CHAPTER 7.

Satellite-based Evidence of Forest Stress and Decline across the Conterminous United States for 2016, 2017, and 2018

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INTRODUCTION

Remote sensing's role in forest monitoring is evolving. Satellite imagery is now systematically used to recognize and track forest disturbances in near-real time (Brown and others 2008, Chastain and others 2015, Hargrove and others 2009, Spruce and others 2011) and for retrospective insights (Meddens and others 2012, Norman and others 2016, Vogelmann and others 2012). Apart from mapping disturbance, high-frequency satellite data provide a reliable way to track vegetation phenology (Hargrove and others 2009, Norman and others 2017), and as vegetation phenology is an important indicator of variation in seasonal climate and the carbon cycle, it warrants being monitored over the long term (Hufkens and others 2012, Wu and others 2014). High-frequency monitoring is slowly shifting the way we monitor forests from periodic or "as needed" efforts toward the systematic tracking of forests and disturbances with remote sensing at weekly to seasonal frequency.

High-frequency monitoring is important as much observed forest change is ephemeral, lasting less than a season. Meanwhile, more consequential impacts to forest structure can be hard to recognize or track except immediately after a disturbance event occurs or during select seasons of the year (Norman and others 2014). Some disturbances have minor or neutral effects, such as leaf stripping in spring or an understory prescribed fire. Others can damage or kill trees, suppress growth for the entire season, or set back succession for decades. As viewed from above using remote sensing, these nuances can blur, yet persistence is a key disturbance indicator that has previously seen little use.

When remote sensing imagery was costly and computational speeds were limiting, research emphasized the refinement of indices that could better identify and map disturbances (e.g., Miller and Thode 2007). As technology has advanced, we now leverage long-underutilized stacks of data for the temporal information they contain (Schroeder and others 2017, Wulder and others 2012). With systematic monitoring across all lands and at broad scales, analysts no longer need to "chase" disturbance events as special projects individually as much as they once did, and this introduces a hierarchical efficiency to monitoring (Chastain and others 2015). High-frequency monitoring allows us to isolate ephemeral from what are more likely to be substantial or impactful changes and to track disturbance events as they unfold during a single growing season or over multiple years. By taking such a systematic, all-lands approach, analysts can detect near-real-time and progressive forest decline, the cumulative effects of multiple disturbances, and successional recovery—all seamlessly across jurisdictions.

Few satellite systems provide enough frequency to produce seamless, long-term maps at continental scale with unobstructed views multiple times per growing season. The twice-daily Moderate Resolution Imaging Spectroradiometer (MODIS) system has that capability. In this chapter, we use a new measure of disturbance, which is based on the magnitude and duration of change, rather than just magnitude at one snapshot in time. Combining both aspects of disturbance allows us to isolate locations with substantive and sustained disturbance impacts indicating forest stress and decline across the conterminous United States.

METHODS

Data Used

For this effort, we required a satellite data stream that had consistently high frequency to provide multiple clear observations each month, or more often, for the conterminous United States and that could be reliably and efficiently processed. We chose the twice-daily MODIS Normalized Difference Vegetation Index (NDVI) data stream from the Terra and Aqua satellites provided by NASA's Global Inventory Monitoring and Modeling Studies (GIMMS) Global Agricultural Monitoring (GLAM) system (see https://glam1.gsfc.nasa.gov). These GIMMS/GLAM products provide separate cloud-filtered, 8-day maximum-NDVI products for both the Terra and Aqua satellites that pass overhead a few hours apart every day. As daytime clouds persist in some locations for weeks, we further processed these paired 8-day products into 24-day compositing periods at 8-day time steps. This provided us with a continuous NDVI time series stack for each of the approximately 145,000,000 MODIS cells in the conterminous United States. The dataset used forms the basis of the U.S. Department of Agriculture Forest Service's *ForWarn II* vegetation change recognition and tracking system (see https://forwarn.forestthreats.org/, Hargrove and others 2009).

Baseline Selection

Any calculation of change requires some formally designated baseline from which comparisons are calculated, and many are possible. As MODIS time series are built from daily data, their history provides a fairly robust record of normal seasonal vegetation phenology, and year-to-year variation in this seasonal dynamic can interfere with the signal from disturbance and vice versa (Norman and others 2017). In this analysis, we use the maximum NDVI value observed during the same 8 weeks over 3 years prior to each of the 3 years analyzed. Had we used the prior year's value, expectations for areas with multiyear drought would be artificially low, as would the NDVI of areas with partial decline within a cell as occurs with progressive beetle kill or logging. However, with a 3-year baseline, severe disturbances that occurred up to 3 years before may linger as they have not yet recovered. This baseline choice may confound estimates of annual disturbance rates because disturbances that are year-exclusive such as non-lethal defoliations or annual drought will not be captured the same way as those disturbances with effects that accumulate such as logging or beetle kill.

