

INTRODUCTION

Virtually all U.S. forests experience droughts, although the intensity and frequency of the droughts vary widely between, as well as, within forest ecosystems (Hanson and Weltzin 2000). Generally, forests throughout the Western United States are subject to annual seasonal droughts, while forests in the Eastern United States can be characterized by one of two predominant patterns: random, occasional droughts (in the Appalachian Mountain region and the Northeast) and common late-summer droughts (in the Southeastern Coastal Plain and near the eastern edge of the Great Plains) (Hanson and Weltzin 2000). In terms of impacts, a reduction in basic growth processes, i.e., cell division and enlargement, is the most immediate plant response to drought; photosynthesis, which is less sensitive than these basic processes, decreases slowly at low levels of drought stress, but begins to decrease more sharply when the stress becomes moderate to severe (Kareiva and others 1993, Mattson and Haack 1987). Drought stress also makes some forests more susceptible to infestations of tree-damaging insects and diseases (Clinton and others 1993, Mattson and Haack 1987). Furthermore, by impeding decomposition of organic matter and reducing the moisture content of downed woody materials and other potential fuels, drought may substantially increase wildland fire risk (Clark 1989, Keetch and Byram 1968, Schoennagel and others 2004).

In the 2008 national report by the Forest Health Monitoring (FHM) Program of the Forest

Service, U.S. Department of Agriculture, we outlined an approach for mapping drought stress using historical, high-spatial-resolution climate data (Koch and others 2012a). We proposed this methodology as a means to generate outputs that would offer forest managers and researchers a finer-scale alternative to spatial data products currently available from such sources as the National Climatic Data Center (NCDC) (NCDC 2007) or the U.S. Drought Monitor program (Svoboda and others 2002). We began by developing annual moisture index maps covering a 100-year period (1907–2006) for the conterminous United States using gridded climate data (approximately 4-km² spatial resolution) created with the Parameter-elevation Regression on Independent Slopes (PRISM) climate mapping system (Daly and others 2002). We then calculated per-map-cell differences between each year's moisture index map and a corresponding long-term "normal" moisture index map, which represented the mean of the 100 annual maps. Based on the resulting difference values as well as characteristics of the values' statistical distribution through time, we assigned each map cell to one of nine categories ranging from extreme wetness to extreme drought, thus allowing us to create national maps of drought conditions for each year in our 100-year study period. Maps demonstrating the methodology can be found in the 2008 FHM National Technical Report (Koch and others 2012a).

Evidence suggests that forests are relatively resistant to short-term drought events (Archaux

CHAPTER 6. An Improved Method for Standardized Mapping of Drought Conditions

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and Wolters 2006), although individual tree species differ in their responses to drought (Hinckley and others 1979, McDowell and others 2008). Arguably, the duration of a drought event is more critical than its intensity (Archaux and Wolters 2006); for instance, multiple consecutive years of drought (2 to 5 years) are more likely to result in high tree mortality than a single dry year (Guarín and Taylor 2005, Millar and others 2007). Therefore, to provide a more realistic characterization of drought impact in forested areas, we expanded our methodology to examine moisture conditions in the United States over longer (i.e., multi-year) time windows. Historical and recent examples illustrating our multi-year methodology, again focusing on a 100-year study period (1908–2007 in this case), can be found in the 2009 FHM National Technical Report (Koch and others 2012b).

In the current chapter, we present a revised drought mapping methodology that expands upon our previous work in two key ways. Primarily, we have implemented a standardized drought indexing method, such that we can more easily compare, for any given location, its drought status during different time windows, regardless of their length (e.g., allowing comparison between 1-year, 3-year, and 5-year time windows). Moreover, this improved standardization permits analysis of specific and relatively short time windows (i.e., a single season rather than an entire year). Such analyses may have great relevance when estimating the risks associated with certain forest pests that are able to exploit acute drought stress in host trees.

We highlight the potential utility of short-term drought analysis using the example of the oak splendor beetle (*Agrilus biguttatus*), a buprestid beetle found throughout Europe but considered a major threat to North American oak forests if it were introduced and successfully able to establish.

METHODS

When we performed these analyses, monthly PRISM grids for total precipitation, mean daily minimum temperature, and mean daily maximum temperature were available from the PRISM group Web site (PRISM Group 2010) for all years from 1895 to 2009. Each gridded dataset covered the entire conterminous United States.

Potential Evapotranspiration Maps

As in our previous analyses (Koch and others 2012a,b), we adopted an approach in which a moisture index value for each location of interest, i.e., each grid cell, was calculated based on both precipitation and potential evapotranspiration values for that location during the time period of interest. Potential evapotranspiration is a measure of the loss of soil moisture through plant uptake and transpiration (Akin 1991). It does not represent actual moisture loss, but rather the loss that would occur under ideal conditions, i.e., if there was no lack 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.

So, to complement the available PRISM monthly precipitation grids, we computed corresponding monthly potential evapotranspiration (PET) grids using the Thornthwaite formula (Akin 1991, Thornthwaite 1948):

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

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 °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 i 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 4-km² grid cell in the conterminous United States [see Thornthwaite (1948) for a table of L correction factors]. We calculated the mean temperature grids for each month by averaging the corresponding PRISM monthly mean minimum and maximum 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., 1910–2009, for the conterminous United States. We used a moisture index, MI' , proposed by Willmott and Feddema (1992), which has the following form:

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

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 the 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 (1910–2009), we used the mean-of-months approach to calculate moisture index grids for three different time windows: one 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 2 years prior through December of each year, and the MI_5' grids are the mean of the 60 consecutive monthly MI' grids from January 4 years prior to December of each year. For example, the MI_1' grid for the year 2010 is the mean of the monthly MI' grids from January to December 2010, the MI_3' grid is the mean of grids from January 2008 to December 2010, and the MI_5' grid is the mean of the grids from January 2006 to December 2010.

