CHAPTER 6

Recent Forest Exposure to Multiyear Drought Across the Conterminous United States

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INTRODUCTION

Drought is an important stressor affecting forests and is commonly defined as a period of moisture deficit resulting from below-average precipitation, high temperatures, or both (Clark and others 2016). Alone or in combination with other disturbances, drought can reduce forest productivity, cause shifts in forest types, affect the ability of forests to regenerate, and diminish the capacity of forests to provide ecosystem services (Brodribb and others 2020, Vose and others 2016). As climate warms and many parts of the world become drier, droughts are expected to become more widespread, frequent, and severe (Ahmadalipour and others 2017, Cook and others 2015).

Measuring moisture conditions directly and determining the direct effects of drought on forests across broad geographic regions is difficult. Therefore, many scientists rely on the concept of meteorological drought (defined as a deficit in precipitation relative to a long-term mean), which can be quantified with only climate data. 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 to trees and other plants (Anderegg and others 2012). The magnitude of these impacts at any forested location depends on the level of drought exposure—the degree to which drought occurs at the location—as well as the sensitivities of the forest community or tree species to drought, the types and mix of surrounding land uses, and nearby human responses to drought (Crausbay and others 2017). However, such information is often lacking, as is a comprehensive picture of how these and related factors interact to affect ecosystem function and services.

This chapter summarizes recent trends in drought exposure for forest land in the conterminous United States (CONUS) using the 36-month Standardized Precipitation Evapotranspiration Index (SPEI; Beguería and others 2014, Vicente-Serrano and others 2010), a meteorological drought index. Meteorological drought indices track relative departure from normal climate conditions for a given location and can be correlated with resulting effects on forests (Druckenbrod and others 2019). The SPEI allows for comparisons among locations and can be computed over multiple time scales, making it useful for monitoring drought in different ecological contexts (Ault 2020, Slette and others 2019). Because it considers temperature (i.e., as a determinant of potential evapotranspiration (PET)), the SPEI is deemed more suitable for research in a warming climate than precipitation-only drought metrics (Vicente-Serrano and others 2010). This study used the 36-month SPEI because prolonged droughts that persist for multiple years are more likely to cause lasting impacts to forests than shorter term droughts of equal magnitude (Archaux and Wolters 2006, Berdanier and Clark 2016, Bunting and others 2017, Guarín and Taylor 2005, Koch and others 2013, Madakumbura and others 2019, Peters and others 2015, Xu and others 2018). In this chapter, the objectives were to: (1) summarize trends in SPEI over time on forest land across the CONUS and within subregions of the CONUS, (2) examine geographic patterns of forest land

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exposure to drought in forested ecoregions, and (3) summarize exposure of forest ecosystems to drought. Results show trends in SPEI for 1950–2021 and then focus on exposure of forests to drought during the most recent 30-year period: 1992–2021. A previous analysis of past drought exposure completed for the 2020 Resources Planning Act (RPA) Assessment (Costanza and others 2023a, 2023b, 2023c) was extended in several ways, including adding 3 more years of recent SPEI data (2019, 2020, and 2021), summarizing drought exposure subregionally, and mapping geographic patterns of exposure. Results are discussed in light of what is known about the sensitivity of forested regions and ecosystems to drought.

METHODS

Climate Data and Calculating SPEI

To analyze drought trends across the CONUS, this study obtained monthly gridded climate data at a spatial resolution of 2.5 arcmin (approximately 4 km) for 1950–2021 from the PRISM Climate Group website (PRISM Climate Group 2023). Calculating SPEI requires monthly precipitation (P) and potential evapotranspiration (PET) data. The PRISM dataset includes monthly precipitation (P) but does not include PET. PET estimation used Hargreaves' (1994) method, which incorporates minimum and maximum temperature, along with latitude, as proxies for radiation. While the Penman-Monteith method (Monteith 1965) is the recommended PET estimation method for SPEI calculations (Beguería and others 2014), calculation of PET via that method was not possible because it requires data on relative humidity and wind speed, which were not available in the PRISM dataset. This study opted to use the PRISM dataset over other climate datasets that include the variables needed for the Penman-Monteith method because the PRISM dataset allowed incorporation of a longer historical period back to 1950 for calibration of SPEI, i.e., the SPEI "reference period" (see below). While several alternative methods are available for calculating PET, the method of Hargreaves (1994) has been recommended for use in SPEI when the data needed for Penman-Monteith are unavailable (Beguería and others 2014, Stagge and others 2015, Venkataraman and others 2016). The *hargreaves* function in the R package SPEI 1.7 (Beguería and Vicente-Serrano 2017) was used to calculate PET, with latitude specified, along with the option to include monthly precipitation as a proxy for insolation (i.e., incoming solar radiation).

As noted previously, this study used a time scale to calculate SPEI. At that time scale, SPEI compares the cumulative climatic water balance (P minus PET) for the previous 36 months to the same cumulative 36-month water balance for all months in a reference period. The result is a set of continuous SPEI values spanning the reference period for each pixel in the climate data, which are normally distributed with a mean of 0 and standard deviation of 1, akin to a *z*-score. Negative SPEI values indicate drier-than-normal conditions for a given location, while positive values are wetter than normal. Here, the reference period was defined as 1950 to

2005. Use of that reference period in this analysis allows calibration of SPEI values based on the historical conditions of each location. Because many forests are adapted to conditions at the time of tree establishment, grounding this exposure analysis in a single historical reference period is useful for determining where existing forests could experience stress from drought. This study used the historical reference period to calculate SPEI for all months in the time period (1950 to 2021). Because of the 36-month accumulation lag, the first month to have a value for SPEI in the time series was January 1953. The *spei* function in the R package SPEI 1.7 (Beguería and Vicente-Serrano 2017) was used 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.

