

Toward a National Early Warning System Using Remotely Sensed Canopy

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“While observing last year’s population upswing, PA Department of Conservation and Natural Resources employees noticed what looked to be a 30% or more mortality rate among the forest tent caterpillar population, while the eastern tent looked to be less: We were optimistic that this year’s population would drop or at least stay the same, but much to our surprise, it looks to have exploded If you haven’t already noticed it somewhere, you may soon notice large areas that have been defoliated by forest tent caterpillars.”
– Potter County News, PA, June 2009

Introduction

Imagine a national system with the ability to quickly identify forested areas under attack from insects or disease. Such an early warning system might minimize surprises such as the explosion of caterpillars referred to in the quotation to the left. Moderate resolution (*ca.* 500m) remote sensing repeated at frequent (*ca.* weekly) intervals could power such a monitoring system that would respond in near real-time. An ideal warning system would be national in scope, automated, able to improve its prognostic ability with experience, and would provide regular map updates online in familiar and accessible formats.

Such a goal is quite ambitious -- analyzing vegetation change weekly at a national scale with moderate resolution is a daunting task. The foremost challenge is discerning unusual or unexpected disturbances from the normal backdrop of seasonal and annual changes in vegetation conditions. A historical perspective is needed to define a “baseline” for expected, normal behavior against which detected changes can be correctly interpreted. It would be necessary to combine temperature, precipitation, soils, and topographic information with the remotely sensed data to discriminate and interpret the changing vegetation conditions on the ground. Conterminous national coverage implies huge data volumes, even at a moderate resolution (250-500m), and likely requires a supercomputing capability. Finally, such a national warning system must carefully balance the rate of successful threat detection with false positives.

Since 2005, the USDA Forest Service has partnered with the NASA Stennis Space Center and Oak Ridge National Laboratory to develop methods for monitoring environmental threats, including native insects and diseases, wildfire, invasive pests and pathogens, tornados, hurricanes, and hail. These tools will be instrumental in helping the Forest Service’s two Environmental Threat Assessment Centers better meet their Congressional mandate to help track the health of the Nation’s forests and rangelands. We envision two scales of forest monitoring: 1) a strategic, satellite-based monitoring of broad regions to identify particular locations where threats are suspected (*i.e.*, early warning), and 2) a fine-scale, tactical tier consisting of airborne overflights and on-the-ground monitoring to check the validity of warnings from the upper tier. The tactical tier is already largely in place within the Forest Service and its State collaborators, consisting of aerial detection surveys (sketch mapping from aircraft), ground surveys, and trapping programs. However, these efforts are expensive and labor-intensive, can be dangerous, and may not provide sufficient broad-area coverage. Far from replacing the tactical tier, the national system will rely on the finer-scale efforts to confirm, validate, and attribute causes of detected forest disturbances. One important objective of the national warning system will be to help direct the focus of the tactical tier, making their efforts more cost efficient and effective.

The Role of Land Surface Phenology

Land surface phenology is the temporal development of differential spectral reflectance in the near infrared and red wavelengths that reveals changes in the vegetated land surface (*e.g.*, leaf out; see Figure 1) (White *et al.* 2005,). Deviations from “normal” land surface phenological development can be the first indications of important changes in forest health, including disturbance and recovery (de Beurs and Henebry 2005, Liang and Schwartz 2009, Morissette *et al.* 2009), carbon status, and even climatic shifts (Cleland *et al.* 2007). Sponsored largely by

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the US Geological Survey, the USA National Phenology Network (<http://usanpn.org>) collects reports of the moment that leaf buds open on both standardized ornamentals and natural vegetation (Betancourt *et al.* 2007).

Seasonal changes in Normalized Difference Vegetation Index (NDVI), a self-standardizing measure of land surface greenness, have proven useful in tracking land surface phenology and identifying areas with suspected forest threats such as storm and insect damage. The cover image of this issue shows a successful same-season detection of an apparent forest tent caterpillar outbreak (like the one from the introductory quotation) across multiple counties in Michigan, USA, as well as the residual linear scar from a tornado two years earlier, obtained using changes in land surface phenology retrieved from NASA's pair of Moderate Resolution Imaging Spectroradiometer (MODIS) spaceborne sensors. Although not yet operating synoptically, such methods may form the basis for a national forest disturbance monitoring capability.