Annual and Multi-Year Drought Maps

To determine degree of departure from typical moisture conditions, we first created a normal grid, MI'_{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 figure 6.1). We also created a standard deviation grid, MI'_{SD} , for each time window, calculated from the window’s 100 individual moisture index grids as well as its MI'_{norm} grid. We subsequently calculated moisture difference z-scores, MDZ_i , for each time window using these gridded data sets:

$$MDZ_i = \frac{MI'_i - MI'_{norm}}{MI'_{SD}} \quad (3)$$

where

i = a particular target year in our 100-year study period, i.e., 1910–2009.

MDZ scores may be classified in terms of degree of moisture deficit or surplus (table 6.1). The classification scheme includes categories (e.g., severe drought, extreme drought) like those associated with the Palmer Drought Severity Index, or PDSI (Palmer 1965). 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. To highlight the potential for comparative analysis, we generated classified MDZ maps, based on all three time windows, for the target year 2009 (figs. 6.2 and 6.3).

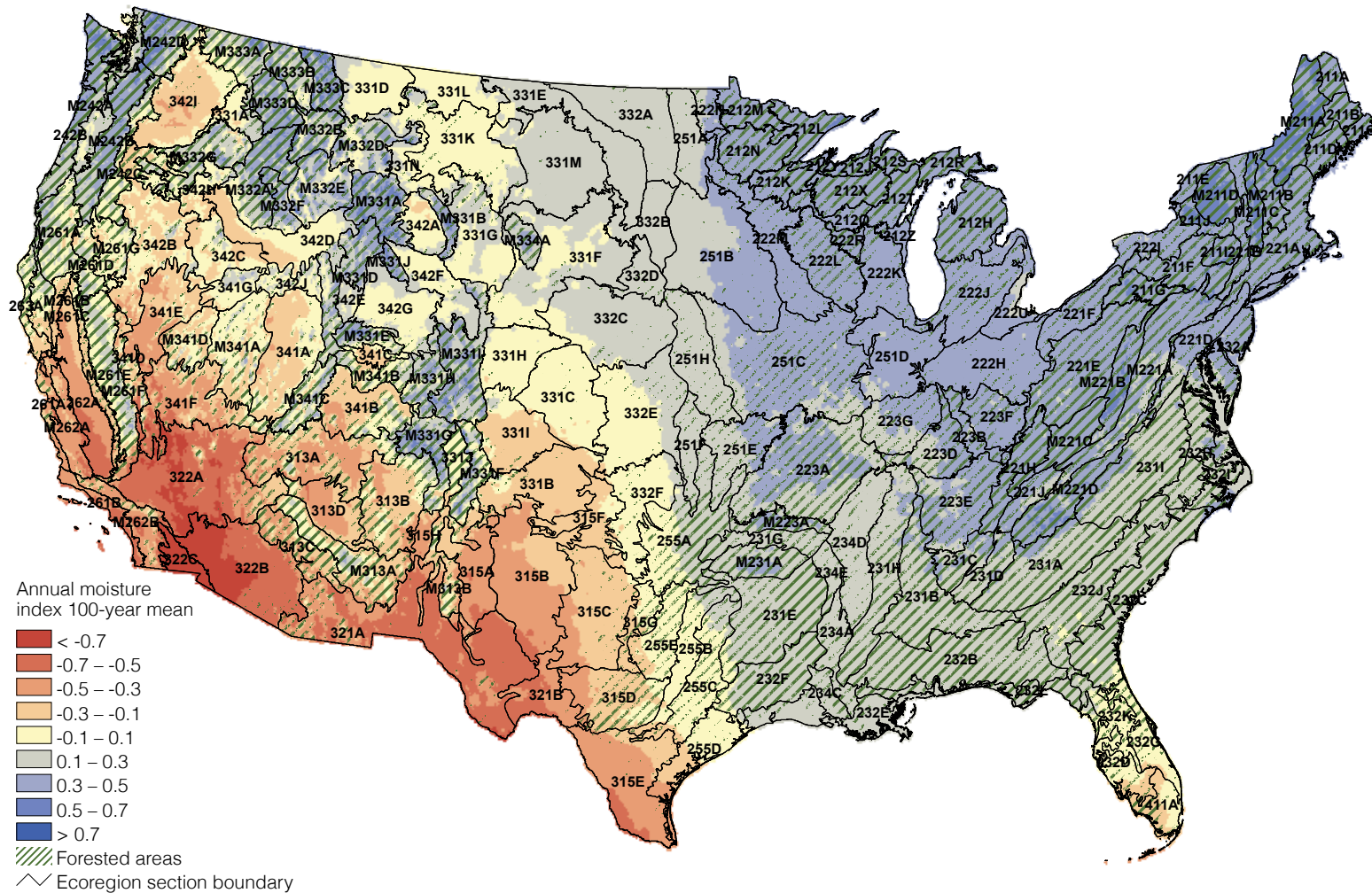


Figure 6.1—The 100-year (1910–2009) mean annual moisture index, or MI₁₀₀, for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

Table 6.1—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
		<i>percent</i>
< -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
-0.5 to 0.5	Near normal conditions	38.2
0.5 to 1	Mild moisture surplus	15
1 to 1.5	Moderate moisture surplus	9.2
1.5 to 2	Severe moisture surplus	4.4
> 2	Extreme moisture surplus	2.3