Vegetation Index Selection

Efforts to estimate forest biomass or cover using foliage-sensitive indices have a long history, but the information that any given index holds can vary greatly across vegetation types and seasons. Therefore, use of a single index is a challenge when interpreting complex landscapes at continental scales, as change may not uniformly equate to the severity of effects (Miller and Thode 2007). With respect to this project, a practical problem with 240-m-resolution MODIS imagery is quantifying changes in fractional forest, grass, or shrub cover, as an NDVI decline in drought-sensitive low-NDVI open forests can imply more consequence than the same percent decline in a high-NDVI dense forest (Norman and others 2016). A simple adjustment to the denominator in the standard NDVI formula reduces this problem, resulting in the relative difference NDVI, or RdNDVI (equation [1]):

$$RdNDVI = (NDVI_{baseline} - NDVI_{current}) / \sqrt{(NDVI_{baseline} + NDVI_{current})} \quad (1)$$

In addition to the mixed or fractional pixel issue, this adjustment also helps partially overcome problems that arise from NDVI's nonlinear responsiveness, that is, the so-called NDVI "saturation" effect. When forest cover is low, adding (or losing) a few trees has a greater effect on NDVI than losing just a few trees in a densely forested cell. By taking the square root of the denominator, cells with high and low NDVI values will decrease more similarly when both areas experience the same absolute change in NDVI.

Thresholding Magnitude and Duration

Only "summer" periods, defined as the 14 periods with end dates between June 9 and September 21, are used for this project. This seasonal choice avoids most interannual variation in the timing of eastern spring and fall in addition to winter irregularities caused by variable snowpack. Across much of the West, however, variability in the timing of the mid-summer NDVI decline may increase the importance of drought as dry, open western forests are substantially more responsive to drought at that time of year than are dense eastern deciduous forests. Use of summer periods also implies that most disturbances that occur after late summer of the calendar year (such as fall fires or hurricanes) will be omitted, although severe disturbances will typically be reflected in the subsequent year's change map.

Somewhat arbitrary thresholds were imposed to isolate forest disturbances of high magnitude and long duration. We reclassed period maps using NDVI values below -9.4-percent change to 1, then summed the number of periods departed at that threshold in excess of 6 to isolate sustained summer impacts whether consecutive or not. We produced annual maps showing cells where seven or more summer periods were departed at that threshold of magnitude. These steps isolated those places that were both more severely and persistently disturbed for three successive summers.

To restrict this analysis to forested cells at 240-m MODIS resolution, we developed a mask based on the 30-m Landsat-based National Land Cover Database (NLCD) for 2010 (see https://www.mrlc.gov/). A MODIS cell was classified as forest when it had a majority NLCD composition of evergreen, deciduous, or mixed forest. For visualization purposes, we used block statistics to sum the number of forested cells that passed the tests for departure described above in a 4-km grid for each year. We then calculated recent trends by comparing the count for 2018 to the mean of 2016 and 2017 to show where 2018's 4-km^2 departure was improving or worsening. We used zonal statistics to identify the 20 counties with the most forest departure in the East and West and assessed the primary causes of NDVI decline for those locations. For this list, we first ranked counties according to the percent of their total forest area disturbed, created a separate ranking using the absolute number of disturbed cells, and then took the mean of these two 2018 ranks. That approach provided an evenly weighted ranking system based on the relative and absolute amount of detected disturbance.

Datasets for Assessment

We leveraged ancillary datasets to determine the primary cause of observed NDVI declines. These include relevant chapters of recent Forest Health Monitoring reports (Koch and Coulston 2017, 2018, 2019; Potter 2019; Potter and others 2018, 2019, 2020), the monthly record of the Palmer Drought Severity Index (https://www.ncdc.noaa.gov/temp-and-precip/drought/historical-palmers), and annual summary reports of insects and diseases from State and Federal monitoring efforts (see https://www.fs.fed.us/foresthealth/publications/fhp/index.shtm). Locations that experienced large wildfires are identified through use of calendar-dated suppression perimeters (https://www.geomac.gov/). Areas of timber production are generally identified using aerial evidence of industrial logging and Forest Service Forest Inventory and Analysis (FIA) reports (see https://www.fia.fs.fed.us/slides/current-data.pdf). Regional insights are available from the various State timber industry product output and use reports published periodically by the FIA program (Bentley and Steppleton 2013, Johnson 2001, Smith and others 2004).

We expect that our summer NDVI decline maps will only partially correspond with full-year drought maps (Koch and Coulston 2017, 2018, 2019) as we ignore autumn and winter drought. Moreover, forests vary in their ability to convey summer drought stress according to their spatial structure and composition (Norman and others 2016). Similarly, we do not expect perfect correspondence with insect and disease surveys due to inconsistencies of aerial monitoring efforts (Potter and others 2018, 2019, 2020) and MODIS' known limitations of detecting scattered or small-patch tree decline (Eklundh and others

2009, Meddens and others 2012, Spruce and others 2011). Correspondence with annual wildfire detections (Potter 2019) is also nuanced by seasonal differences in the timing of fire and our summer analysis period.

RESULTS AND ASSESSMENTS

Using our MODIS-based approach, we generated three seamless maps of the conterminous United States that show where substantive and sustained summer disturbance occurred during 2016, 2017, and 2018. Through concerted use of magnitude and duration—two quasi-independent measures of severity—we capture growing season impacts better than simply estimating severity from change observed during just part of the growing season. In the sections below, we assess the emergent patterns and their likely primary causes.

2016 Assessment

South—Late summer annual drought helps explain NDVI declines in Georgia, north Florida, and the southern edge of the Appalachians (fig. 7.1A). The extensive Appalachian wildfires of 2016 occurred after summer, so they are not indicated on this year's map. The South-Central United States (eastern Texas, eastern Oklahoma, Arkansas, and Louisiana) were experiencing wetter-than-normal conditions, yet they exhibit significant departure, much like the broader band of southeastern U.S. Coastal Plain States. As our approach detects all forms of canopy disturbance, most of this change in the Southeast likely resulted from timber harvesting as the regional pattern is recurrent across years (Hansen and others 2013). Forest Inventory and Analysis data show that private lands of the South have consistently produced the most pulpwood and timber products in the United States. Comparisons of MODIS cells having strong NDVI decline with recent aerial photos confirm industrial logging's importance, even within areas of drought in the Coastal Plain. Drought in areas of recent clearcuts may amplify this pattern due to nonforest's high sensitivity to drought stress.

