CHAPTER 4.

Drought Patterns in the Conterminous United States, 2012

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INTRODUCTION

Droughts are a regular occurrence in most U.S. forests. However, the frequency and intensity of these droughts vary widely between, as well as within, forest ecosystems (Hanson and Weltzin 2000). In the Western United States, forests commonly experience annual seasonal droughts. In the Eastern United States, forests usually exhibit one of two prevailing drought patterns: random (i.e., occurring at any time of year) occasional droughts, as typically seen in the Appalachian Mountains and the Northeast, or frequent late-summer droughts, as typically seen in the Southeastern Coastal Plain and the eastern edge of the Great Plains (Hanson and Weltzin 2000).

Plants initially respond to drought stress by decreasing fundamental growth processes such as cell division and enlargement. Photosynthesis, which is less sensitive than these basic processes, decreases slowly when drought stress is low, but more sharply when the stress becomes moderate to severe (Kareiva and others 1993, Mattson and Haack 1987). Drought stress often makes forests prone to attack by tree-damaging insects and diseases (Clinton and others 1993, Mattson and Haack 1987, Raffa and others 2008). Moreover, drought increases wildland fire risk by inhibiting organic matter decomposition and diminishing the moisture content of downed woody materials and other potential fire fuels (Clark 1989, Keetch and Byram 1968, Schoennagel and others 2004).

In general, forests are relatively resistant to short-term drought conditions (Archaux and Wolters 2006), although individual tree species have differing degrees of resistance (Hinckley and others 1979, McDowell and others 2008). The duration of a drought event may be more important than its intensity (Archaux and Wolters 2006); for instance, multiple consecutive years of drought (2-5 years) are more likely to cause high tree mortality than one very dry year (Guarín and Taylor 2005, Millar and others 2007). Therefore, a comprehensive account of drought impact in forested areas should include analysis of moisture conditions over multi-year time windows.

In the 2010 FHM national report, we presented a methodology for mapping drought conditions across the conterminous United States (Koch and others 2013). Our goal with this methodology was to generate drought-related spatial data sets that are finer scale than similar products available from sources such as the National Climatic Data Center (2007) or the U.S. Drought Monitor program (Svoboda and others 2002). The principal inputs are gridded climate data (i.e., monthly raster maps of precipitation and temperature over a 100-year period) created with the Parameter-elevation Regression on Independent Slopes (PRISM) climate mapping system (Daly and others 2002). Notably, the methodology employs a standardized drought indexing approach that allows us to compare a given location's moisture status during different time windows, regardless of their length. In this chapter, we apply the methodology to the most currently available climate data (i.e., the monthly PRISM data through 2012), thereby providing a fourth time step in an ongoing annual record of drought status in the conterminous United States from 2009 forward (Koch and others 2013a, 2013b, 2014).

METHODS

We acquired monthly PRISM grids for total precipitation, mean daily minimum temperature, and mean daily maximum temperature for the conterminous United States from the PRISM group Web site (PRISM Group 2013). At the time of these analyses, gridded data sets were available for all years from 1895 through 2012. However, the grids for December 2012 were only provisional versions (i.e., the PRISM group had not yet released a finalized grid for this month). For analytical purposes, we treated these provisional grids as if they were the final versions. 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 data sets, all 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 Maps

As in our previous drought mapping efforts (Koch and others 2012a, 2012b, 2013a, 2013b, 2014), we adopted an approach in which a moisture index value for each location of interest (i.e., each grid cell in a map of the conterminous United States) was calculated based on both precipitation and potential evapotranspiration values for that location during the time period of interest. 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). The inclusion of both precipitation and potential evapotranspiration provides a fuller accounting of a location's water balance than precipitation alone.

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

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

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, calculated as

$$I = \sum_{m=1}^{12} \left(\frac{T_m}{5}\right)^{1.514}$$

where

T_m = 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 the empirical derivation of *a*]

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 calculated the mean monthly temperature grids as the mean of the corresponding PRISM daily minimum and maximum monthly temperature grids.

Moisture Index Maps

We used the precipitation *(P)* and *PET* grids to generate baseline moisture index grids for the past 100 years (i.e., 1913–2012) for the conterminous United States. We used a moisture index, *MI'*, described by Willmott and Feddema (1992), with 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

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

This set of equations yields a dimensionless index scaled between -1 and 1. *MI'* can be calculated for any time period, but is commonly calculated on an annual basis using summed *P* and *PET* values (Willmott and Feddema 1992). An alternative to this summation approach is to calculate *MI'* from monthly precipitation and potential evapotranspiration values 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 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., 1913–2012), 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 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 two 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 four years prior to December of the target year. For example, the MI_1' grid for the year 2012 is the mean of the monthly *MI'* grids from January to December 2012, while the MI_3' grid is the mean of the grids from January 2010 to December 2012 and the MI_5' grid is the mean of the grids from January 2008 to December 2012.