An idealized land surface phenology profile based on NDVI for deciduous vegetation has a flat-topped "mesa-like" shape as shown in Figure 2, where the left-hand rise represents leaf-out in spring and the right-hand decrease depicts leaf senescence and drop in the fall. Multiple approaches have been employed to detect the key change points in land surface phenologies, based on time series from MODIS and the Advanced Very High Resolution Radiometer (AVHRR) (Zhang *et al.* 2003). NASA's MOD12Q2 phenology product, for example, searches for the inflection points in the phenology profile, recording the two moments in spring and fall when the direction of change reverses (Zhang *et al.* 2003). We have taken a simpler approach to standardizing recordable instants in phenological development by defining points that are 20% and 80% of the maximum NDVI value in the spring and fall, respectively. Although these points have no particular ecological significance across the wide variety of vegetation types within the conterminous USA, these definitions can be applied uniformly across all vegetation types, thus standardizing the definition of key points in phenological development. Each red point in Figure 2 produces two national maps at 231 m resolution: one for the NDVI value and one for the day of the year (DOY) when it was attained. The area integrated under the land surface phenology curve, which we find is highly correlated with Gross Primary Production, is also generated as a geospatial data layer.



Figure 1. Up-looking photos of a selected scarlet oak near the Southern Research Station of the USDA Forest Service in Asheville, NC, showing the timing of leaf emergence in the spring. Note the differences in timing of leaf-out compared to adjacent species. New national-scale data sets on land surface phenology may make it possible to remotely monitor aspects of the health of forests and rangelands.

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A New National Phenology Data Set

Through this work, a new National Phenology Data Set covering the period from 2002 through 2008 has been produced. Data from 2000 and 2001 were excluded, because there are more missing data with only a single MODIS sensor available. Using time series and phenology data processing software developed at the NASA Stennis Space Center, an idealized phenology curve (like that in Figure 2) was fit

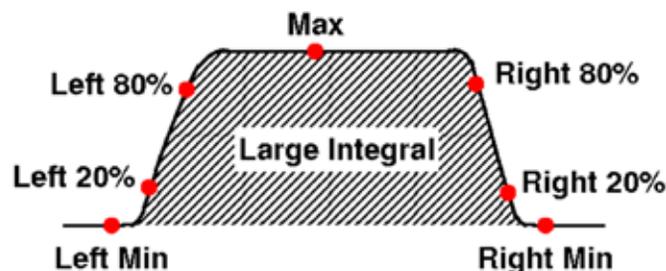


Figure 2. An idealized land surface phenology profile for deciduous vegetation showing a set of “standardized” phenological development points, where the vertical axis is Normalized Difference Vegetation Index (NDVI) and the horizontal axis is day-of-year (DOY). The red points are identified as phenological parameters describing the form of the land surface phenology profile, using 20% and 80% of the maximum NDVI value attained in that season. National maps of both the NDVI value and the DOY it was reached are produced for each red point as part of a National Phenological Data Set.

to each 231m cell annually through time using 16-day composites from MOD13 Collection 5 data. After eliminating outliers and temporally interpolating to fill gaps, each cell underwent an independent temporal curve-fitting process using a signal-processing algorithm in MATLAB®; no use was made of cells in the spatial neighborhood. All geospatial data sets were then produced by mosaicking the 14 MODIS tiles into a continuous United States coverage and reprojecting to Lambert Azimuthal Equal Area.

The three parts of our National Phenology Data Set are Phenological Parameters, Cumulative Phenology, and Derived Products. Phenological Parameters consist of the pair of national maps (NDVI value and DOY) corresponding to each of the seven red NDVI-profile-parameter points shown in Figure 2, as well as the integral area under the curve, totaling 15 maps per year for the seven-year historical period. For Cumulative Phenology, the NDVI values in each successive 16-day interval are summed to form a monotonically increasing accumulation total, resetting at the beginning of each year. Treating NDVI in a cumulative way causes differences to become more pronounced throughout the year. There are 22 Cumulative Phenology maps per year, one for each interval in each of the seven years. Derived Products consist of higher-order maps constructed using the Phenology Parameters as building blocks, and represent a more ecologically interpretable product. For example, the difference between the DOY when 20% of the maximum NDVI in the fall is attained and the DOY when 80% of the maximum NDVI in the fall is attained can be used as an indicator of the duration of fall. Figure 3 shows how the duration of fall varies across the seven-year history of measurements. Black areas, like the agricultural Midwest, are constant in fall duration, while in white areas like southern Texas, the duration of fall varies by as much as 40 days from year to year. The timing of rainfall events may be important for ending fall senescence in such arid areas. Similar maps of variability in duration of spring, duration of growing season