Northeast—Moderate to extreme drought emerged across southern New England during late 2015, and by the summer of 2016 its effects on NDVI commingled with an extensive gypsy moth (*Lymantria dispar dispar*) defoliation, particularly across Rhode Island and eastern Connecticut. By June of 2016, western New York was in moderate drought, and then by July, drought extended into central Pennsylvania where gypsy moths also contributed to localized NDVI decline. Declines in the upper Midwest are scattered and include spruce budworm (*Choristoneura fumiferana*) defoliation in Michigan's Upper Peninsula and extreme wind/hail damage in Montmorency County, MI, and Lake of the Woods County, MN.

West—South Dakota's Black Hills show extensive NDVI decline, which likely reflects the moderate drought and the cumulative effects of mountain pine beetles (*Dendroctonus ponderosae*) over the prior 3 years. From Wyoming, Montana, and Idaho, widespread but patchy declines result from drought combined with western spruce budworm (*Choristoneura freemani*)

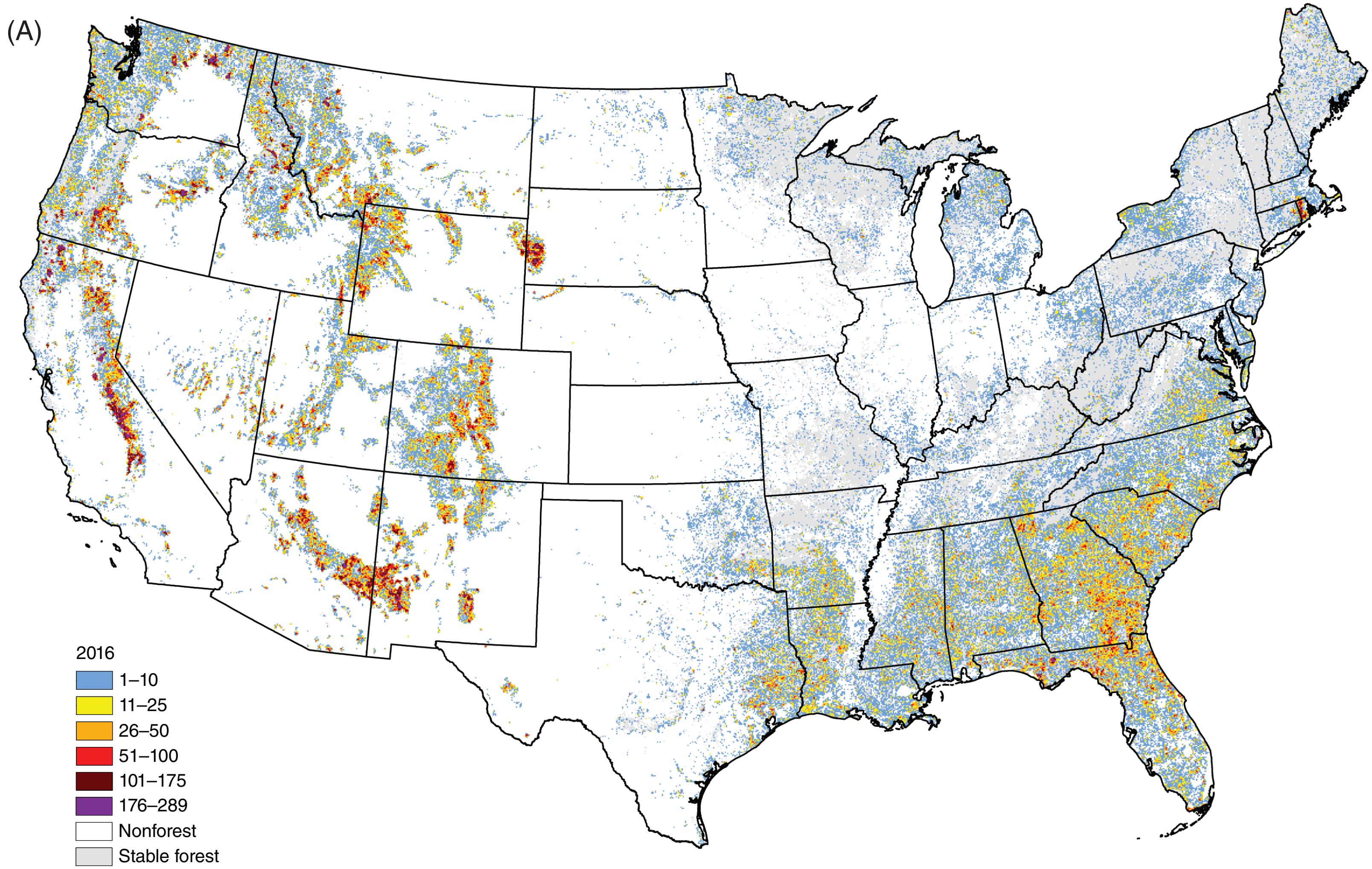

Figure 7.1—Number of forested MODIS cells per 4 km² having NDVI decline of at least 9.5 percent over 3 years for (A) 2016, (B) 2017, and (C) 2018. *(continued to next pages)*

