

INTRODUCTION

National-scale satellite-based forest monitoring can provide uniform and timely insights into forest health. Monitoring across jurisdictions satisfies a basic need, since disturbances such as insects and diseases, wildfire, or severe weather do not respect Federal, State or local boundaries. Monitoring across seasons at high frequency satisfies a second basic need, because early detections can affect the choice of actions that managers take, such as altering the progress of a defoliator or deciding where to prioritize post-disturbance remediation.

These two strengths of satellite-based monitoring—cross-jurisdictional uniformity and high-frequency detection—do not come without effort. One of the greatest challenges for development of a high-frequency change detection product is knowing what to expect from healthy forests in terms of a meaningful baseline normal, since such expectations change from place to place, throughout the year, and according to the various needs of land managers. With an appropriate baseline in place, clouds, snowpack, and the seasonal effects of variations in temperature and precipitation may still cause anomalies that appear similar to damage caused by insects and disease, wildland fire, extreme weather, and other disturbances. Actual change recognition often requires not only maps of change, but an integration of knowledge that includes ancillary datasets presented in an accessible way.

This chapter highlights recent monitoring results from *ForWarn*, a satellite-derived change detection system operating across the conterminous United States that can be accessed at <http://forwarn.forestthreats.org> (Hargrove and others 2009). *ForWarn* is a joint effort of the U.S. Department of Agriculture Forest Service's Eastern and Western Threat Assessment Centers and NASA-Stennis Space Center that is designed to monitor and interpret all types of forest change. *ForWarn* has been largely funded by the National Forest System in response to a Congressional mandate to develop an early warning system for forests as part of the Healthy Forests Restoration Act of 2003.

THE SATELLITE-BASED TECHNOLOGY

Since January 2010, the *ForWarn* system has been used to detect environmental threats to forests caused by insects and disease, wildfires, extreme weather, and other natural and man-made events (see Norman and Hargrove 2012, Norman and others 2013, and Spruce and others 2011 for case studies). *ForWarn* disturbance detections rely on changes in the timing of vegetation “greenness” as measured by the Normalized Difference Vegetation Index (NDVI) derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensors. NDVI compares wavelengths in the red and infrared range to measure and track changes in the health status of vegetation. Seasonal periodicities in NDVI reflect the collective leaf

CHAPTER 6.

Monitoring Forest Disturbances across Seasons Using the *ForWarn* Recognition and Tracking System

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phenologies of plants on the land surface, while departures from this natural rhythm denote stress or disturbance (Spruce and others 2011).

Phenology can be thought of as both a driver and a response variable. Acting as a driver, phenology controls ecosystem functions and services like productivity, leaf area, and biomass, and it is strongly correlated with vegetation structure, standing stocks, and carbon across a broad range of forested ecosystems. As a response variable, phenology is largely influenced by vegetation reactions to primary growing conditions such as climatic and edaphic factors, but localized changes in phenology can indicate disturbance. Because of these sensitivities, phenology has been broadly recognized as a useful indicator of ecosystem health and function.

ForWarn captures seasonal phenological change by dividing the year into 46 overlapping 24-day periods. Each period overlaps the next by 16 days to minimize cloud contamination (table 6.1). The maximum NDVI observed for each pixel in each period is used as the current greenness value for all but one of the *ForWarn* change products, while the most recent clear value is used for the *Early Detect* product. The *Early Detect* product may sometimes suffer from clouds, smoke, or haze, but it is better than other baselines for detecting disturbances quickly.

Forest disturbance and recovery can be rapid—appearing from one *ForWarn* period to the next—or they can occur gradually over the course of months or years. Our ability to

detect all these changes requires a suite of baseline normals that capture different prior conditions. *ForWarn*'s baselines empower analysts to detect change relative to the prior year, the maximum of the last three years, and the maximum since January of 2000, when MODIS first became available. Some landscapes experience considerable variability in NDVI from year to year due to climatic variation, and that seasonal variability can make the use of simple maximums problematic for detecting disturbance during seasonal transitions. *ForWarn* addresses this problem by including two additional baselines that define normal from the average conditions at each period over time. One baseline uses the average of each site's maximum NDVI since 2000, and the other combines phenologically similar neighbors for a landscape average condition during each interval through time. When baselines are carefully selected and used comparatively, forest disturbances from fast- or slow-acting insects

Table 6.1—Basic characteristics of *ForWarn* forest disturbance products

Attribute	Value
Cell spatial resolution	231.7 m (5.4 ha)
Spatial extent	Conterminous United States
Temporal window length	1 to 24 days
Product frequency	8 days (46 NDVI values per year)
Seasonal coverage	Year round
Years of <i>ForWarn</i> change products	January 2010 to present
Years of baseline data	January 2000 to present

NDVI = Normalized Difference Vegetative Index.

and disease, flooding, hail, wind, or wildfire can be distinguished from the effects of extreme interannual variation in temperature and precipitation (table 6.2).

ForWarn products can be viewed by anyone using the online *Forest Change Assessment Viewer* (<http://forwarn.forestthreats.org/fcav>). The *Assessment Viewer* contains all current and historical *ForWarn* maps, along with co-registered maps of insect and disease outbreaks, wildfire perimeters, and other relevant information on disturbances, vegetational cover types, terrain, hydrography, land ownership,

and climate. Users can also click on any pixel to obtain a pop-up graph showing the entire NDVI greenness history of vegetation for that location. The ability to quickly review past forest performance at any location shows evidence of many disturbances, and aids greatly in interpretation and attribution of the causative agents. Such NDVI time-series graphs are included in several figures here. During the growing season, the *ForWarn* Team uses the *Assessment Viewer* to examine potential forest disturbances detected in each new set of *ForWarn* products, alerting Federal, State, and local forest managers when warranted.