Annual and Multi-year Drought Maps

To determine degree of departure from typical moisture conditions, we first created a normal grid, $MI_{i\,norm}'$, for each of our three time windows, representing the mean 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 data sets:

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

where

i = the analytical time window (i.e., 1, 3, or 5 years)

j = a particular target year in our 100-year study period (i.e., 1913–2012)

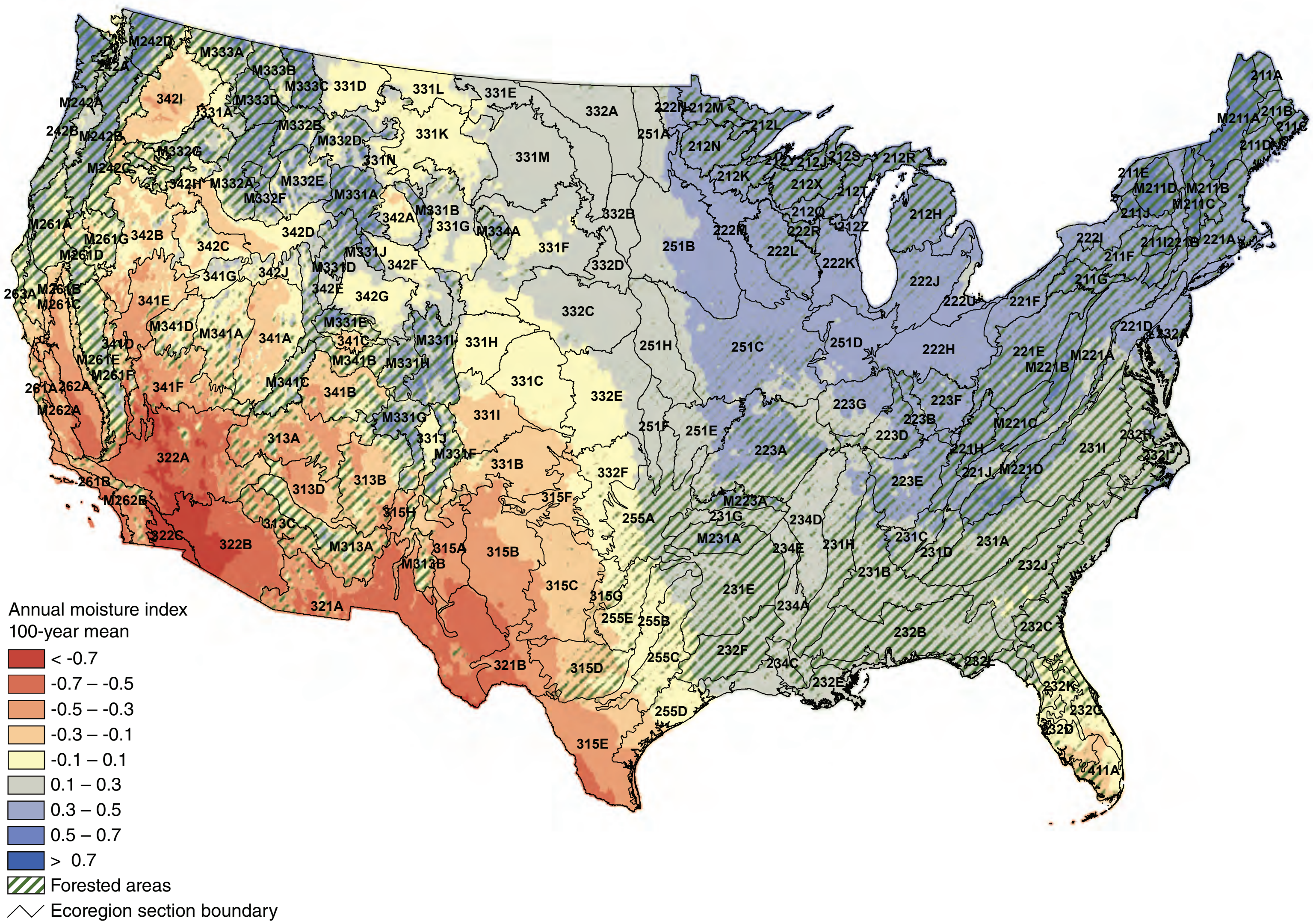

Figure 4.1—The 100-year (1913–2012) mean annual moisture index, or $\mathrm{MI}_1{}'_{\mathrm{norm}}$*, for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)*

