CHAPTER 4

Satellite Observations of Forest Disturbances for the Conterminous United States During the 2021 Growing Season

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INTRODUCTION

Accurate forest disturbance mapping is a critical aspect of forest monitoring, but efforts have been inconsistent over landscapes and time (Coleman and others 2018, Housman and others 2018, Potter and Paschke 2022). Remote sensing is particularly adept at monitoring change in canopy cover from patch mortality or defoliation at scale, but it struggles to resolve dispersed tree impacts common to mixed species forests, gradual declines, delayed mortality, and cumulative impacts. As our need for precise mapping and understanding of disturbance grows, technology has provided invaluable solutions, but efficient causal attribution and impact assessment remain obstacles at broad scales. Recent advances in high-spatial-resolution imagery and high-speed computation have revolutionized forest canopy monitoring. With more efficient use of higher resolution imagery, our capacity to understand the mechanisms of forest change and precise disturbance impacts at scale has grown (Norman and Christie 2022).

Coordinated use of remote sensing datasets of different temporal and spatial resolution can satisfy a range of forest monitoring needs. For example, imagery is often of sufficiently high spatial resolution to resolve change in the canopy status of tree clusters if not that of individual trees. While such high-resolution imagery can also be generalized to map change in forest patches, coarser 250-m-resolution imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) (i.e., Terra and Aqua satellites) and the 300-m-resolution European Space Agency's Sentinel-3 satellites can often satisfy this need as well but do so more efficiently at scale due in part to their high pass-over frequency. Such spatially coarse but frequent imagery tracks large canopy disturbances at subseasonal temporal resolution in ways that distinguish persistent disturbance from ephemeral disturbance. Of particular concern in eastern deciduous forests are early season fire, wind, frost, or defoliation events, which may be detectable for just a few weeks or months of the growing season and yet be the target of forest monitoring efforts. Moreover, frequent observations give us more opportunities to acquire clear canopy views during the most optimal time of year for a given region. That is, with high-frequency streaming data, analysts can avoid issues related to seasonal weather-related differences in spring and fall timing and better target disturbances based on their optimal phenological characteristics.

This chapter provides a broad overview of disturbance during the 2021 growing season for the conterminous United States (CONUS) using spatially coarse but temporally frequent satellite imagery. We demonstrated the scalability of this general technique in an earlier publication, which described mapping of prominent disturbances for the United States at 10-m resolution (Norman and Christie 2022).

METHODS

We used Google Earth Engine (Gorelick and others 2017) to calculate the Normalized Difference Vegetation Index (NDVI) for the CONUS for a portion of the 2020 and 2021

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growing seasons using surface-corrected MODIS 8-day composite NDVI from the Terra and Aqua satellites (MOD09Q1 and MYD09Q1, respectively) at 250-m resolution. We calculated the maximum value of these 8-day NDVI values over regionally adaptive 1–2-month windows. This regional modification of date windows lets us avoid months with heavy clouds and strong seasonal phenological change, while letting us capture key ephemeral disturbances during the growing season. For areas west of the 100th meridian, the NDVI composite window was July 15 to August 31 during the warm season; for the Northeast above the 36.5° N parallel, it was June 15 to July 15 to capture the effects of early summer defoliators; for the South, we used June 1 to July 15 given the region's early growing season and patchy persistent cloud cover; for peninsular Florida south of the 29° N parallel, we used September 1 to October 31 when clouds were less frequent compared to earlier in the summer. Comparison of NDVI values for 2021 with 2020 provided a regionally mosaiced map of 1-year change in NDVI.

We filtered the MODIS grid cells to only include those having majority forest cover based on the 30-m classification of the North American Land Change Monitoring System (NALCMS) for 2015 for a portion of Canada (http://www.cec.org/north-american-land-change-monitoring-system/) (Latifovic and others 2012) and the National Land Cover Dataset for 2016 for the United States (https://www.mrlc.gov/) (Jin and others 2019). Forests included evergreen, deciduous, mixed forest, and woody wetland types.

We thresholded NDVI departure at -0.05 and used values lower than that to define departure. We summed the majority-forest MODIS cells with NDVI departures and the total number of forest cells overall by 834-km^2 hexagons to provide landscape-scale insights useful for broad-scale monitoring (Norman and Christie 2022, Potter and others 2016). This gave us the percentage of majority-forest MODIS cells with NDVI departures for each hexagon. Where tree cover was sparse or absent, such as across the Great Plains, we imposed a minimum forest area requirement of 1500 ha (3,700 acres) for a hexagon.