Table 6.2—*ForWarn* change detection products and their suggested uses

Product name	Current state	Baseline state	Suggested use
Early Detect	Most recent clear view (1 to 24 days)	Prior year’s 24-day maximum for one site	Used to detect initial change for new disturbances
1 Year	Maximum of 24-day window	Prior year’s 24-day maximum for one site	Used to detect disturbance and recovery < 1 year old when the prior year had normal seasonal weather
3 Year Max	Maximum of 24-day window	Maximum of 24-day maximums of 3 prior years’ values for one site	Used to detect disturbances that are < 3 years old when the prior 3 years had normal seasonal weather
All Year Max	Maximum of 24-day window	Maximum of 24-day maximums since 2000 for one site	Used to detect slow or sequential disturbances and to monitor recovery relative to the greenest conditions ever observed
All Year Mean of Maximums	Maximum of 24-day window	Mean of 24-day maximums since 2000 for one site	Used to isolate disturbance and current year weather effects on sites that are sensitive to year-to-year climate variability
Similar Neighbor Mean	Maximum of 24-day window	Mean of 24-day maximums since 2000 for phenologically similar sites	Used to isolate disturbance and current year weather effects on landscapes sensitive to year-to-year climate variability

Note: *ForWarn* works by comparing the current and baseline states of vegetation for corresponding periods of the year for each individual site.

CROSS-SEASONAL EXAMPLES

Change During the Growing Season

Detecting a drop in vegetation greenness at the peak of the growing season is straightforward for most forest types. Monitoring the condition of open stands with grassy or herbaceous understories or in areas with mixed land cover can be challenging, however, as non-woody vegetation is sensitive to variation in moisture. A reduction in forest NDVI may result from defoliation from insects, discoloration from disease, leaf damage or loss from wind or hail, deforestation, or combustion from fire. Drought can result in the broad-scale loss of vigor in the canopy or visible understory. NDVI can drop from either a decline in a portion of a site (e.g., scattered tree defoliation or partial deforestation) or from a more uniform decline across all vegetation at a site (e.g., drought or a uniform loss). The amount of decline reflects the severity of the stressor(s), given the limitations of the product's resolution and vegetation homogeneity.

ForWarn can detect and track certain native and nonnative insects and diseases that occur during the growing season. In the Malheur National Forest of central Oregon, *ForWarn* captured an outbreak of the native, but normally uncommon, pine butterfly (*Neophasia menapia*) that peaked in 2011. According to the national Insect and Disease Survey (IDS), defoliation in this National Forest is more usually caused by the western spruce budworm (*Choristoneura occidentalis*) and mountain pine beetle (*Dendroctonus ponderosae*), but not so in 2011.

A comparison of targeted aerial sketchmapping of pine butterflies with *ForWarn*'s 1-year change for September 29, 2011 shows close agreement (fig. 6.1).

Wildfires cause some of the steepest declines in NDVI, particularly in the Western United States, where large forest fires of high intensity are common. Prior to severe fire, dense evergreen trees are associated with high NDVI values with low interseasonal amplitude. After fire, an increase in grass dominance is often

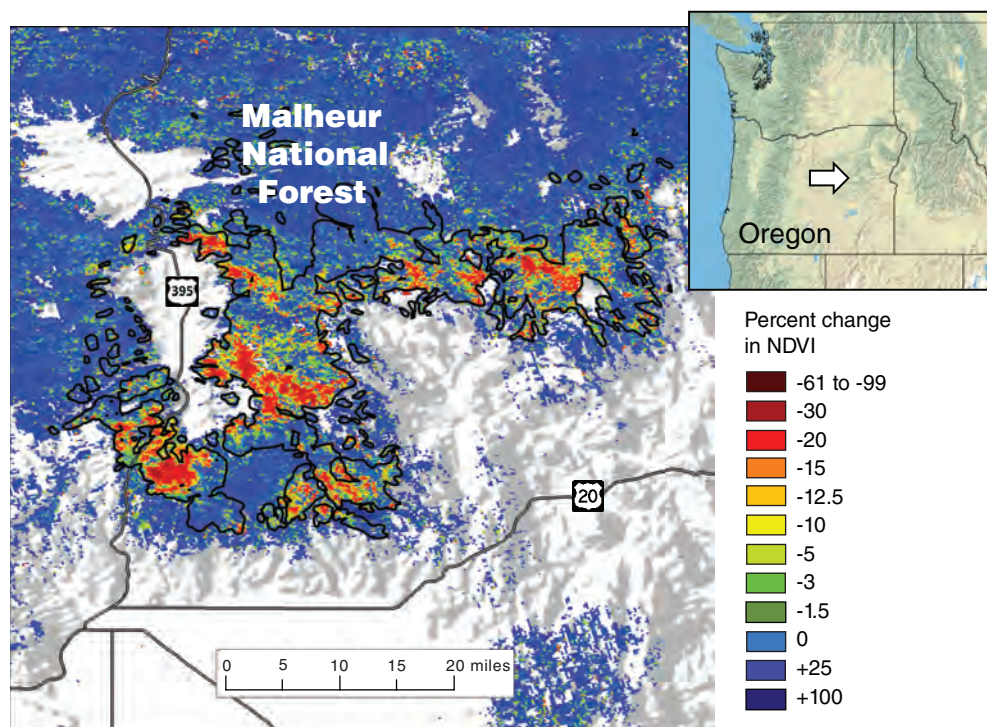


Figure 6.1—Areas defoliated by pine butterflies as mapped by aerial surveys (black outlines) compare well to *ForWarn*'s 1-year change anomalies for the Malheur National Forest, Oregon, for September 29, 2011. NDVI= Normalized Difference Vegetative Index.

indicated by lower NDVI and sharp growing-season peaks in the NDVI time series. In low burn-severity areas, a more limited drop in greenness occurs, and this shows the spatial heterogeneity in burn severity. *ForWarn*'s initial patterns of fire severity compare well with the higher resolution burn severity mapping efforts of the Forest Service's Remote Sensing Applications Center (RSAC).

