CHAPTER 4

Drought and Moisture Surplus Patterns in the Conterminous United States: 2020, 2018–2020, and 2016–2020

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INTRODUCTION

Droughts can have significant impacts on forests. They can give rise to considerable tree stress, particularly when they co-occur with heat waves (L.D.L. Anderegg and others 2013, Peters and others 2015, Williams and others 2013). While trees and other plants can defend against this stress by restricting fundamental growth processes and photosynthesis (Kareiva and others 1993, Mattson and Haack 1987), prolonged drought stress can lead to failure of a tree's hydraulic system, causing crown death and eventual tree mortality (Choat and others 2018). Research suggests that large trees may be more sensitive to drought stress than small trees and experience comparatively higher rates of growth decline and mortality (Bennett and others 2015, Stovall and others 2019). Furthermore, drought stress can make trees vulnerable to damaging insects and diseases (Clinton and others 1993, Kolb and others 2016, Mattson and Haack 1987, Raffa and others 2008). In addition, droughts heighten the risk of more frequent and more severe wildfires by hindering organic matter breakdown and reducing the moisture content of downed woody debris, leading to higher fuel loads (Clark 1989, Collins and others 2006, Keetch and Byram 1968, Schoennagel and others 2004, Trouet and others 2010). Regional-scale relationships between drought and fire occurrence are complex, but generally, projections of increased drought frequency and severity under a warming climate imply that wildfires will be more prevalent and extensive in many U.S. forest systems, especially in the Western United States (Abatzoglou and Williams 2016, Dennison and others 2014, Littell and others 2016).

Ecologists define the concept of drought inconsistently and disagree about the best way to measure its severity (Slette and others 2019, 2020; Zang and others 2020). For example, in a review of 564 ecological drought studies, Slette and others (2019) found that less than one-third explicitly defined drought or cited a definition from another source. Furthermore, about 30 percent of the studies merely treated the term "drought" as synonymous with "dry conditions" without characterizing or quantifying how dry the conditions were relative to normal conditions. Bearing these issues in mind, a meaningful definition applicable to forests is that a drought is a period of precipitation deficit that persists long enough to deplete available soil water, resulting in impacts to trees and other plants that may include injury or death (Anderegg and others 2012, Hanson and Weltzin 2000). By this definition, droughts affect most forests in the United States, although there are regional variations in drought frequency, timing, and intensity (Hanson and Weltzin 2000). These variations characterize the regions' predominant drought regimes. In the Western United States, most forests receive a large majority of their precipitation during a relatively brief period of 2–3 months, so they experience seasonal droughts each year. By comparison, forests in the Eastern United States usually exhibit a pattern of random (i.e., occurring at any time of year) but occasional droughts, as observed in the Appalachian Mountains and the Northeast, or frequent late-summer droughts, as commonly observed in the Southeastern Coastal Plain and the eastern Great Plains (Hanson and Weltzin 2000).

Most forests can tolerate short-term droughts, although individual tree species differ in their level of tolerance (Archaux and Wolters 2006, Berdanier and Clark 2016, Peters and others 2015). Because of this tolerance, drought duration may be more important for forests than drought intensity (Archaux and Wolters 2006). For example, forests that endure multiple consecutive years of drought are likelier to experience high tree mortality or other negative impacts than forests subject to a single year of extreme drought (Bigler and others 2006, Guarín and Taylor 2005, Jenkins and Pallardy 1995, Millar and others 2007). Indeed, effects on tree growth and function from 1 year of drought are probably still reversible for many forests (Bigler and others 2006). In other words, forests may not encounter significant deleterious effects until they undergo a prolonged period of comparatively intense drought conditions. Hence, comprehensive evaluations of drought impact in forests should include analyses of moisture conditions at multiple timescales. Such approaches were once rare among broad-scale assessments (Norman and others 2016), but multiscale drought indices such as the Standardized Precipitation Evaporation Index (SPEI) have grown in popularity (Vicente-Serrano and others 2010).

In the 2010 FHM national report, we described a method for mapping drought conditions across the conterminous United States (Koch and others 2013b). Our objective was to generate fine-scale, drought-related spatial datasets that build upon products available from sources such as the National Centers for Environmental Information (e.g., Vose and others 2014) or the U.S. Drought Monitor program (Svoboda and others 2002). The primary inputs are gridded climate data (i.e., monthly raster maps of precipitation and temperature over a 100-year period) created with the Parameter-elevation Regressions on Independent Slopes (PRISM) climate mapping system (Daly and others 2002). The method uses a standardized indexing approach that facilitates comparison of a given location's moisture status during different time windows, regardless of their length. The index is more straightforward to calculate than the commonly used Palmer Drought Severity Index, or PDSI (Palmer 1965), and avoids some criticisms of the PDSI (see Alley 1984) regarding its underlying assumptions and limited comparability across space and time. Here, we applied the method outlined in the 2010 FHM Report to the most currently available climate data (i.e., the monthly PRISM data through 2020), thereby providing the twelfth installment in an ongoing series of annual drought assessments for the conterminous United States (Koch and Coulston 2015, 2016, 2017, 2018, 2019, 2020, 2021; Koch and others 2013a, 2013b, 2014, 2015).

This is the seventh year in which we also mapped levels of moisture surplus across the conterminous United States during multiple time windows. While recent refereed literature (Adams and others 2009, Allen and others 2010, Martínez-Vilalta and others 2012, Peng and others 2011, Williams and others 2013) has typically focused on reports of regional-scale forest decline and mortality due to persistent drought conditions, surplus moisture availability can likewise affect forests. Unusually high moisture can be a short-term stressor (e.g., an extreme rainfall event with subsequent flooding) or a long-term stressor (e.g., persistent wetness caused by a macroscale climatic pattern such as the El Niño-Southern Oscillation), either of which may lead to tree dieback and mortality (Rozas and García-González 2012, Rozas and Sampedro 2013). Such impacts have been observed in tropical, temperate, and boreal forest systems (Hubbart and others 2016, Laurance and others 2009, Rozas and García-González 2012). For example, larch (*Larix*) species that predominate in eastern Siberian forests appear to be drought-resistant yet highly sensitive to excessively wet conditions (Tei and others 2019). While surplus-induced impacts in forests may be less common than drought-induced impacts, a single index that depicts moisture surplus as well as deficit conditions provides a more comprehensive indicator of potential forest health issues.

