CHAPTER 7

Association of Multidecadal Repeat Dryness With Wildfire and Bark Beetle Forest Disturbances in the Conterminous United States, 2000–2022

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INTRODUCTION

Forest disturbances have occurred throughout the conterminous United States (CONUS) within the 20th and 21st centuries in conjunction with dry multidecadal time periods (Clarke and others 2016, Danneyrolles and others 2021, Hicke and others 2020, Morgan and others 2008, Pernin 1971, Wickman 2005). These dry periods are influenced by the long-term dynamics of Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, and Northern Hemisphere temperatures (McCabe and others 2004).

In the Western United States (defined as conterminous States including and west of Montana, Wyoming, Colorado, and New Mexico), climatic conditions promote coniferous vegetation primarily found within the Dry Domain ecological classification, with coastal areas falling into the Humid Temperate Domain. These conditions influence species distributions across ecological divisions while also excluding trees across substantial areas that are too arid to support forested vegetation (Perry and others 2022). In these domains, dry periods have commonly reoccurred throughout the Western United States, often with numerous multiyear droughts occurring each century from 800 A.D. to 2021 (Williams and others 2020, 2022). Multidecadal dry periods, referred to as "megadroughts," have been associated with widespread, synchronized wildland fire and bark beetle disturbances. These disturbance periods occurred in the early 20th century (1917–1940) as well as in the early 21st century (2000–2022) when exposure to dry conditions promoted widespread vulnerability to disturbance in forests across the Western United States (Hicke and others 2020, Iglesias and others 2022, Jenne and Egan 2019, Morgan and others 2008, Wickman and others 2005). Dry periods reduce fuel moisture and soil moisture conditions, resulting in increased vegetation flammability while promoting physiological stress within trees as carbon assimilation, water conductivity, tree vigor, and synthesis of chemical defensive compounds that protect trees from bark beetle attacks are compromised (Kolb and others 2016, Nolan and others 2020). Interactions between wildfire and bark beetles can be amplified with dry conditions as bark beetles can colonize fire-injured trees after wildfire incidents and, conversely, wildfire behavior can be impacted by the changes in fuel structure and moisture content resulting from bark beetle attacks that induce tree mortality (Fettig and others 2022c, Hood and Bentz 2007, Jolly and others 2012, Moriarty and others 2019).

For wildland fire incidents, precipitation wetting days during the warm season (May–September) have been identified as a primary driver that influenced the spatial extent of wildfire area burned, along with lesser contributions of vapor pressure deficit (Holden and others 2018). Similarly, numerous studies of bark beetle outbreaks in the Western United States identified that reduced precipitation, especially during spring and/or summer months, affects physiological tree stress by reducing defensive capacity and can increase overall forest vulnerability to severe and widespread bark beetle outbreaks (Egan and others 2010, 2016; Fettig and others 2022a, 2022b; Lestina and others 2019).

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Differing from dry periods, wet multidecadal periods can reduce potential for widespread, synchronized, and compounding wildfire and bark beetle disturbances while promoting tree recruitment, biomass growth, forest densification, and shade-tolerant species expansions (Brown 2006, Brown and Wu 2005). A multidecadal wet period occurred throughout the Western United States from the 1940s through the 1990s during warm season months (May–September) that interacted with anthropogenic fire suppression activities to mute spatially widespread and synchronized wildfire and bark beetle disturbances (Bollenbacher and others 2014, Iglesias and others 2022, Morgan and others 2008, Westerling and others 2016). As an example, the fire-prone forests of the Northern Rocky Mountains in Idaho and western Montana had no regional-fire years (i.e., years when numerous wildfire events are spatially synchronized by climate over a broad region) between 1935 and 1987. This contrasts to regional-fire years frequently occurring during the modern (2000–2022) and historic (1917–1940) periods when the Northern Rocky Mountains were exposed to repeated years of dry conditions during the warm season (Morgan and others 2008).

In the Central and Eastern United States (hereafter referred to as Central-Eastern United States, defined as conterminous States excluding and east of Montana, Wyoming, Colorado, and New Mexico), climatic conditions are generally wetter relative to the West. These conditions have promoted forests with a majority of deciduous species with areas of coniferous tree species across a Humid Domain that is further refined by primarily Hot Continental and Subtropical ecological divisions (Perry and others 2022). Typically, these conditions are not conducive to synchronized and widespread wildfire or bark beetle disturbances to the extent observed in the Western United States (Fettig and others 2022a); however, severe wildfires and bark beetle outbreaks still occur in conjunction with dry conditions (Clarke and others 2016, Danneyrolles and others 2021, Pernin 1971).

Across the CONUS, human development has expanded since the 20th century with communities and their surrounding ecosystems being directly impacted by spatially widespread wildfire and bark beetle outbreaks (Hicke and others 2020, Strader 2018). Climatic conditions have amplified forest disturbances and promoted forest vulnerability and are anticipated to promote increased and compounding wildfire and bark beetle disturbances as global warming intensifies (Allen and others 2015, Barbero and others 2015, Bentz and others 2010, Heeter and others 2023, UNEP 2022, Wion and others 2022).

To address changed conditions with climate-amplified disturbances, the U.S. Department of Agriculture (USDA), the USDA Forest Service, and other USDA agencies completed Climate Adaptation Plans (CAPs) that identify climate risks and mitigation activities needed to meet agency missions and continued delivery of services to the public. The Forest Service CAP Action 3 identified risk of chronic climate-amplified stressors on ecosystem function and recommended integrating climate vulnerability assessments into land management planning activities across all land ownerships (Action 3b; USDA Forest

Service 2022). Similarly, the USDA's Office of the Secretary released Memorandum 1077-004, which requires the Forest Service to provide spatially explicit climate data to identify where climate-based exposure and vulnerability to disturbance is elevated across the Nation for management support (Action 2a; USDA 2023). This chapter presents a spatially explicit climate-based indicator derived by the Forest Service's Forest Health Monitoring Program to support these mandates.

The goals of this study were to (1) identify, across 481,631 site-specific locations in the CONUS, whether precipitation conditions changed during 2000–2021 relative to the long-term average for 1948–1999 and (2) to evaluate a new indicator, the Multidecadal Repeat-Dryness Exposure Index (MRDEI), by assessing spatial association with wildfire and bark beetle disturbance records for 2000–2022 in forested locations. Specifically, objectives were to:

1. Assess site-specific forested locations for changed precipitation, by season, that occurred during 2000–2021 relative to a long-term average.
2. Determine whether annual, spring, or warm season periods had changed precipitation conditions at a scale associated with recently widespread forest disturbances for indicator development.
3. Identify differences in site-specific dryness dynamics across the Central-Eastern United States and Western United States since 1980.
4. Validate the MRDEI indicator by evaluating whether forest disturbances increased in conjunction with elevated repeat-dryness exposure rates during multidecadal (2000–2022) and recent (2017–2022) timescales.

METHODS

Geospatial Data for the Conterminous United States

Multiple spatial datasets were geospatially compiled for analysis across the CONUS using ArcGIS Pro 2.8.8. These included forested area locations, Standardized Precipitation Index (SPI), bark beetle spatial records for 2000–2022, and certified wildland fire perimeters for 2000–2022. Each dataset was geospatially attributed across the CONUS through a network of 16-km^2 grid cells that contained >10 percent forested vegetation as indicated by 2019 National Land Cover Database (NLCD) classification groups that included deciduous, evergreen, and mixed forest designations (Dewitz and USGS 2021). Bark beetle disturbance records, operationally collected by the Forest Service's Forest Health Protection Program and State partners, were aggregated from the national Insect and Disease Survey (IDS) by filtering annual geospatial datasets for the CONUS to include all damage causal agents (DCAs) identified as bark beetles (coded as 11000–11999). Then, records from all DCAs were dissolved or combined into a single record where spatial overlap occurred within ESRI ArcGIS Pro across 2000–2022 and 2017–2022 time periods to produce a bark beetle indicator feature class

(McConnell and others 2000, USDA Forest Service 2005).