ForWarn's long-term monitoring capabilities empower managers to monitor in a time frame that extends beyond immediate fire effects. For example, in the Gila National Forest of New Mexico, large wildfires are now reburning vegetation that previously burned during the MODIS period (fig. 6.2). In these forests, such frequent fires could reduce undesired fuel loads and stand densities, and restore desired

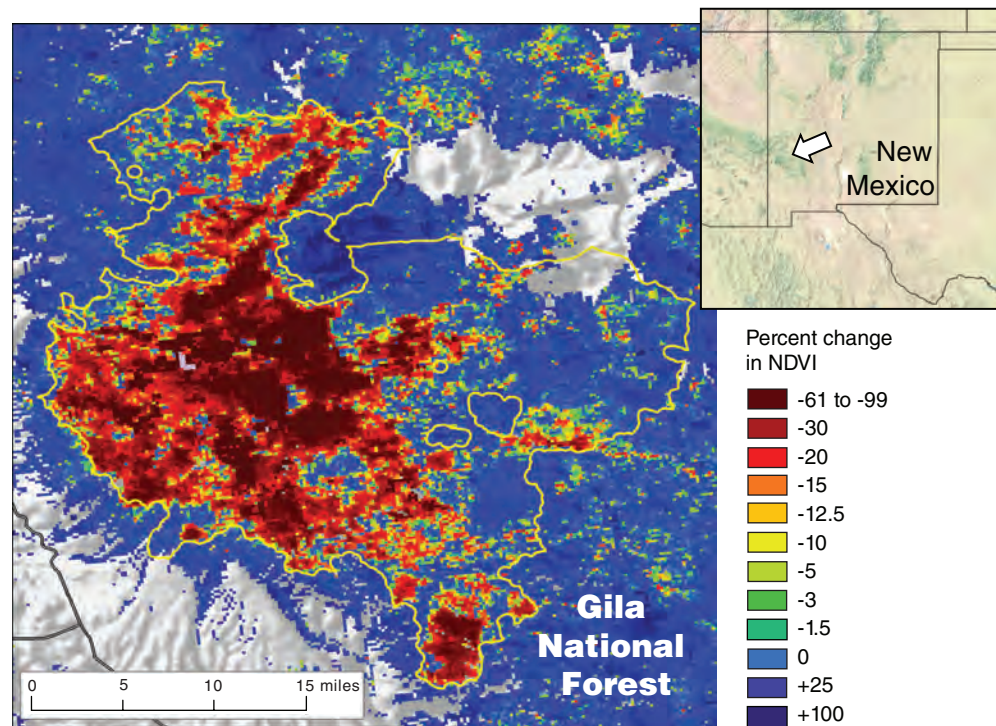


Figure 6.2—The severity of the Whitewater-Baldy Complex fire on the Gila National Forest, New Mexico, varied greatly. This *ForWarn* map shows change as of August 3, 2012, using the 1-year baseline with the fire perimeter shown as a yellow line. The majority of the eastern portion of this fire, shown in blue, had burned in recent years, and that likely reduced the severity of this portion of the event. NDVI= Normalized Difference Vegetative Index.

conditions overall, or they could contribute to sudden or incremental type conversion. This long-term condition can be measured by integrating observations of forest fire's immediate effects and the cross-seasonal pattern of NDVI recovery.

Drought stresses both woody and herbaceous vegetation, and these can be difficult to distinguish in open or mixed forests. The exceptional drought of 2011 in the southwestern United States resulted in the documented decline and mortality of trees in Texas, particularly in the western half of the State. These conditions also led to one of the most intense wildfire seasons ever experienced in this region. By distinguishing the degree of change, *ForWarn* captured the regional decline of vegetation due to drought and the even more extreme change from wildfire (fig. 6.3). While grass areas somewhat recovered during 2012, areas in which tree mortality was predominant experienced a sustained decline.

Change During Winter

In northern latitudes and high elevations, winter can be the most challenging time of year to detect disturbance, due both to the general absence of leaves on deciduous vegetation and

to the episodic masking effects of snowpack. Heavy snow can blanket understory evergreen vegetation and, in some climates, can persist on conifer boughs for weeks. The resultant reduction in NDVI from this winter-to-winter snow variation can be very difficult to separate from actual damage to trees caused by severe winter weather or other agents. At lower elevations, lower latitudes, or during years where or when there is no persistent snowpack, snow effects are not a problem because of *ForWarn*'s 24-day sampling period.

The most practical insights into winter change in NDVI come from mixed evergreen–deciduous forest types and how they change over multiple years. Pure evergreen forests can be effectively monitored from above at any time of year, but change in the evergreen fraction of a mixed evergreen–deciduous forest may be most apparent when deciduous vegetation no longer dilutes the NDVI signal. In the southern Appalachians, eastern and Carolina hemlock (*Tsuga canadensis* and *T. caroliniana*) are experiencing a rapid decline due to the nonnative hemlock woolly adelgid (*Adelges tsugae*). In the NDVI signal, this decline shows up as a gradual reduction in the winter minimum