Figure 3. A duration of fall map was computed by subtracting the Day of Year (DOY) when the fall 20% is attained from the DOY when the fall 80% is attained (see Figure 2). Doing this annually, from 2002 to 2008, the standard deviation of the duration of fall can be mapped, showing places where length of fall is relatively constant or variable from year to year.

(DOY 20% fall minus DOY 80% spring), and many others are also possible. A kml file that allows viewing all of the maps within the National Phenology Data set from 2002 to 2008 within Google Earth is available at <http://data.forestthreats.org/phenology/>.

What is Normal?

Land surface phenologies can be used to characterize normal, “expected” conditions and thus can help a warning system determine where and when vegetation has changed. Many changes are part of the normal annual seasonal cycle, and should not be construed to indicate problems. Our strategy has been to characterize and use normal phenological behavior as an expected trajectory against which forest threats can be discriminated. The MODIS historical period from 2002 (with two sensors) to 2008 is long for remote sensing, but is still rather short relative to the lifespan of trees and successional trajectories.

We have experimented with using several phenological parameters as normal “baselines” against which current comparisons can be made. For example, Figure 4 shows an RGB composite using the 20% spring NDVI value from 2006 as a green and blue baseline, and the 20% spring NDVI value from 2004 as red. The vegetation damage (along with subsequent forest harvests) from three hurricanes hitting the US Gulf coast during the interim can be seen as red impact zones, which are more severe along the right-hand side of the track. Use of the 20% spring phenological parameter may be particularly useful for visualizing changes to coniferous forests, which are green even before substantial deciduous leaf-out. A loss of greenness along coastal marsh areas due to saltwater intrusion is evident from Ivan and Katrina. Using phenology, it is possible to see these footprints in a straightforward visualization, before performing a complex in-depth analysis.

Another potential baseline is the largest NDVI for a given pixel across a given sampling period of the entire time series. This approach may result in increased commission errors, but this is preferable to omission for a warning system. Figure 5 shows an RGB composite image of northern Arkansas, USA, in June 2009, showing first-year phenological effects of a major ice storm. The maximum NDVI over a six-year baseline was compared to the maximum NDVI from mid-