Wildfire footprint records for all certified fire perimeters >100 acres were aggregated from the national Burned Area Boundaries dataset compiled within the Wildland Fire Management Research, Development, and Application (WFMRDA) data for 1984–2021 and the Wildland Fire Interagency Geospatial Services (WFIGS) data for 2022 wildfire incident records (WFIGS 2022, WFMRDA 2021). Fire perimeter footprints were dissolved to erase yearly records that overlapped in 2000–2022. Then, the wildfire footprint derived layer was cross-referenced with the Monitoring Trends in Burn Severity (MTBS) geospatial fire data for 2000–2022, which is limited to >500- or >1,000-acre incidents depending on location, to cross-validate WFMRDA and WFIGS data to ensure wildfire records were not missing any large wildfire perimeters (Eidenshink and others 2007). Footprint data were intersected to identify overlapping co-occurrence of wildfire and bark beetle disturbance data. Finally, all three disturbance footprint layers built were stratified to represent the 2000–2022 multidecadal period as well as a recent 2017–2022 period, with acres impacted summed across individual 4-km^2 grid cells to match climatic data indicated below.

All disturbance footprint datasets were compiled from best-available datasets and were considered authoritative at the time accessed for this study. However, limited cases of incomplete disturbance records are possible. The national IDS does not survey every forested acre annually due to capacity and logistic limitations (McConnell and others 2000). Similarly, the national WFMRDA and WFIGS wildfire datasets may have occasional missing records and are often updated when additional wildfire records become available.

Standardized Precipitation Index (SPI)

The SPI (Guttman 1999, McKee and others 1993) is a widely used drought index that represents the deviation between measured precipitation and the long-term climatological average for precipitation at the same location. This metric is beneficial for site-specific, long-term comparisons over multiyear periods (Hoylman and others 2022). Site-specific standardization allowed for consistency to assess changed precipitation conditions and disturbance associations across vastly different Dry and Humid ecological domains found throughout the CONUS (Perry and others 2022).

SPI was calculated for each of the 481,631 grid cells across the CONUS through an iterative process. First, the monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation values for 1948–2021 were partitioned to calculate spring (March–May), warm season (May–September), and calendar year (January–December) totals (Daly and others 1994, PRISM Climate Group 2023). Using the PRISM data, SPI anomalies were calculated for each seasonal time window relative to the 1948–2021 average and normalized across each year in the 1948–2021 period by fitting gamma distribution, using observations to compute Cumulative Distribution Function (CDF), and then evaluating CDF with inverse

Gaussian function to derive final SPI anomaly values (Holden and Hoylman 2023). Data were only summarized back to 1948 because weather measurement stations, which serve as the base input data for PRISM, had sparse occurrence and were limited to valley bottoms in some locations prior to that year.

SPI, which represents precipitation relative to local baseline conditions, was specifically selected to calculate repeat dryness spatially without temperature influences for various reasons. First, PRISM records suggest temperatures trended higher ubiquitously across respective Western and Central-Eastern U.S. regions with limited within-region spatial variation in the modern (2000–2021) dry period (fig. 7.1; Daly and others 1994). Warming trends are anticipated to continue and co-occur with cyclic precipitation events that have a level of repeatability due to the influence of static terrain and topographic complexity (Daly and others 1994, Heeter and others 2023, IPCC 2022, Johnson and Hanson 1995). This repeatability is evident with reoccurrence of severe and widespread wildfire and bark beetle disturbances across the Western United States where forest conditions were susceptible during the 1917–1940 and 2000–2022 dry periods (Jenne and Egan 2019; Morgan and others 2008). Thus, identification of forested areas prone to repeat dryness when combined with increased temperature assumptions can highlight forested areas with potential for aridification, especially in the Western United States. Second, temperature and precipitation variables have dependency with each other. This dependance can compound errors when these variables are combined, especially in mountainous areas of the Western United States and where monitoring stations were limited across the 1948–2021 period of normalization. For these areas, greater reliance on spatial interpolation is needed to derive PRISM site-specific variable estimates (Daly and others 1994, Trenberth and Shea 2005, Wazneh and others 2020).

Multidecadal Repeat-Dryness Exposure Index (MRDEI)

The MRDEI is a climate-based indicator that represents locations exposed to repeat dryness during the warm season (May–September) throughout long-term time periods of interest. The SPI data were used to parameterize the MRDEI through a severity-weighted area statistic that combines years of dry conditions with severity of dryness. Index values represent the percentage of the timescale evaluated during which multiyear dry exposure was equivalent to a severe dry SPI (<-3 standard deviation) baseline by applying a scaling factor. Scaling factors (table 7.1) were applied to grid cell acres that were summed across respective multidecadal time periods (1948–1959, 1960–1979, 1980–1999, and 2000–2021) and divided by the total (nonscaled) grid cell acres multiplied by the total years within the time period. In effect, the frequency of SPI <0 substantially influences the final multidecadal index statistic. The magnitude of SPI values <0 provides for limited influence as the index was designed to identify where forested areas are prone to repeated occurrence of dry conditions rather than estimate site-specific impacts of cumulative dryness. Overall, a value of 100 percent represents baseline conditions and would indicate every

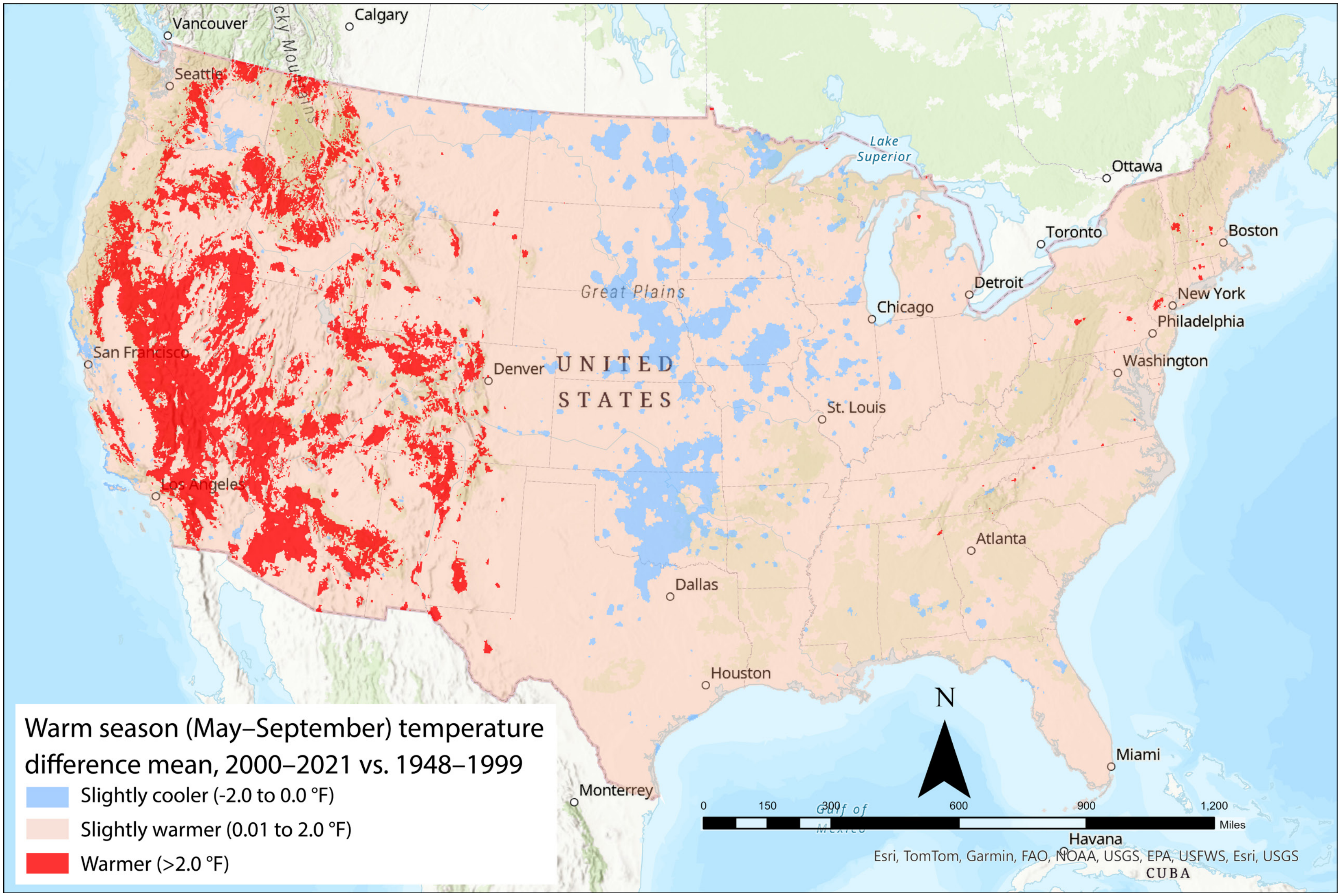

Figure 7.1—Magnitude of warm season (May–September) mean temperature differences during 2000–2021 relative to the long-term average for 1948–1999.