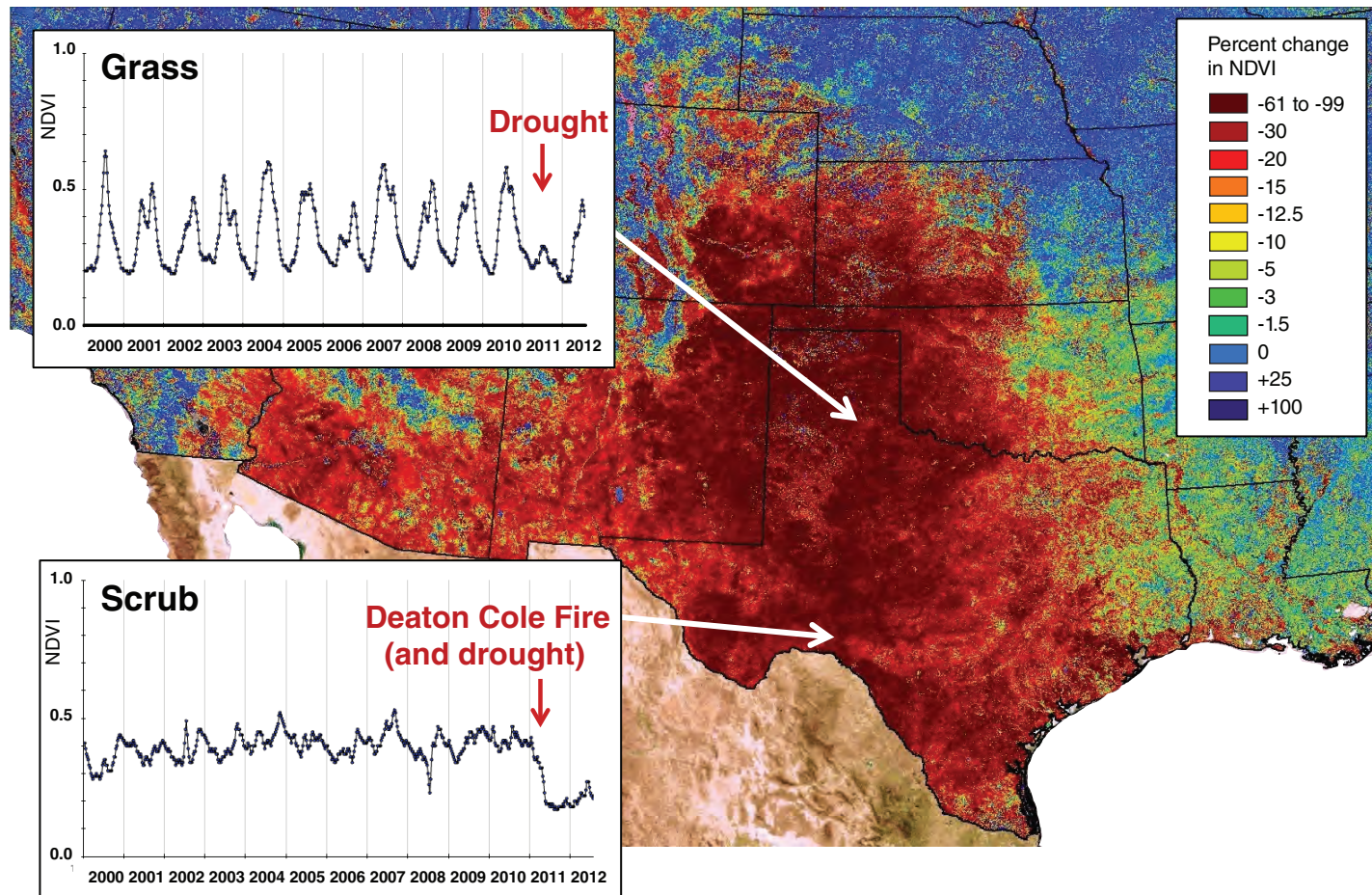


Figure 6.3—This ForWarn map for July 11, 2011, shows regional departure from the all-year baseline that resulted from an exceptionally severe drought and localized wildfire. The graph insets show the 12.5-year Moderate Resolution Imaging Spectroradiometer (MODIS) history of two areas: at top, the effects of drought on grass are reflected by the strong annual drop in Normalized Difference Vegetative Index (NDVI); at bottom, the effects of wildfire on evergreen scrub resulted in a stronger and more sustained departure from the period of record.

over a 4- to 6-year period, which is consistent with the time required for defoliation and tree mortality in this region (Vose and others 2013). The intensity of region-wide leaf-off trends in NDVI indicate that the hemlock-rich Cataloochee Valley of Great Smoky Mountains National Park ranks among the areas most significantly affected (fig. 6.4).

Rapid disturbances that occur during winter in deciduous forests are the most difficult to detect. Late winter wind, ice, and hail storms can damage branches and pre-emerged buds and reduce subsequent greenness. Such a storm occurred in western Virginia on March 24, 2012, the most intense portion of which formed