(B)

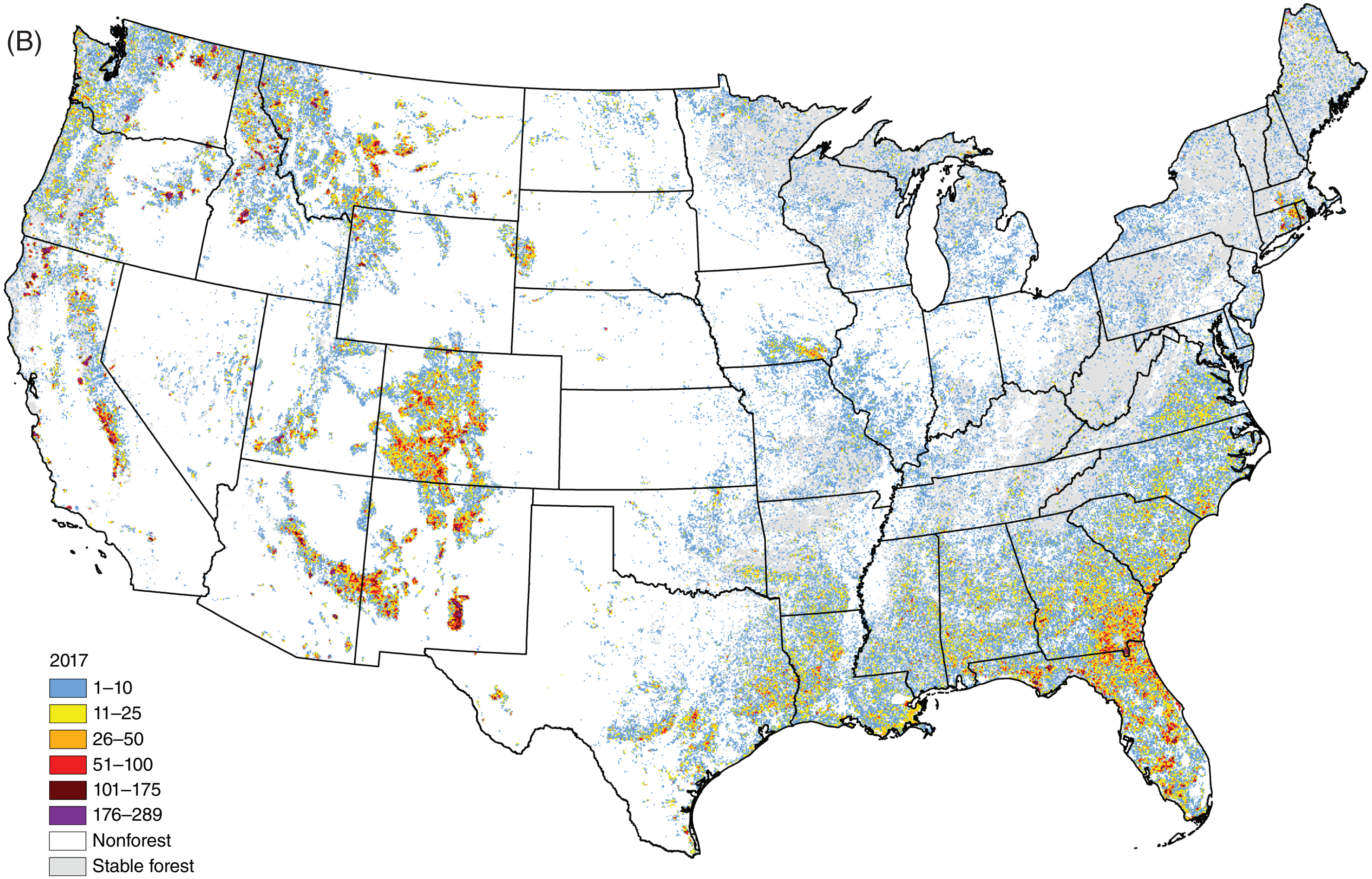

Figure 7.1 (continued)—Number of forested MODIS cells per 4 km^2 having NDVI decline of at least 9.5 percent over 3 years for (A) 2016, (B) 2017, and (C) 2018. (continued to next page)