Table 7.1—Weighting factors utilized to scale area within grid cells based on Standardized Precipitation Index (SPI) magnitude of dry anomaly for cumulative analysis

SPI category	Scaling factor to represent severe dry (percent)
SPI ≥ 0	0
0 > SPI ≥ -1	65.90
-1 > SPI ≥ -2	86.40
-2 > SPI ≥ -3	97.90
SPI < -3	100

year during 2000–2021 was exposed to severe conditions during the warm season. With the temporally cumulative assessment, wet years (>0 SPI) do not reduce, nor contribute further, to MRDEI index values. This methodology was designed to reflect multiyear soil moisture trends reconstructed for the warm season that identified progressive reductions in soil moisture since 2000 across the Western United States without upward changes to that trajectory during individual wet years (Martin and others 2020; Williams and others 2020, 2022).

Statistical Assessment

All statistical analyses were performed in R software (version 4.3.1; R Core Team 2021). Precipitation was evaluated by assessing whether average SPI conditions changed through time within each respective 4-km^2 grid cell within various seasons and annually. Specifically, spring, warm season, and annual periods were evaluated to assess whether mean SPI differed during the recent (2000–2021) multidecadal period relative to the previous period (1948–1999). Analyses in R used two-sample Welsh t-tests under the normality assumption with the *t.test* function (Student 1908). MRDEI was evaluated for spatial association with forest disturbances across the CONUS with descriptive and inferential approaches. First, the percentage of forested area impacted by wildfire, bark beetles, and wildfire-bark beetle co-occurrence, for 2000–2022 and 2017–2022, were classified by MRDEI exposure class and descriptively evaluated to see if disturbance increased with the increasing MRDEI exposure classes. Then, MRDEI was statistically evaluated for spatial association with respective wildfire, bark beetle, and wildfire-bark beetle co-occurrence footprints for 2000–2022 and 2017–2022. For this, the proportion of grid cells with each disturbance was assessed for equivalency or deviation relative to the baseline proportion of forested area grid cells that had lower (1–3) or higher (4–5) MRDEI classes. This statistical assessment occurred in R using a two-sample test for proportions with the *prop.test* function (Newcombe 1998).

RESULTS AND DISCUSSION

Assessment of Precipitation Exposure Changes to Forested Areas by Season

Forested areas across the CONUS were assessed for site-specific precipitation differences, across 228,581 forested 4-km^2 grid cells, by assessing mean spring, warm season, and annual SPI for the 2000–2021 and 1948–1999 multidecadal periods (table 7.2). Spring mean SPI was significantly different between periods for only 5 percent of CONUS forested areas, with drier conditions identified during the 2000–2021 period primarily within the Southwest and limited areas in the Southeast (fig. 7.2, table 7.2). Warm season mean SPI was significant between periods for 16 percent of the CONUS with differences being primarily in the Western United States where nearly half (48 percent) of forests were exposed to drier conditions during 2000–2021 (fig. 7.3, table 7.2). A minimal (<1 percent) of Central-Eastern U.S. forests, limited to forested areas near the Great Lakes, were exposed to drier conditions. Similarly, annual mean SPI values indicated exposure to dry conditions was elevated across a substantial portion of the Western United States in the recent multidecadal period with significant differences being detected only in rare, isolated locations in the Central-Eastern United States. Assessments of warm season and annual SPI changed conditions found that locations with significant warm season precipitation differences also had annual precipitation changes. Thus, warm season SPI changes were depicted and used for indicator development as this season heavily influenced the annual changed precipitation results. Additionally, the locations with warm season SPI changes appeared spatially correlated with wildfire and bark beetle disturbance indicators, which suggested utility for climate-based indicator development.

Table 7.2—Forested area with significantly drier Standardized Precipitation Index mean values in 2000-2021 relative to the long-term average for 1948-1999

Season	Western United States		Central-Eastern United States		Conterminous Untied States	
	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres
Spring (March–May)	18.7	12	4.4	1	23.0	5
Warm season (May–September)	75.8	48	1.4	0.5	77.2	16
Annual (January–December)	59.3	37	0.6	0.2	59.9	13
Total acres	159.0		309.8		468.8	

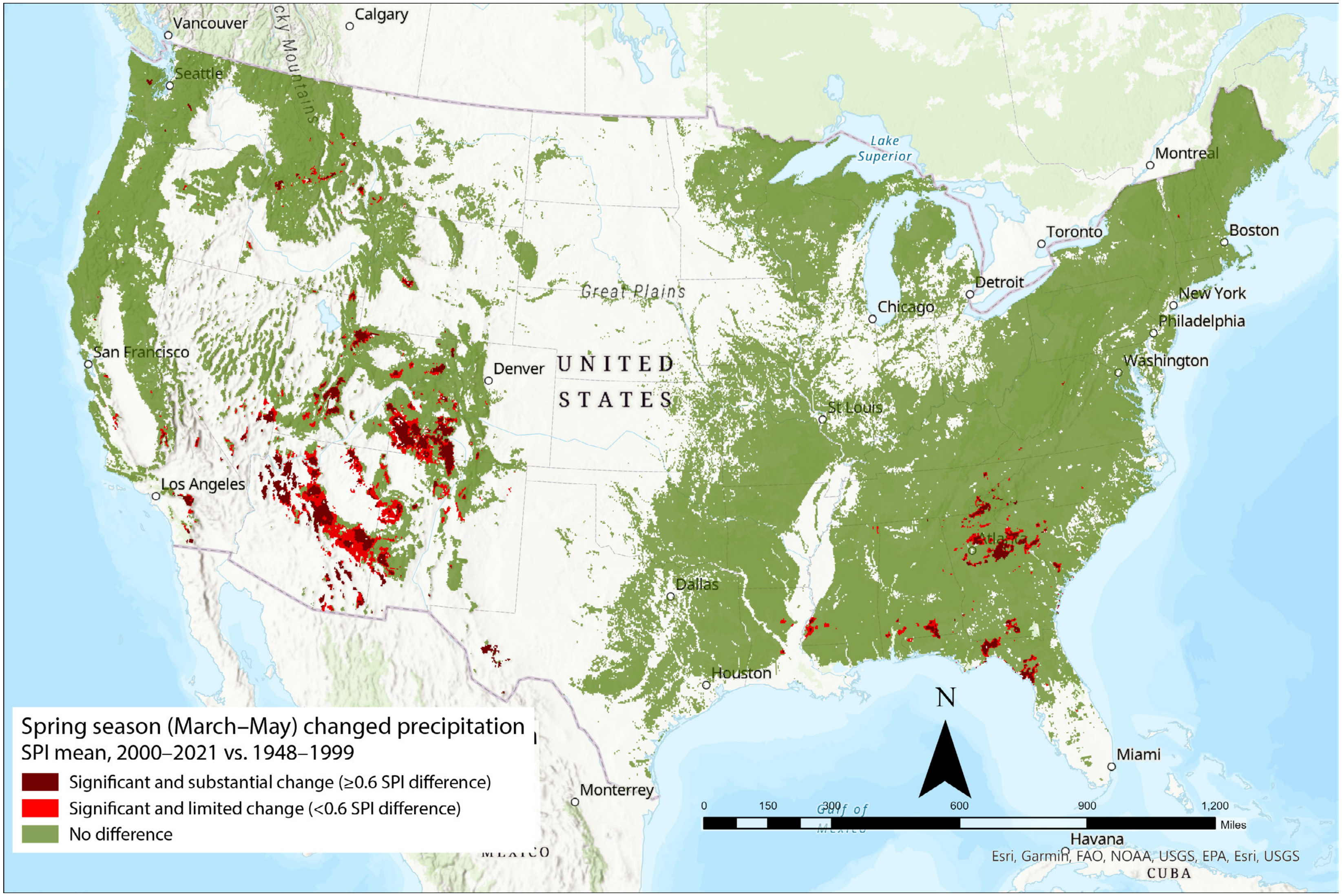

Figure 7.2—Forested areas with significantly drier mean Standardized Precipitation Index (SPI) values for spring (March–May) during 2000–2021 relative to the long-term average for 1948–1999.