Forest Inventory Data

Monthly SPEI values were extracted for forested locations across the CONUS using geographic coordinates of plots in the U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) Database (FIADB version 8.0; Burrill and others 2018). The FIA Program applies a nationally consistent sampling design, with one permanent plot established for every ~2428 ha of land (Westfall and others 2022). Forest Service personnel classify plots into forest types by using a decision-tree approach based on the combination of species that comprises the highest stocking values (Arner and others 2001). Related forest types are aggregated into forest type groups (fig. 6.1). To protect sensitive plot information, especially on privately owned lands, the publicly available FIA Database contains plot coordinate information that has been altered slightly from the true coordinates. True plot coordinates were used here to extract SPEI values. Because FIA plots have fixed locations and a fixed design, a plot can straddle multiple forest type groups (Burrill and others 2018). To track those differences, multiple "conditions" can be identified within a plot, each with a unique forest type group. Each of these conditions has a corresponding area expansion factor, indicating the area of forest it represents. These expansion factors were used for all conditions to summarize the areas and proportions of forest area exposed to drought over time. Hereafter, plot conditions are simply referred to as "plots." To ensure inclusion of the full set of plots for each State in the CONUS, this study selected a set of plots for each State that FIA used to produce an evaluation of forest conditions ca. 2016. The resulting FIA plot database consisted of 163,283 plots, representing a total forest area of 277 147 000 ha (2 771 470 km^2).

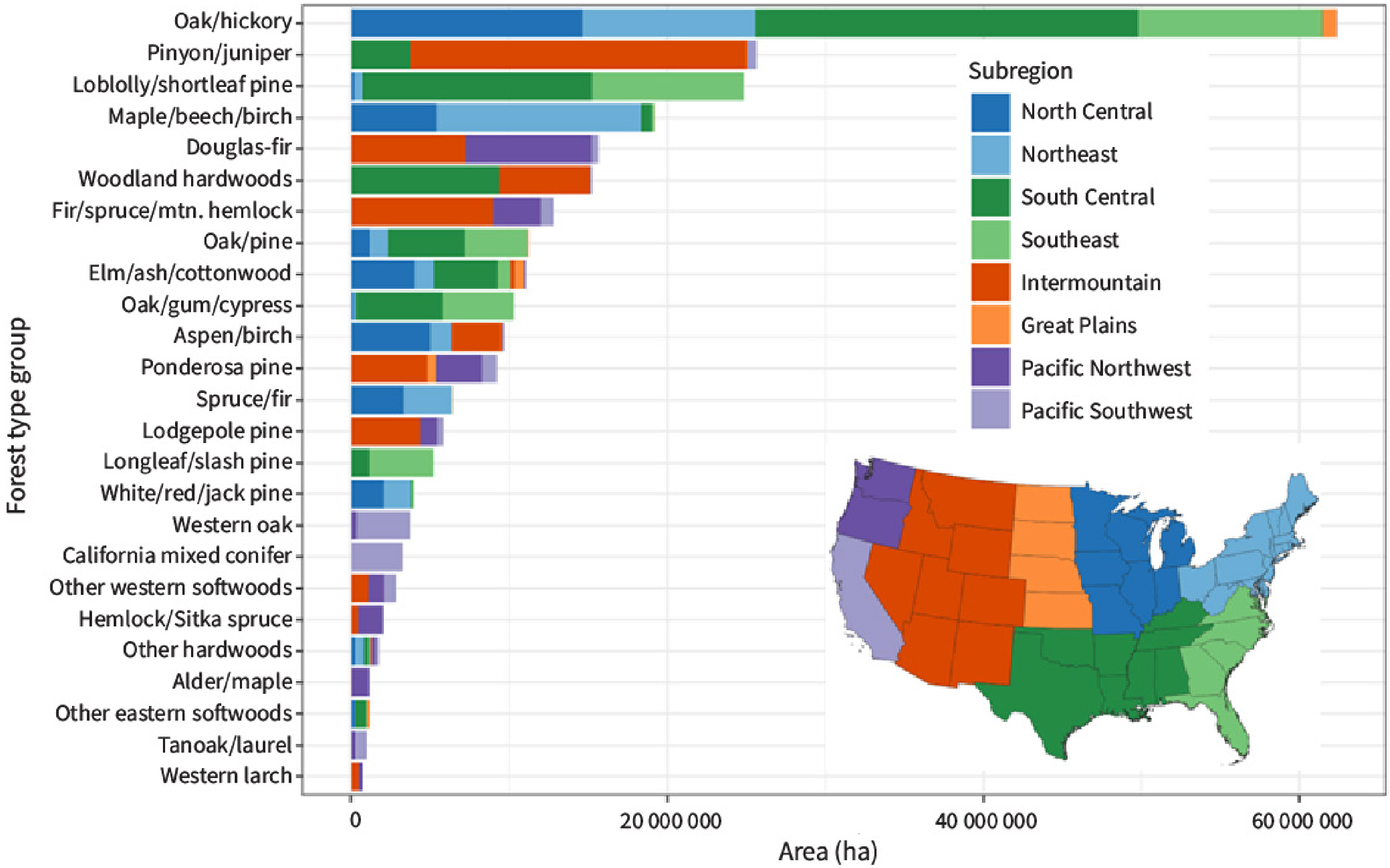

Figure 6.1—The areas of forest in each of the forest type groups included in the summary of drought exposure by type group. Inset map shows the conterminous States corresponding to each of the Forest Service Resources Planning Act (RPA) Assessment subregions used in this analysis. Colors on the bars by forest type group indicate the areas in each of the RPA Assessment subregions. (Data source: U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