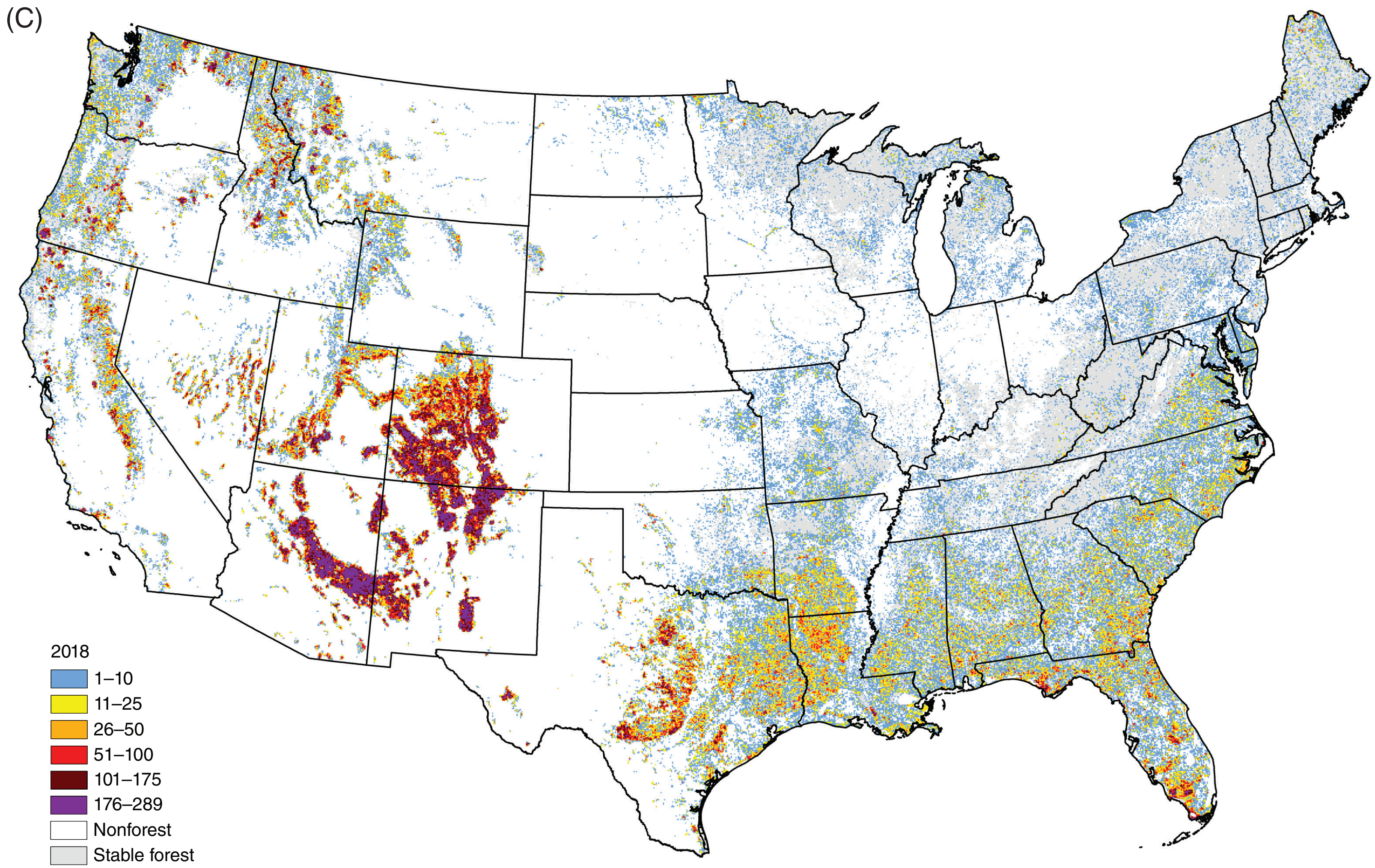

Figure 7.1 (continued)—Number of forested MODIS cells per 4 km² having NDVI decline of at least 9.5 percent over 3 years for (A) 2016, (B) 2017, and (C) 2018.

and localized wildfires. In eastern Oregon's Blue Mountains, western (*D. brevicomis*) and mountain pine beetles, moderate to severe drought, and wildfire contributed to NDVI declines. Across the Coast and Cascade Ranges, insects and wildfire were likely more important causes of decline than the mild drought. In California's Sierras, an exceptional multiyear drought caused mass tree mortality from bark beetles and woodborers. Wildfire led to additional localized NDVI decline. In central Arizona and New Mexico, moderate drought combined with wildfire, beetles, and spruce aphids (*Elatobium abietinum*) to produce declines. In southern Utah, western spruce budworm and other insects during an abnormally dry summer led to spotty declines, and in Colorado, patchy dry weather was likely less important than spruce beetles, western spruce budworms, bark beetles, and localized wildfire. Commercial logging is common in some landscapes including portions of the coastal range of the Pacific Northwest and low to middle elevations of the interior. With cumulative stressors across the West, few forested landscapes escaped NDVI declines for 2016.

2017 Assessment

South—The drought that prevailed across the Piedmont and Appalachians during late 2016 persisted locally into early summer of 2017, but it had largely abated by mid- to late summer with evidence of a few fall 2016 wildfires remaining (fig. 7.1.B). From eastern Texas to Alabama, much wetter than average conditions prevailed. Late-season moisture came from Hurricane Harvey that made landfall in late August, causing widespread flooding in eastern Texas, yet it occurred too late in the summer to be reflected in these maps. Wind damage from Hurricane Irma is absent, as it made landfall in early September—also too late for this 2017 map. Mortality from pine bark beetles spread across Mississippi, Alabama, Georgia, north Florida, and western North Carolina, and much of the NDVI decline shows results from logging activity over the prior 3 years.

Northeast—Most of the Northeast experienced normal or above-normal precipitation during the summer of 2017. The anomaly north of Iowa's southern border is from local drought. Dryer-than-average conditions had occurred from the Chesapeake Bay through southern New England during the early summer, but drought only persisted through the growing season in Long Island, Connecticut, and coastal Maine. Rhode Island experienced gypsy moth defoliation again in 2017, but more activity was observed in eastern Connecticut and nearby Massachusetts. Insect and disease reports describe emerald ash borer (*Agrilus planipennis*) mortality for many Northeastern States, yet MODIS's coarse spatial resolution is ill-suited for detecting scattered canopy damage in mixed vegetation or in species-rich forests, and this limitation is reflected by this map.

