type groups that fall within ecological sections where there is high agreement regarding future drought exposure. The top bar in each case represents the proportion of the forest type group's area within ecological sections expected to have greater than average exposure to drought, and the bottom bar represents the proportion of the forest type group's area within ecological sections where the increase in exposure is expected to be greater than average. See Figure 3a,b for where those ecological sections occur. Seven forest type groups analyzed elsewhere in this paper are not listed here because they were entirely outside areas of high agreement.

of regions where an increase in drought exposure is expected. Although past research has indicated that oaks are relatively drought-tolerant, recent evidence suggests that the ability of oak trees to survive drought in the future may be more limited or at best uncertain as vapor pressure deficits rise (Novick et al., 2022).

This analysis of exposure to long-term drought as measured by a meteorological index provides a set of tools that can be used to screen forests for their future drought susceptibility. In order to fully measure and project ecological drought—that is, a deficit in water availability that causes an adverse deviation from the upper limit of the performance of an organism or ecosystem—both the sensitivity and adaptive capacity of forests and tree species to drought must be combined with the exposure analysis (Crausbay et al., 2017; Munson et al., 2020). While a full assessment of drought sensitivity and adaptive capacity for all forest types across the United States is not available, our results could be combined with existing information on sensitivity and adaptive capacity. For example, our analysis points to pinyon/juniper as the forest type group that is expected to see the greatest drought exposure. Other research has shown that pinyon-juniper ecosystems are sensitive to drought, both as a direct stressor and as a trigger for other disturbance agents, primarily fire and insects (Flake & Weisberg, 2019; Floyd et al., 2009; Gaylord et al., 2013; Hartsell et al., 2020). There are signs that regeneration, particularly of pinyon pines, is already a problem (Hartsell et al., 2020; Minott & Kolb, 2020), and thus irreversible transformations could occur in terms of species composition and structure of pinyon-juniper ecosystems (Kannenberg et al., 2021; Shriver et al., 2021). The cumulative evidence supports the idea that these forests are among the most highly vulnerable to increasing drought (Hartsell et al., 2020). Management actions such as conserving seed trees, limiting fire to retain mature trees that survived severe droughts, and assisting migration may be useful for enabling those forests to adapt to future droughts (Minott & Kolb, 2020).

Just as future exposure to drought varies across the distributions of forest ecosystems, so too will the effects of drought (Bell et al., 2018). The specific mix of tree species, their sizes and ages, and the landscape context of local sites can all help determine the impacts of drought. For example, large trees appear to be more sensitive to severe drought stress than small trees in some ecosystems, based on evidence that large trees experience higher rates of growth decline and mortality in response to the stress (Bennett et al., 2015; Stovall et al., 2019). Within the distribution of a given forest ecosystem, larger than anticipated effects could occur in places that are already under stress, such as the trailing edges of species' ranges where climate conditions have begun to shift (Liang et al., 2018; Rodman et al., 2022; Zhu et al., 2012) or when droughts co-occur with heat waves (Allen et al., 2010; Anderegg et al., 2013). In addition, the effects of drought may be amplified by the co-occurrence with other disturbances such as wildfire and insect outbreaks (Bendall et al., 2022; Nolan et al., 2021; Robbins et al., 2022). Conversely, drought effects at specific sites within some forest ecosystems could be tempered by individual species' tolerances for drought or microclimate conditions or by higher moisture retention in certain soil or topographic conditions acting as drought refugia (Davis et al., 2019; McLaughlin et al., 2017).

Forests have experienced distributional shifts, species compositional changes, and changes in forest structural characteristics over time as they exhibit succession and experience drought and other global change drivers, and will continue to experience these changes in the future (Brodribb et al., 2020; Fei et al., 2017; McDowell et al., 2020; Thom et al., 2017). These changes make it difficult to predict the precise ecological effects of drought exposure, especially tree mortality (Trugman et al., 2021; Wion et al., 2022). By linking the FIA database to the time series of past and future SPEI, we have created a framework that can improve analytical precision in subsequent analysis of drought impacts on forests. For example, in the eastern United States, recent range shifts have been documented, and future range shifts have been projected for tree species in response to a combination of a number of climate and nonclimate factors (Fei et al., 2017; Iverson et al., 2019). Future work could integrate that information with exposure to drought to investigate more precisely the specific role of drought in recent and future changes in species composition, structure, ages, or other forest attributes.