Late Spring-Early Summer Drought Maps for Pest Risk Analysis

In its Invasive Species Information Program Area, the Forest Health Technology Enterprise Team (FHTET) of the Forest Service develops national-scale products for the detection, prevention, and control of nonnative insect and disease species with the potential to significantly impact U.S. forests (USDA Forest Service 2010). Among the products developed by FHTET are risk maps that depict the introduction and establishment potential of the species of interest. Typically, these are species that have either recently been discovered in the United States or that are considered highly likely to be introduced. One pest of interest is the oak splendor beetle (*Agrilus biguttatus*), which is found throughout Europe as well as in Northern Africa, the Middle East, and Russian Asia (Davis and others 2005, Moraal and Hilszczanski 2000). The oak splendor beetle has been implicated in oak decline in Europe (Moraal and Hilszczanski 2000), and while it has not been discovered in the United States, most of the country is believed to be climatically suitable for its establishment (Davis and others 2005).

The primary concern about possible U.S. invasion by the oak splendor beetle is that it could cause extensive mortality in the Nation’s oak forests, particularly those already stressed by defoliating insects or drought (Ciesla 2003). A committee convened by FHTET (including the authors of this chapter) determined that two factors were most critical to the establishment potential of the beetle in the United States:

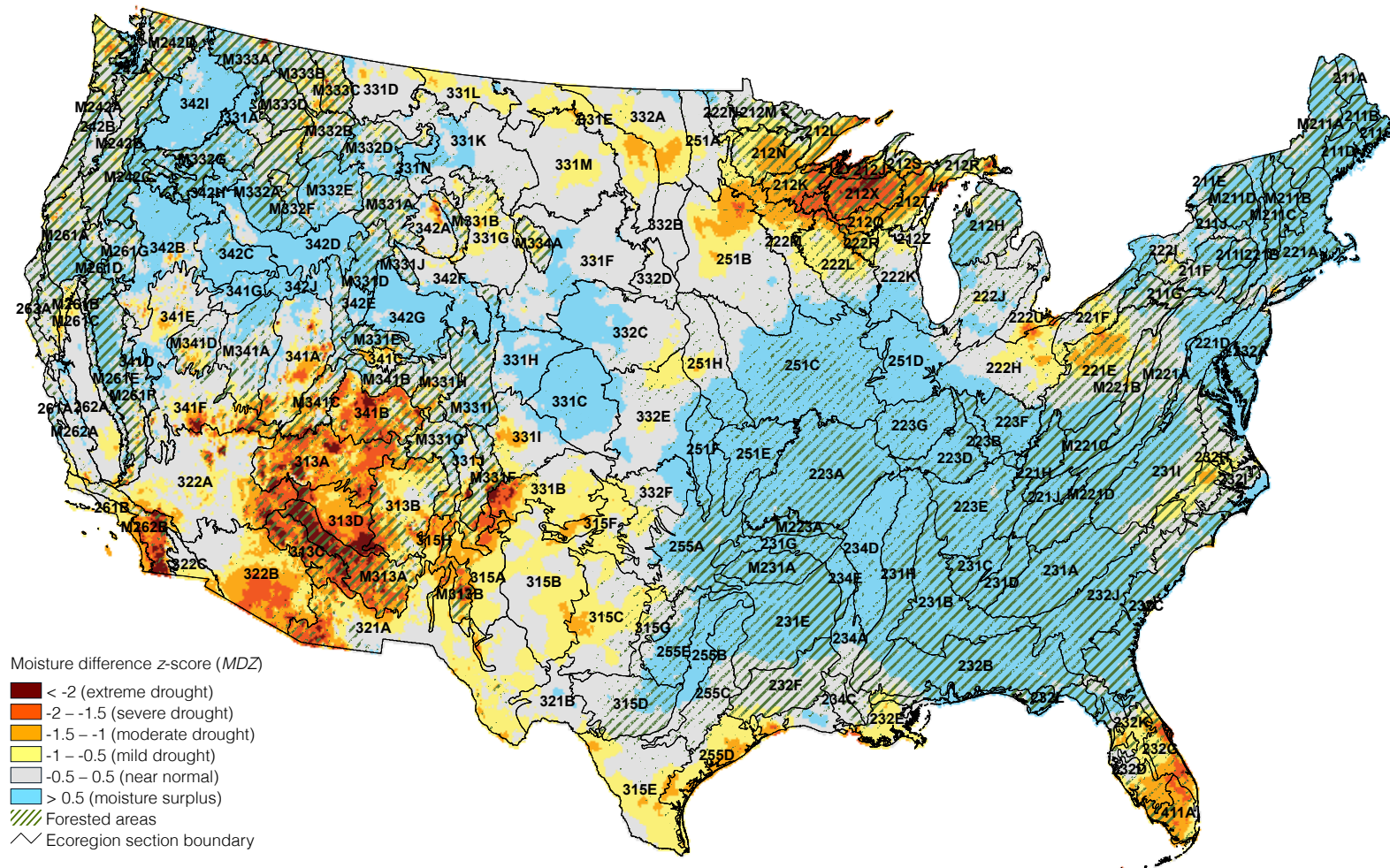


Figure 6.2—The 2009 annual (i.e., 1-year) moisture difference z-score, or MDZ, for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