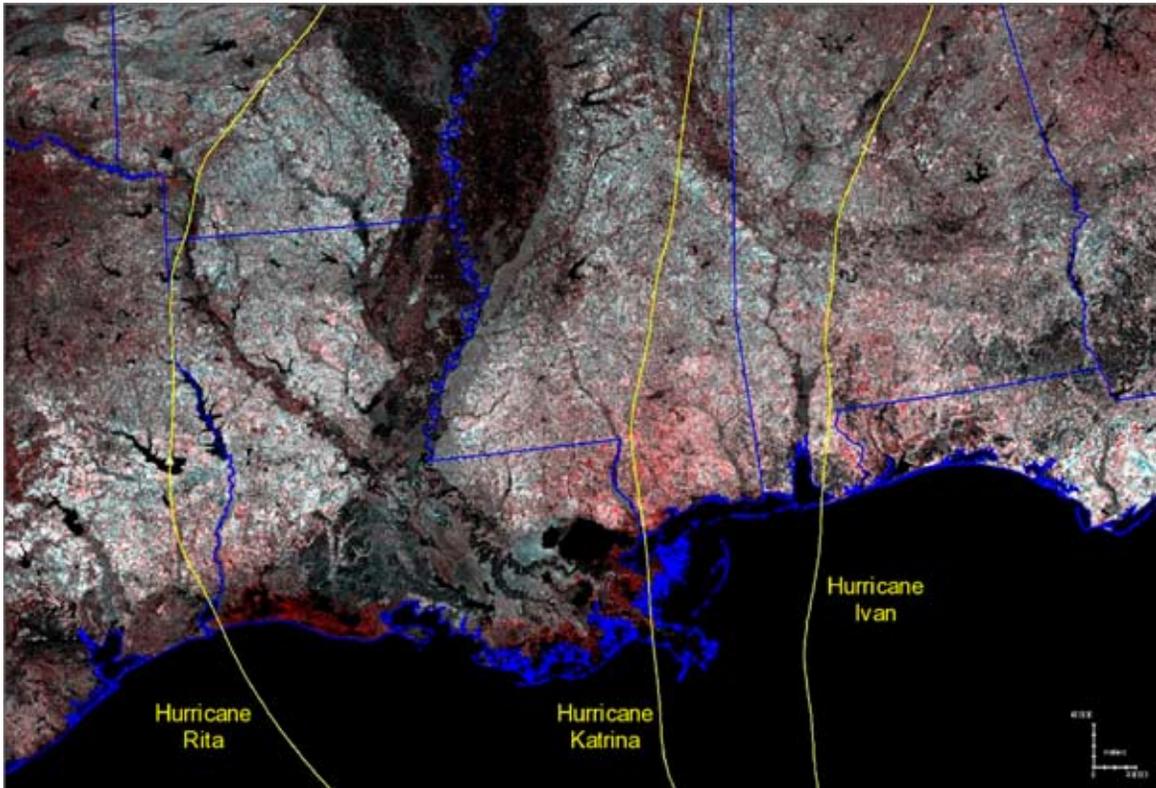


Figure 4. View of hurricane-induced decline in vegetation greenness, computed by assigning the 20% left NDVI values from the National Phenology Data Set from 2006 for green and blue, and the 20% left NDVI values from 2004 for red, forming a composite image that shows the lasting footprint of three recent hurricanes impacting the Gulf coast region of the United States. Red colors depict vegetation with reduced greenness levels. Travel tracks of each hurricane are shown in yellow.