West—During the summer of 2017, severe drought prevailed in Montana and the western Dakotas with localized moderate drought elsewhere. This pattern of stress contrasts with that of 2016 when drought prevailed across most of the West. Even though affected by drought in both 2016 and 2017, the condition of the Black Hills shows more impact in 2016. Elsewhere, the patchiness of decline is clearly evident in 2017, and this likely results from reduced drought stress combined with localized fire and insect-related decline caused by fir engraver (*Scolytus ventralis*), spruce beetles, and mountain pine beetles. As a 3-year baseline is used in these change maps, severity for 2017 reflects cumulative mortality since the fall of 2014.

2018 Assessment

At the time of this analysis, complete insect and disease aerial survey data for 2018 were not yet available, so a complete assessment of defoliators and borers is not yet possible. However, the extensive insect defoliation that plagued southern New England in 2016 and 2017 was greatly abated, as shown on figure 7.1C. Bark beetles continued to kill trees across much of the West, and as a 3-year baseline is used, local areas of mortality since 2015 can persist on the 2018 map.

For much of the summer, severe to extreme drought impacted a vast area from southern California to Texas. Hardest hit was the Four Corners area of Utah, Colorado, Arizona, and New Mexico, and this region shows extreme departure unlike anything seen for 2016 or 2017. In late 2017, Hurricane Irma severely impacted southwestern Florida, and some impacts have become evident on the 2018 map, such as in the coastal mangrove forest. Absent, however, are impacts from 2018's Hurricanes Florence and Michael that occurred too late to show up on this map. Damage from October's Hurricane Michael was particularly extensive across Florida's panhandle into southwestern Georgia and southeastern Alabama, so it will show up strongly on the 2019 map with the same approach.

Figures 7.1A, 7.1B, and 7.1C reveal where substantive and sustained disturbances were observed annually for 2016, 2017, and 2018, respectively. Figure 7.2 provides a contextual interpretation of the 2018 season that reveals the directional change in disturbance compared to the mean NDVI decline of the prior 2 years. Areas in blue show less disturbance relative to the recent past (i.e., "gain" or "improvement"), while reds show where declines worsened during 2018's summer. Accordingly, blue areas relate to where 2016 or 2017 experienced severe disturbance and 2018 saw a reprieve from further loss. Note in particular southern New England's gypsy moth activity and the areas of drought and beetle damage in California's Southern Sierra and North Dakota's Black Hills region. Consistent with figure 7.1C, the most extensive area of red includes Texas and the Four Corners area; in 2018, drought stress was far worse there than it was during the 2 prior years. The mosaic of light blue and light red in north Georgia and surrounding States generally reflects the patchiness of industrial logging, with the landscape experiencing a continuous cycle of clearcutting and regeneration as a shifting mosaic. In the West, large burn scars show up as both coarse patches of red or blue depending on when they occurred, with red having burnt recently and blue representing a recovering state.