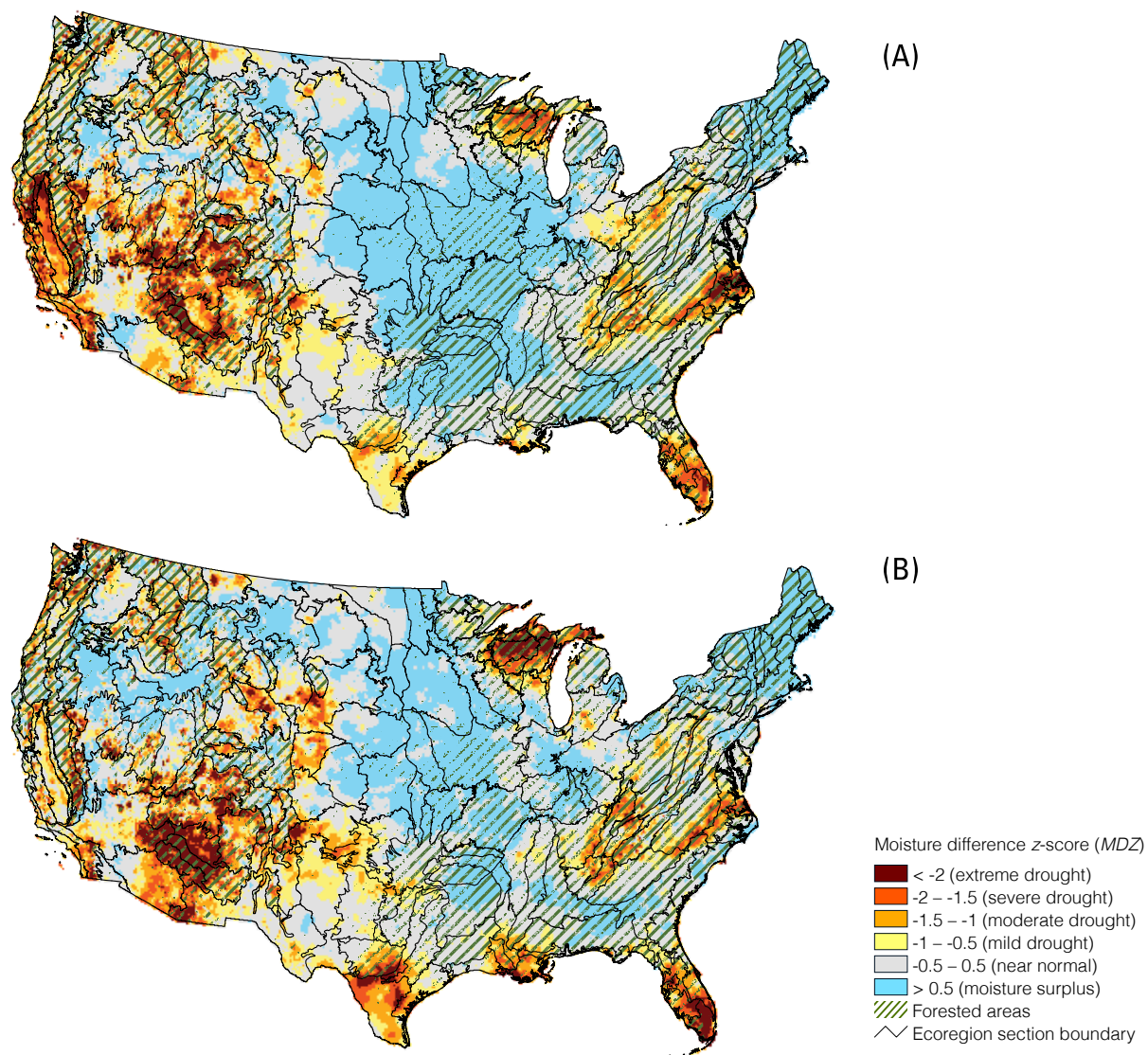


Figure 6.3—(A) The 2007–09 (i.e., 3-year) moisture difference z-score, or MDZ, for the conterminous United States; (B) the 2005–09 (i.e., 5-year) MDZ for the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

(1) abundance of host, i.e., oak forests, both natural and urban, and (2) the level of drought stress on host trees during late spring-early summer, an approximately 3-month “season” coinciding with beetle emergence from the host trees (Ciesla 2003). With respect to the first factor, phase 2 plot data collected by the Forest Inventory and Analysis (FIA) Program of the Forest Service were spatially interpolated to create a national-scale map of oak host distribution, which was supplemented by the use of National Land Cover Data to estimate forest cover in urban areas. To characterize and represent drought stress for risk mapping purposes, we employed our new, standardized drought mapping methodology to identify areas of the United States that recently (i.e., in the last few years, 2007–09) experienced severe or extreme drought during the late spring-early summer period.

As opposed to the mean-of-months approach used in the previously described analyses, i.e., for 1-year, 3-year, and 5-year time windows, in this case we calculated MI' (Eq. 2) based on the total P and PET values summed over the 3-month period. Notably, late spring-early summer represents a different time window depending on geographic location within the conterminous United States (i.e., depending on latitude, elevation, and climatic regime). For this reason, we actually calculated nationwide MI' grids for three different 3-month windows during each year of our 1910–2009 study period: March–May, April–June, and May–July.