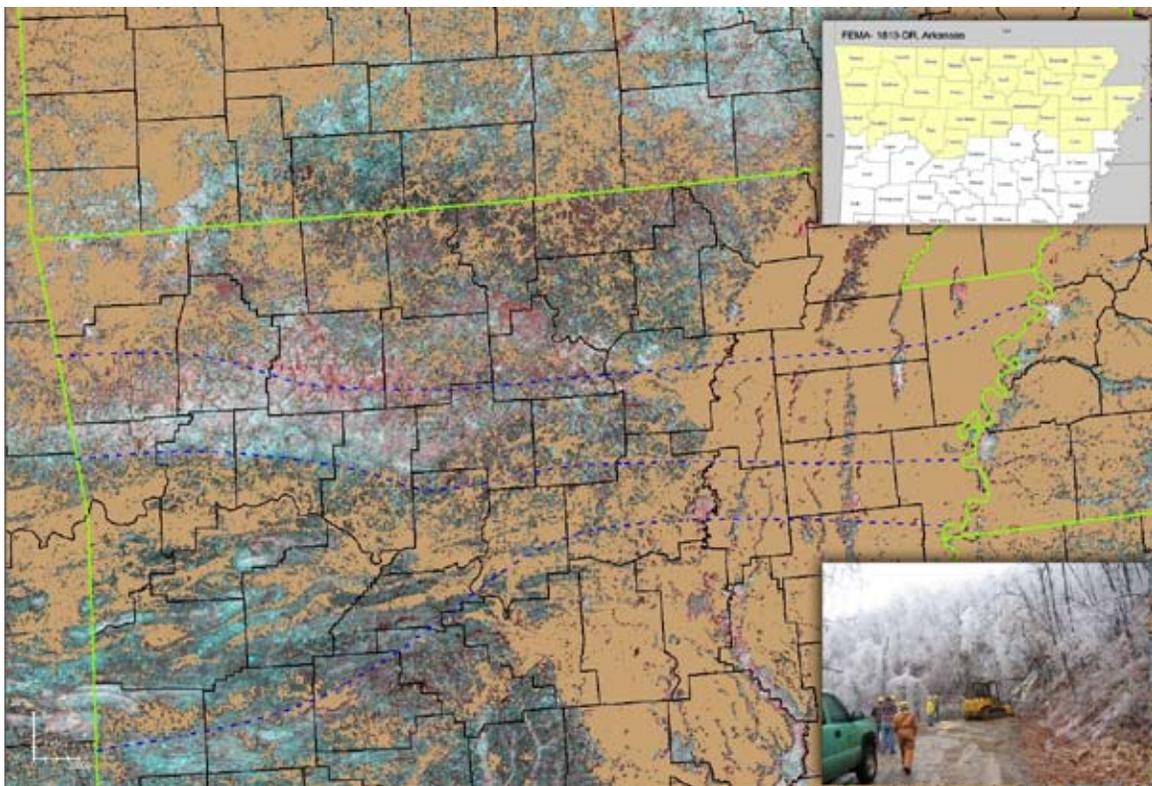


Figure 5. View of forest damage from a major ice storm across northern Arkansas, USA, January 26–28, 2009. RGB composite image was made by loading the maximum 2009 NDVI for June 10–July 15 in the blue and green, and loading the maximum 2001–2006 NDVI for June 10–July 27 into red. Areas with drops in maximum NDVI are shown in red tones, and correspond well to dotted blue ice accumulation isopleths (1-2+ in, 0.5-1 in, and 0.25-0.5 in from north to south, respectively) and Federal Emergency Management Agency declared disaster counties shown in the upper right inset. This was the worst icing since December 2000, leaving 350,000 residents without power and causing 18 fatalities.

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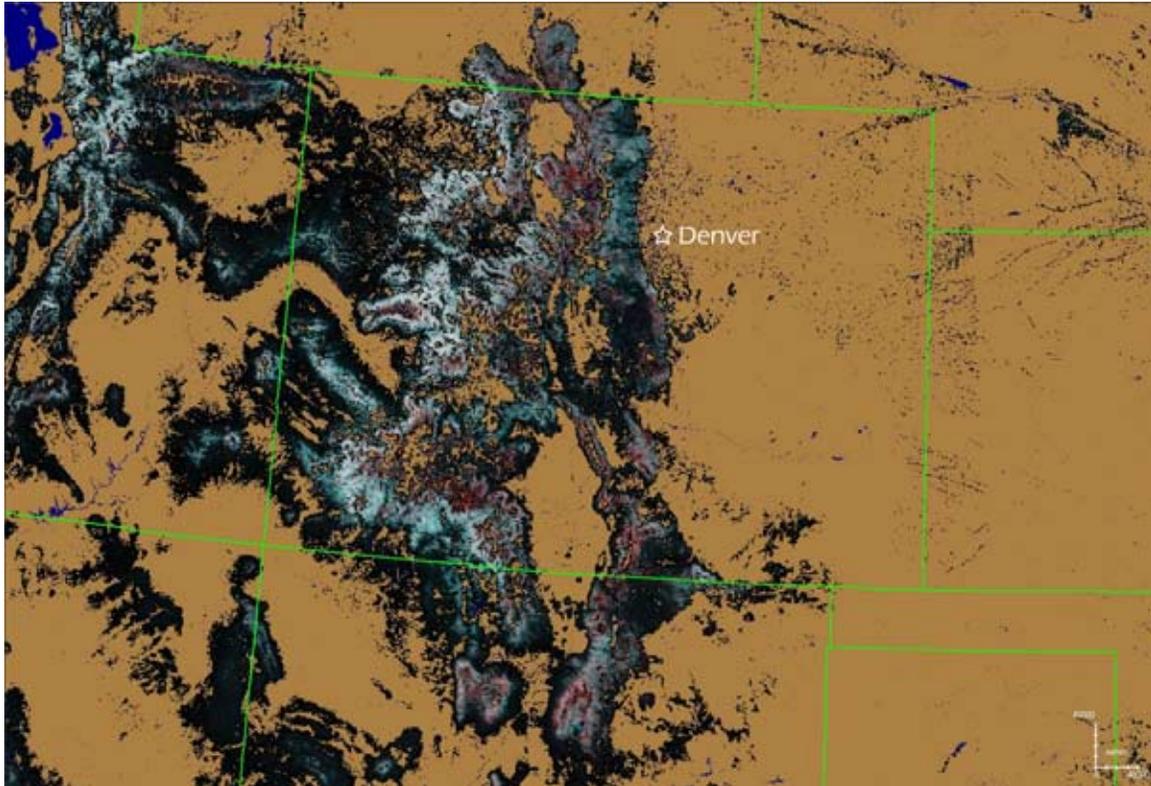