RESULTS AND DISCUSSION

At a broad scale, the pattern of prominent forest disturbances across the CONUS for 2021 reflected that of prior years (fig. 4.1) (Norman and Christie 2020, 2022). The strongest NDVI departures occurred in the West, followed by the South, then the Northeast. States or ecoregions having these large anomalies often shift, however, in response to specific regional disturbances, such as drought, and more local disturbances, such as fire, insect outbreaks, and hurricanes.

West

The major disturbance detected for the West during 2021 was drought. According to the U.S. Drought Monitor (USDM), by August 2021, severe to exceptional drought was widespread and affecting every State west of the 100th meridian except for the southern Great Plains (https://droughtmonitor.unl.edu/). Other

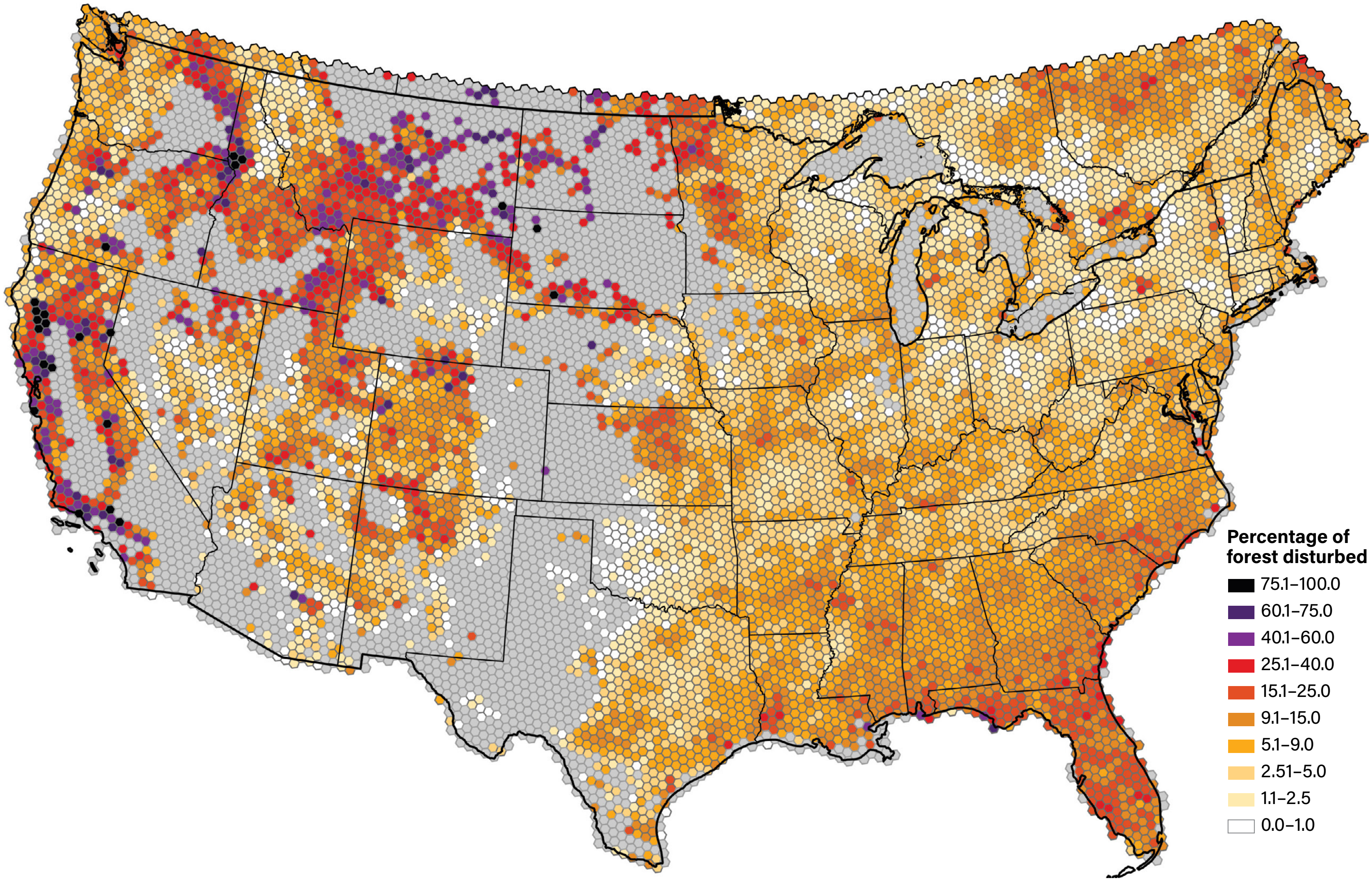

Figure 4.1—Percentage of majority-forest 250-m Moderate Resolution Imaging Spectroradiometer grid cells with disturbance in 2021 compared to 2020 using a Normalized Difference Vegetation Index departure threshold of ≤-0.05 summarized by 834-km² hexagons for the conterminous United States and southern Canada. Gray hexagons had too little forest cover to reliably map.

regional exceptions where drought was minor or absent included the Cascades and coastal forests of western Washington, coastal Oregon, northwestern Montana, the Black Hills of South Dakota, and central Colorado. Through summer, the USDM showed severe to exceptional drought building northward, with Southwestern States experiencing summer drought of longer duration than the Northwestern States. Figure 4.1 reflects more NDVI anomalies in California and in the Northwestern States than for Arizona, New Mexico, Colorado, and Utah, so the general pattern seen in figure 4.1 does not reflect differences in summer drought duration. It may, however, reflect differences in the baseline NDVI values from 2020 as there was more drought in the Southwest in 2020. The 1-year NDVI departure for those areas may reflect a less reliable expectation of "normal."

Known limitations of tracking evergreen tree stress associated with drought in the West from coarse remote sensing and NDVI are within-grid-cell mixed vegetation cover and the relative insensitivity of conifer NDVI to drought stress. From an optical remote sensing perspective, grass is highly sensitive to drought stress compared to evergreen trees, so 13-ha MODIS grid cells with a mixed grass and evergreen tree cover may be overwhelmed by variation in grass productivity or phenological responses more than any direct tree response to drought (Norman and others 