METHODS

We acquired grids for monthly precipitation and monthly mean temperature for the conterminous United States from the PRISM Climate Group website (PRISM Climate Group 2021). At the time of these analyses, gridded datasets were available for all years from 1895 to 2020. The spatial resolution of the grids was approximately 4 km (cell area = 16 km^2). For future applications and to ensure better compatibility with other spatial datasets, output grids were resampled to a spatial resolution of approximately 2 km (cell area = 4 km^2) using a nearest neighbor approach. The nearest neighbor approach is a computationally simple resampling method that avoids the smoothing of data values observed with methods such as bilinear interpolation or cubic convolution.

Potential Evapotranspiration (PET) Maps

As in our previous drought mapping efforts (in particular, see Koch and others 2013b), we adopted an approach in which a moisture index value is calculated for each location of interest (i.e., each grid cell in a map of the conterminous United States) during a given time period. Moisture indices are intended to reflect the amount of water available in a location (e.g., to support plant growth). In our case, the index is computed using an approach that considers both the amount of precipitation that falls on a location during the period of interest as well as the level of potential evapotranspiration during this period. Potential evapotranspiration measures the loss of soil moisture through plant uptake and transpiration (Akin 1991). It does not measure actual moisture loss, but rather the loss that would occur if there was no possible shortage of moisture for plants to transpire (Akin 1991, Thornthwaite 1948). Potential evapotranspiration serves as a basic measure of moisture demand. By incorporating potential evapotranspiration along with precipitation, our index thus documents the long-term balance between moisture demand and supply for each location of interest.

To complement the available PRISM monthly precipitation grids, we computed monthly potential evapotranspiration (*PET*) grids using Thornthwaite's formula (Akin 1991, Thornthwaite 1948):

$$PET_m = 1.6 L_{l\,m} (10 \frac{T_m}{I})^a \qquad (1)$$

where

PET_m = the potential evapotranspiration for a given month m in cm

L_{lm} = a correction factor for the mean possible duration of sunlight during month m for all locations (i.e., grid cells) at a particular latitude l (see Table V in Thornthwaite [1948] for a list of L correction factors by month and latitude)

T_m = the mean temperature for month m in degrees C

I = an annual heat index ranging from 0 to 160, calculated as, $I = \sum_{m=1}^{12} \left(\frac{T_m}{5} \right)^{1.514}$ where T_m is the mean temperature for each month m of the year

a = an exponent calculated as $a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239$ [see Appendix I in Thornthwaite (1948) regarding calculation of I and the empirical derivation of a in relation to I]

Although only a simple approximation, a key advantage of Thornthwaite's formula is that it has modest input data requirements (i.e., mean temperature values) compared to more sophisticated methods of estimating PET such as the Penman-Monteith equation (Monteith 1965), which requires less readily available data on factors such as humidity, radiation, and wind speed. While the Thornthwaite method is considered less accurate than Penman-Monteith and some other PET estimation methods (Amatya and others 1995, Sentelhas and others 2010), it is coupled with the moisture index that serves as the foundation for our analysis (see equation [2]). If we used another PET estimation method, we would have to recalibrate and potentially revise the moisture index to conform to the expected distribution of PET values under that method. We intend to address this aspect in future work.

To implement equation (1) spatially, we created a grid of latitude values for determining the L adjustment for any given grid cell (and any given month) in the conterminous United States. We extracted the T_m values for the grid cells from the corresponding PRISM mean monthly temperature grids.

Moisture Index Maps

To estimate baseline conditions, we used the precipitation (P) and PET grids to generate monthly moisture index grids for the past 100 years (i.e., 1921–2020) for the conterminous United States. We used a moisture index described by Willmott and Feddema (1992), which has been applied in a variety of contexts, including global vegetation modeling (Potter and Klooster 1999) and climate change analysis (Grundstein 2009). Willmott and Feddema (1992) devised the index as a refinement of one described earlier by Thornthwaite (1948) and Thornthwaite and Mather (1955). Their revised index, MI', has the following form:

$$MI' = \begin{cases} P/PET - 1 & , \quad P < PET \\ 1 - PET/P & , \quad P \geq PET \\ 0 & , \quad P = PET = 0 \end{cases} \qquad (2)$$

where

P = precipitation

PET = potential evapotranspiration, as calculated using equation (1)

(P and PET must be in equivalent measurement units, e.g., mm.)

This set of equations yields a symmetric, dimensionless index scaled between -1 and 1. A primary advantage of this symmetry is that it enables valid comparisons between any set of locations in terms of their balance between moisture demand and supply. MI' can be calculated for any time period but is commonly calculated on an annual basis using P and PET values summed across the entire year (Willmott and Feddema 1992). An alternative to this summation approach is to calculate MI' on a monthly basis (i.e., from total measured precipitation and estimated potential evapotranspiration in each month), and then, for a given time window of interest, calculate its moisture index as the mean of the MI' values for all months in the time window. This "mean-of-months" approach limits the ability of short-term peaks in either precipitation or potential evapotranspiration to negate corresponding short-term deficits, as would happen under a summation approach.

For each year in our study period (i.e., 1921–2020), we used the mean-of-months approach to calculate moisture index grids for three different time windows: 1 year (MI_1'), 3 years (MI_3'), and 5 years (MI_5'). Briefly, the MI_1' grids are the mean (i.e., the mean value for each grid cell) of the 12 monthly MI' grids for each year in the study period, the MI_3' grids are the mean of the 36 monthly grids from January 2 years prior through December of the target year, and the MI_5' grids are the mean of the 60 consecutive monthly MI' grids from January 4 years prior through December of the target year. Thus, the MI_1' grid for the year 2020 is the mean of the monthly MI' grids from January to December 2020, while the MI_3' grid is the mean of the grids from January 2018 to December 2020, and the MI_5' grid is the mean of the grids from January 2016 to December 2020.

Annual and Multiyear Drought Maps

To determine degree of departure from typical moisture conditions, we first created a normal grid, $MI_i'_{norm}$, for each of our time windows, representing the mean (i.e., the mean value for each grid cell) of the 100 corresponding moisture index grids (i.e., the MI_1', MI_3', or MI_5' grids, depending on the window; see fig. 4.1). We also created a standard deviation grid, $MI_i'_{SD}$, for each time window, calculated from the window's 100 individual moisture index grids as well as its $MI_i'_{norm}$ grid. We subsequently calculated moisture difference *z*-scores, MDZ_{ij}, for each time window using these derived datasets:

$$MDZ_{ij} = \frac{MI_i' - MI_i'_{norm}}{MI_i'_{SD}} \qquad (3)$$

where

i = the analytical time window (i.e., 1, 3, or 5 years) and j = a particular target year in our 100-year study period (i.e., 1921–2020)

MDZ scores may be classified in terms of degree of moisture deficit or surplus (table 4.1). The classification scheme includes categories (e.g., severe drought, extreme drought) like those associated with the PDSI. The scheme has also been adopted for other drought indices such as the Standardized Precipitation Index, or SPI (McKee and others 1993). Moreover, the breakpoints between *MDZ* categories resemble those used for the SPI, such that we expect the *MDZ* categories to have theoretical frequencies of occurrence that are similar to their SPI counterparts (e.g., approximately 2.3 percent of the time for extreme drought; see McKee and others 1993, Steinemann 2003). More importantly, because of the standardization in equation (3), the breakpoints between categories remain the same regardless of the size of the time window of interest. For comparative analysis, we generated and classified *MDZ* maps of the conterminous United States, based on 1-, 3-, and 5-year windows, for the target year 2020.