MDZ scores may be classified in terms of degree of moisture deficit or surplus (table 4.1). The classification scheme is composed of the same categories (e.g., severe drought, extreme drought) as those used in the Palmer Drought Severity Index (Palmer 1965) and widely adopted for other drought indices. Although the breakpoints between the categories in table 4.1 are defined somewhat arbitrarily, they yield theoretical frequencies of occurrence for each category that are comparable to the frequencies observed with other indices, especially the Standardized Precipitation Index (see table 4.2 in Koch and others 2012a). 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 classified *MDZ* maps of the conterminous United States, based on all three time windows, for the target year 2012. Because our analysis focused on drought (i.e., moisture deficit) rather than surplus conditions, we combined the four moisture surplus categories from table 4.1 into a single category for map display.

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 score	Category	Frequency
		%
<-2	Extreme drought	2.3
-2 to -1.5	Severe drought	4.4
-1.5 to -1	Moderate drought	9.2
-1 to -0.5	Mild drought	15.0
-0.5 to 0.5	Near-normal conditions	38.2
0.5 to 1	Mild moisture surplus	15.0
1 to 1.5	Moderate moisture surplus	9.2
1.5 to 2	Severe moisture surplus	4.4
>2	Extreme moisture surplus	2.3

RESULTS AND DISCUSSION

The 100-year (1913–2012) mean annual moisture index, or $MI_1'_{norm}$, grid (fig. 4.1) offers a general overview of climatic regimes in the conterminous United States. (The 100-year $MI_3'_{norm}$ and $MI_5'_{norm}$ grids did not differ substantially from the mean $MI_1'_{norm}$ grid and are not shown here.) Wet climates ($MI' > 0$) are common in the Eastern United States, particularly the Northeast. A noteworthy exception is southern Florida, especially ecoregion sections 232G–Florida Coastal Lowlands-Atlantic, 232D–Florida Coastal Lowlands-Gulf, and 411A–Everglades. This region appears to be dry relative to other parts of the East. Although southern Florida usually receives a high level of precipitation over the course of a year, this is countered by a high level of potential evapotranspiration, which results in negative *MI'* values. This is fundamentally different 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 but precipitation levels are very low. In fact, dry climates ($MI' < 0$) are typical across much of the Western United States because of generally lower precipitation than the East. Nevertheless, mountainous areas in the central and northern Rocky Mountains as well as the Pacific Northwest are relatively wet, such as ecoregion sections M242A–Oregon and Washington Coast Ranges, M242B–Western Cascades, M331G–South-Central Highlands, and M333C–Northern Rockies. This may be partially driven by large amounts of winter snowfall in these regions.

Figure 4.2 shows the annual (i.e., 1-year) *MDZ* map for 2012 for the conterminous United States. Most of the Central United States, including much of the Great Lakes and Southwest regions, experienced at least mild drought conditions during 2012. Most prominently, the map displays a large contiguous area of extreme drought (*MDZ* < -2) extending from the northwestern portion of the Great Plains and into the eastern portion of the central and northern Rocky Mountains. Much of this contiguous area is spread across ecoregion sections that are partially or sparsely forested, such as 331I–Arkansas Tablelands, 332C–Nebraska Sandhills, 332D–North Central Great Plains, and 331F–Western Great Plains. However, it also extends into more heavily forested sections such as M331H–North Central Highlands and Rocky Mountains, M331I–Northern Parks and Ranges, and M334A–Black Hills.

Beside this large contiguous area of extreme drought, there were a few additional “hot spots” of severe to extreme drought (*MDZ* < -1.5) in the central portion of the country. The first of these spanned the southern portion of the Great Lakes region, extending from section 251B–North Central Glaciated Plains in the West to 222U–Lake Whittlesey Glaciolacustrine Plain in the East, although the affected area is only sparsely forested. Another hot spot included forested portions of sections 223A–Ozark Highlands, M223A–Boston Mountains, 231G–Arkansas Valley, M231A–Ouichita Mountains, and 255A–Cross Timbers and Prairie, as well as the sparsely forested sections 251E–Osage Plains and 251F–Flint Hills. A third hot spot occurred in the Southwest, primarily in sections 313C–Tonto Transition, M313A–White Mountains-San Francisco Peaks-Mogollon Rim, M313B–Sacramento-Monzano Mountains, and the sparsely forested section 313D–Painted Desert.