For each of these 3-month windows, we calculated distinct MI'_{norm} and MI'_{SD} grids based

on the window’s 100 individual MI' grids. We then applied equation 3 to generate distinct MDZ grids for each window in each year of our study period. To combine the March–May, April–June, and May–July MDZ grids for each year into a single nationwide grid depicting late spring-early summer moisture conditions, we first subset them using spatial data related to frost-free period. Basically, these data served to represent the approximate beginning of spring and the growing season. In summary, we divided the conterminous United States into three geographic regions (called zones) (fig. 6.4), based on the 30-year mean Julian date of the last spring freeze: Zone 1, including all areas with a mean Julian date ≤ 90 (i.e., last freeze prior to April 1); Zone 2, all areas with a mean Julian date between 90 and 120 (i.e., last freeze between April 1 and April 30); and Zone 3, all areas with a mean Julian date > 120 (i.e., last freeze after April 30). Next, we matched each 3-month window to the most appropriate zone (fig. 6.4), and then clipped the corresponding MDZ grid to the zonal boundaries. Finally, we mosaicked these clipped grids into a single grid covering the conterminous United States.

For the FHTET model for potential establishment of the oak splendor beetle, we analyzed the late spring-early summer MDZ grids for 2007–09 (fig. 6.5). For each of these 3 years, we identified all U.S. areas that exhibited severe or extreme drought stress during this season. The resulting binary grids (where 1 = severe or extreme drought stress during late spring-early summer and 0 = moderate to no drought stress during this period) were added together using

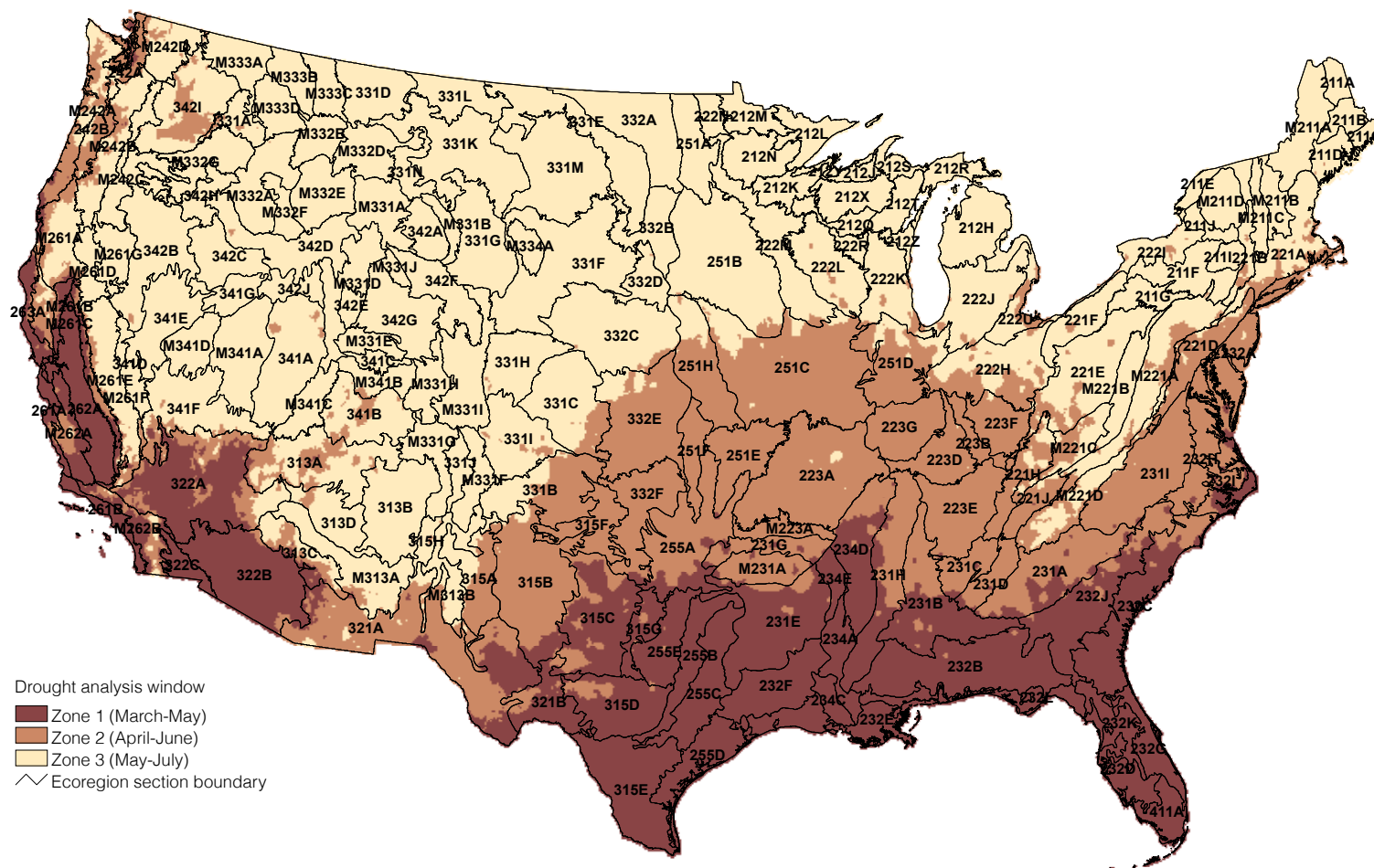


Figure 6.4—Three analysis zones, each corresponding to a particular 3-month time window used when calculating late spring-early summer drought conditions for the associated areas of the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries and labels are included for reference. Zones were developed from data describing frost-free period. (Data source: The Climate Source, LLC, Corvallis, OR)

map algebra, generating a frequency map with values from 0 (no late spring-early summer drought in 2007–09) to 3 (drought during all 3 years). Details about how the drought frequency map and host distribution data were combined to create a final establishment risk map are provided in Downing and others (2010). For comparison, both the 3-year drought frequency map and the final establishment risk map are included here (fig. 6.6).