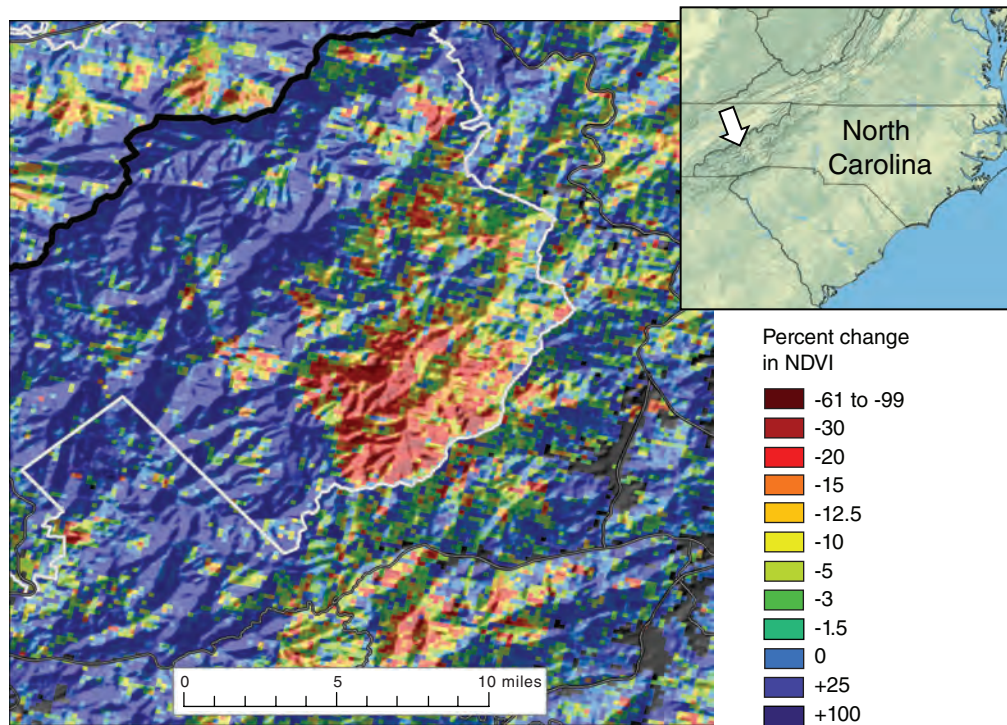


Figure 6.4—An epicenter of hemlock woolly adelgid mortality in the Southern Appalachians is the Cataloochee Valley of Great Smoky Mountains National Park, North Carolina. This ForWarn map shows change on February 17, 2012, compared to the maximum value observed during the prior decade. That long-term baseline is necessary here because hemlock decline is a slow process that takes several years. NDVI= Normalized Difference Vegetative Index.

a 1-mile wide track over Smith Mountain Lake, southeast of Roanoke (fig. 6.5). When they occur in the spring instead, such physical defoliation from storm events can be followed by rapid secondary leaf flushes, making the damage ephemeral. This Virginia hail event showed up clearly once canopy green-up occurred, apparently due to the severity of this portion of the storm.

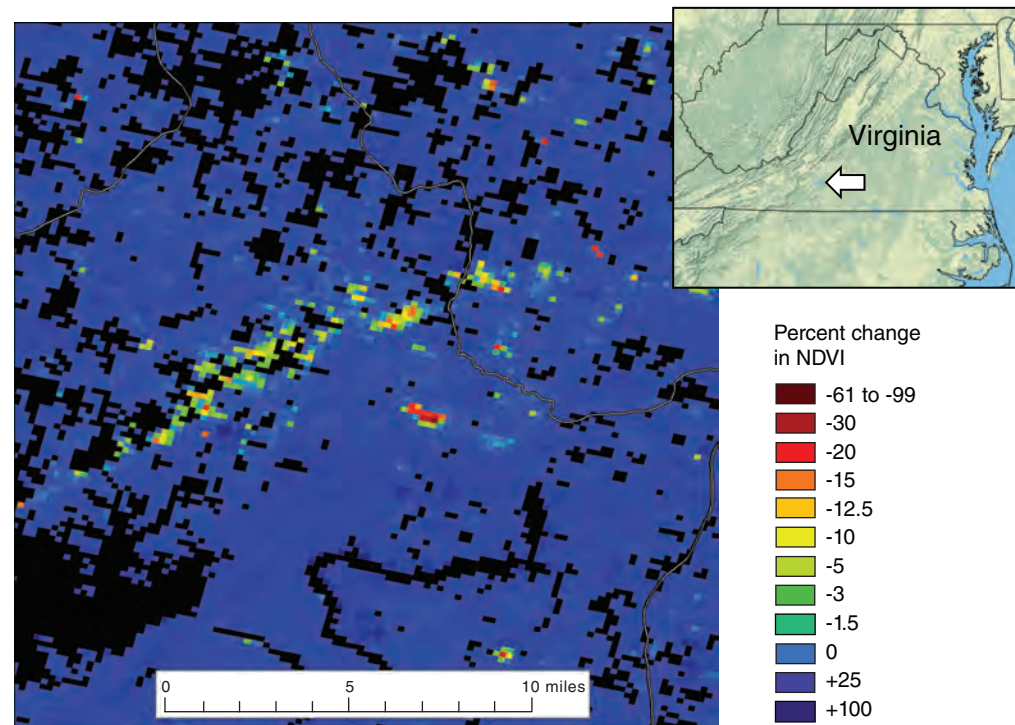


Figure 6.5—This hail storm damage in western Virginia occurred prior to green-up based on ground observations. The storm track became apparent by April 29, 2012 (1-year baseline). NDVI= Normalized Difference Vegetative Index.

Change During Spring Green-up and Fall Senescence

During the spring and fall, detecting forest change from disturbances can be challenging due to the variability in baseline conditions. If spring green-up and fall senescence were timed exactly the same across years this would not be a problem, but one to three weeks difference in spring green-up is not uncommon in temperate deciduous forests of the United States. Disturbances occurring during these seasonal transitions may be more likely to go unnoticed. Compare the variable progression of 2007, 2009, and 2012 for deciduous forests within Great Smoky Mountains National Park (fig. 6.6).

Using a 1-year baseline, *ForWarn* identified extreme hail damage during early May of 2012 in the Asheville Watershed—an ephemeral loss of leaves that occurred when leaves had only half emerged (fig. 6.7). The value of the 1-year baseline is also evident in NDVI profiles, such as that of the historical April 5-9, 2007 spring freeze event in the forests of western Kentucky that reduced NDVI in some areas, while it slowed the rate of green-up in others (figs. 6.6 and 6.8). This regional freeze caused widespread damage to crops and fruit trees (Gu and others 2008).