Overall, 2012 was a very dry year relative to historical data. The percent area of the conterminous United States with moderate or worse drought conditions according to the U.S. Drought Monitor peaked at 65.5 percent in September, which was a record in the 13-year history of the Drought Monitor (National Climatic Data Center 2013). Similarly, the percent area of the country in moderate or worse drought according to the Palmer Drought Severity Index reached 61.8 percent in July, representing the highest recorded percentage since December 1939 (National Climatic Data Center 2013). These record-setting extents are clearly reflected in the 2012 annual *MDZ* map (fig. 4.2). Indeed, the areas of the conterminous United States that experienced a moisture

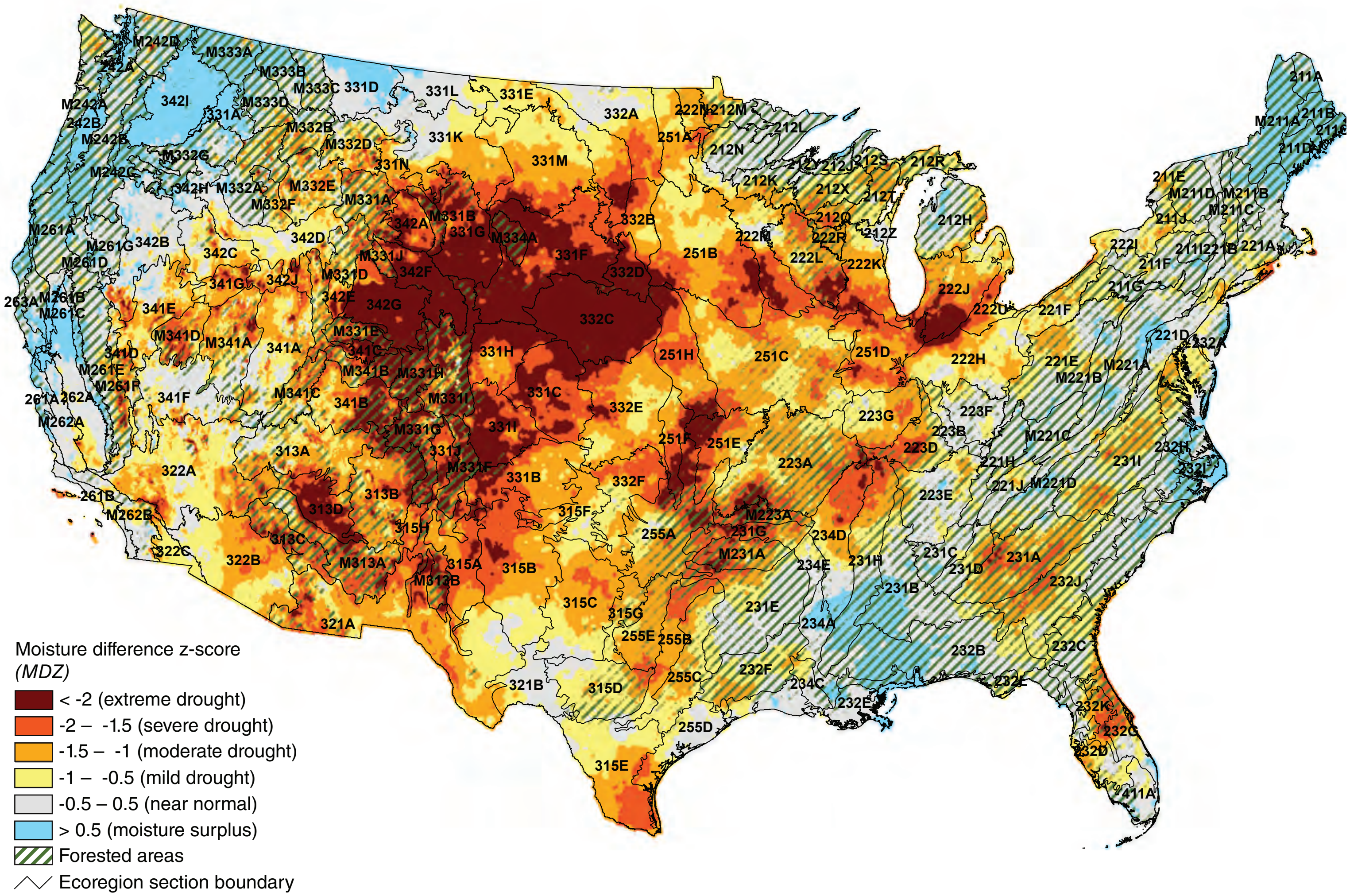

Figure 4.2—The 2012 annual (i.e., 1-year) moisture difference z-score, *or* MDZ, *for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)*

surplus in 2012 were primarily limited to a small portion of the Southeastern United States along the Gulf of Mexico, eastern North Carolina (portions of sections 232H–Middle Atlantic Coastal Plains and Flatwoods and 232I–Northern Atlantic Coastal Flatwoods), New England, as well as the Pacific Northwest and northern California.