Summaries of SPEI and Drought Exposure

The positive and negative values of SPEI were grouped into nine categories ranging from extreme wetness to extreme drought after Costanza and others (2023b; see table 6.1). Monthly trends were summarized in those categories of SPEI for forest land across the CONUS and within the subregions used in the 2020 Resources Planning Act Assessment (RPA subregions; fig. 6.1) for the entire time period (1953–2021). This study also specifically considered the combined categories of severe (-2 < SPEI < -1.5) and extreme drought (SPEI <-2) to be "exposed to drought" with a focus on drought exposure over the most recent 30 years in the study period: 1992–2021. Ecoregion sections (representing a moderate level of ecoregional classification; Cleland and others 2007) that contained each FIA plot location as well as the forest type group of each plot were identified. For forest land across the CONUS, by forest type group, and by ecoregion section, calculations were performed for the monthly proportion of forest with SPEI <-1.5 over the recent 30-year time period using the plot area expansion factors in the FIA Database. That was the principal metric of drought exposure. A metric was also developed for summarizing the frequency of forest exposure to relatively widespread drought by first calculating the overall monthly average proportion of forest across the CONUS that was exposed to drought (i.e., severe and extreme drought). Then, for ecoregion sections and by forest type group, a summary was developed for the number of months in the recent period for which the

Table 6.1—Values of Standardized Precipitation Evapotranspiration Index (SPEI) and corresponding categories, ranging from extreme wetness to extreme drought

SPEI values	Category
SPEI > 2	Extremely wet
1.5 < SPEI < 2	Severely wet
1 < SPEI < 1.5	Moderately wet
0.5 < SPEI < 1	Slightly wet
-0.5 < SPEI < 0.5	Near normal
-1 < SPEI < -0.5	Slightly dry
-1.5 < SPEI < -1	Moderate drought
-2 < SPEI < -1.5	Severe drought
SPEI < -2	Extreme drought

Groupings follow Costanza and others (2023b).

proportion of forest exposed to drought was greater than that average.

For analysis of drought for all forests across the CONUS and within ecoregion sections, all plots were included. For summaries of exposure for individual forest type groups, all type groups were included except nonstocked, exotic hardwoods, exotic softwoods, redwood, tropical hardwoods, and western white pine type groups (fig. 6.1). The nonstocked type group represents places with few, if any, trees. Exotic type groups were excluded because they were considered low priority with respect to drought adaptation. The other three type groups were limited in extent (<600 000 ha each, <0.2 percent of total forest land in the FIA Database). Because of their restricted distributions, this study assumed those type groups would respond more to local environmental factors and that the relatively coarse spatial resolution (~4 x 4 km) of the climate data would be less relevant. Excluded type groups accounted for a total of 3.9 percent of forest land area in the FIA Database, with nonstocked plots accounting for the majority (85 percent) of that excluded land.

RESULTS AND DISCUSSION

The major trends in observed SPEI values for forest land across the CONUS showed periods of more forest exposed to dry conditions (negative SPEI values) alternating with periods of more exposure to wet conditions (positive SPEI values; fig. 6.2). Forest land in the CONUS was exposed to overall drier conditions in the 1950s and 1960s, the late 1980s, and the early 2000s. These past trends for the CONUS and the corresponding trends by subregion (fig. 6.3) accord with known incidence of past drought. In the 1950s, drought periods occurred across much of the Intermountain, Great Plains, North Central, South Central, and Southeast subregions (Andreadis and others 2005, Heim 2017). Drought occurred throughout the 1960s across much of the North Central and Northeast subregions (Barlow and others 2001, Namias 1966). Starting in approximately 2000 and continuing through the end of the analysis period (2021), large portions of forests in subregions of the West (Pacific Northwest, Pacific Southwest, and Intermountain subregions) were exposed to dry conditions (fig. 6.3). Other research has shown that for the Western United States, the period from 2000 to 2021 was among the driest periods in the last several centuries (Williams and others 2022). In contrast, during much of that time, forests in the eastern subregions were exposed to wet conditions (fig. 6.3; also shown for the Northeast by Krakauer and others (2019)), amounting to large proportions of extremely wet conditions across the CONUS as a whole from 2005 to 2021 (fig. 6.2). This difference between the wet conditions in the eastern subregions and the dry conditions in the western subregions over the last two decades illustrates the complexity of the recent moisture regime across the CONUS.