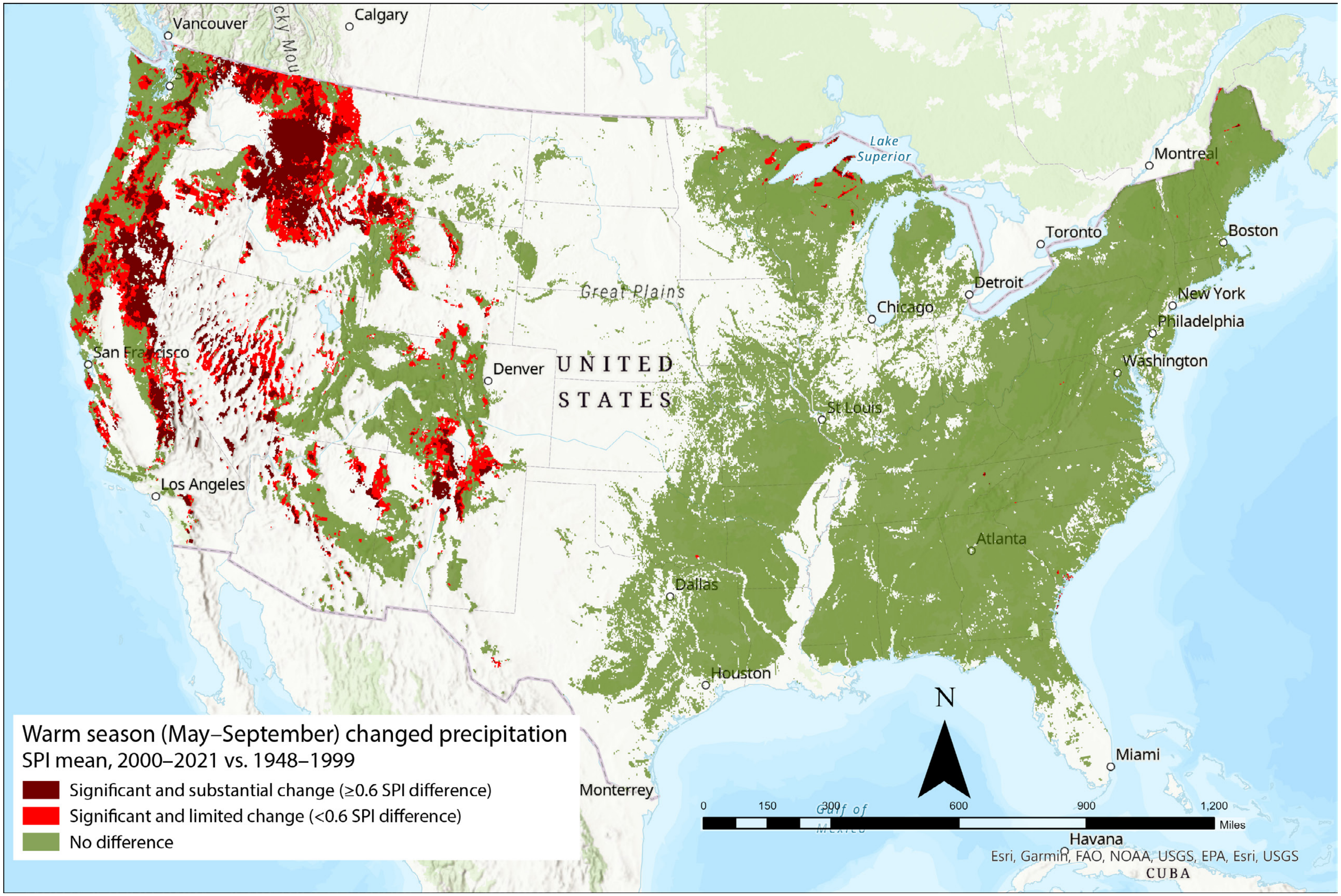

Figure 7.3—Forested areas with significantly (p <.0001) drier mean Standardized Precipitation Index (SPI) values for the warm season (May–September) during 2000–2021 relative to the long-term average for 1948–1999.

Assessment of Wildfire, Bark Beetle, and Disturbance Co-Occurrence in Forested Areas, 2000–2022

Wildfire and bark beetle disturbances, respectively, impacted 12 percent of CONUS forested area in 2000–2022 and co-occurred across 3 percent of this area (table 7.3). These disturbances occurred extensively across the Western United States, where approximately one-third of forested area had respective wildfire and bark beetle disturbances with a 7-percent forested area having both disturbances documented (fig. 7.4). Bark beetle agents that contributed most to the bark beetle footprint layer included mountain pine beetle (*Dendroctonus ponderosae* Hopkins; 26.2 million acres) and fir engraver (*Scolytus ventralis LeConte*; 15.4 million acres) (table 7.4). In the Central-Eastern United States, wildfire and bark beetle disturbances were rare and only impacted 2 percent of total forested area. During 2017–2022, forest disturbance was observed primarily in Western U.S. forested areas while Central-Eastern U.S. forested areas had substantially less impact (fig. 7.5). Other forest disturbances beyond the scope of this analysis, such as native and nonnative insect defoliators and pathogens were commonly recorded in Central-Eastern U.S. forests.

Forested areas with wildfire and bark beetle disturbances were documented across similar magnitude of area in the Western United States; however, bark beetle records include live and dead trees within damaged areas as disturbance being mapped is commonly spatially discontinuous. After adjustment (see Egan and others 2019), calculations that include the severity of bark beetle-caused tree mortality were reduced to 15.2 million acres of aggregate tree mortality from bark beetles, which totaled only one-third of the wildfire disturbance area footprint. Forested areas that experienced both disturbance agents primarily had bark beetle activity initially followed by subsequent wildfire (table 7.3).

Forest disturbances occurred across the Western United States at a similar scale as warm season changes in SPI conditions were identified during the recent 2000–2021 period relative to the long-term average during 1948–1999 (figs. 7.2 and 7.3). Similarly, disturbances rarely occurred in the majority of Central-Eastern U.S. forested areas that did not exhibit exposure to reduced precipitation conditions. This confirmed that the season Holden and others (2018) identified as being important for wildfire area burned was also important for bark beetle disturbances and the co-occurrence of bark beetles and wildfire. Thus, warm season was selected for creation and analysis of the MRDEI indicator variable.

Table 7.3—Forested area with wildfire and bark beetle disturbances documented in 2000–2022 and 2017–2022

Disturbance (period)	Western United States		Central-Eastern United States		Conterminous Untied States	
	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres
Bark beetles (2000–2022)	54.9	35	2.5	1	57.4	12
Wildfire (2000–2022)	48.8	31	7.4	2	56.2	12
Bark beetle and wildfire overlap (2000–2022)	11.6	7	0.3	0	11.8	3
Bark beetles (2017–2022)	16.6	10	1.2	0.4	17.8	4
Wildfire (2017–2022)	23.1	15	5.1	2	28.3	6
Bark beetle and wildfire overlap (2017–2022)	2.2	1	0	0	2.2	0.5

Table 7.4—Top five bark beetle mortality agents recorded through the national Insect and Disease Survey (IDS) across the conterminous United States, 2000–2022

Bark beetle common name	Bark beetle scientific name	Number of IDS records	IDS impacted area[a] (millions of forested acres)
Mountain pine beetle	*Dendroctonus ponderosae* Hopkins	1,281,233	26.2
Fir engraver	*Scolytus ventralis* LeConte	337,659	15.4
Western pine beetle	*D. brevicomis* Hopkins	274,859	6.4
Pinyon ips	*Ips confusus* LeConte	60,833	5.2
Douglas-fir beetle	*D. pseudotsugae* Kirby	443,792	5.0
Total		2,398,376	58.2

[a] Does not adjust for overlap between species or severity of mortality in impacted forest areas.