Figure 4.3 shows a map of the change in *MDZ* category between 2011 and 2012 for the conterminous United States. The depicted increases and decreases reference the *MDZ* categories listed in table 4.1. As was the case for figure 4.2, all of the moisture surplus categories in table 4.1 have been combined into a single category, yielding a six-point scale from extreme drought to moisture surplus. Thus, a five-category decrease indicates a change from moisture surplus in 2011 to extreme drought in 2012, while a five-category increase indicates a change from extreme drought to moisture surplus. The other map classes depict less extreme changes between years. For instance, a two-category decrease represents one of four possibilities: a change from moisture surplus to mild drought; from near-normal conditions to moderate drought; from mild to severe drought; or from moderate drought in 2011 to extreme drought in 2012.

Most of the aforementioned areas of the Central United States that were in extreme drought in 2012 displayed a five- or four-category decrease in *MDZ* from 2011 (fig. 4.3). This represents a dramatic decline from surplus or near normal moisture conditions in just 1 year. Conversely, an area near the Gulf of Mexico, particularly in eastern Texas and Louisiana, displayed a three- to five-category increase in *MDZ*. Both of these States were historically dry in 2011, and also experienced record high temperatures in the summer months (National Climatic Data Center 2012). Fortunately, it appears that these conditions abated substantially by the following year. Another area in the Southeast, primarily in the part of section 232I that falls in eastern North Carolina, displayed a similarly large improvement in moisture conditions between 2011 and 2012.

The 3-year (fig. 4.4) and 5-year (fig. 4.5) *MDZ* maps illustrate the recent history of moisture conditions in the conterminous United States. For instance, the Southwestern United States has been regularly subject to intense and widespread droughts for more than two decades (Groisman and Knight 2008, Mueller and others 2005; National Climatic Data Center 2010, 2011; O'Driscoll 2007). The persistence of these conditions is partially reflected in the 3-year and 5-year *MDZ* maps, which both show numerous areas of severe to extreme drought in this region. In fact, the 5-year *MDZ* map displays more extensive or severe drought conditions in the Southwest than the 3-year map. This difference likely reflects a short-term temporal fluctuation in a long-term pattern of persistent drought for the region. Additionally, the 3-and 5-year *MDZ* maps show that severe to extreme drought conditions are persistent elsewhere in the West, such as a relatively small area