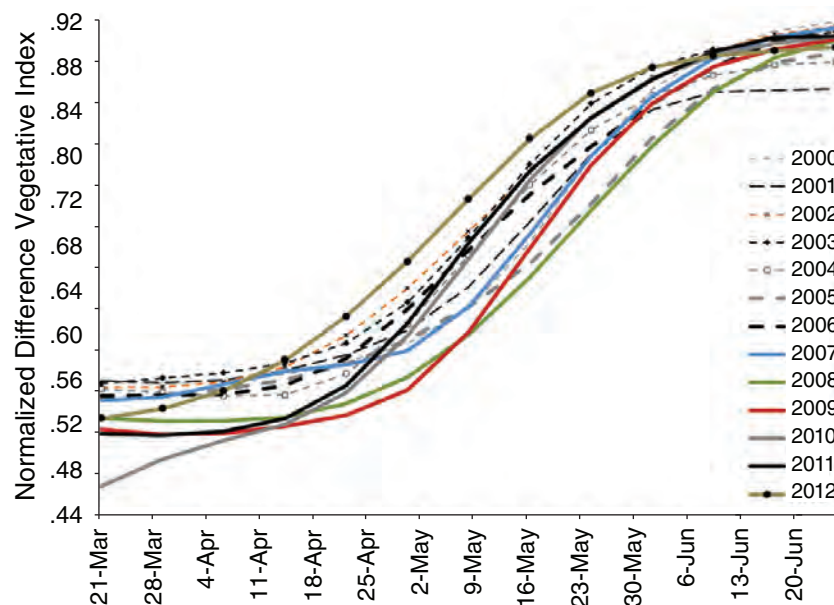


Figure 6.6—The onset and progression of spring varied considerably from 2000–12 across Great Smoky Mountains National Park in Tennessee and North Carolina. This graph shows the average behavior of spring vegetation for 18,030 Moderate Resolution Imaging Spectroradiometer (MODIS) pixels that were identified as pure deciduous forest using the 2006 National Land Cover Dataset. Note that 2012 experienced the earliest spring during the 13-year period of MODIS data collection.

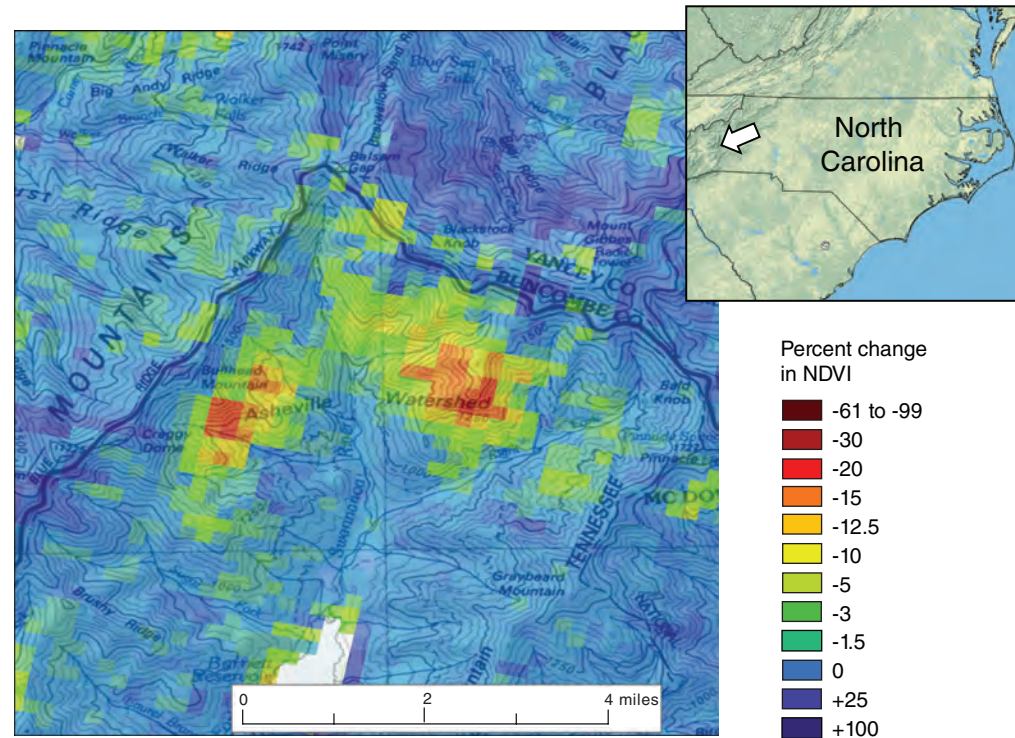


Figure 6.7—This spring hail damage near Asheville, NC, occurred when most deciduous leaves were half emerged, based on field observations. This damage went unnoticed until it was detected in ForWarn despite this being a heavily monitored urban water source. This map shows departure on June 16, 2012, using the 1-year baseline. NDVI= Normalized Difference Vegetative Index.

Relatively few insect defoliators are active in the fall in the Northeastern United States other than the fall webworm (*Hyphantria cunea*). These caterpillars cause leaf defoliation during the same months as natural seasonal NDVI decline. Because early leaf loss may occur normally

following the early arrival of cold temperatures, fall defoliation can be difficult to detect. Despite this challenge, *ForWarn* captured two successive outbreaks in the western portion of the Allegheny National Forest, PA, in 2011 and 2012 (fig. 6.9).