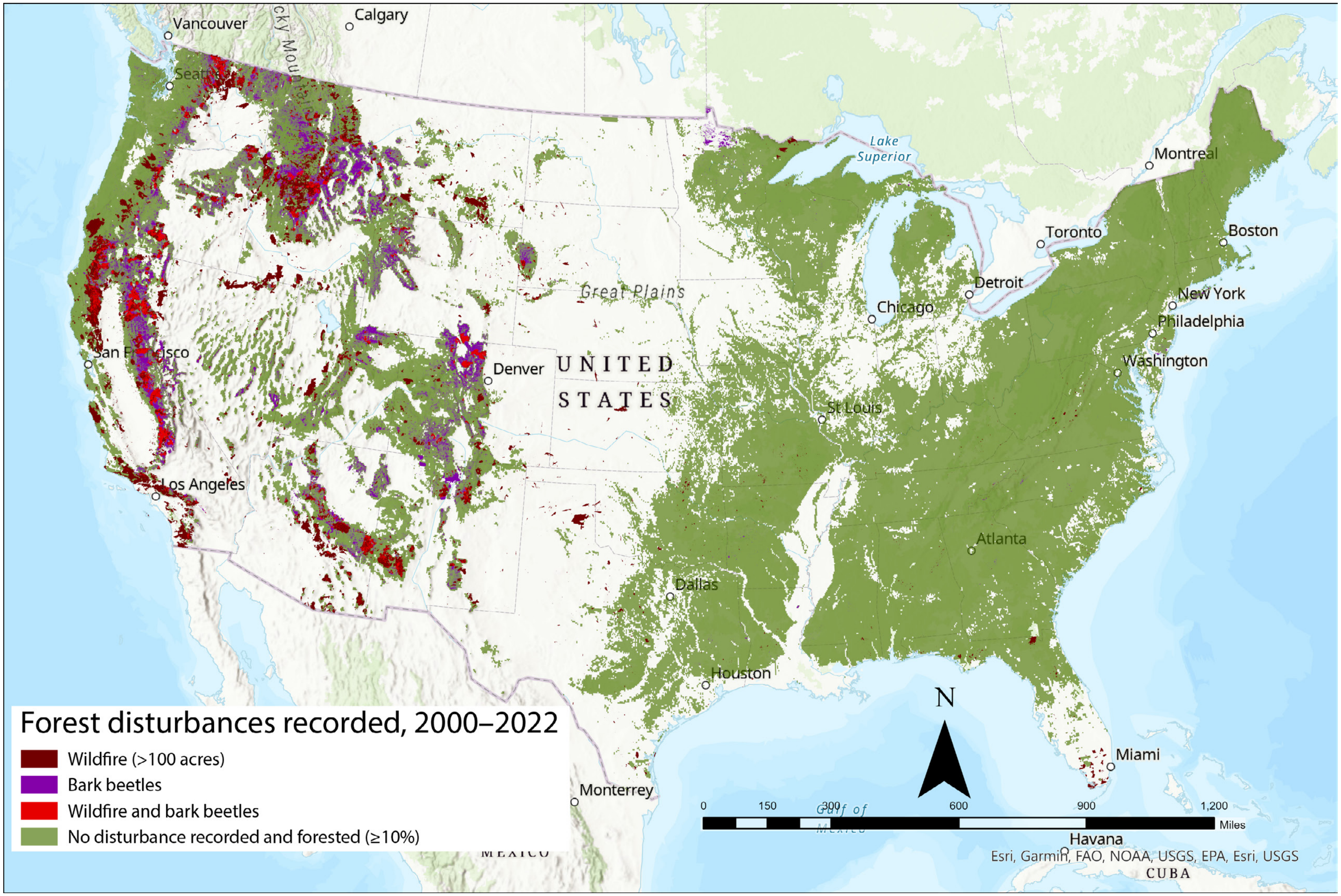

Figure 7.4—Wildfire and bark beetle forest disturbances recorded across the conterminous United States, 2000–2022.

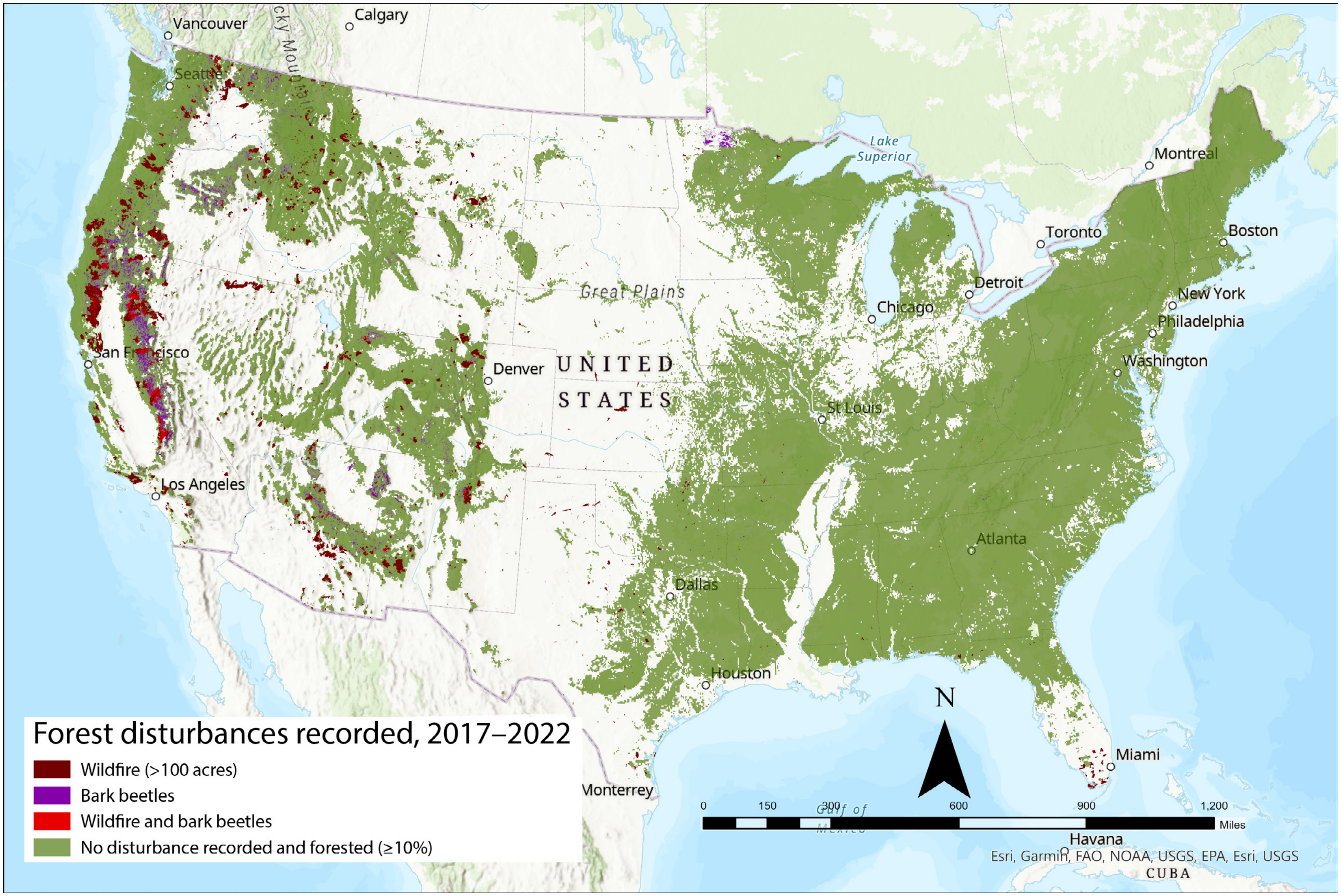

Figure 7.5—Wildfire and bark beetle forest disturbances recorded across the conterminous United States, 2017–2022.