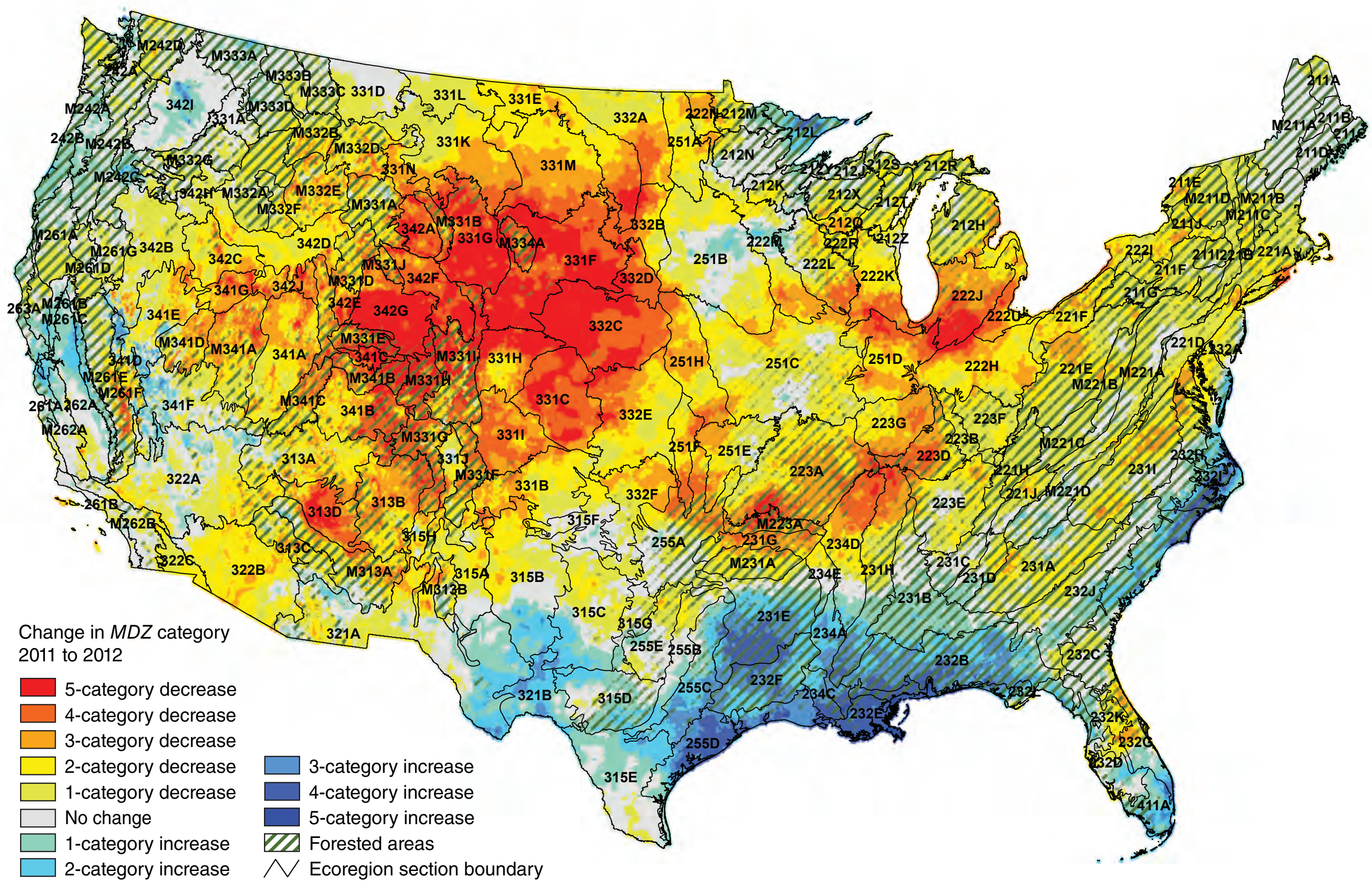

Figure 4.3—Change in moisture difference z-score *(*MDZ*) category between 2011 and 2012. See table 4.1 for a list of the* MDZ *categories used in this analysis; a five-category decrease indicates a change from moisture surplus in 2011 to extreme drought in 2012, while a five-category increase indicates a change from extreme drought in 2011 to moisture surplus in 2012. 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. Forest Service Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)*