2016). Spatial patterns of NDVI departure may then be a function of the fraction of the MODIS cell that supports the sensitive (grass) cover type rather than a meaningful measure of tree stress. Adding to the assessment challenge, extensive western forests have recently lost their conifer cover to fire, drought, or insects, but these remain classified as "forest" by NLCD. As disturbance and mortality become more widespread, this is a growing problem that can only be resolved by a more accurate or current forest mask or through use of finer resolution imagery, such as Sentinel-2 that reduces the mixed cover-type problem (Norman and Christie 2022).

Large local anomalies are readily seen across the West in figure 4.1, and these usually related to large wildfires that occurred between the fall of 2020 and early 2021. The most prominent nondrought disturbance that is evident on figure 4.1 is the million-acre (418 000 ha) August Complex that burned a large part of the Mendocino National Forest and adjacent areas in northwestern California during late 2020. Based on perimeters from the Monitoring Trends in Burn Severity (MTBS) project (https://www.mtbs.gov/) and satellite-detected thermal hot spots, wildfires from late 2020 or early 2021 also explain most isolated hexagon anomalies elsewhere in California, Oregon, Idaho, Colorado, and Arizona. In less treed areas, such as northern Nevada, eastern Montana, and the Dakotas, however, figure 4.1 shows forest disturbances not associated with wildfires. These areas could have been responding to drought, which is likely given their tendency to occur in riparian zones that include considerable edge with drought-sensitive grass. These areas experienced moderate to exceptional drought during the 2021 growing season.

Insect and Disease Survey (IDS) maps, coordinated by the U.S. Department of Agriculture, Forest Service, Forest Health Protection program, showed extensive tree defoliation or mortality across forest areas of all Western States, including areas experiencing drought in 2021, but not exclusively. Wherever the 2021 insect damage exceeded that of 2020, it would add to the fraction of the hexagon measured as disturbed. However, as the COVID-19 pandemic may have impacted the extent of mapping in 2020 (Potter and Paschke 2022), the influence of a single-year baseline in 2020 cannot be easily resolved. In 2020, IDS maps showed large areas of canopy damage in Colorado, New Mexico, Montana, Idaho, Washington, and Oregon. In California, however, COVID-19 precautions prevented aerial survey flights from occurring in 2020, making comparisons impossible.