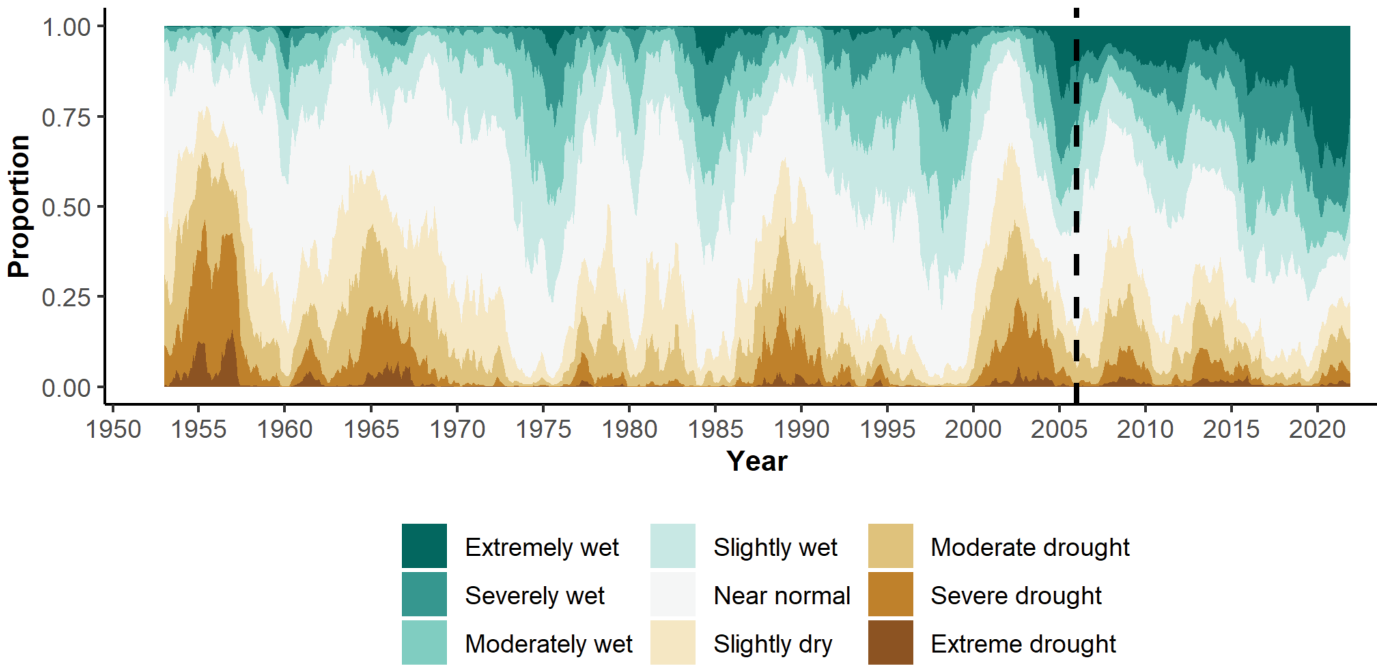

Figure 6.2—Recent and past trends in Standardized Precipitation Evapotranspiration Index (SPEI) for forest land in the conterminous United States. For each month in the time series, colors indicate the proportion of forest in each SPEI category. Values of SPEI corresponding to each category can be found in table 6.1. The period to the left of the dashed line was the reference period for calculating SPEI. (Data sources: PRISM Climate Group 2023; U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

Summaries of the proportion of forest exposed to drought (severe or extreme drought, SPEI <-1.5) for the most recent 30 years in the dataset (1992–2021) allow examination of drought in more detail than the national and subregional summaries. Maps of annual average drought exposure by ecoregion section show the geographic extent of drought over time (fig. 6.4). Over the recent period, an average of 4.5 percent of forest was exposed to drought per month.

Summaries of drought exposure by ecoregion section highlight that (1) in some years (e.g., during much of the 1990s), low levels of drought were present across the CONUS, but, in most years, drought affected >50 percent of forests in at least one ecoregion section of the country; and (2) nearly every forested region of the country was exposed to drought at some point in the last 30 years.