Table 4.1—Moisture difference *z*-score *(MDZ)* value ranges for nine wetness and drought categories, along with each category's approximate theoretical frequency of occurrence

MDZ	Category	Frequency
		percent
≤-2	Extreme drought	2.3
-1.999 to -1.5	Severe drought	4.4
-1.499 to -1	Moderate drought	9.2
-0.999 to -0.5	Mild drought	15
-0.499 to 0.5	Near normal conditions	38.2
0.501 to 1	Mild moisture surplus	15
1.001 to 1.5	Moderate moisture surplus	9.2
1.501 to 2	Severe moisture surplus	4.4
>2	Extreme moisture surplus	2.3

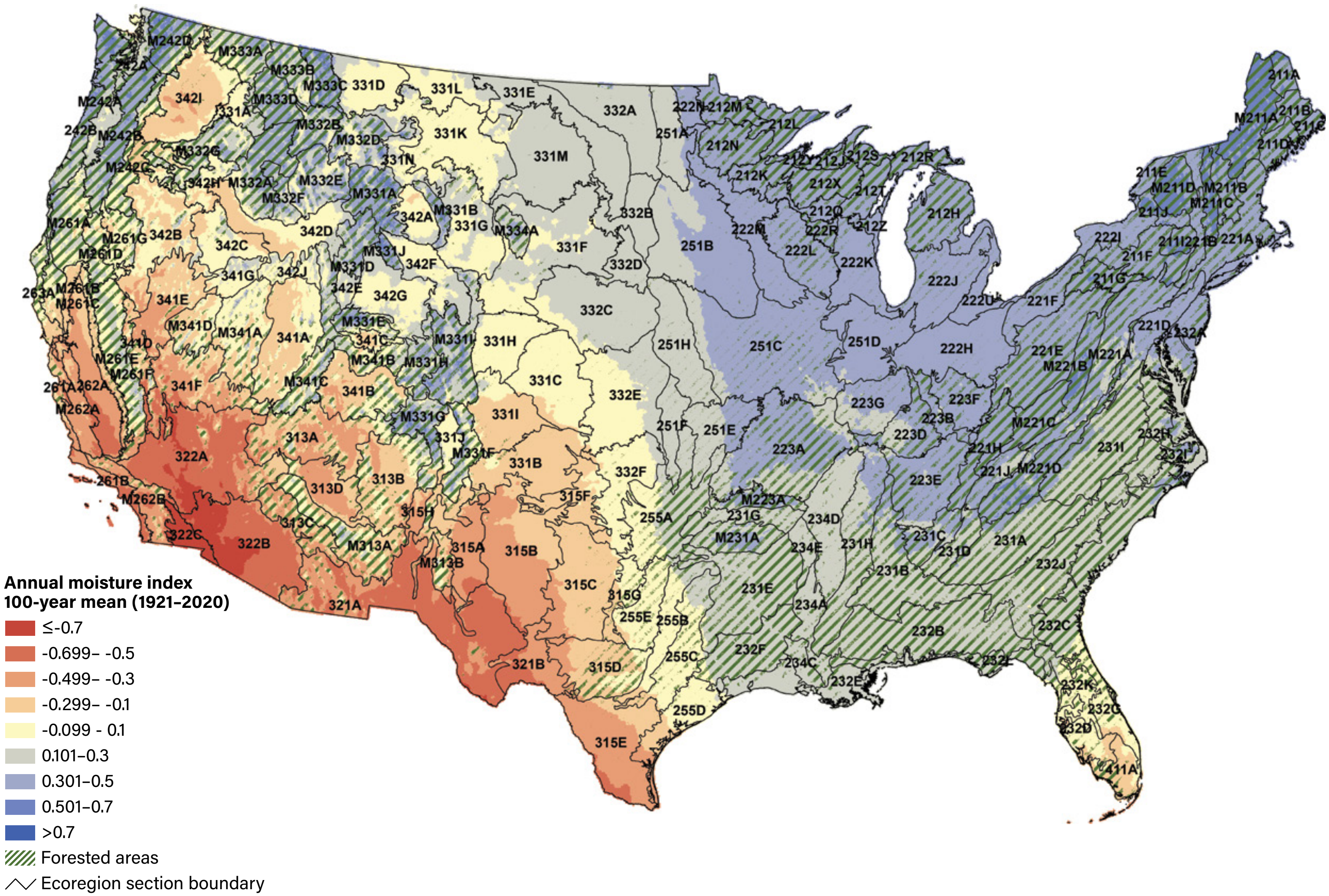

Figure 4.1—The 100-year (1921–2020) mean annual moisture index, or $MI_{1'norm}$, for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center. (Data source: PRISM Climate Group, Oregon State University)

RESULTS AND DISCUSSION

The 100-year (1921–2020) mean annual moisture index, or $MI_1{'}_{norm}$, grid (fig. 4.1) provides a summary of long-term moisture regimes in the conterminous United States. (The 100-year $MI_3{'}_{norm}$ and $MI_5{'}_{norm}$ grids were very similar to the mean $MI_1{'}_{norm}$ grid, and so are not shown here.) Wet climates ($MI' > 0$) are typical in the Eastern United States, especially the Northeast. An exception worth noting is southern Florida, primarily ecoregion sections (Cleland and others 2007) 232D–Florida Coastal Lowlands-Gulf, 232G–Florida Coastal Lowlands-Atlantic, and 411A–Everglades. This region appears to be dry relative to other parts of the East, which is an effect of its tropical climate, which has distinct wet (primarily summer months) and dry (late fall to early spring) seasons. Although southern Florida usually receives a high level of precipitation during the wet season, it can be insufficient to offset the region's lengthy dry season (Duever and others 1994) or its high level of temperature-driven evapotranspiration, especially during the late spring and summer months, resulting in negative MI' values. This differs from the pattern observed in the driest parts of the Western United States, especially the Southwest (e.g., sections 322A–Mojave Desert, 322B–Sonoran Desert, and 322C–Colorado Desert), where potential evapotranspiration is very high, as in southern Florida, but precipitation levels are typically very low. In fact, because of generally lower precipitation than the East, dry climates ($MI' < 0$) are typical across much of the Western United States. Nonetheless, some mountainous areas in the Pacific Northwest as well as the central and northern Rocky Mountains, such as ecoregion sections M242A–Oregon and Washington Coast Ranges, M242B–Western Cascades, M331G–South Central Highlands, and M333C–Northern Rockies, have been wetter historically than other parts of the West. Principally, this has been driven by large amounts of winter snowfall (Hanson and Weltzin 2000). Under warming climatic conditions, many of these areas are expected to shift toward markedly drier moisture regimes due to a decrease in winter snowpack (Fyfe and others 2017).