Northeast

The USDM showed severe to exceptional drought in Minnesota and Iowa and minor drought in northernmost New England and central Appalachia during the summer of 2021. Low to severe drought was also a factor in New England in 2020. Figure 4.1 shows strong forest NDVI departure in central and western Minnesota that is consistent with the extreme drought of midsummer, but there was not a clear association with drought for northern New England nor the central Appalachians.

Moderate forest NDVI decline was evident over broad portions of many Midwestern States where tree cover is fragmented or limited to riparian zones. The IDS maps were incomplete for most of these areas with limited forest, so the cause of this decline was difficult to interpret from the available data. A portion of this decline may be from emerald ash borer (*Agrilus planipennis*) mortality. When ash (*Fraxinus* spp.) occurs in mixed stands and declines gradually over several years, it can be challenging to accurately map these declines based on anything other than aerial flights or very high-resolution remote sensing.

During early summer 2021, spongy moth (*Lymantria dispar*) caused large patches of tree defoliation in Michigan, Pennsylvania, New Jersey, New York, Connecticut, New Hampshire, Maine, and Ontario, Canada. These show up well on figure 4.1 and agree with the raw maps of NDVI change and with IDS maps of spongy moth defoliation (fig. 4.2). The spongy moth outbreak in Michigan was especially notable and follows a similar large outbreak there in 2020. Elsewhere in the Northeast, extensive patches of eastern spruce budworm (*Choristoneura fumiferana*) defoliation were mapped in northeastern Minnesota, and Lophodermium needle cast of pines was mapped in Cape Cod, MA. Also detected were emerald ash borer damage in southeastern Pennsylvania, and in the South, winter ice storm damage in eastern Kentucky. Other than the spongy moth defoliation, none of these other damage agents is indicated in the hexagons on figure 4.1. This is either because they were of low impact or limited extent, or their mapped impacts were relatively minor when taken as a percentage of the available forest in that hexagon. As shown on figure 4.2, MODIS has no problem mapping large patches of spongy moth defoliations at 250-m resolution (Spruce and others 2011). Detection of smaller patches often requires higher resolution imagery, such as Sentinel-2 (Norman and Christie 2022).