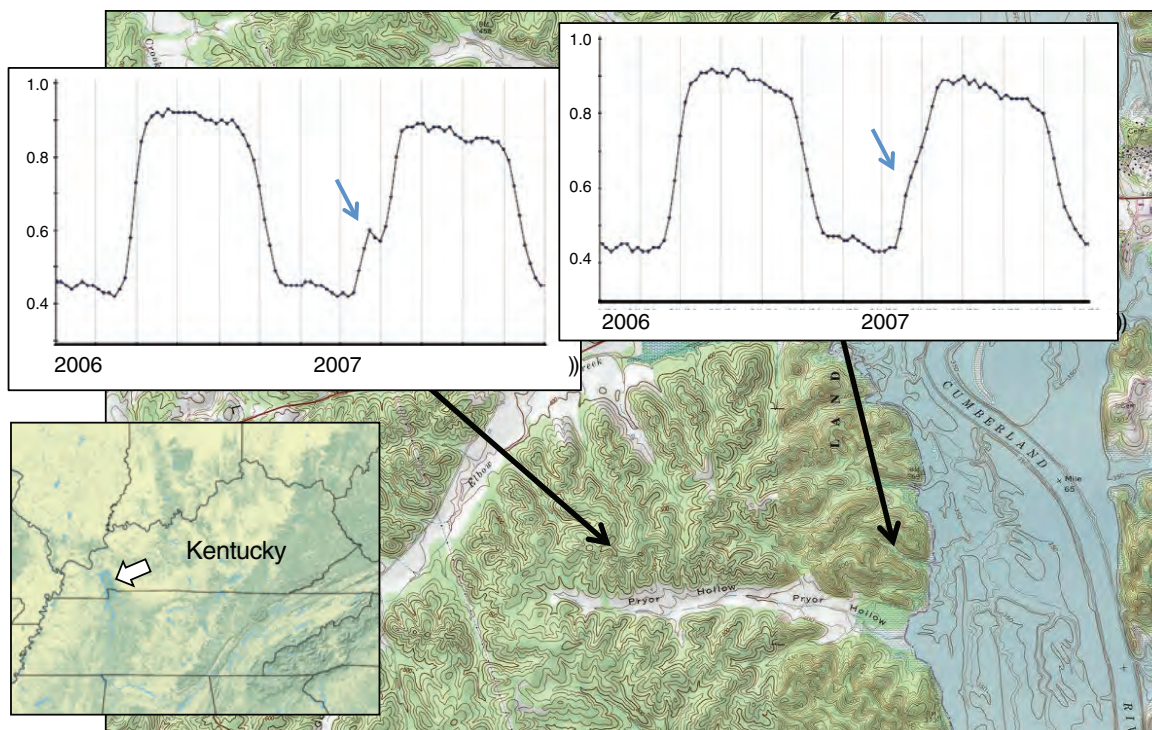


Figure 6.8—The variable effects of the April 5-9, 2007, spring freeze are shown here using Moderate Resolution Imaging Spectroradiometer-(MODIS) based Normalized Difference Vegetative Index profiles for two sites at Land Between the Lakes in Kentucky. These sites are roughly a mile and a half apart and suggest that the lake may have provided a partial temperature buffer. A normal profile for 2006 is included for comparison.

Fall is often a time of damaging storm events, such as hurricanes. Hurricane Sandy struck New Jersey, New York and New England on October 29, 2012 with severe, sustained winds. A comparison with the normal NDVI decline for all prior MODIS years indicates that these forests were roughly halfway through their fall decline, although that varied with forest type and location. Figure 6.10 shows change relative to the prior year after the 24-day rolling window excluded any pre-storm values. Note the coast-

to-interior gradient, the variable mainland intensity with respect to Long Island and Cape Cod, and the linear streaks that conform to exposed ridgelines across New Jersey, upstate New York, and eastern Pennsylvania. These patterns are consistent with expectations of leaf loss and tree damage from wind across the landscape. The long-term persistence of such effects can help distinguish severe forest damage from the more ephemeral effects of wind-stripped leaves.

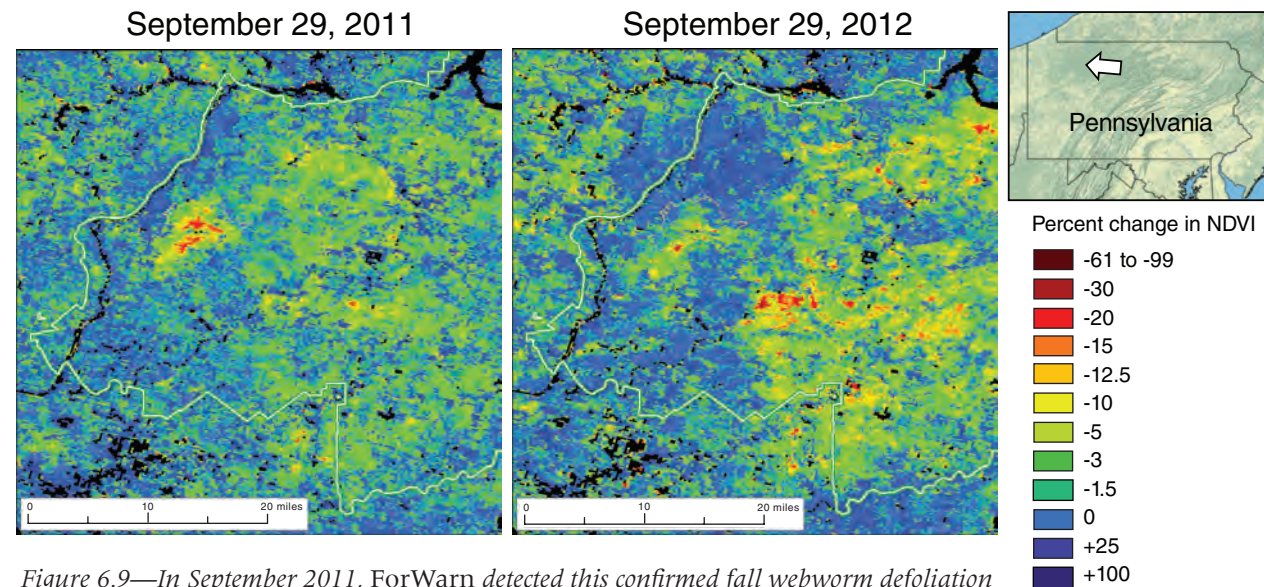


Figure 6.9—In September 2011, ForWarn detected this confirmed fall webworm defoliation in the Allegheny National Forest using the 3-year baseline. A subsequent outbreak appears to have occurred to the southeast in the fall of 2012. These detections were made despite seasonal leaf decline. NDVI= Normalized Difference Vegetative Index.