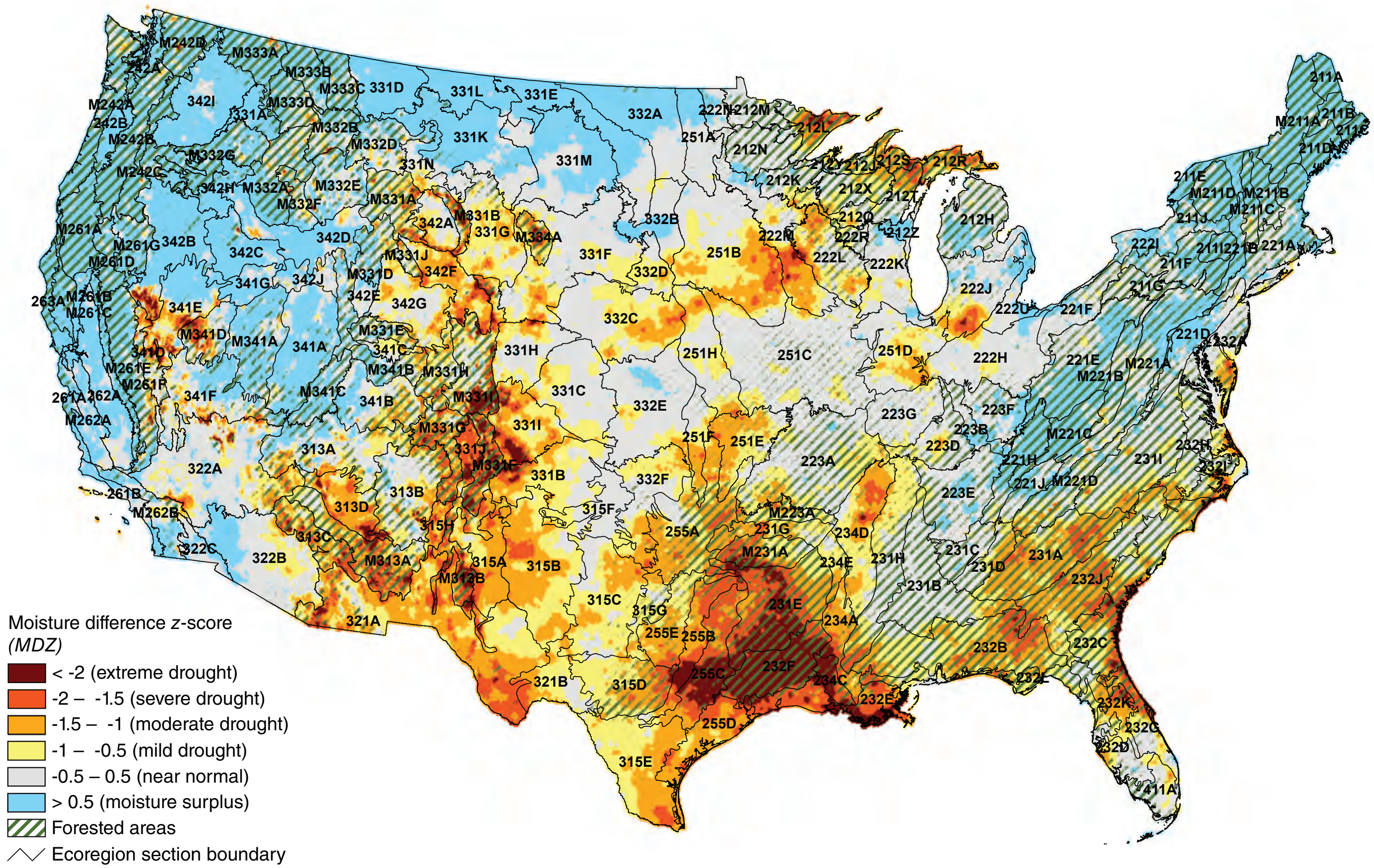

Figure 4.4—The 2010–12 (i.e., 3-year) moisture difference z-score (MDZ) for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