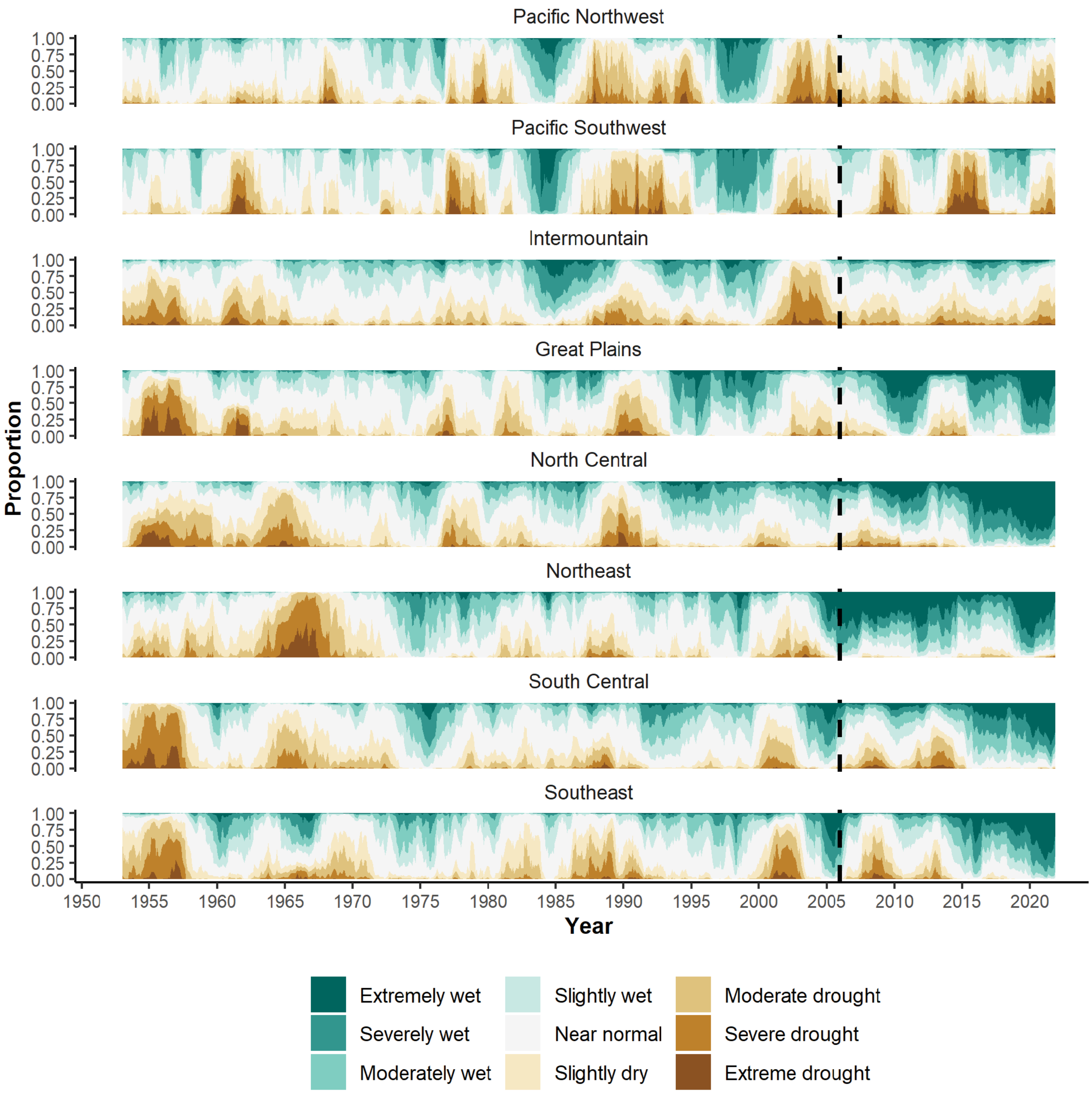

Figure 6.3—Recent and past trends in Standardized Precipitation Evapotranspiration Index (SPEI) for forest land by Resources Planning Act Assessment subregion. For each month in the time series, colors indicate the proportion of forest in each SPEI category. Values of SPEI corresponding to each category can be found in table 6.1. The period to the left of the dashed line was used as the reference period for calculating SPEI. (Data sources: PRISM Climate Group 2023; U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

In general, more widespread than average drought exposure (greater than the national average of 4.5 percent of forest exposed per month) occurred most often in ecoregion sections of the Western United States, with moderate frequency in the Southeast, and least often in the Northeast (fig. 6.5). For many ecoregion sections in the Northeast, 10 percent of months in the recent period had >4.5 percent of the forests exposed to drought, in contrast with sections in western California and other parts of the West, where >40 percent of the months in the recent period had >4.5 percent of the forests exposed to drought (fig. 6.5). One ecoregion section in western Montana had >4.5 percent of the forests exposed to drought for 50 percent of the months in the recent period (fig. 6.5). Since 2000, drought exposure has been widespread in the Western United States during most years, especially in 2002–2004, 2009, and 2013–2015, and has returned recently in 2020–2021 (fig. 6.4). The persistent drought in the Western United States since 2000 has been called a "megadrought" because it has been more intense and long lasting than any observed drought in the region (Cook and others 2022, Williams and others 2020). Within the Western United States, forests in ecoregion sections in California were exposed to drought during the mid-2010s, a period that has been shown to be drier than any historical precedent in California (Robeson 2015). The period corresponded with high wildfire activity and insect outbreaks in the region, and widespread forest tree mortality during that time has been attributed to drought in combination with those other disturbances (Fettig and others 2019, Goulden and Bales 2019, Halofsky and others 2020, Steel and others 2023). Forests in the Southwestern United States and near the Four Corners area of Utah, Colorado, New Mexico, and Arizona have also experienced frequent widespread drought exposure over the past 30 years (figs. 6.4 and 6.5). A multiyear drought there in 2002–2004 led to wildfire and bark beetle outbreaks, causing extensive tree mortality (Breshears and others 2005), and dry conditions have been present there frequently in the past two decades (Lisonbee and others 2022).

In Texas and other parts of the Central United States, widespread exposure to drought in 2011–2014 (fig. 6.4) reflects one of the worst droughts on record in 2011, which occurred in conjunction with a heat wave (Fernando and others 2016, Grigg 2014, Hoerling and others 2013, Nielsen-Gammon 2012). A combination of drought and historically high temperatures killed an estimated 301 million trees in Texas, or >6 percent of trees statewide (Hoerling and others 2013, Moore and others 2016). In the Southeastern United States, many ecoregion sections experienced relatively widespread exposure to drought between 10 and 20 percent of the time over the last 30 years (fig. 6.5). Some notable droughts in the Southeast occurred in 2001–2002, 2007–2009, and 2012–2013 (fig. 6.4). While those droughts were not associated with widespread, acute tree mortality as in many Western and Central U.S. subregions, evidence suggests that prolonged exposure to drought events in the Southeastern United States has led to growth declines and eventual mortality (Berdanier and Clark 2016).