RESULTS AND DISCUSSION

The 100-year mean annual moisture index, or MI_1' , grid (fig. 6.1) serves as a general representation of the climatic regimes for the conterminous United States. (The 100-year mean MI_3' and MI_5' grids differed negligibly from the mean MI_1' grid, and so are not shown here.) In general, wet climates ($MI' > 0$) are typical through the Eastern United States, especially the Northeast. Notably, it appears that southern Florida—in particular, ecoregion sections 232C-Florida Coastal Lowlands-Atlantic, 232D-Florida Coastal Lowlands-Gulf, and 411A-Everglades—is the driest region of the Eastern United States. Although the region typically has a high level of precipitation, the precipitation is more than offset by a high level of potential evapotranspiration, which results in negative MI' values. This pattern, i.e., high P offset by high PET , greatly contrasts with the pattern observable in the driest regions of the Western United States, particularly the Southwest, e.g., ecoregion sections 322A-Mojave Desert, 322B-Sonoran Desert,

and 322C-Colorado Desert, where potential evapotranspiration is very high but precipitation levels are typically very low. In fact, dry climates ($MI' < 0$) are common across much of the Western United States because of generally lower precipitation than in the Eastern United States. However, mountainous areas in the central and northern Rocky Mountains as well as the Pacific Northwest are relatively wet, e.g., ecoregion sections M242A-Oregon and Washington Coast Ranges, M242B-Western Cascades, M331G-South-Central Highlands, and M333C-Northern Rockies. This wet climate is likely influenced, at least in part, by winter snowfall.

Figure 6.2 shows the annual (i.e., 1-year) MDZ map for 2009 for the conterminous United States. Much of the country exhibited a moisture surplus for 2009, particularly in the East. There were pockets of drought scattered throughout the United States, such as an area of mild to moderate drought in the eastern portion of ecoregion section 232E-Louisiana Coastal Prairie and Marshes, as well as moderate to severe drought in the aforementioned ecoregion sections in southern Florida. Regarding the latter region, the observed conditions for 2009 partially reflect lingering effects from the previous year, with drought peaking in April before shifting back towards near-normal conditions (NCDC 2010). In addition to these and other drought pockets, there were a few U.S. regions with sizeable areas of severe to extreme drought during 2009: the Upper Midwest, especially ecoregion sections 212J-Southern Superior Uplands, 212X-Northern Highlands, and 212Y-Southwest Lake Superior Clay Plain;

the Desert Southwest, especially the forested portions of ecoregion sections M313A-White Mountains-San Francisco Peaks-Mogollon Rim, 313A-Grand Canyon, and 313C-Tonto Transition; and southern California in the forested areas of ecoregion section M262B-Southern California Mountain and Valley.

In fact, the Upper Midwestern United States experienced persistent drought conditions during most of the 7-year period from 2003 to 2009 (NCDC 2010). Likewise, much of the Western United States, particularly the Southwest region, has been regularly subjected to some level of drought for the last 10 to 15 years (Groisman and Knight 2008, Mueller and others 2005, NCDC 2010, O'Driscoll 2007). These prolonged drought conditions are partially captured by the 3-year and 5-year *MDZ* maps for the conterminous United States (fig. 6.3). When combined with the annual *MDZ* map in figure 6.2, these multi-year maps provide an overview of the recent chronology of moisture conditions. For instance, the 5-year *MDZ* map (fig. 6.3B) appears to show more extensive and/or severe drought conditions than the 3-year *MDZ* map (fig. 6.3A) in nearly all of the aforementioned geographic regions: southern Florida, the Desert Southwest, the Upper Midwest, as well as southern Texas, i.e., forested areas in section 315D-Edwards Plateau. This discrepancy may reflect longer-term persistence of drought in the regions of interest; however, it may also mean that the historically worst drought years in these regions are simply less recent than in, for instance, a region of the Southeastern United States, i.e., in parts of ecoregion sections 231I-Central Appalachian

Piedmont, 232H-Middle Atlantic Coastal Plain and Flatwoods, and 232I-Northern Atlantic Coastal Plain and Flatwoods, where the 3-year *MDZ* map shows worse drought conditions than the 5-year map. In the latter case, a historically exceptional drought that occurred during 2007 (O'Driscoll 2007) is likely the major factor behind the difference in the two maps. Note also that the 1-year *MDZ* map for 2009 (fig. 6.2) shows only mild to moderate drought conditions in this region, suggesting that the 2007 exceptional drought was a relatively short-term event.

Similarly, the 3-year *MDZ* values (fig. 6.3A) in much of northern California (e.g., ecoregion sections M261C-Northern California Interior Coast Ranges, M261F-Sierra Nevada Foothills) and M262A-Central California Coast Ranges, are lower than the corresponding 5-year *MDZ* values (fig. 6.3B). Since this region experienced persistent drought starting in 2007 (NCDC 2010), the difference between the two multi-year maps serves to highlight the fact that the region must have also experienced near normal or even moisture surplus conditions during 2005 and 2006 (NCDC 2009a, b), offsetting somewhat the apparently severe or extreme drought conditions during subsequent years. The 2009 annual *MDZ* map (fig. 6.2) suggests a recent improvement of moisture conditions in northern California. This apparent fluctuation of conditions over the course of the last several years suggests a need for future monitoring of the region.