Figure 6. A 2009 visualization depicting forest greenness status along the Front Range of Colorado, USA, near Denver. Red shades include forests damaged by mountain pine beetles and wildfire. Tan areas are non-forest. As in Figure 5, white areas are higher NDVI forests and black areas are very low NDVI woodland forests, such as pinyon-juniper. Because of smaller NDVI values in western forests, a different contrast stretch was used for the western United States versus the eastern United States images (Figures 4 and 5).

summer 2009. Tan areas are non-forest. Black areas are low NDVI forests on each date, white areas are high NDVI forests, and light cyan areas had a larger maximum NDVI in 2009 than in the 2001 to 2006 historical sampling period. The cyan areas along the south edge of the ice storm may indicate pruning or a forest gap effect.

Figure 6 depicts another use of maximum NDVI over a historical period relative to any particular year to resolve vegetation changes in western Colorado, USA, and surrounding states. Red areas in the front range of the Rockies (just west of Denver) indicate forest damage associated with mountain pine beetles. A few dark red spots are the result of wildfires. Because of smaller NDVI values in the more open evergreen forests of the west, a different contrast stretch was used from that in the eastern United States examples (Figures 4 and 5).

Clustering Regions Based on Phenology

Two of the authors (Hargrove and Hoffman, with others) used a statistical clustering procedure running on a supercomputer to delineate 500 global phenological ecoregions, or phenoregions, based on similarities in monthly climate and NDVI data from 17 years of 8km AVHRR images (White *et al.* 2005). By looking for minimum potential human impacts, a subset of global phenoregions was identified, within which any observed phenological changes might be most directly attributable to climatic shifts.

The National Phenological Data Set provides an opportunity to statistically define higher resolution national phenoregions in several

new ways. Figure 7 shows 15 National Phenological Ecoregions based on similarities in timing of Cumulative Phenology over a five-year period from 2002 to 2006. At this relatively coarse level of division, the mixed pine-hardwoods of the southeastern United States and the northeast (shown as a mixture of black and green), the agricultural areas of the upper Midwest (light blue), and the Rockies and desert southwest (teal) are all grouped into regions having similar phenology. Such Cumulative NDVI phenoregions may more closely represent productivity than vegetation type.

One can also cluster the Cumulative Phenology data by year over the same period, producing unique phenoregions for each calendar year. The five annual phenoregion classifications for each map cell can now be compared, and the degree of constancy of the phenological classification can be mapped. The inset map in Figure 7 shows red if all five years from 2002 to 2006 are given the same phenoregion classification (regardless of that classification), then shows purple, blue, green, and yellow for other levels of phenological constancy. Only the majority phenological classification is counted; adjacency in successive years is not required. The southern Appalachians are red because they remain eastern deciduous forest. Iowa is red because it remained corn-dominated agriculture, and the Pacific Northwest is red because it was always mixed conifer and Douglas fir-dominated forests. Thus, this analysis uses phenology to move beyond the type of vegetation present to show the constancy of the general vegetation type. In contrast, southern Texas and western Kansas are assigned a different phenological classification in each of the five years. These differences may result from grass crops that have multiple harvests per year.