Figure 4.2 shows the annual (i.e., 1-year) *MDZ* map for 2020 for the conterminous United States. Moderate to extreme drought conditions ($MDZ \leq -1$) were common across much of the Western United States in 2020, including forested areas in the central Rocky Mountains (e.g., ecoregion sections M331G, mentioned above, and M331I–Northern Parks and Ranges) and California (e.g., ecoregion sections M261B–Northern California Coast Ranges and M261E–Sierra Nevada). However, forested portions of the northern Rocky Mountains (e.g., M332B–Northern Rockies and Bitterroot Valley) and Pacific Northwest (e.g., M242D–Northern Cascades) experienced near normal or moisture surplus conditions. On the other side of the country, moderate to extreme surplus conditions were widespread throughout the Southeast and Mid-Atlantic regions in 2020, maybe most distinctly in sections 232H–Middle Atlantic Coastal Plains and Flatwoods and 232I–Central Appalachian Piedmont, although there were exceptions (e.g., 232K–Florida Coastal Plains Central Highlands). Areas of extreme moisture surplus also appeared in the Great Lakes region (e.g., 212H–Northern Lower Peninsula). In contrast, nearly all of New England experienced drought conditions, including areas of severe to

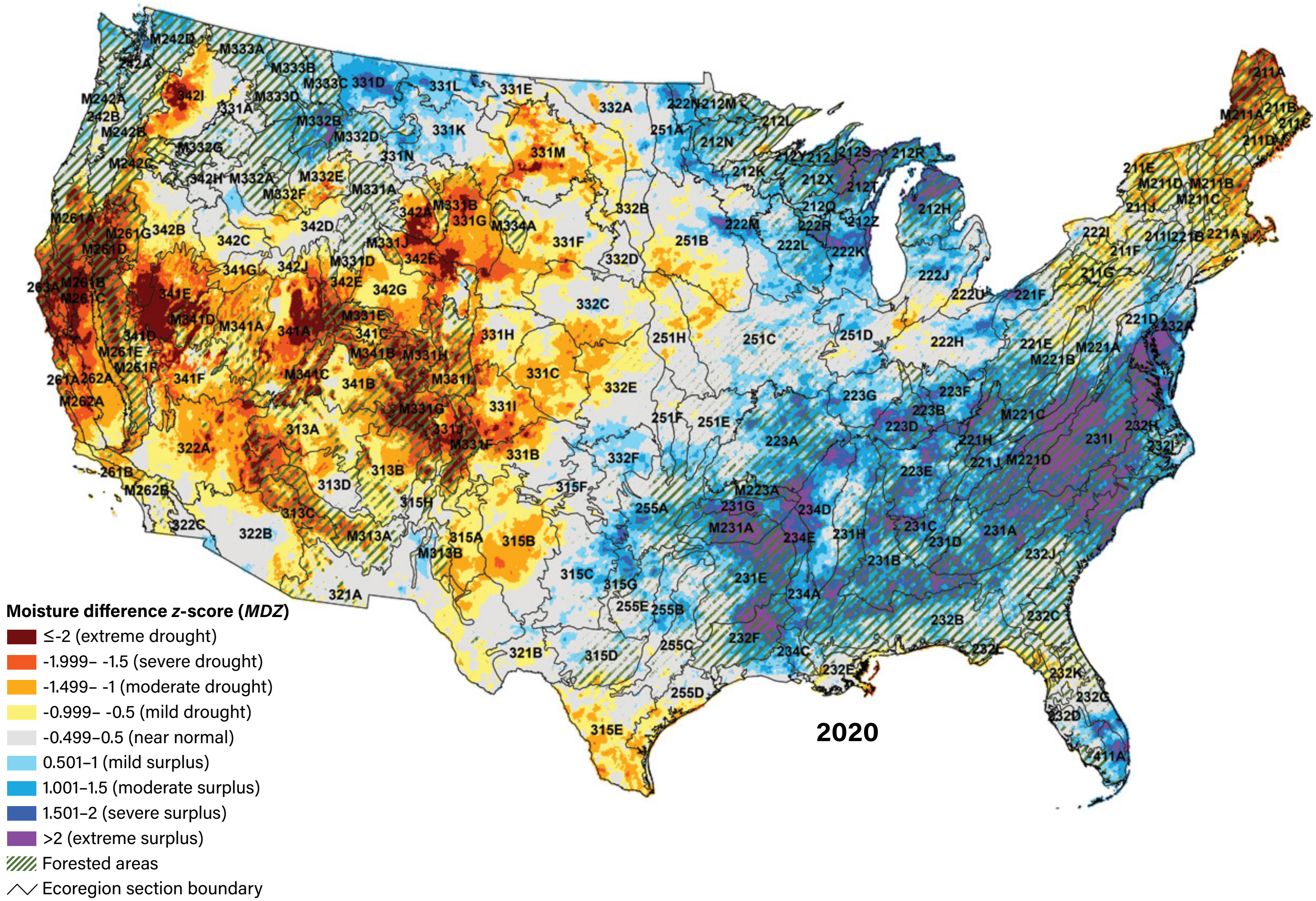

Figure 4.2—The 2020 annual (i.e., 1-year) moisture difference z-score, or MDZ, *for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center. (Data source: PRISM Climate Group, Oregon State University)*

extreme drought (*MDZ* ≤-1.5) in the northern portions of sections 211A–Aroostook Hills and Lowlands and M211A–White Mountains.