The late spring-early summer *MDZ* maps (fig. 6.5) depict a fairly dramatic shift in seasonal moisture conditions during the 3-year

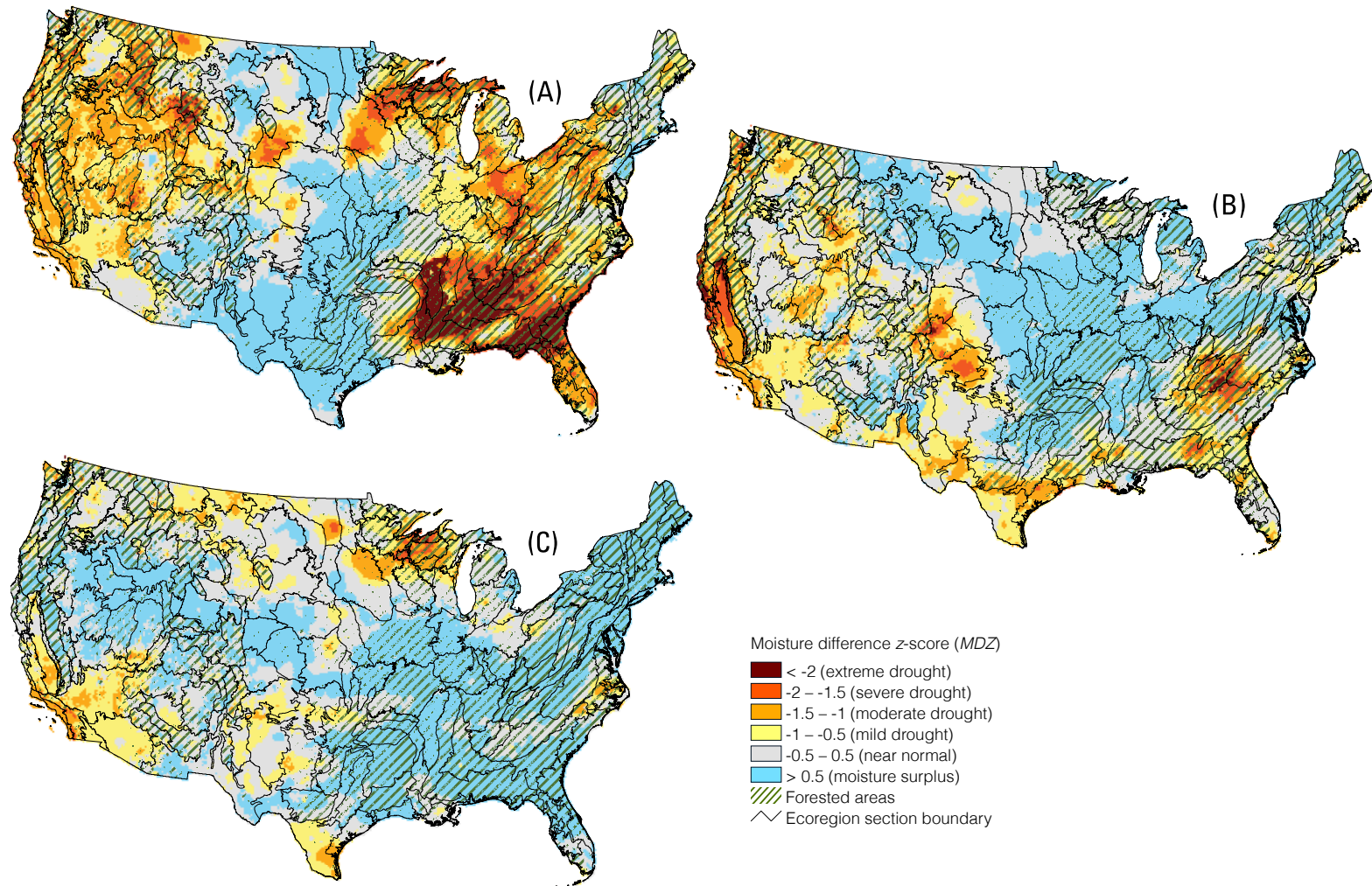


Figure 6.5—(A) The 2007 late spring-early summer moisture index z-score, or MDZ, for the conterminous United States; (B) the 2008 late spring-early summer MDZ; (C) the 2009 late spring-early summer MDZ. Ecoregion section (Cleland and others 2007) boundaries are included for reference. Forest cover data (overlaid green hatching) derived from MODIS imagery by the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. (Data source: PRISM Group, Oregon State University)

period from 2007 to 2009. Foremost, a large portion of the Southeastern United States was subjected to extreme drought during late spring-early summer 2007 (fig. 6.5A). At the same time, much of the remainder of the East experienced mild to severe drought, as did most areas west of the Rocky Mountains. In contrast, most of the Great Plains region experienced a moisture surplus. In late spring-early summer 2008 (fig. 6.5B), most of the country faced no worse than mild drought conditions, although there were hot spots of severe to extreme drought in northern California, especially ecoregion section M263-Northern California Coast; east of the Central Rocky Mountains reaching into forested areas of ecoregion section M331I-Northern Parks and Ranges; and in the Southern Appalachian Mountains, especially the southern portion of ecoregion section M221D-Blue Ridge Mountains. In late spring-early summer 2009, most of the country experienced near normal or moisture surplus conditions, with the most notable exceptions being two geographic regions previously noted in the annual and multi-year *MDZ* maps (figs. 6.2 and 6.3): southern California and the Upper Midwest.