Multidecadal Repeat-Dryness Patterns Across the Conterminous United States, 1980–2021

The MRDEI represents the frequency of repeat dry, warm season conditions across multidecadal time periods for the CONUS. During the most recent period (2000–2021), >80 percent of forested areas in the Western United States experienced >40 percent frequency of repeat dryness, whereas the Central-Eastern United States had only 5 percent exposure (table 7.5, fig. 7.6). Interestingly, the MRDEI for the multidecadal period of 1980–1999 shows that climatic conditions were opposite relative to 2000–2021 as repeat-dryness exposure during the warm season occurred throughout the Central-Eastern United States and rarely in the Western United States (table 7.5, fig. 7.7). As such, MRDEI based on multidecadal dry conditions in 2000–2021 is most appropriate for the Western United States while assessment of Central-Eastern U.S. locations prone to repeat-dryness conditions could be informed by the 1980–1999 MRDEI. However, formal validation to assess association between the 1980–1999 MRDEI with forest disturbances is still needed, and disturbance records from that period were not standardized nationwide.

Validation of MRDEI Spatial Associations with Wildfire, Bark Beetle, and Co-Occurring Forest Disturbances

MRDEI was first evaluated for spatial association with forest disturbances for 2000–2022 and 2000–2017 by assessing whether the percentage of forest area impacted by wildfire, bark beetle, and wildfire/bark beetle co-occurrences increased across the higher MRDEI classes that depicted greater exposure to warm season dry conditions. The data for the CONUS suggest this (fig. 7.8A); however, the majority of forested areas in the CONUS are found within the Central-Eastern United States, which were only minimally exposed to repeat-dryness conditions during 2000–2021 (table 7.5, fig. 7.6). Considering only the Western United States where the vast majority of disturbance occurred, each forest disturbance group had the percentage of forested area impacted increase in conjunction with increased MRDEI classes (fig. 7.8B). This included >35 percent of all forested area exposed to MRDEI classes 4 and 5 being impacted by respective wildfire or bark beetle disturbances (fig. 7.8B). Similarly, the co-occurrence of wildfire and bark beetle disturbances was prevalent in forested areas exposed to MRDEI classes 4 and 5 (fig. 7.8).

While disturbances were proportionally greater in the highest MRDEI exposure classes, they occurred in all MRDEI classes in 2000–2022, with ample bark beetle activity documented in classes 1 and 2 (fig. 7.8B). This showcases that extreme weather and shorter repeat-dryness durations were associated with disturbance, such as for bark beetle activity that occurred at the

Table 7.5—Multidecadal Repeat-Dryness Exposure Index (MRDEI) class distribution across forested areas, 2000–2021 and 1980–1999

MRDEI classes	Western United States		Central-Eastern United States		Conterminous Untied States	
	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres	Area (millions of acres)	Percent of forested acres
2000–2021						
Class 1: <30% exposure	2.0	1	191.2	62	193.2	41
Class 2: 30–39.9% exposure	28.9	18	101.6	33	130.5	28
Class 3: 40–49.9% exposure	78.9	50	16.1	5	95.0	20
Class 4: 50–59.9% exposure	46.0	29	0.7	0	46.7	10
Class 5: ≥60% exposure	3.2	2	0.0	0	3.2	1
1980–1999						
Class 1: <30% exposure	127.6	80	24.0	8	151.6	32
Class 2: 30–39.9% exposure	26.8	17	99.8	32	126.6	27
Class 3: 40–49.9% exposure	4.5	3	122.0	39	126.5	27
Class 4: 50–59.9% exposure	0.1	0	57.7	19	57.8	12
Class 5: ≥60% exposure	0	0	6.2	2	6.2	1

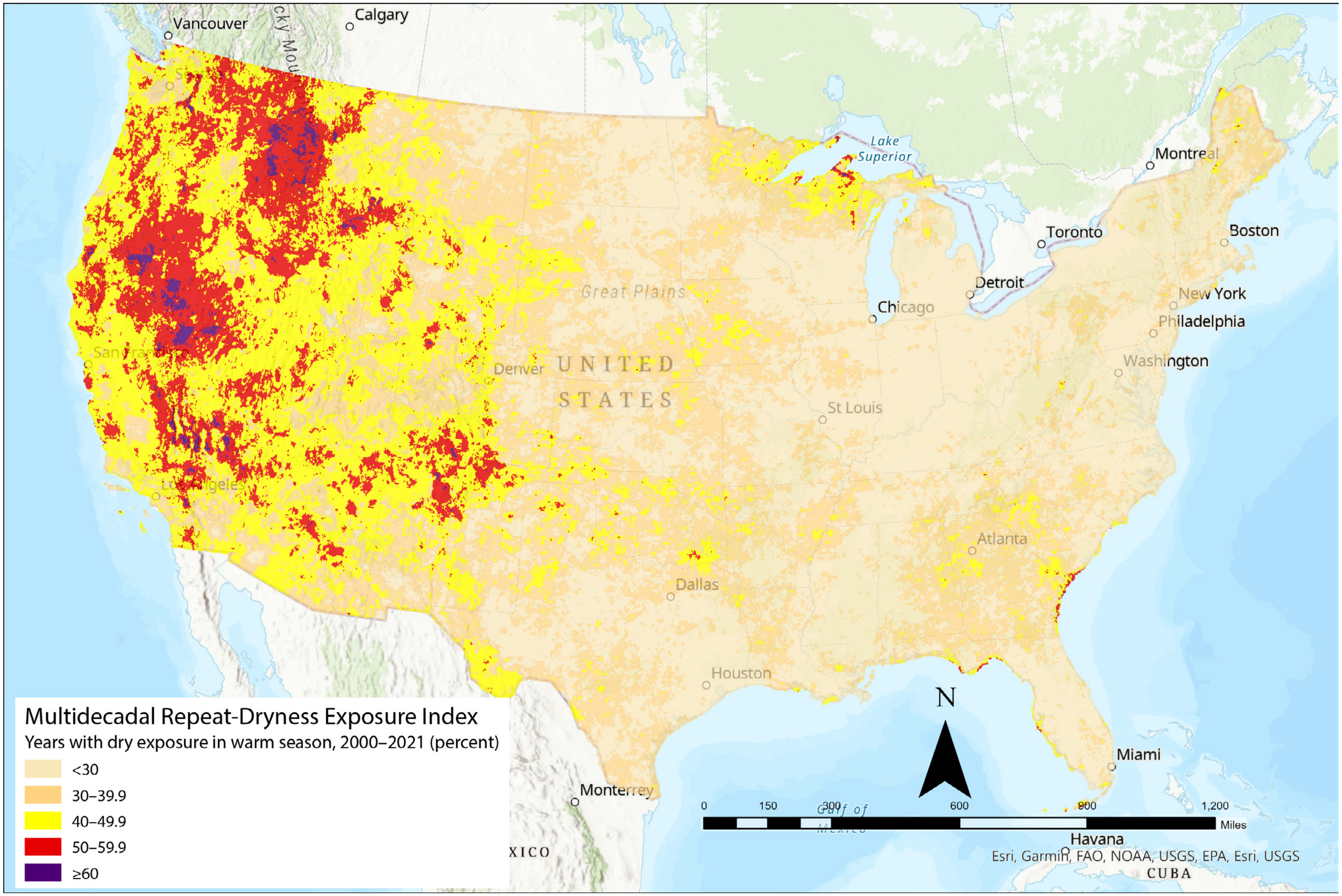

Figure 7.6—Multidecadal Repeat-Dryness Exposure Index showcasing recurring dry conditions for the warm season (May–September) across the conterminous United States, 2000–2021.