The 2020 *MDZ* map is consistent with summary statistics reported elsewhere. According to the U.S. Drought Monitor, the percentage of area of the conterminous United States with drought conditions peaked at 49.0 percent in December (NOAA National Centers for Environmental Information 2021b). In the Western United States, the percentage of area experiencing moderate or worse drought conditions exceeded 75 percent for the last 3 months of 2020. In terms of climatological ranks relative to the historical record, it was the third driest and fourth warmest year for the Western United States since 1895, and the second driest and third warmest year for the Southwest region, specifically (NOAA National Centers for Environmental Information 2021a, 2021b). On the other side of the country, the Southeast experienced its third wettest year on record, but 2020 was also its second warmest year in terms of average temperature. It was a similarly warm year in the Northeast—the region's third warmest since 1895—but unlike in the Southeast, precipitation levels remained close to historical averages, enabling the development of drought conditions across the region.

Comparing the 2020 *MDZ* map with the 2019 *MDZ* map (fig. 4.3), much of the conterminous United States shifted from surplus to deficit conditions, or vice versa, between the 2 years. For example, the Southeast and Mid-Atlantic regions saw scattered areas of mild to moderate drought during 2019, but these were replaced by surplus conditions in 2020 (fig. 4.2). Conversely, areas of severe to extreme moisture surplus that appeared in the Desert Southwest in 2019 (i.e., 322A–Mojave Desert, 322B–Sonoran Desert, and 322C–Colorado Desert) were nearly gone in 2020. (Note that none of these ecoregion sections contains significant forest.) There is some evidence that a rapid swing between drought and surplus conditions can induce tree mortality directly (Tei and others 2019), although this is presumably influenced by the swing's magnitude (e.g., from extreme drought to extreme surplus over the course of a few months). Regardless, the observed disparities between 2019 and 2020 are partly explained by the fact that the former was an anomalously wet year: the second wettest nationally since 1895, and the wettest ever across the Midwest and the Northern Great Plains (NOAA National Centers for Environmental Information 2021a, 2021b). Furthermore, the Northeast and a large share of the West had precipitation levels that were above average (sometimes well above average) in 2019; the only regions with average or below average precipitation were the Southeast and Pacific Northwest. It is also important to recognize that, alongside this high degree of moisture variability, most of the country experienced temperatures that were significantly above average in both years (NOAA National Centers for Environmental Information 2021a, 2021b). This is in keeping with a steady warming trend that has been observed worldwide since the 1970s, signaling future climatic conditions that are expected to feature greater drought frequency, severity, and

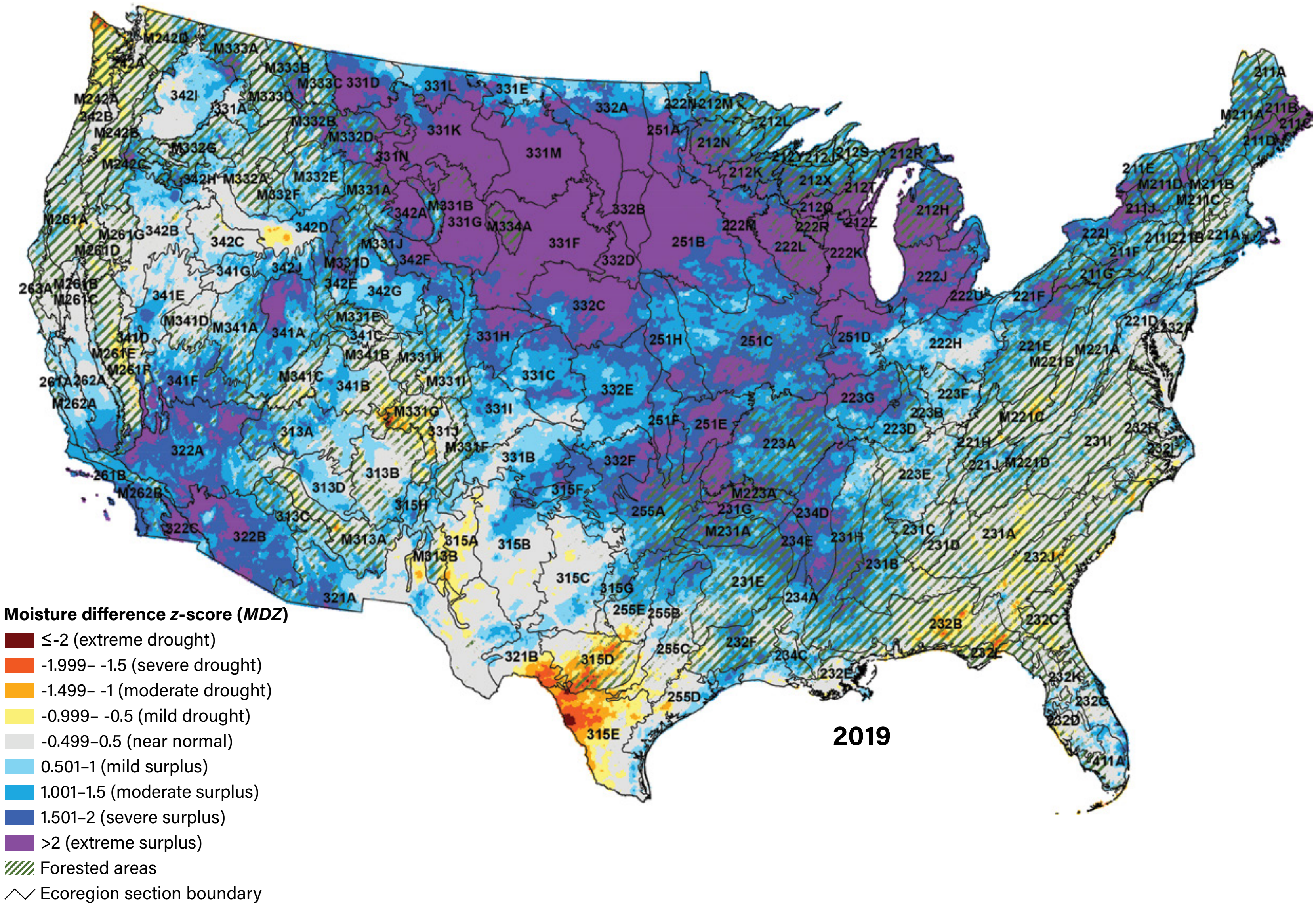

Figure 4.3—The 2019 annual (i.e., 1-year) moisture difference z-score, or MDZ, *for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center. (Data source: PRISM Climate Group, Oregon State University)*

duration, particularly in drier locales such as the Western United States (Peltier and Ogle 2019, Rahmstorf and others 2017, Williams and others 2013). Indeed, warmer temperatures have the capacity to magnify moderate droughts into "megadroughts" that can have highly destructive impacts on forest systems (Brodribb and others 2020, Williams and others 2020). In fact, this may already be happening in the Southwest (Williams and others 2020).