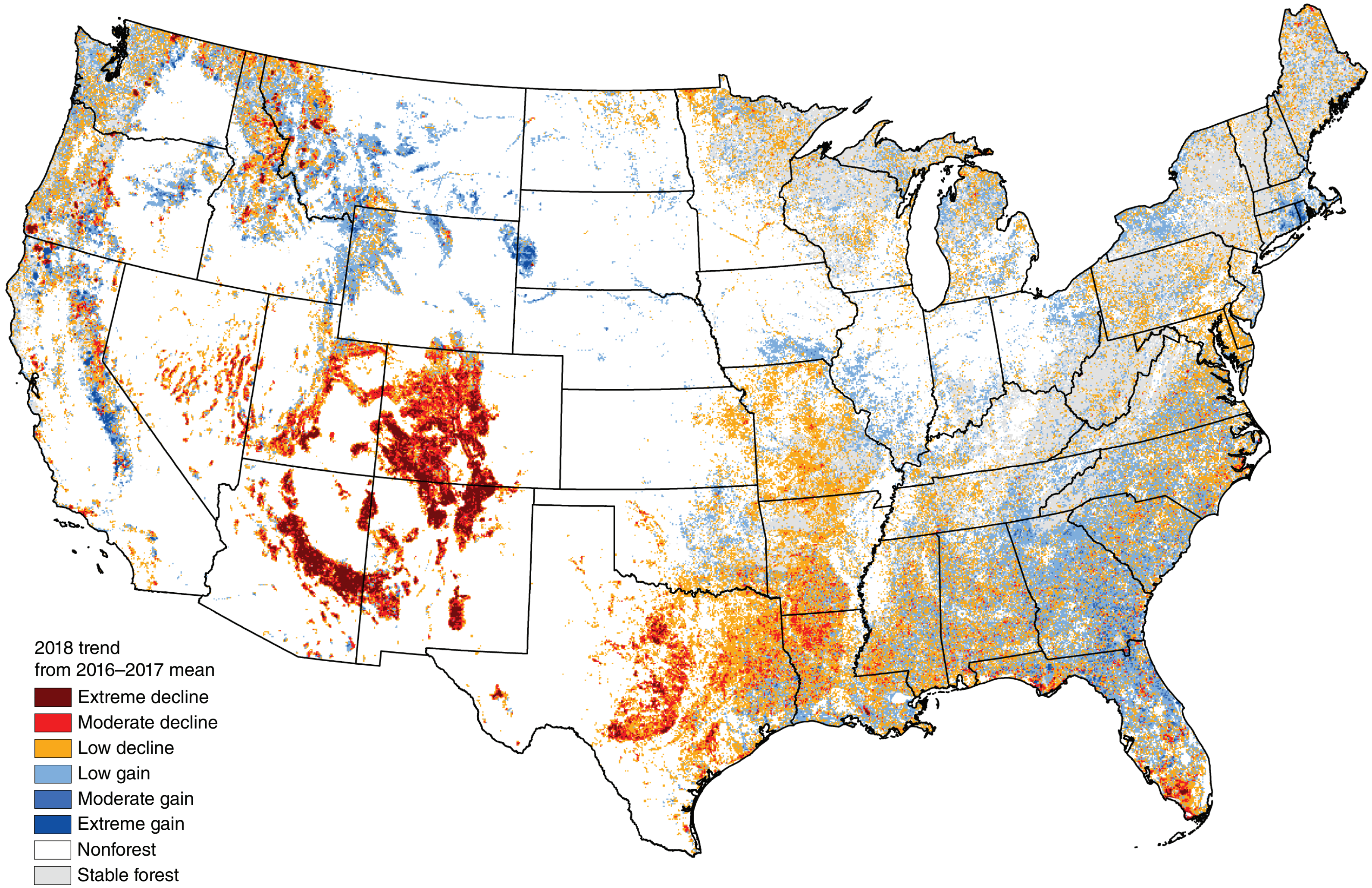

Figure 7.2—The 3-year trend in substantive and sustained forest disturbances from the summers of 2016–2017 (figs. 7.1A and 7.1B) compared to summer 2018 (fig. 7.1C).

Blue may also represent relief from just one of several compounding causes. Note that while the Southern Sierra Nevada was in drought during 2018, the hard-hit centers of mortality in red during all 3 years (figs. 7.1A, 7.1B, 7.1C) show up in blue on figure 7.2. Blue does not necessarily denote successional recovery, although it can be that, as noted with the response from wildfires, given the shifting 3-year window being used.

Drought is the leading disturbance cause for the 20 counties in the East and West that show the strongest relative NDVI declines for 2018 (table 7.1). Two southern Florida counties that were impacted by Hurricane Irma made the eastern list. All western counties ranking high in terms of substantive and sustained disturbance did so because of the influence of the extreme drought in the Four Corners area. Many of these counties had compounded disturbances from drought, beetles, and wildfire, and while the 2018 drought appears to be the primary stressor, mortality from other causes since late 2015 may also explain why these counties ranked high.

DISCUSSION AND CONCLUSIONS

Routine broad-scale use of remote sensing is practical for assessing many forest health concerns. Every remote sensing data stream has its strengths, and the high-temporal-frequency MODIS imagery used in this chapter is exceptional because it allows disturbance tracking in near-real time, and with that it provides a more nuanced consideration of growing season impacts as measured by

Table 7.1—Eastern (top) and Western (bottom) U.S. counties exhibiting the most substantive and sustained disturbance during the summer of 2018

2018 Rank[a]	County and State	Percentage of county forested	Percentage of forest disturbed in 2018[b]	Leading disturbance causes[c]
East				
1	Jeff Davis Co., TX	8.8	87.2	Drought
2	San Saba Co., TX	12.2	87.3	Drought
3	Palo Pinto Co., TX	28.0	70.8	Drought
4	Eastland Co., TX	11.3	86.0	Drought
5	Stephens Co., TX	11.1	79.1	Drought
6	Lampasas Co., TX	9.3	94.9	Drought
7	Comal Co., TX	37.3	61.6	Drought
8	Coryell Co., TX	17.4	63.8	Drought
9	Gillespie Co., TX	6.5	90.8	Drought
10	Erath Co., TX	7.5	82.2	Drought
11	Bosque Co., TX	17.2	61.8	Drought
12	Burnet Co., TX	23.5	57.5	Drought
13	Llano Co., TX	9.0	77.0	Drought
14	Uvalde Co., TX	17.1	54.1	Drought
15	Collier Co., FL	53.0	37.1	Fire, Hurricane Irma
16	Hays Co., TX	26.5	54.8	Drought
17	Monroe Co., FL	31.7	40.1	Hurricane Irma
18	Real Co., TX	47.3	44.5	Drought
19	Young Co., TX	6.9	81.4	Drought
20	Kimble Co., TX	5.6	77.0	Drought
West				
1	Gila Co., AZ	35.4	91.6	Drought, fire
2	Navajo Co., AZ	10.8	84.5	Drought, fire, insects
3	Colfax Co., NM	34.2	80.2	Drought, fire, insects
4	Rio Arriba Co., NM	40.0	78.8	Drought, fire, insects
5	Montrose Co., CO	28.6	81.0	Drought, fire, insects
6	Apache Co., AZ	22.3	76.3	Drought, fire, insects
7	Fremont Co., CO	47.6	78.8	Drought, fire, insects
8	Lincoln Co., NM	10.6	82.6	Drought, insects

continued

Table 7.1 (continued)—Eastern (top) and Western (bottom) U.S. counties exhibiting the most substantive and sustained disturbance during the summer of 2018

2018 Rank[a]	County and State	Percentage of county forested	Percentage of forest disturbed in 2018[b]	Leading disturbance causes[c]
9	Otero Co., NM	15.8	76.6	Drought, insects
10	San Miguel Co., CO	36.0	79.4	Drought, insects
11	Taos Co., NM	50.3	73.0	Drought, insects
12	La Plata Co., CO	47.5	74.3	Drought, fire, insects
13	Graham Co., AZ	14.7	74.3	Drought, fire, insects
14	Costilla Co., CO	32.5	78.4	Drought, fire, insects
15	Sandoval Co., NM	19.2	73.3	Drought, fire, insects
16	Greenlee Co., AZ	42.8	72.4	Drought, fire, insects
17	Las Animas Co., CO	14.2	73.0	Drought, insects
18	Park Co., CO	38.1	69.5	Drought, fire, insects
19	Garfield Co., UT	18.7	66.9	Drought, fire, insects
20	San Juan Co., UT	5.8	74.3	Drought, insects

[a] Counties rank highest for having more absolute disturbed area and for a higher percentage of their total forest disturbed.