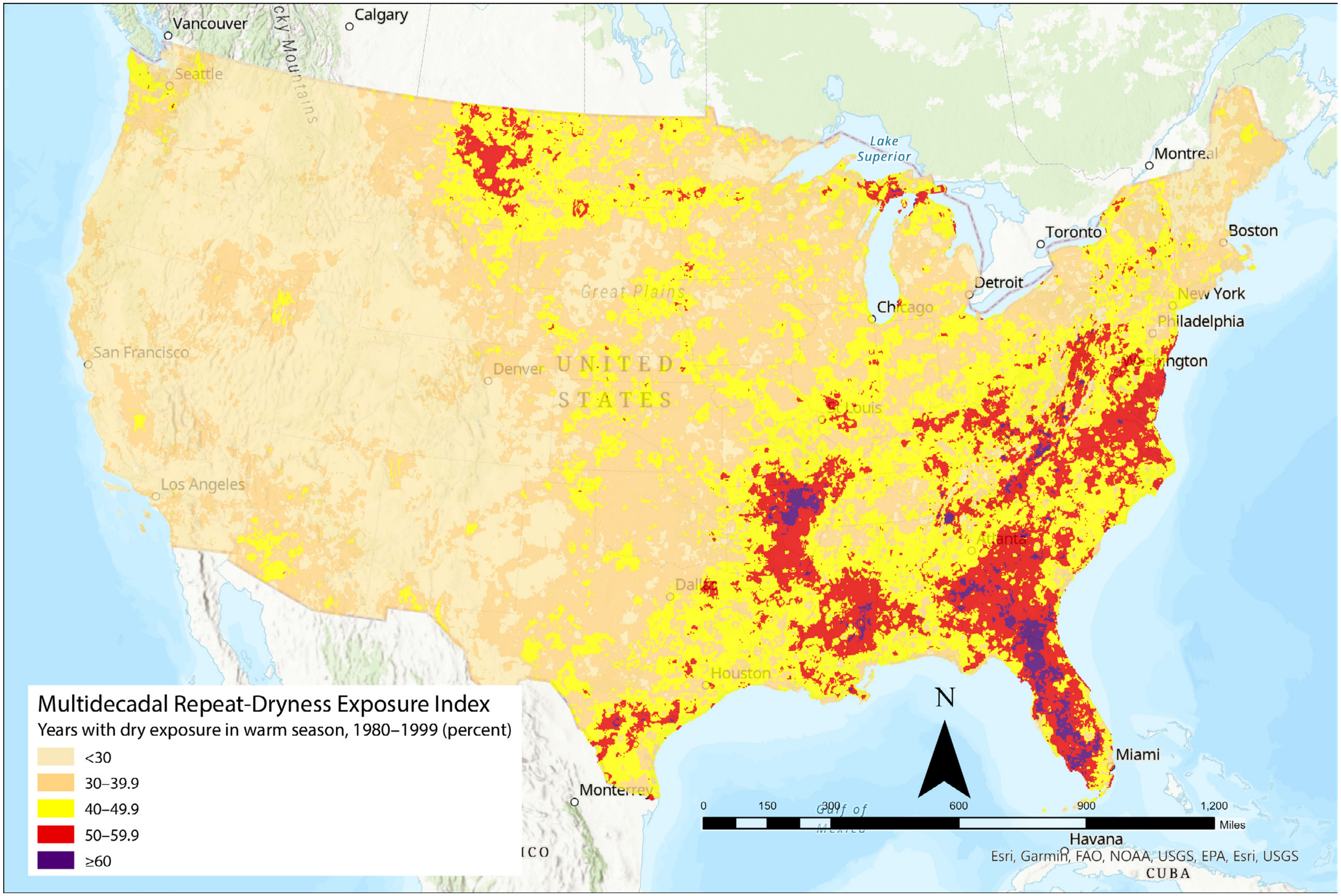

Figure 7.7—Multidecadal Repeat-Dryness Exposure Index showcasing recurring dry conditions for the warm season (May–September) across the conterminous United States, 1980–1999.

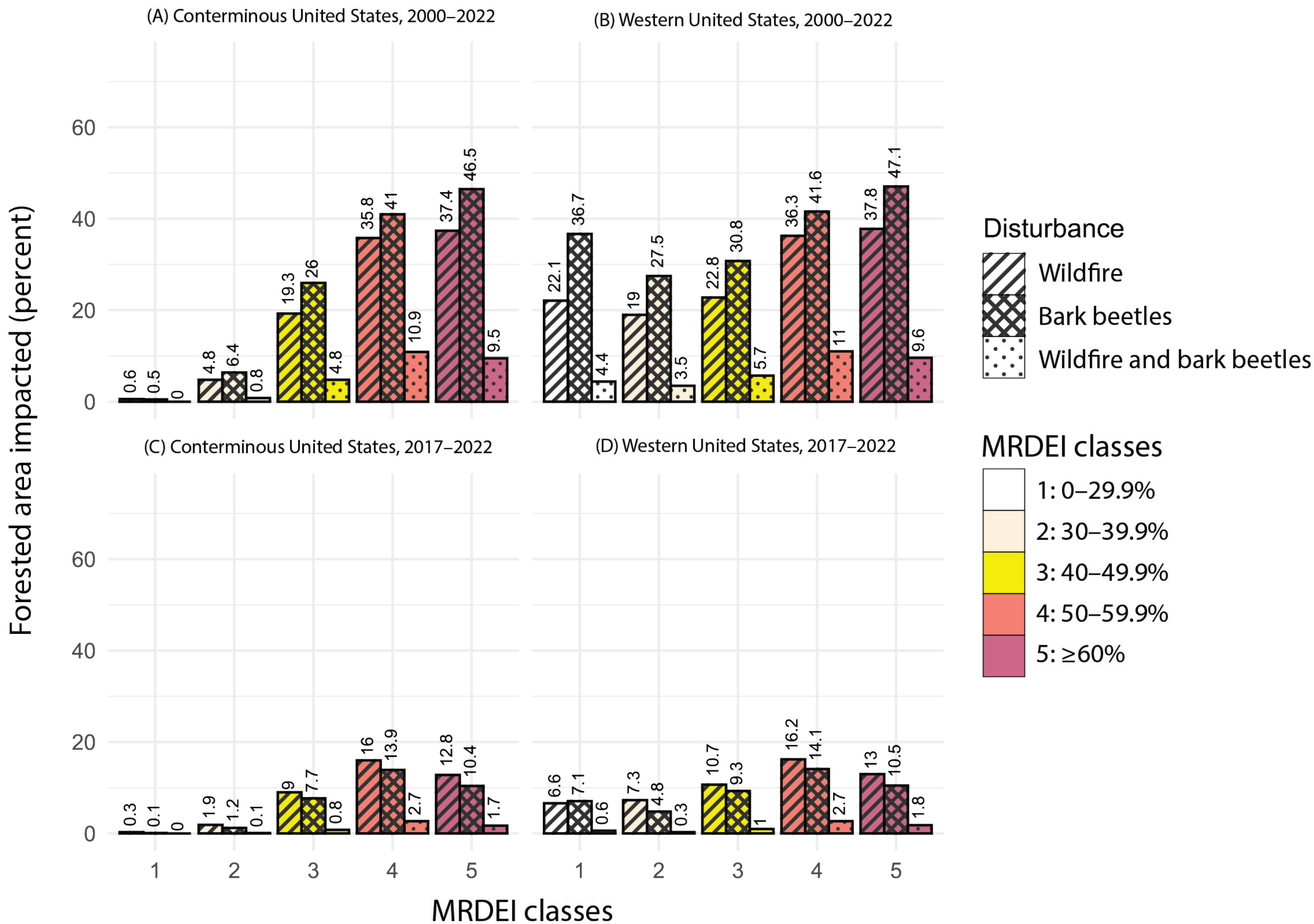

Figure 7.8—Percentage of forested area, stratified by Multidecadal Repeat-Dryness Exposure Index (MRDEI) classes, impacted by disturbance across 2000–2022 (A and B) and 2017–2022 (C and D) periods for conterminous U.S. (A and C) and Western U.S. (B and D) forested areas.

beginning of the multidecadal period in early 2000s. More recent disturbance records for 2017–2022 provide a more reasonable timespan for MRDEI assessment as it represents disturbance proportions in MRDEI classes that had sufficient time for repeat-dryness exposure. For 2017–2022, bark beetle and wildfire disturbances increased with increasing MRDEI classes. When aggregated, forested areas across the Western United States exposed to MRDEI classes 4 and 5 had twice the percentages of area impacted than those with reduced exposure rates in classes 1 and 2 (fig. 7.8D).