With their longer time windows, the 3-year (2018–2020; fig. 4.4) and 5-year (2016–2020; fig. 4.5) *MDZ* maps are less influenced by year-to-year variation in moisture status. Thus, they can highlight areas where drought or surplus conditions have been persistent and intense, at least in the short term. Taken together, the two maps show an obvious disparity between the East and West. From the Rocky Mountains westward, few areas with severe to extreme moisture surpluses (*MDZ* >1.5) appeared in both maps (i.e., persisted for 5 years). Furthermore, only two of these surplus areas extended appreciably into forested ecoregion sections (i.e., M332B–Northern Rockies and Bitterroot Valley and M333A–Okanogan Highland). Perhaps more concerning are areas of severe to extreme drought that appeared in both the 3- and 5-year *MDZ* maps. These occurred primarily in southwestern Colorado and northern New Mexico (including parts of M331F–Southern Parks and Rocky Mountain Range, M331G–South Central Highlands, M331H–North Central Highlands and Rocky Mountains, and M331I–Northern Parks and Ranges) and in northern California (parts of M261A–Klamath Mountains, M261B–Northern California Coast Ranges, M261D–Southern Cascades, and M261E–Sierra Nevada). As noted, the occurrence of severe to extreme drought in both the 3- and 5-year maps indicates persistence, but it also points to minimal improvement in drought status during the last couple of years and downplays the significance of the near normal to surplus conditions that many of these areas experienced in 2019 (see fig. 4.3).

In the Eastern United States, only a few isolated hot spots of moderate or worse drought conditions appeared in both the 3- and 5-year *MDZ* maps (figs. 4.4 and 4.5): in northern Maine (ecoregion sections 211A–Aroostook Hills and Lowlands and M211A–White Mountains) and southern Florida (411A–Everglades and 232G–Florida Coastal Lowlands-Atlantic). The relative rarity of drought hot spots at the 3- and 5-year timescales provides support for the idea that prolonged droughts may not be a major issue for eastern forests (but see Clark and others 2016, Swanston and others 2018). Areas of prolonged moisture surplus were far more common and tended to be more extensive and spatially contiguous. While both the 3- and 5-year *MDZ* maps showed areas of surplus in the Ozark Mountains (e.g., ecoregion sections 231G–Arkansas Valley and M223A–Boston Mountains) and throughout the Mid-Atlantic (e.g., 231I–Central Appalachian Piedmont), the most notable area was in the Great Lakes region. This contiguous area of extreme surplus extended across almost every forested ecoregion section near Lakes Huron, Michigan, and Superior, including 212H–Northern Lower Peninsula, 212J–Southern Superior Uplands, 212K–Western Superior

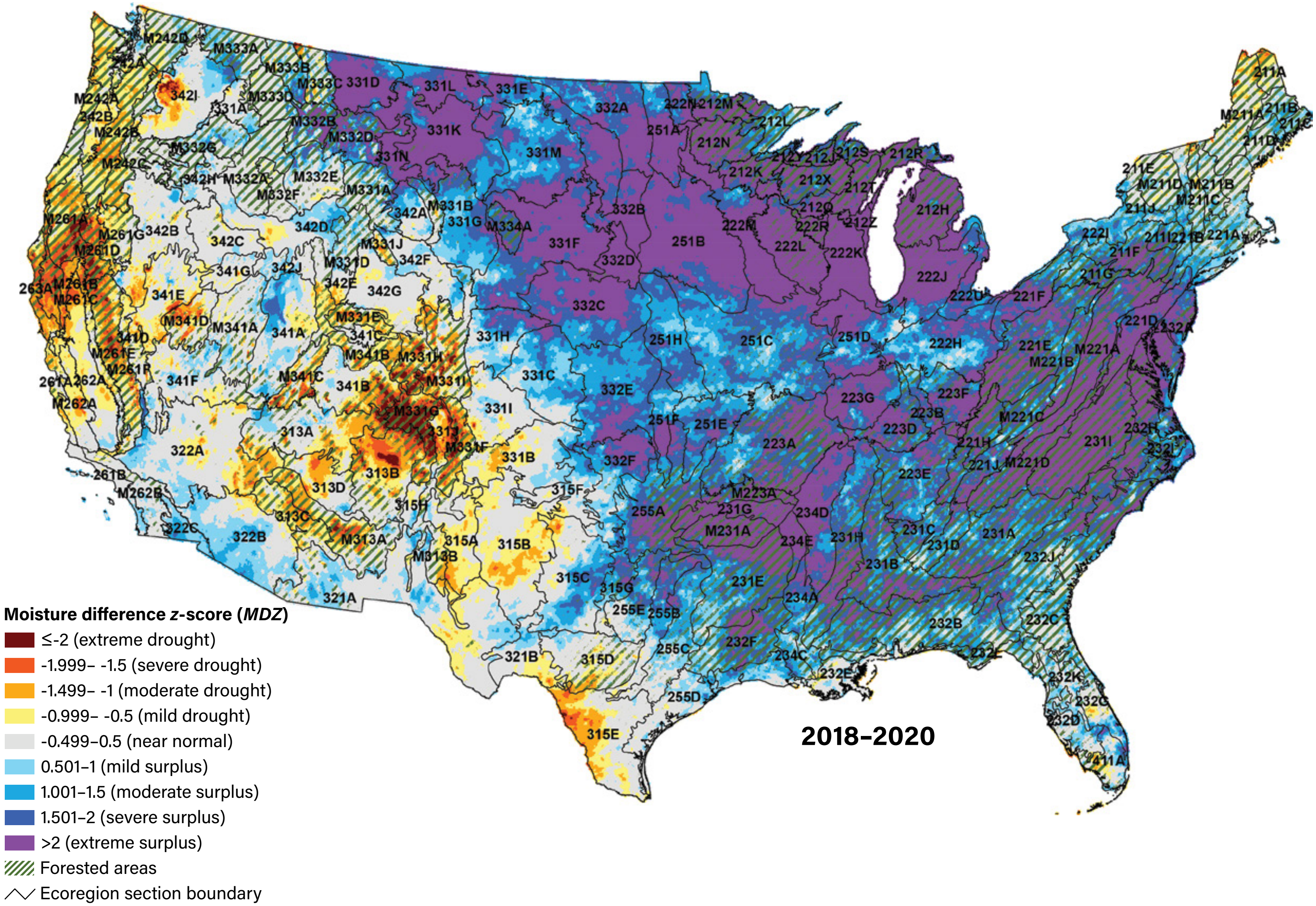

Figure 4.4—The 2018–2020 (i.e., 3-year) moisture difference z-score, or MDZ, *for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center. (Data source: PRISM Climate Group, Oregon State University)*