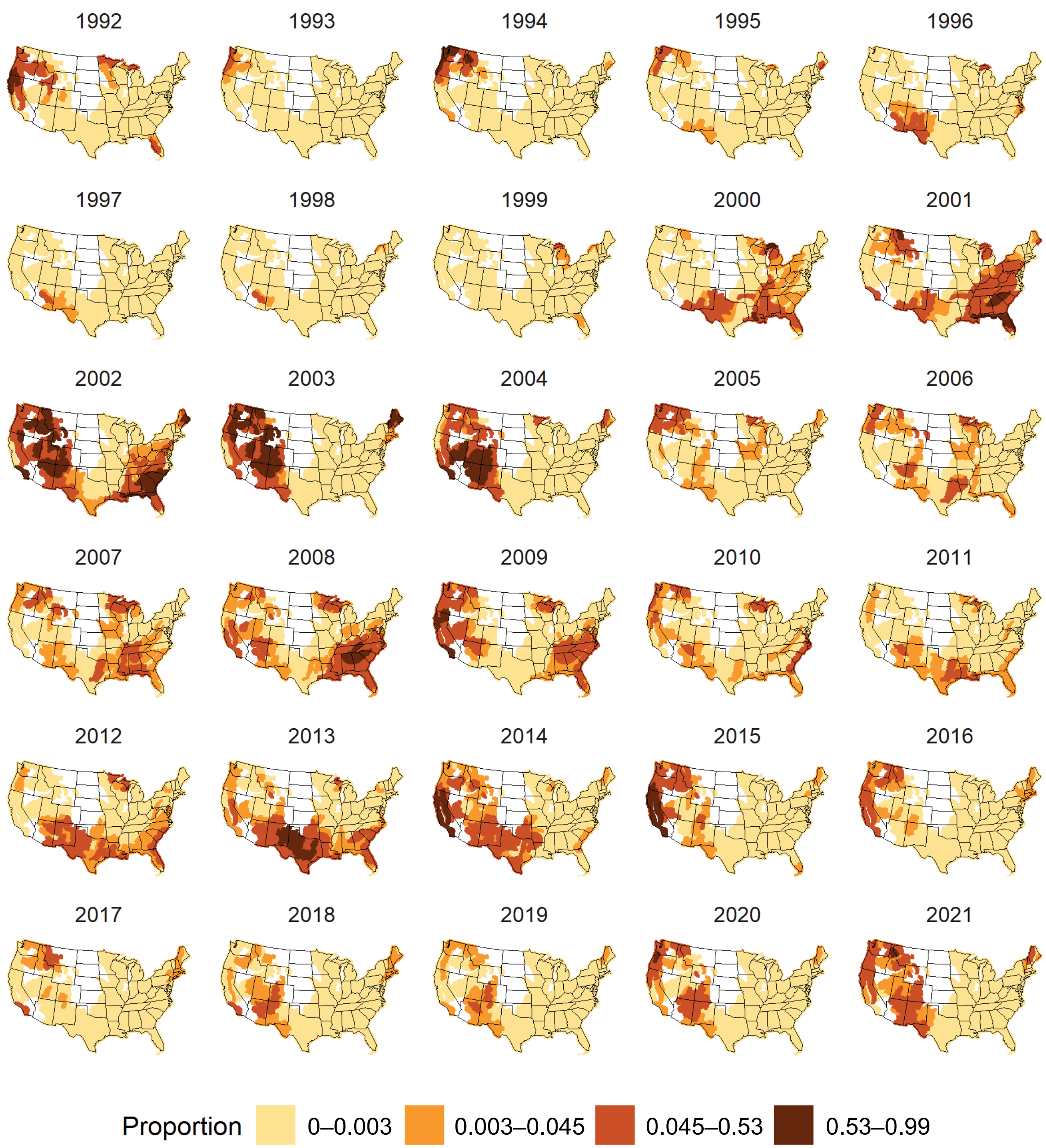

Figure 6.4—Average monthly proportion of forest in each ecological section exposed to severe or extreme drought (36-month SPEI ≤-1.5) in the recent 30-year period summarized annually. Ecological sections containing <10 percent forest land are not shown. (Data sources: Cleland and others 2007; PRISM Climate Group 2023; U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