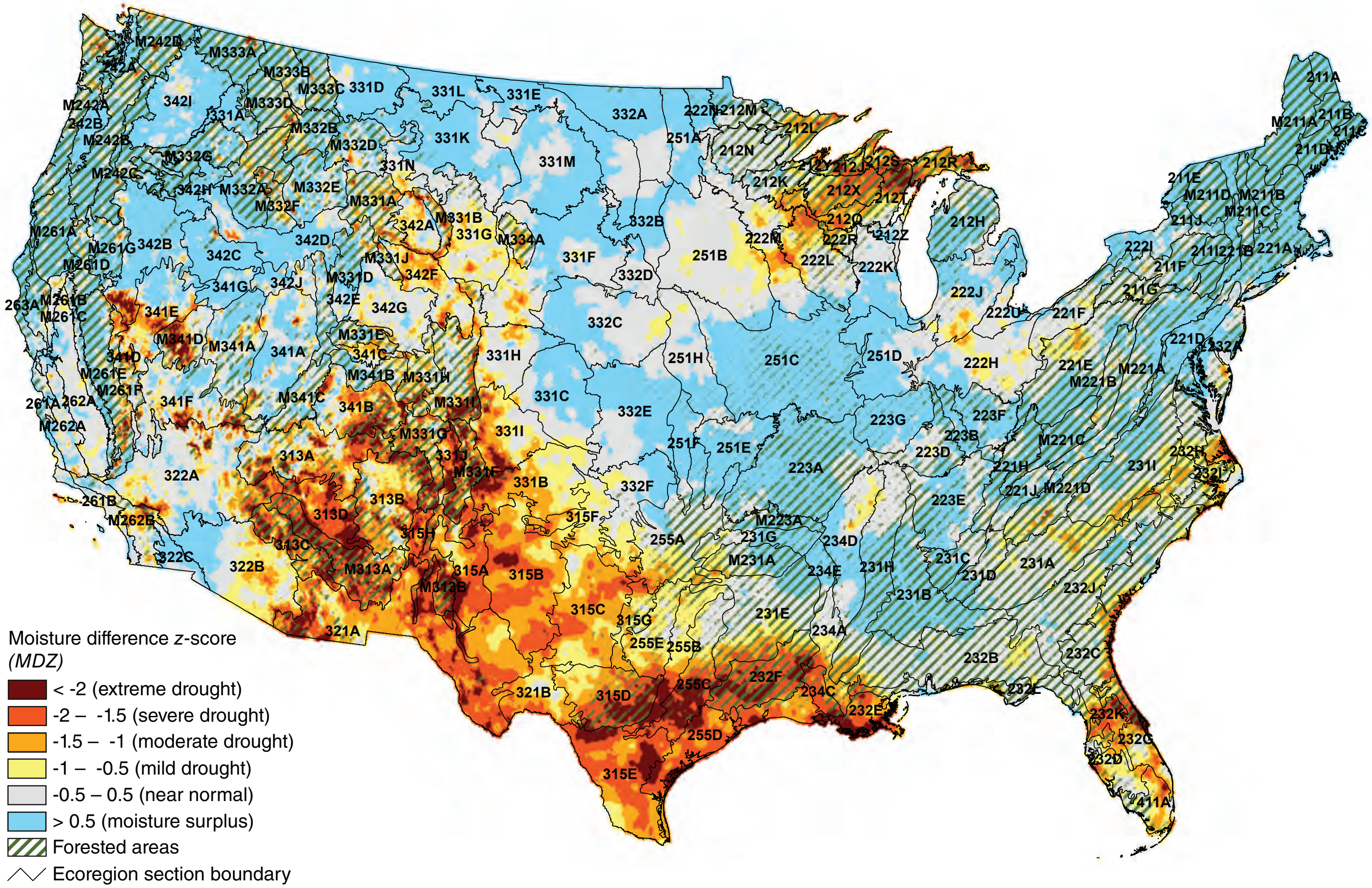

Figure 4.5—The 2008–12 (i.e., 5-year) moisture difference z-score (MDZ) for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

consisting of portions of sections 341D–Mono, 341E–Northern Mono, 342B–Northwestern Basin and Range, and M341D–West Great Basin and Mountains. However, only the latter two sections have substantial forest in drought-affected areas.

The 3-year *MDZ* map (fig. 4.4) displays some influence of the major drought event that affected the Central United States in 2012 (see fig. 4.2), with several areas of severe to extreme drought occurring in the northern Rocky Mountain and Great Plains regions. While the latter region contains few such areas in the 5-year *MDZ* map (fig. 4.5), numerous small pockets of moderate to extreme drought (*MDZ* < -1.5) still appear in the northern Rocky Mountains, suggesting that drought has been fairly persistent at a local scale in this region. Because the region's forests may not be as well adapted to drought as those in the Southwest, these persistent conditions may represent a more immediate threat to forest health.

Regardless, the 3-year map's most pronounced feature is a sizeable area of extreme drought near the Gulf of Mexico, especially in sections 231E–Mid Coastal Plains-Western and 232F–Coastal Plains and Flatwoods-Western Gulf. This area also displays severe or extreme drought conditions in the 5-year *MDZ* map. Notably, this is largely the same area that, in figure 4.3, showed a substantial improvement in moisture conditions between 2011 and 2012, which should have positive implications for affected forests. Likewise, a drought hot spot in the upper Great Lakes region (i.e., in ecoregion section 212L–Northern Superior Uplands) that is clearly visible in both the 3-year and 5-year *MDZ* maps may have been partially counteracted by a moisture surplus in 2012 (see figs. 4.2 and 4.3). Unfortunately, moisture conditions do not appear to have improved as dramatically in other parts of the Great Lakes region. For instance, for sections 212R–Eastern Upper Peninsula, 212S–Northern Upper Peninsula, 212T–Northern Green Bay Lobe, and 212X–Northern Highlands, severe to extreme drought conditions occupy a smaller area in the 3-year *MDZ* map than in the 5-year map. Nonetheless, while severe to extreme conditions occupy even less area in the 1-year *MDZ* map (fig. 4.2), mild to moderate drought conditions extend almost entirely throughout these four ecoregion sections.

Future Efforts

If the appropriate spatial data (i.e., high-resolution maps of precipitation and temperature) remain available for public use, we will continue to produce our 1-year, 3-year, and 5-year *MDZ* maps of the conterminous United States as a regular yearly component of national-scale forest health reporting. However, users should interpret and compare the *MDZ* maps presented here cautiously. Although the maps use a standardized index scale that remains consistent regardless of the size of the time window, the window size may still merit some consideration; for example, an extreme drought that persists over a 5-year period has substantially different forest health implications than an extreme drought over a 1-year period.

Furthermore, while the 1-year, 3-year, and 5-year *MDZ* maps may together provide a reasonably comprehensive short-term overview, it may also be important to consider a particular region's longer-term pattern of moisture deficit or surplus when assessing the current health of its forests. In future work, we hope to provide forest managers and other decisionmakers with better quantitative evidence regarding some of these critical relationships between deviations in moisture availability and forest health.

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