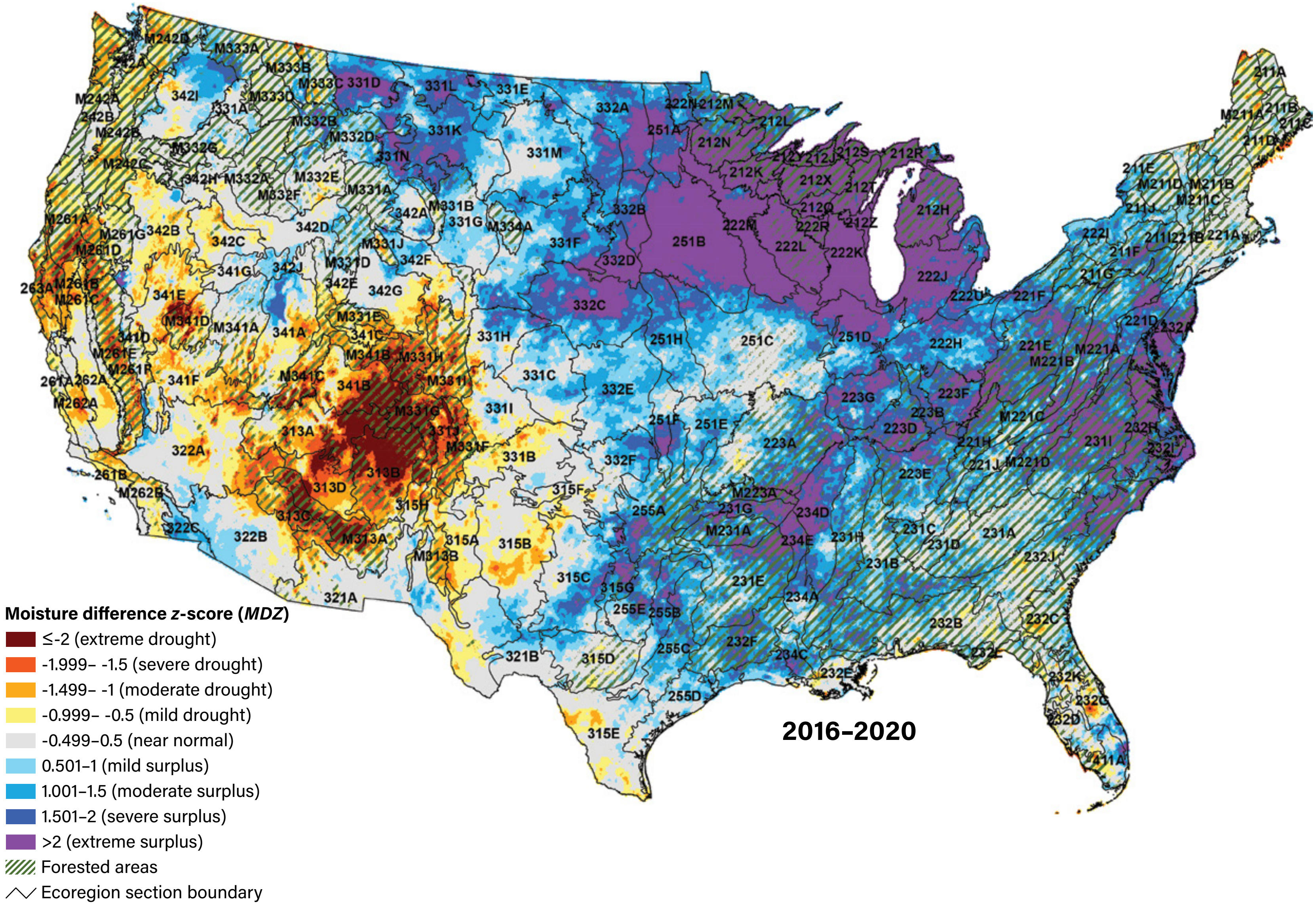

Figure 4.5—The 2016–2020 (i.e., 5-year) moisture difference z-score, *or* MDZ, *for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Geospatial Technology and Applications Center. (Data source: PRISM Climate Group, Oregon State University)*

Uplands, 212N–Northern Minnesota Drift and Lake Plains, 212Q–North Central Wisconsin Uplands, 212R–Eastern Upper Peninsula, 212T–Northern Green Bay Lobe, and 222R–Wisconsin Central Sands. The implications of this major surplus, which was essentially uniform across the region, are not entirely clear, but persistent excess moisture can make forests more vulnerable to pathogens and other disease-causing agents, especially when wet and warm conditions co-occur (Hubbart and others 2016). Moisture surpluses can also present a challenge for forest management. For example, wet conditions can act as a barrier to prescribed burning by restricting burn windows, i.e., the times when conditions are appropriate for implementing prescribed fire treatments (Chiodi and others 2018).

When attempting to understand the significance of conditions captured in the *MDZ* maps, it may be useful to consider them in the context of longer term moisture trajectories. Figure 4.6 shows full trajectories for the 1921–2020 period for eight ecoregion sections in the conterminous United States. The values on the y-axis of each plot are the mean 5-year *MDZ* values, by year, across an ecoregion section. A benefit of using 5-year *MDZ* is that it yields smoother trajectory curves than the 1-year and 3-year *MDZ*, and thus makes it easier to discern trends through time. A few notable aspects emerge from figure 4.6. Foremost, moisture conditions have been highly variable through time. All eight ecoregion sections have seen pronounced periods of deficit and surplus in the last 100 years. In some cases, these periods have been of relatively long duration, such as the period of moisture surplus that lasted through the 1960s and 1970s in 232J–Southern Atlantic Coastal Plains and Flatwoods. In other cases, the periods have been of very high intensity, such as the drought periods in the mid-1950s and mid-1960s in M231A–Ouachita Mountains and in the mid-1960s in 221A–Lower New England; these droughts are noted as the worst in recent history for their respective regions (Haavik and others 2011, Seager and others 2012, Xue and Ullrich 2021).