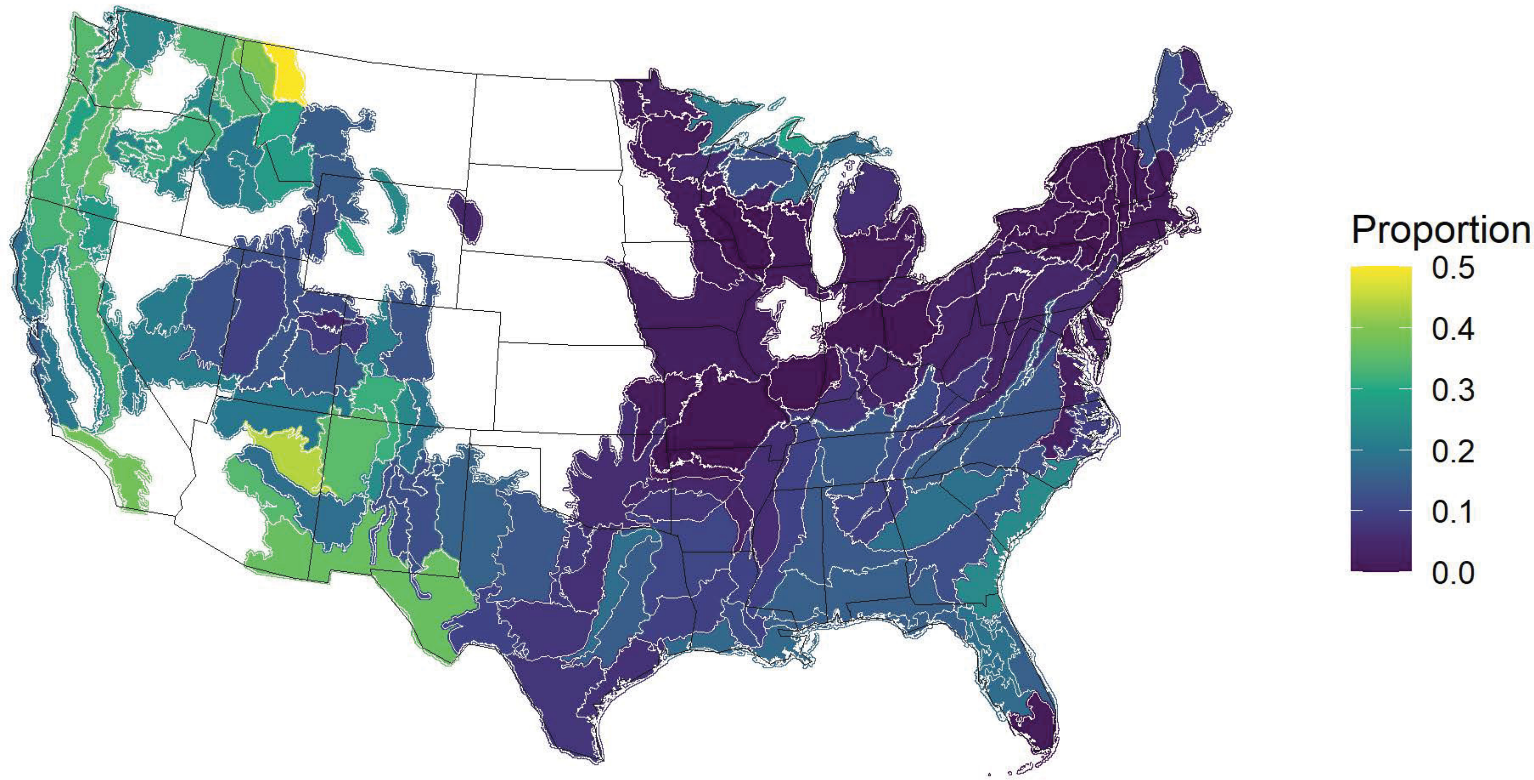

Figure 6.5—Proportion of months in the recent 30-year period (1992–2021) during which exposure to drought in each ecological section was more widespread than average (greater than the national average of 4.5 percent of forest exposed per month). Ecological sections containing <10 percent forest land are not shown. (Data sources: Cleland and others 2007; PRISM Climate Group 2023; U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

Summaries of drought exposure by forest type group reflect the geographic ranges of those type groups, and thus mirror the trends seen in the previous (i.e., subregional) summaries. However, together with existing information on the sensitivities and adaptive capacities of tree communities and species, the type group summaries can provide insights into the vulnerabilities of forest ecosystems to drought. The six forest type groups that have experienced the highest exposure on average all occur in the Western United States: fir/spruce/mountain hemlock, lodgepole pine, Douglas-fir, other western softwoods, western larch, and ponderosa pine (fig. 6.6A). Those type groups also have been exposed to widespread drought (greater than the national average of 4.5 percent of forest exposed per month) more frequently than other type groups (fig. 6.6B). These six type groups can be found in a variety of conditions throughout the West, but most have relatively wide distributions and occur especially in the Pacific Northwest and Intermountain subregions (fig. 6.1). The wide distributions of some type groups mean that the sensitivities of forests to drought exposure can vary considerably across their ranges. For example, recent mortality of Douglas-fir (*Pseudotsuga menziesii*) associated with drought stress and subsequent insect infestations has been higher in forests growing on hotter and drier sites compared with other sites (Bennett and others 2023). The ponderosa pine type group also occurs across a broad range. In the Southwestern United States, widespread drought-induced mortality of ponderosa pines (*Pinus ponderosa*) has been followed by limited regeneration (Minott and Kolb 2020). Other forest and woodland types in the region, including pinyon/juniper forests, have experienced widespread mortality due to dry conditions, followed by limited recruitment of constituent species (Minott and Kolb 2020, Redmond and others 2015, Shriver and others 2022). In ponderosa pine forests in California, drought has led to widespread mortality from bark beetle outbreaks, and research has shown that carbon storage, an important ecosystem service in those forests, may not return to pre-drought levels before the end of the 21st century (Robbins and others 2023).

Several type groups experienced widespread drought exposure several times in the recent 30-year period (fig. 6.6B), even though when averaged across the 30 years, the monthly proportion exposed to drought was lower than other type groups (fig. 6.6A). Those include western oak, California mixed conifer, and tanoak/laurel. Those forest type groups occur in California, where drought exposure has varied greatly in recent years, with widespread exposure in some years and little to none in others (fig. 6.4; Swain and others 2018). Climate projections for California suggest even more variability in precipitation by the end of the 21st century, with extreme dry and wet precipitation events becoming more common as mean precipitation undergoes only modest changes (Swain and others 2018).

Forest type groups occurring predominantly in the East have been less exposed to severe or extreme drought than western type groups in general, having lower median monthly exposures and lower numbers of months with widespread exposure than most western type groups (figs.