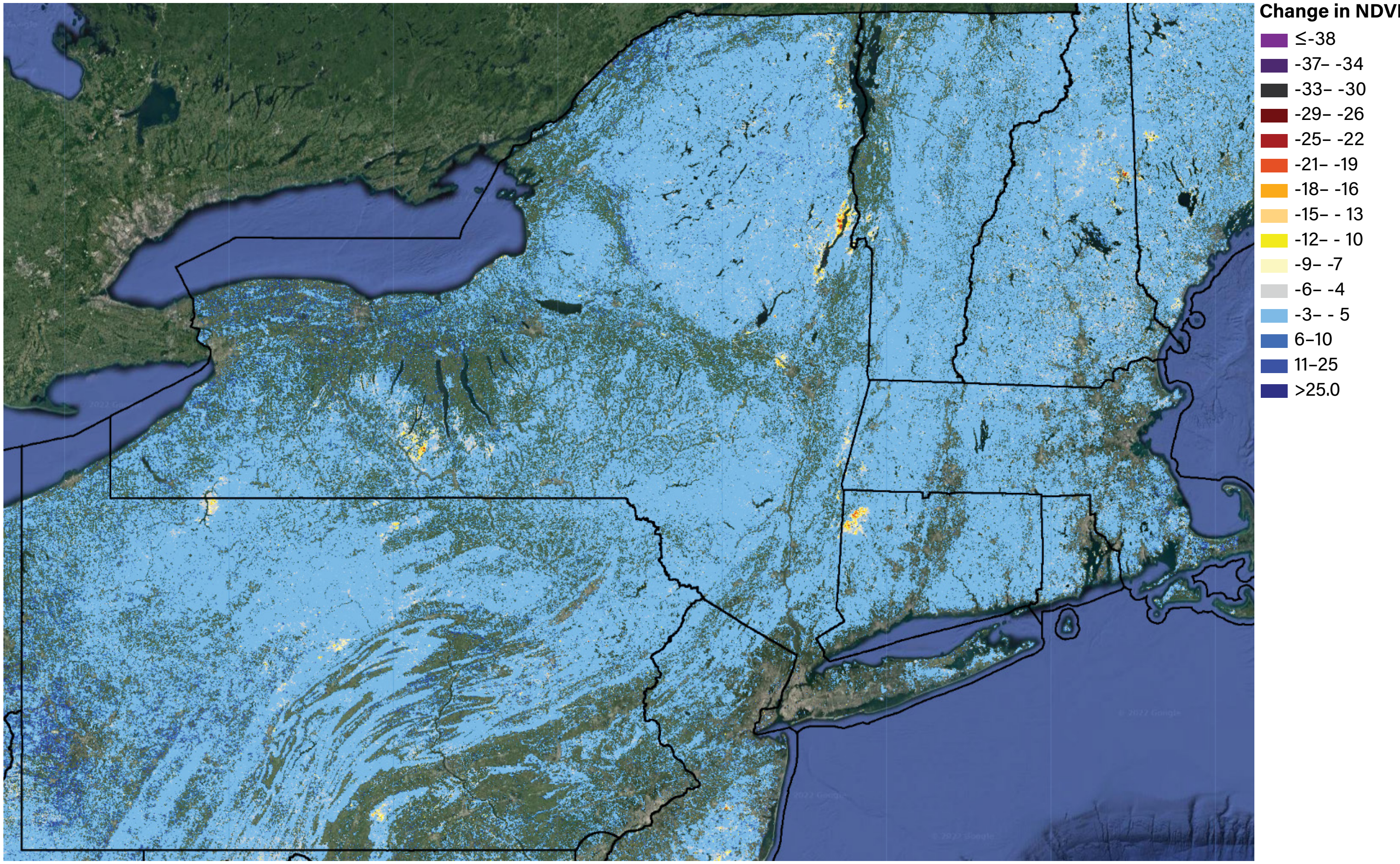

*Figure 4.2—A comparison of absolute 1-year change in Normalized Difference Vegetation Index (NDVI) at 250 m from the Moderate Resolution Imaging Spectroradiometer showing the regional occurrence of insect defoliation, mostly from spongy moth (*Lymantria dispar*) in the Northeast (6/15 to 7/15 composites for 2021 versus 2020).*

South

As has been observed recurrently, the leading cause of forest disturbance in the South has been commercial logging operations, and much of the NDVI departure seen in the Southeast's Coastal Plain on figure 4.1 reflects this cause (Hansen and others 2013; Norman and Christie 2020, 2022). It is common for hexagons of the Southeast to exhibit 5 to 15 percent of their forest as departed from NDVI values of the prior year.

There are numerous hot spots of disturbance activity shown on figure 4.1 that can be attributed to other or more complex causes. Damage from Hurricane Laura in southwestern Louisiana and from Hurricane Sally in southern Alabama are evident. A subsequent increase in logging compared to the prior baseline year may have also contributed to these patterns there. Florida also shows spotty NDVI departures; which relates to the variable rate of logging in places. The rate of logging may have increased in the wake of Hurricane Michael in Florida's panhandle, but most areas shown in red for Florida on figure 4.1 are not directly or indirectly associated with storm damage. This may be a combination of fire and logging operations and, in some places, lingering atmospheric problems not fully removed by this analysis.

CONCLUSIONS

Remote sensing has a proven record of mapping and tracking large patch disturbances at coarse scales (Hansen and others 2013, Kennedy and others 2018, Spruce and others 2011). The patterns shown on figure 4.1 represent those more prominent disturbances while contextualizing them within the forested landscape in which they occur. The research frontier lies with precise mapping of disturbances at much finer resolution (i.e., with sufficient detail to capture the status of individual canopy trees); similar techniques have been, and can be, used with 10-m-resolution Sentinel-2 imagery or finer using Google Earth Engine (Norman and Christie 2022). This finer resolution is useful for mapping tree mortality in mixed stands, which are common in areas of the Eastern United States, in addition to resolving cause when multiple drivers of forest change co-occur. For example, mapping emerald ash borer mortality has been resolved by integrating Landsat with Sentinel-2 and lidar height data in Minnesota (Host and others 2020). In the Southern Appalachians, gradual tree mortality from the nonnative hemlock woolly adelgid (*Adelges tsugae*) could be partially distinguished from fire regime mortality using Landsat over a longer period than the 1-year analysis used in this current study (Khodaee and others 2020). Regional or national analyses provide a coarse-filter perspective on forest disturbance, but a full understanding requires landscape or site analysis that involves multiple years of context and regional expertise.

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