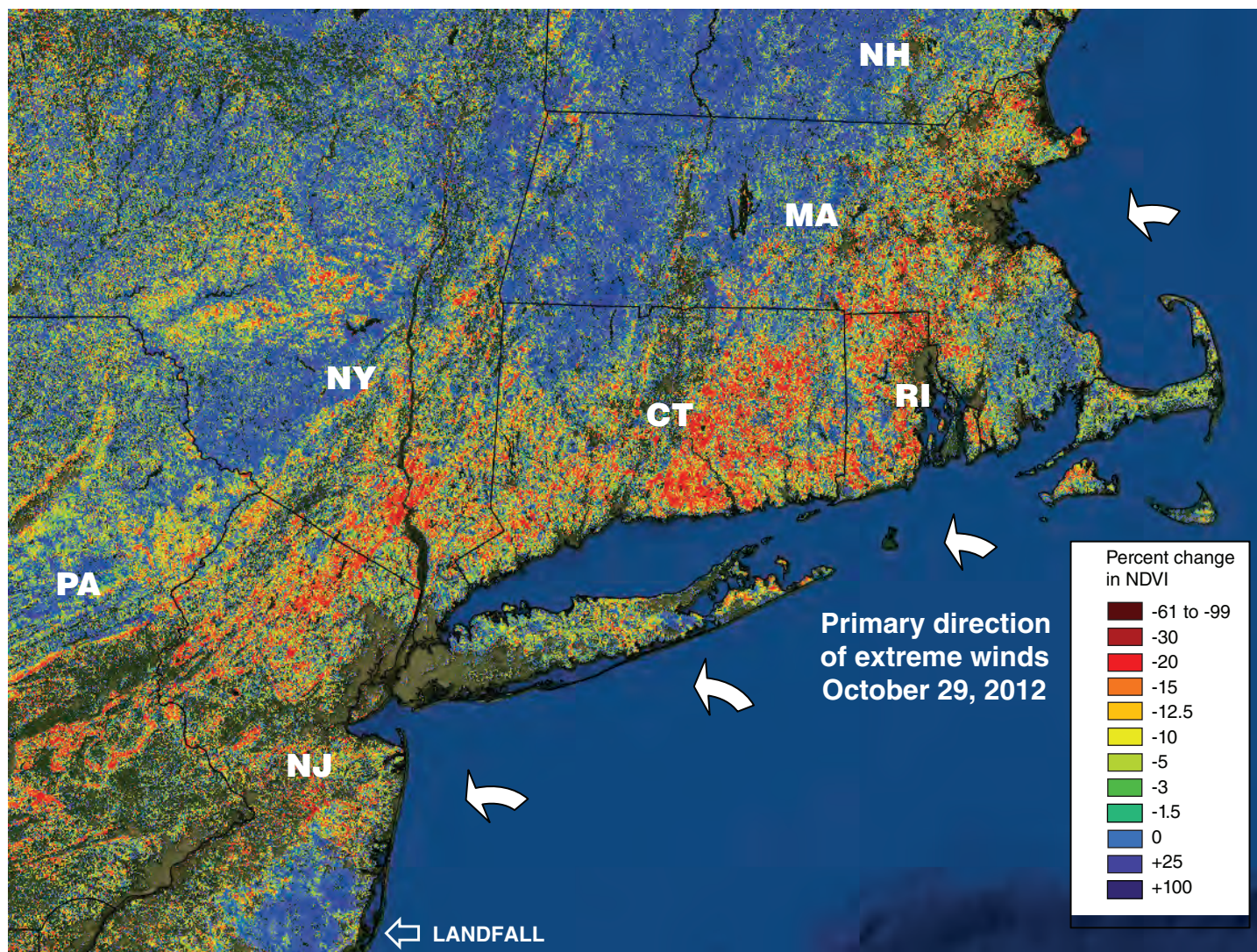


Figure 6.10—Hurricane Sandy struck the Northeast on October 29, 2012, with mixed effects to forests. The change in Normalized Difference Vegetative Index (NDVI) shown here soon after the event likely reflects accelerated fall leaf loss as much as more severely damaged trees. This ForWarn map may not reflect damage to extensive conifer stands, such as the New Jersey Pine Barrens near landfall, as evergreen trees retain their needles after blowdown; however, tree loss could materialize during subsequent months as a change in winter greenness.

DISCUSSION

Satellite-based forest monitoring in near real time presents fundamental challenges related to normal seasonal change and interannual climate variation from drought, snowpack, and the variable timing of spring and fall. *ForWarn* overcomes the problem of seasonal change by taking a phenology-based approach that includes multiple perspectives on what is expected for that time of year using a suite of baseline normals. This shifting seasonal sense of normal is analogous to the way the National Weather Service compares current monthly weather conditions to that of last year and to the average or record monthly values of the last thirty years or the prior century. Having this seasonally adjusted context is how *ForWarn* can detect the occurrence, severity, progression, and recovery of a broad range of disturbances within and across years.

ForWarn's ability to monitor and track forest recovery may be significant for aiding forest management in the future. *ForWarn's* multiple baselines and cross-seasonal product lines provide a rich context for understanding the duration of disturbance effects and the cumulative effects of management in the months to years that follow. This ability to efficiently quantify the long-term consequences of disturbances has long evaded us, preventing the adoption of a more thorough risk-based approach for forest management. Forest managers are generally well informed about the likelihood of particular disturbances in their forests, such as insects and disease, logging, wildfire, or severe weather events, thanks to

existing monitoring and extension. They are less well informed about how conditions have changed or recovered from a decade earlier. Having a more effective means to monitor, with both a short- and long-term perspective, can empower forest managers to recognize a broader set of concerns so they may better achieve their goals.

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