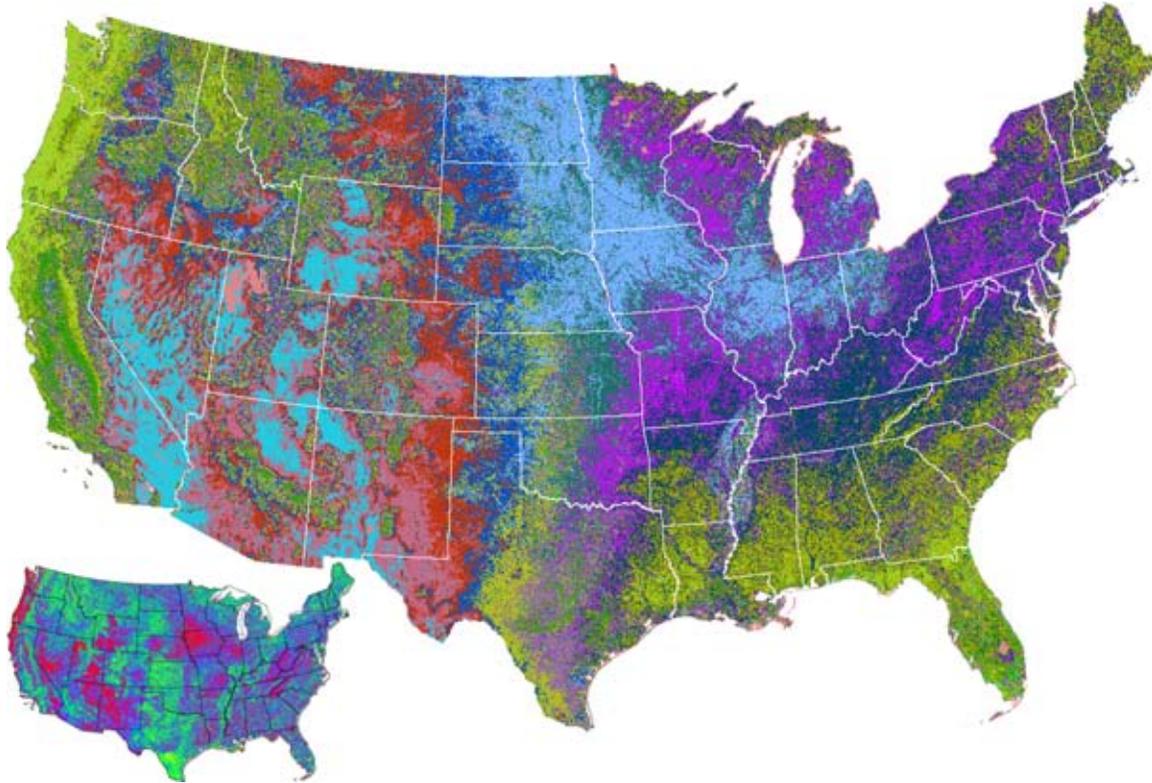


Figure 7. Map of 15 national phenological ecoregions, or phenoregions, based on statistical clustering of the 22 x 5 annual Cumulative NDVI values. Each phenoregion class contains areas having similar timing of foliage green-up and brown-down during the 2002–2006 period. The inset map shows locations in red that had the same phenological classification in each of the five years of record, no matter what that classification was (e.g., Southern Appalachian forests, Iowa agriculture, Rocky Mountains, and Pacific Northwest). The phenoregion class changes each sampled year in south Texas and western Kansas.

Because they generate an “instant history” that is couched in common terms for comparison, such enormous unsupervised classifications through time may provide a basis for change detection that is ideal for defining the bounds of “normal” behavior at every location across the country (Hargrove and Hoffman 2004). Provided with such a history for comparison, a national early warning system could identify locations that seem to be deviating from their usual behavior.

Conclusions

We anticipate three stages associated with the development of a national early warning system for forest threats. Successful implementation will begin with deployment of an operational observation and monitoring system. Even at this initial step of development, such a system will enable uniform, large-scale monitoring of national forest and non-forest resources in a frequent and consistent manner. The long-term monitoring record from such a system will be an invaluable reference against which longer term changes like climatic shifts can be detected. We hope to progress quickly to a change-detection system, based on national-scale, unsupervised classification through time using large-scale computing resources. The even-handed application of a statistical clustering method will create an “instant” national historical sequence back to 2002, couched in a single set of clustered classes that provide a common basis for comparison.

The final step in the evolution of a national system will be to add methods that allow the discrimination of normal, expected seasonal changes from unusual or suspicious ones—methods that allow the

question of “What is normal?” to be answered at each location. Bayesian statistical methods may be one useful avenue of approach, given the wealth of information on prior probabilities offered by the historical perspective. Only with the development and addition of an ability to recognize deviations from expectation can a system transform into an early warning capability. “Early” may get earlier and earlier as the prognostic ability of the system improves.

Although its use seems promising, phenology alone is not a panacea for forest disturbance monitoring. The same integrative properties of phenology can confound and complicate interpretation of change. Remotely sensed phenology is always seen through the lens of the existing vegetation, which changes across space and through time. Ultimately, we plan to take a multivariate approach toward detection and early warning for forest disturbances, considering other ecological variables to untangle the causes and complex interactions among various forest threats. The National Phenological Data Set is available for distribution, and we encourage everyone to explore its utility with us.

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