In the Southern Appalachian Mountains, the Upper Midwest, and northern California, there were sizeable areas where severe or extreme seasonal drought occurred in 2 out of 3 years between 2007 and 2009 (fig. 6.6A). In turn, these areas have been labeled as having extreme establishment potential for the oak splendor beetle (fig. 6.6B), despite a fair

amount of variation between the regions in terms of the distribution and abundance of oak hosts. There were a handful of small patches where severe or extreme drought occurred during late spring-early summer of all 3 years (2007–09), in the previously noted ecoregion sections M262A and M262B, as well as M242B-Western Cascades, M242D-Northern Cascades, and M333A-Okanogan Highland (fig. 6.6A). However, none of these locations showed an elevated establishment potential for the beetle, presumably because of a lack of suitable host.

In summary, these results demonstrate the kinds of analyses that are possible with our newly standardized moisture difference index. If the most recent spatial data, i.e., the high-resolution maps of precipitation and temperature, underlying these analyses continue to be made available for public use, then the approaches described here—or similar approaches—could be installed as standard components of national-scale forest health reporting. Nevertheless, it is important for users to interpret and compare the *MDZ* drought maps cautiously. Although the maps use a standardized index scale that applies regardless of the window, it should also be understood that, for example, an extreme drought (i.e., where $MDZ < -2$) that persists over a 5-year period has substantially different forest health implications than an extreme drought over a 1-year period. Because this is a new methodology, we are still in the process of determining what analyses are most appropriate and possible. This will be a focus of future work.

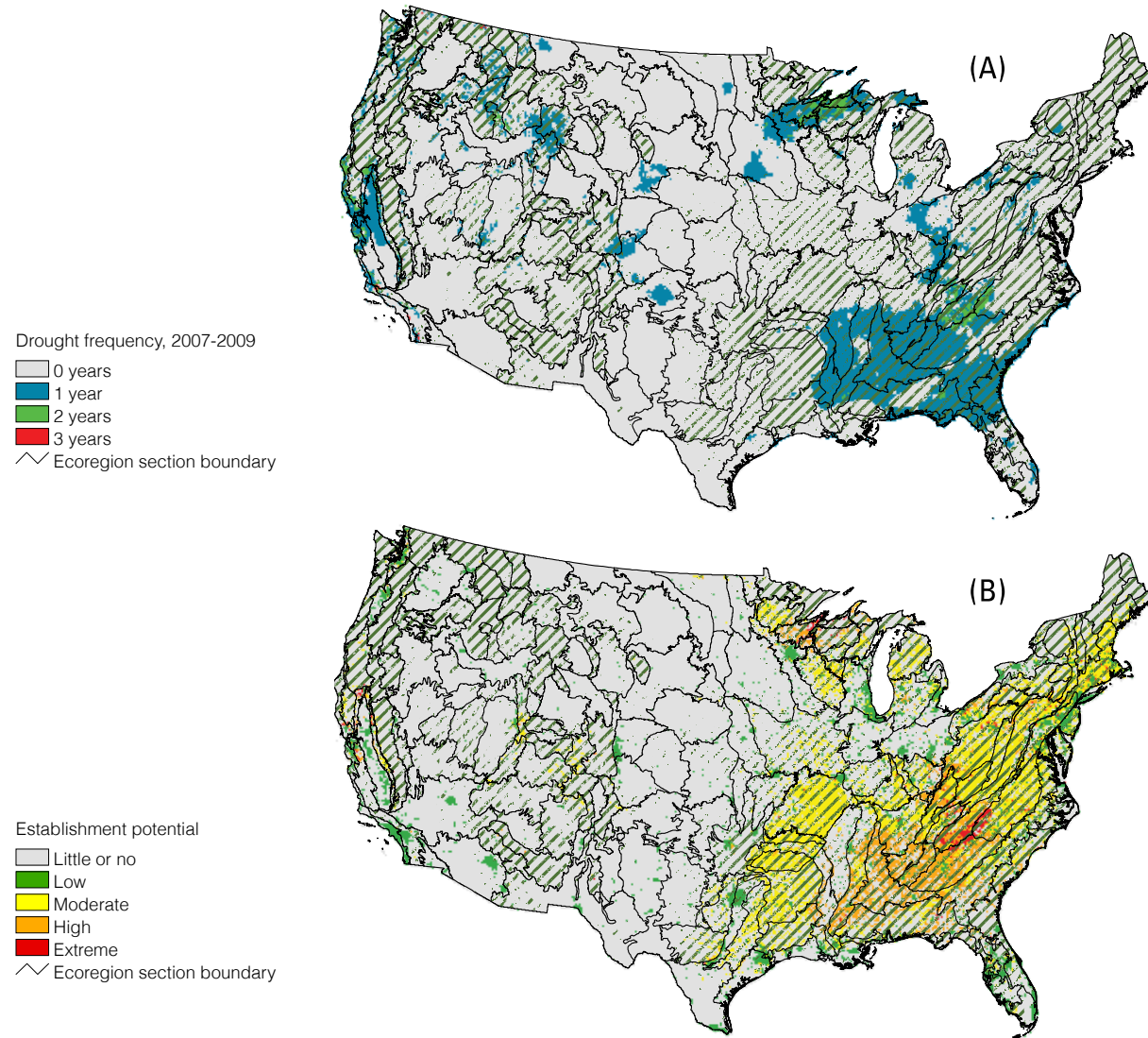


Figure 6.6—(A) The annual frequency of severe or extreme drought during late spring-early summer over a 3-year period, 2007–09; (B) establishment potential for oak splendor beetle (*Agrilus biguttatus*) in the conterminous United States. Ecoregion section (Cleland and others 2007) boundaries are included for reference. [Data sources: PRISM Group, Oregon State University (drought frequency); U.S. Department of Agriculture Forest Service, Forest Health Technology Enterprise Team (establishment potential)]

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