Although their long-term trajectories differ, the four ecoregion sections in the Eastern United States (i.e., 212H–Northern Lower Peninsula, as well as 221A–Lower New England, 232J–Southern Atlantic Coastal Plains and Flatwoods, and M231A–Ouachita Mountains) generally have been wetter during the last 50 years than the 50 years prior. The most distinctive case is 212H, which just experienced its wettest year as well as its wettest decade. By comparison, parts of the West have seen their worst drought conditions develop over the last 20 years. In section M331G–South Central Highlands, drought conditions have persisted since 2000 but reached their most extreme level in 2020. This may foretell prevalent tree mortality in pinyon-juniper (*Pinus-Juniperus* spp.) woodlands, as has already been reported in nearby regions (Kannenberg and others 2021). In M261E–Sierra Nevada, the drought conditions that have developed during the last several years are significantly more severe than at any other time in the last century. Broad-scale forest mortality associated with these conditions has been well documented in this and neighboring ecoregion sections (Fettig and others 2019, Goulden and Bales 2019).

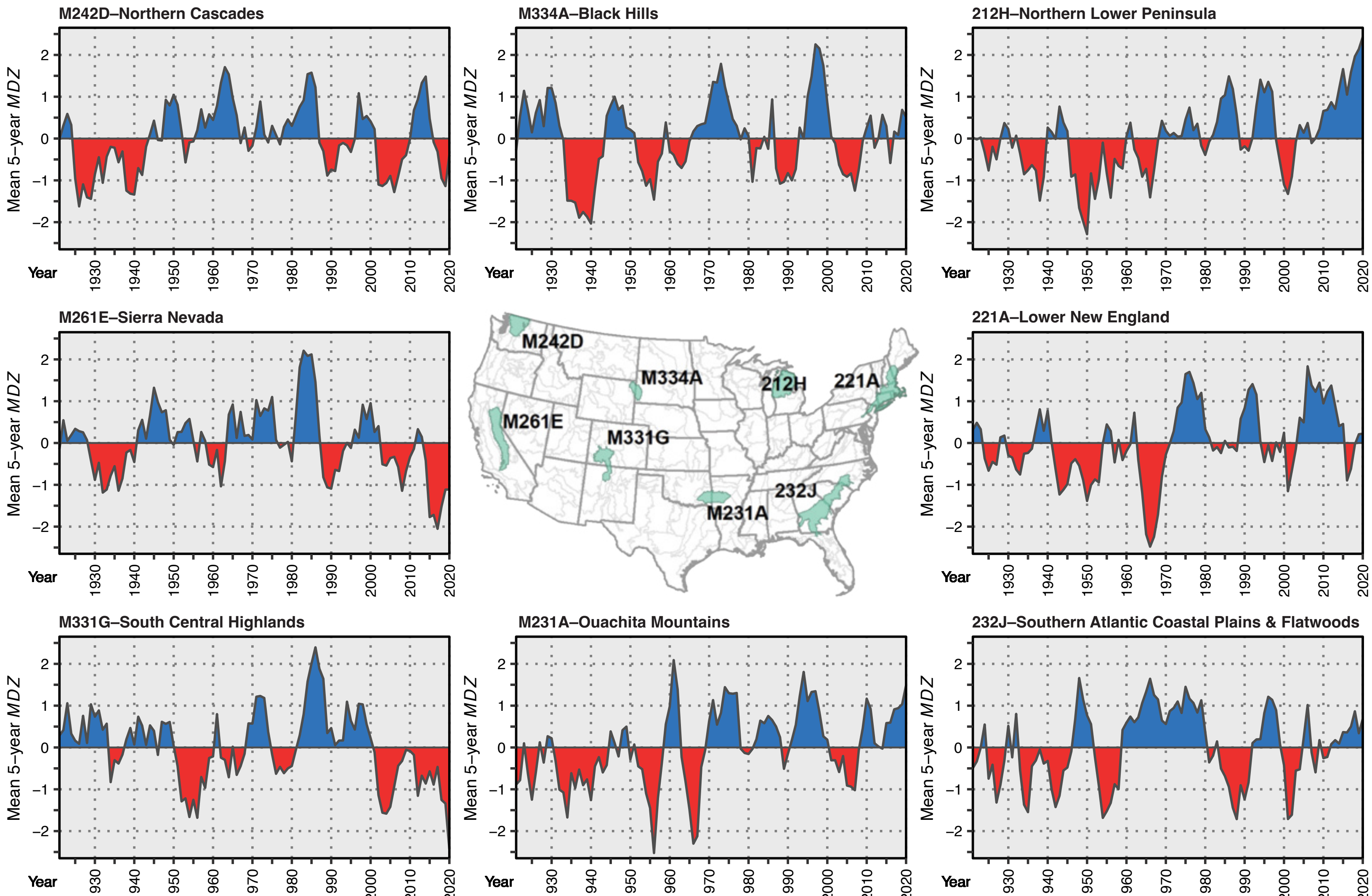

Figure 4.6—Long-term (1921–2020) trajectories in mean 5-year moisture difference z-score, or MDZ, *for eight ecoregion sections (Cleland and others 2007) in the conterminous United States. Periods of moisture deficit are shown in red and moisture surplus in blue. Sections are shown in green on the map for reference. (Data source: PRISM Climate Group, Oregon State University)*

Future Efforts

One-year, 3-year, and 5-year *MDZ* maps of the conterminous United States are a recurring component of national forest health reporting. For interpretive purposes, it is critical to understand their limitations. Most notably, the *MDZ* approach omits certain factors that influence a location's moisture supply at finer spatial and temporal scales, such as winter snowpack, surface runoff, or ground water storage. Furthermore, while the maps use a standardized index scale that can be used with time windows of any size, it is still important to choose a window size that is analytically appropriate. For example, an extreme drought that lasts for 5 years will have different forest health ramifications than an extreme drought that ends after only 1 year. While the 1-year, 3-year, and 5-year *MDZ* maps provide a reasonably complete short-term picture, a region's longer term moisture trajectory may also be meaningful with respect to forest health. For instance, in regions where droughts have been historically frequent, some tree species are more drought-adapted than others (McDowell and others 2008). At any rate, long periods of persistent moisture extremes could initiate changes in regional forest composition (McEwan and others 2011, Mueller and others 2005). Such changes are likely to affect responses to future drought or surplus conditions, fire regimes, and the status of ecosystem services such as nutrient cycling and wildlife habitat (W.R.L. Anderegg and others 2013, DeSantis and others 2011). In future reporting, we hope to provide forest managers and other decision makers with quantitative evidence about relationships between moisture extremes and significant forest health impacts such as regional-scale tree mortality (e.g., Edgar and others 2019, Mitchell and others 2014). Deciphering such relationships can be difficult at broader spatial scales. Nonetheless, we also intend to investigate the capacity of moisture extremes to serve as inciting factors for other forest threats such as wildfire or pest outbreaks.

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