MRDEI was next evaluated for spatial association with forest disturbances by statistically evaluating whether the proportion of grid cells with disturbance deviated from a baseline proportion of forested area that was exposed to either lower (1–3) or higher (4–5) MRDEI classes (fig. 7.9). All disturbance types, for both 2000–2022 and recent 2017–2022 time periods, occurred at significantly (p <.0001) lower proportions than the forested area baselines within lower exposure MRDEI classes and at significantly higher proportions than baselines within the higher exposure MRDEI classes for the Western United States and the CONUS (fig. 7.9). Interestingly, the co-occurrence of wildfire and bark beetle footprints in the Western United States had the greatest deviation from the forested baseline in MRDEI classes 4 and 5, suggesting disturbance co-occurrence was heavily impacted by forest exposure to repeat dryness represented by MRDEI (figs. 7.9B and D).

Overall, both the general and the statistical assessment of MRDEI classes with forest disturbances confirmed higher MRDEI classes were spatially associated with increased disturbance occurrence. These efforts validate that MRDEI is a useful tool for identifying areas predisposed to repeat-dryness occurrence during the warm season and can assist forest managers by highlighting areas with climate-induced vulnerability to wildfire, bark beetle, and co-occurring forest disturbances.

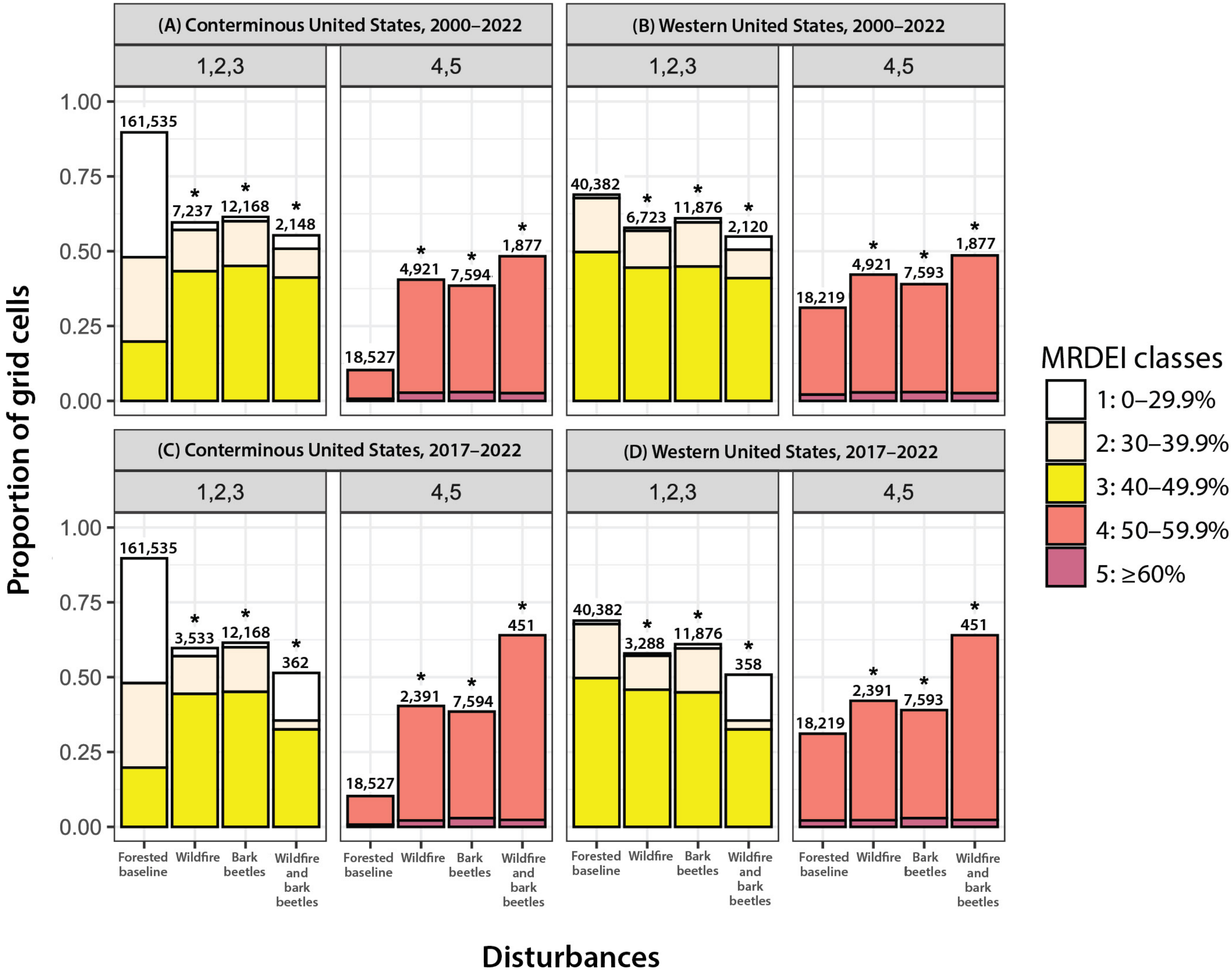

*Figure 7.9—The proportion of forested area baseline and disturbance grid cells that had Multidecadal Repeat-Dryness Exposure Index (MRDEI) class exposure of <50 percent (classes 1–3 based on 2000–2021 MRDEI) and proportion of grid cells that had MRDEI class exposure of ≥50 percent (classes 4–5) impacted by disturbance during 2000–2022 (A and B) and 2017–2022 (C and D) for the conterminous United States (A and C) and Western United States (B and D). * = significant deviation from baseline forested conditions for disturbance type while numbers underneath indicate the total number of grid cells within disturbance categories.*

CONCLUSIONS

Often, forest health assessments focus on a temporally discrete disturbance event in limited spatial forested area to identify absolute weather and climatic thresholds that were catalysts and/or facilitators of disturbance occurrence and severity. This study's approach was the opposite. For all forested areas in the CONUS, this study identified whether a spatial association existed between wildfire and bark beetle records with repeated exposure to dry warm season climatic conditions represented by MRDEI classes. This approach identified site-specific locations in the CONUS that experienced chronic exposure to reduced precipitation during the warm season and demonstrated that wildfires, bark beetles, and co-occurrence of these disturbances are associated with the rate of dry exposure.

With this effort, the MRDEI has been validated by independent disturbance records to showcase areas in the CONUS with repeat exposure to warm season dryness and, where vegetation has composition and structure susceptible to disturbance, areas that are more vulnerable to wildfire and bark beetles due to this exposure. This information is critical for strategic resource management planning efforts to prioritize forested areas because it identifies locations prone to repeat dry exposure where climate adaptation management tactics may be needed to adjust forest density, structure, and/or composition in response to reduced precipitation (Fettig and others 2022b). Specifically, MRDEI was built as a climate-based indicator to be used as an overlay for mid-, broad-, and national-level assessments including the National Insect and Disease Forest Risk Assessment, Climate Risk Viewer tool, regional out-year planning efforts, and forest plan revision assessments, as well as State and Tribal forest action plans (Krist and others 2014, USDA Forest Service 2023).

Finally, this study identified that compounding wildfire and bark beetle disturbances co-occurred in numerous locations across the Western United States with higher MRDEI classes during 2000–2022. Most areas with disturbance co-occurrence experienced bark beetle activity prior to wildland fire incidents. Standing-dead fuels associated with prior bark beetle-caused tree mortality, under certain fire weather conditions, have been associated with unexpected and extreme fire behavior (Fettig and others 2022c, Moriarty and others 2019). This suggests there may be further utility for the aggregated bark beetle records as an indicator of prior disturbance. This indicator may provide useful information related to the risk of wildfire occurrence or potential for extreme fire behavior. Further investigation into the associations between bark beetle disturbances and wildland fire behavior is warranted.

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