[b] The percentage of county disturbed in 2018 is derived from the number of majority-forested MODIS cells having at least 9.5-percent 3-year NDVI decline for seven or more 8-day periods during the summer months.

[c] The primary disturbance cause is inferred from ancillary datasets described in the methodology section. When multiple causes of disturbance are present, only one needs to increase for 2018 for this rank.

magnitude and duration. Like every forest monitoring approach, this too brings its share of caveats, with the most important outlined below.

MODIS' 240-m resolution can be too coarse to recognize some forest damage of concern such as loss of individual species in mixed stands, particularly in the East. Only when species are sufficiently dominant within a MODIS grid cell can decline or mortality be clearly resolved. Surviving trees or other vegetation can compensate for minor losses, particularly in the productive East when using NDVI. This is illustrated by the inability of MODIS to capture mortality from the emerald ash borer or the southern pine beetle (*Dendroctonus frontalis*), but it applies more generally to mixed stands. For such fine-textured monitoring needs, tailored applications of 30-m Landsat, 10-m Sentinel 2, or sub-meter-resolution imagery are warranted.

Forests that experience gradual decline over multiple years are hard to capture with short-term baselines. The 3-year baseline used in this chapter helps with that, but some NDVI declines occur over many years or a decade. These declines are not captured by this particular technique, but longer baselines are possible. However, in mixed forests, slow mortality often allows compensatory growth from adjacent vegetation that can mask damage entirely. This also relates to the limitation of the vegetation indices that can only separate species when they occur as dominants in simple vegetation types.

Even with the corrective use of RdNDVI and forest masking, MODIS' coarse resolution means that edge or open forests often have high proportions of grass and shrub cover. Since grass and shrubs are highly sensitive to summer drought, observed changes may not be a direct measure of forest change akin to canopy damage or tree mortality.

Four thresholds in this analysis are somewhat subjective. First, use of a moving 3-year baseline adds complexity to the interpretation of maps, as some disturbances persist longer than others sometimes apart from ecological impacts. Second, the choice of an RdNDVI departure magnitude threshold of -9.5 percent means that results may be less sensitive to the loss of individual species in mixed stands than severe annual drought in open forests that may just include reduced tree growth. Third, the choice of calendar dates to define the summer analytical period is phenologically imperfect for some regions. Finally, our choice of duration thresholds is similarly limiting because of how it relates to differing phenological growing seasons. We have attempted to convey more clarity and transparency in these maps by simplifying these assumptions with judicious thresholds.

With this, like any coarse-resolution remote sensing product, there is a critical need for assessment and interpretation, which may need to occur at landscape to local scales. In many cases, though not all, field observations or detailed ancillary data are critical for accurately assigning causation. This is most important where there are multiple agents of change present at the same place and time.

These maps show only areas of relative NDVI decline, not recovery, and understanding that balance would help address the higher-level question of sustainability that we are not pursuing here. For example, forest recovery can contextualize disturbance in areas that experience clearcut logging or patch-mosaic wildfires. Within productive mixed forests with finer resolution gap phase processes at work, however, NDVI recovery and disturbance can occur concomitantly within a single MODIS cell.

The maps in this chapter reveal summer patterns of stress and decline across the conterminous United States from all causes that had a substantive and sustained impact on forest canopies. This change includes mid- to large-sized patchy tree mortality and NDVI declines caused by logging, development, mining, insects and disease, fire, wind, hail, and drought somewhat indiscriminately, though not inclusively as MODIS's resolution is ill-suited for resolving low-density canopy damage in mixed stands. In areas such as the Southeastern U.S. Coastal Plain and Piedmont that experience continuous and patchy logging, it is difficult to reliably isolate forest disturbance impacts from insects and disease, wind, or wildfire at MODIS resolution. While this problem is not eliminated by higher resolution imagery (e.g., Hanson and others 2013), more intense analysis that leverages frequent, high-resolution imagery may be needed to separate the various interactive causes of forest change with confidence.

The power of MODIS is that it is rooted in twice-daily observations that permit a product quality and efficient seamlessness that is unmatched by any existing finer resolution datasets. With a reliable history that goes back to 2003 (and less reliably to 2000), monitoring questions can be addressed at sub-seasonal frequency looking back over a decade and a half. With high-frequency observations, MODIS also provides enough monitoring consistency to systematically address seasonal disturbance duration, not just magnitude. Seasonal duration introduces a new dimensionality to the concept of severity that in many cases can likely result in more accurate estimates of disturbance impacts while providing nuanced insights into the disturbances that may be present.

As remote sensing technologies and processing capabilities evolve, we are poised to advance forest health monitoring in novel ways. National maps such as these convey where large-scale stressors are problematic and how regions and landscapes differ in terms of the structure and variability of their disturbance dynamic. More focused monitoring questions are necessarily pursued at finer resolution to understand landscape and local change. Together, such scaled efforts can provide a hierarchical sense of forest stress and decline with unparalleled context and precision.

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