In our analysis, projections of forest exposure to drought at a national level varied more among GCMs than RCPs; under both RCPs, the hot, dry, and middle climate models projected higher exposure at mid-century than the wet or least warm models. Generally, in climate projections that span four to five decades, uncertainty among climate models is larger than emissions scenario uncertainty (Hawkins & Sutton, 2009). Furthermore, the GCMs were deliberately chosen to span a maximum range of temperature and precipitation across the United States as a whole (Joyce & Coulson, 2020a), so we anticipated that the variation among them would be relatively large. Drought exposure could be higher for some forested regions or ecosystems in another GCM not used here, but we chose to present a set of combined climate and radiative forcing scenarios that was large enough to span a range of future climates and yet small enough to examine the results from each individually.

The SPEI has been extensively used to characterize drought exposure in an ecological context and to compare drought exposures among locations as climate change occurs, but it has its limitations. Many critiques of the index focus on the uncertainty associated with extreme values, and by defining drought exposure in terms of SPEI or values less than or equal to −1.5, we have minimized the effects of extreme values on this analysis. In addition, we used SPEI to calculate drought exposure for forested locations based on their water balance values during the reference period of 1950–2005. In that way, our exposure analysis is grounded in the historical conditions of each location. However, drought projections may also be conceptualized in terms of a "shifting baseline," which states that dry periods that were relatively extreme in a past reference period may become commonplace in the future, and thus it may be more useful to characterize extremes that occur after accounting for that baseline trend (Stevenson et al., 2022). While shifting baselines may be useful for determining where conditions might be unfavorable for species that can adapt to steadily changing baseline conditions, many forests are adapted to conditions at the time of tree establishment (Aitken et al., 2008; Alberto et al., 2013). Grounding our exposure analysis in a single historical reference period is useful for determining where existing forests could experience stress from drought (Um et al., 2017), or where regeneration of a prior forest ecosystem may fail following a major disturbance event such as a severe wildfire because conditions are drier than past conditions (Anderegg et al., 2013). However, we acknowledge that changes in the characteristics of forests may occur over time in response to water deficits, such as increases in water use efficiency of trees (Hatfield & Dold, 2019). Such changes could make some future forests gradually adapt to more drought, and a shifting reference period for SPEI might better account for that.

This analysis presents an in-depth examination of forest exposure to drought at mid-century across the United States. We found that on average, exposure to drought more than tripled between the recent and mid-century periods, and we highlighted differences among forested regions and forest ecosystems in their exposure to drought. This information can be used as screening tool to prioritize forest ecosystems expected to be most exposed to drought and thus in need of further information on drought effects or management actions to minimize the effects of drought. In some of the forest ecosystems expected to be most exposed to drought in the future and that are known to be sensitive to drought, including ponderosa pine and pinyon pine forests, thinning to lower stand density may be one management action for mitigating future drought impacts and helping those forests adapt (Bottero et al., 2017; Bradford et al., 2022; Bradford & Bell, 2017; van Mantgem et al., 2020). In other forest ecosystems, such as oak-hickory forests, drought exposure could increase substantially, but future drought impacts are less certain (Novick et al., 2022), so further investigations of future drought impacts may be needed. By providing this mid-century drought outlook for forest ecosystems, we hope it can help facilitate adaptation to ensure forests are resilient to future climate change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Monthly rasters of Standardized Precipitation-Evapotranspiration Index data (Costanza et al., 2022) are available from the Forest Service Research Data Archive: https://doi.org/10.2737/RDS-2022-0075. The data associated with each Forest Inventory and Analysis (FIA) plot except for true plot coordinates are available from the USDA Forest Service's FIA database: https://apps.fs.usda.gov/fia/datamart/datamart.html. The list of evaluation groups that was used to obtain the set of FIA plots used in this analysis is included as Appendix S1: Table S1, and further details regarding the plots selected can be found in *Methods*. True coordinates for FIA plots are sensitive and not available publicly. True coordinates for FIA plots are available to qualified researchers from the USDA Forest Service by contacting FIA Spatial Data Services at SM.FS.FIANATLDR@usda.gov.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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