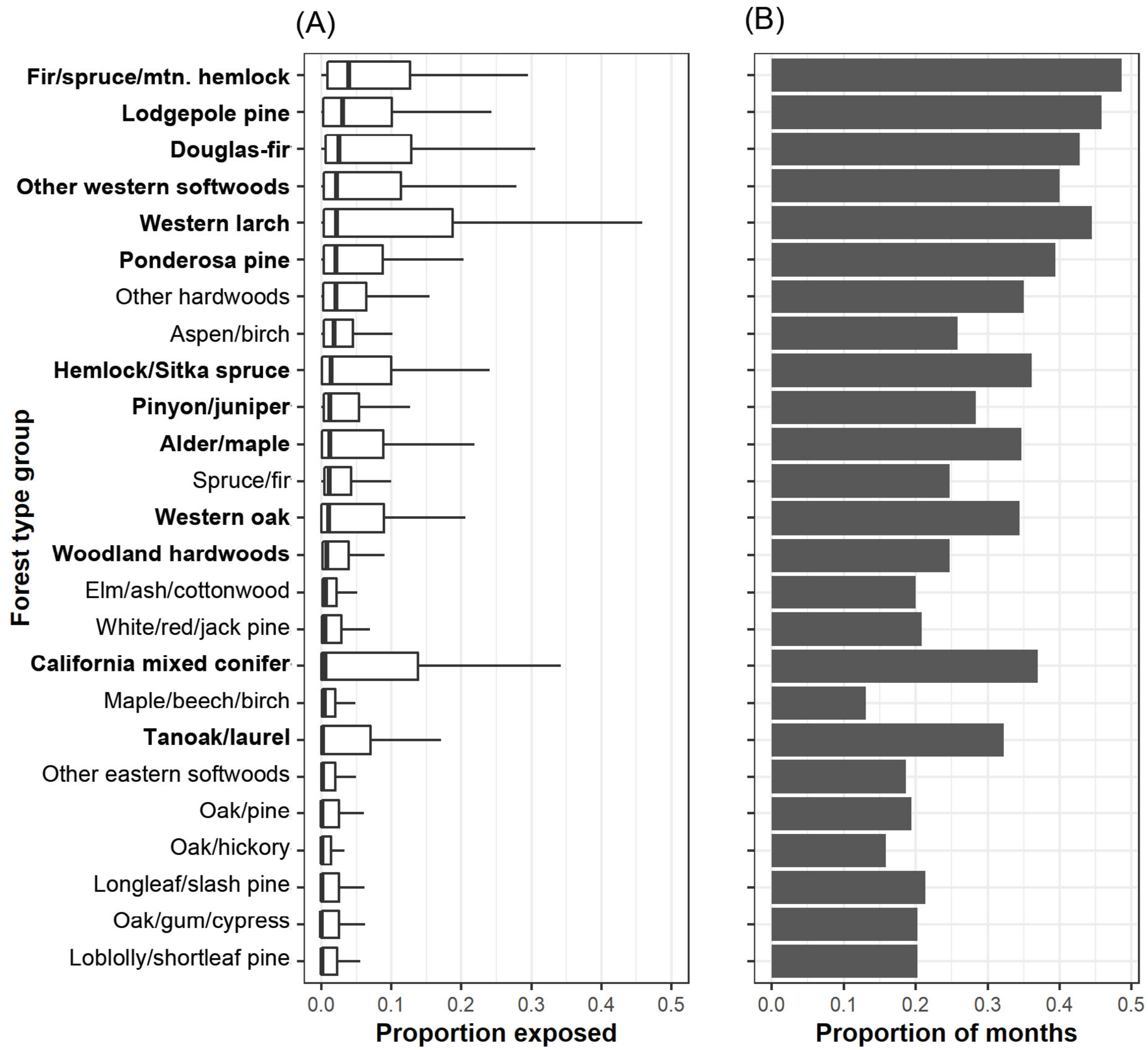

Figure 6.6—Exposure of forest type groups to drought (severe or extreme drought, 36-month Standardized Precipitation Evapotranspiration Index (SPEI) ≤-1.5) in the recent 30-year period (1992–2021). (A) shows boxplots of monthly proportion exposed and (B) is the proportion of months during which the proportion of each forest type group exposed to drought was more widespread than average (greater than the national average of 4.5 percent of forest exposed per month). In the boxplots, the dark line within the box represents the median monthly proportion exposed, and forest type groups are listed in descending order according to that value. Left and right edges of the box represent the first and third quartiles, respectively, and the whiskers extend to 1.5 times the interquartile range of the data. Outliers extending beyond that range were omitted from the figure for readability, but many forest type groups had >50 percent exposure in a few months. Bold indicates forest type groups primarily distributed in the Western United States. (Data sources: PRISM Climate Group 2023; U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Database)

6.6A and B). Worth noting, however, is that although spruce/fir forests had moderate exposure overall, that type group had one of the highest exposure rates of all eastern type groups (figs. 6.6A and B). Those forests occur at relatively high elevations and are adapted to cool and moist conditions, so they are likely to be sensitive to drought conditions. In addition, drought exposure for oak/hickory forests has been low in the recent period, but future drought impacts in those forests are less certain (Novick and others 2022), so further investigations of future drought impacts may be needed.

Results emphasize that over the past 30 years, while forests in some regions of the CONUS have been more exposed to drought than others, widespread forest exposure to drought somewhere in the CONUS has been commonplace rather than an exception. Drought events are already being attributed to anthropogenic climate trends (Williams and others 2020), and research suggests that drought will become even more common and more severe in many places as climate warms (Seidl and others 2017, Ullrich and others 2018). In fact, some of the forested portions of the CONUS as well as some forest type groups that have had the highest rates of drought exposure in the recent past (figs. 6.4, 6.5, and 6.6) may be among the most exposed in the future, including the Southwestern United States and associated forest type groups like ponderosa pine and pinyon/juniper (Costanza and others 2023b). Assessments of forest exposure to meteorological drought in the future compared with recent past exposure are important for prioritizing which forests need mitigation, increasing adaptive capacity, and determining where further research into potential future drought impacts is necessary (Costanza and others 2023b). Although this study focuses on drought exposure, by linking the FIA Database to recent SPEI, this study, along with recent work on future forest exposure (Costanza and others 2023b) can set the stage for further investigations of drought impacts on forests nationwide using the observed trends in forest conditions from the forest inventory.

Studies of forest responses to recent droughts have produced some evidence that management can help ameliorate the worst effects of drought in some cases and may facilitate resilience to future drought. In ponderosa pine and pinyon/juniper forests, thinning to lower stand density has helped mitigate impacts and may be one management action for helping those forests adapt to future climate (Bottero and others 2017, Bradford and Bell 2017, Bradford and others 2022). Thus, examining forest exposure to past droughts alongside drought's effects on forests can be a critical first step toward informing management and policy that help forests be more resilient in the future.

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