



Assessment of MODIS NDVI time series data products for detecting forest defoliation by gypsy moth outbreaks

Joseph P. Spruce^{a,*}, Steven Sader^b, Robert E. Ryan^c, James Smoot^a, Philip Kuper^a, Kenton Ross^d, Donald Prados^e, Jeffrey Russell^f, Gerald Gasser^g, Rodney McKellip^h, William Hargroveⁱ

^a Computer Sciences Corporation, John C. Stennis Space Center, Mississippi, formerly with Science Systems and Applications, Inc., John C. Stennis Space Center, Mississippi, United States

^b University of Maine, Orono, Maine, United States

^c Innovative Imaging & Research, John C. Stennis Space Center, Mississippi; formerly with Science Systems and Applications, Inc., John C. Stennis Space Center, Mississippi, United States

^d Science Systems and Applications, Inc., Lanham, Maryland, United States

^e Diamond Data Systems; formerly with Computer Sciences Corporation, John C. Stennis Space Center, Mississippi, United States

^f Naval Research Laboratory, John C. Stennis Space Center, Mississippi, formerly with Computer Sciences Corporation, John C. Stennis Space Center, Mississippi, United States

^g Lockheed Martin Mission Services—Civil Programs, John C. Stennis Space Center, Mississippi, United States

^h National Aeronautics and Space Administration, John C. Stennis Space Center, Mississippi, United States

ⁱ United States Forest Service, Eastern Forest Environmental Threat Assessment Center, Asheville, North Carolina, United States

ARTICLE INFO

Article history:

Received 1 July 2009

Received in revised form 5 September 2010

Accepted 18 September 2010

Keywords:

MODIS NDVI time series data

Gypsy moth

Regional forest defoliation detection products

Defoliation classification accuracy

National forest threat early warning system

Temporal data processing

ABSTRACT

This paper discusses an assessment of Moderate Resolution Imaging Spectroradiometer (MODIS) time-series data products for detecting forest defoliation from European gypsy moth (*Lymantria dispar*). This paper describes an effort to aid the United States Department of Agriculture (USDA) Forest Service in developing and assessing MODIS-based gypsy moth defoliation detection products and methods that could be applied in near real time without intensive field survey data collection as a precursor. In our study, MODIS data for 2000–2006 were processed for the mid-Appalachian highland region of the United States. Gypsy moth defoliation maps showing defoliated forests versus non-defoliated areas were produced from temporally filtered and composited MOD02 and MOD13 data using unsupervised classification and image thresholding of maximum value normalized difference vegetation index (NDVI) datasets computed for the defoliation period (June 10–July 27) of 2001 and of the entire time series. These products were validated by comparing stratified random sample locations to relevant Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) reference data sets. Composites of 250 m daily MOD02 outperformed 16-day MOD13 data in terms of classifying forest defoliation, showing a lower omission error rate (0.09 versus 0.56), a similar Kappa (0.67 versus 0.79), a comparable commission error rate (0.22 versus 0.14), and higher overall classification agreement (88 versus 79%). Results suggest that temporally processed MODIS time-series data can detect with good agreement to available reference data the extent and location of historical regional gypsy moth defoliation patches of 0.25 km² or more for 250-meter products. The temporal processing techniques used in this study enabled effective broad regional, “wall to wall” gypsy moth defoliation detection products for a 6.2 million ha region that were not produced previously with either MODIS or other satellite data. This study provides new, previously unavailable information on the relative agreement of temporally processed, gypsy moth defoliation detection products from MODIS NDVI time series data with respect to higher spatial resolution Landsat and ASTER data. These results also provided needed timely information on the potential of MODIS data for contributing near real time defoliation products to a USDA Forest Service Forest Threat Early Warning System.

© 2010 Elsevier Inc. All rights reserved.

1. Introduction

The forests of the United States (U.S.) are currently subjected to a variety of biotic and abiotic threats that result in ephemeral and stand replacement disturbances involving millions of hectares. Native and

non-native insects and diseases collectively damage across the U.S. nearly 45 times more total area of forest than wildfires and cause at least 5 times more economic impact (Dale et al., 2001). Exotic pests caused annual economic losses in U.S. forest products estimated at 2 billion dollars per year (Pimentel et al., 2000). Among these pests is the European gypsy moth (*Lymantria dispar*), which recently defoliated in excess of 400,000 ha per year (USFS, 2009) across the Eastern U.S. and is spreading south and west into other parts of the country (Tobin and Blackburn, 2007).

* Corresponding author.

E-mail address: joseph.p.spruce@nasa.gov (J.P. Spruce).

The U.S. Healthy Forests Restoration Act (HFRA) of 2003 mandates that the Secretary of Agriculture develop a national Early Warning System (EWS) for early detection, monitoring, and mitigation of forest health threats (Bosworth, 2006). In response to the HFRA, the United States Department of Agriculture U.S. Forest Service (USFS) has established Eastern and Western Regional Threat Assessment Centers. These forest threat centers have been tasked to develop an operational EWS, which will include integrated geospatial data to characterize and track forest environmental threats at multiple scales (USFS, 2004, 2005; Hargrove et al., 2009). This EWS will consider threats from native and exotic forest-damaging insect and diseases. It will also regard abiotic threats such as damage from hurricanes and ice storms. One goal of this USFS EWS is to detect, map, and monitor forest defoliation and other disturbances at broad regional to continental scales. Since 2005, The National Aeronautics and Space Administration (NASA) at Stennis Space Center (SSC) and Oak Ridge National Laboratories have been assisting the USFS threat centers to evaluate and integrate MODIS (Moderate Resolution Imaging Spectroradiometer) time series data products for inclusion into the EWS, particularly in detecting forest disturbance (e.g., defoliation) from exotic insects, such as the gypsy moth (Spruce et al., 2007; Hargrove et al., 2009).

This EWS will regard two required scales of forest monitoring: 1) a strategic, national level satellite-based scale of monitoring to identify apparent locations of disturbances where threats are suspected (i.e., early warning), and 2) a finer-scale, local (e.g., states, counties, and smaller regions) tactical tier consisting of airborne overflights and on-the-ground monitoring to assess the validity and nature of warnings from the upper tier (Hargrove et al., 2009). The tactical tier is largely already in place within the Forest Service and its State collaborators, consisting of Aerial Detection Surveys (ADS) of forest disturbances (sketchmapping from aircraft), ground surveys, and insect trapping programs (Ellenwood, 2006; Hargrove et al., 2009). Below is a description of aerial sketch mapping surveys, including the advantages and limitations, followed by a discussion of the connection and complementary relationship of aerial sketch mapping and MODIS-based forest monitoring in the implementation of a national forest threat EWS.

The ADS aerial sketchmapping surveys provide an important means for gathering geospatial information at regional to national scales on the general location and severity of forest disturbances during a given growing season (McConnell et al., 2000; Johnson and Wittwer, 2008). For gypsy moth defoliation, these surveys result in maps depict detected defoliated areas in terms of 2 severity classes: moderate (30–50% defoliation) and heavy defoliation (>50% defoliation) at a 2 km resolution (USFS, 2007). In sketchmapping forest disturbances, as the airplane traverses an area of interest, an analyst interactively screen digitizes the outlines of apparent forest change or defoliation boundaries onto Global Positioning System-synchronized geographic information system (GIS) map displays of the overflow areas (Schrader-Patton, 2003).

Although aerial sketch mapping of forest defoliation and mortality events is an important facet of the current forest threat monitoring capability of the USFS, the system has some limitations. These efforts tend to be expensive and labor-intensive, can be dangerous, can also be affected by persistent cloud cover, and may not provide complete broad-area coverage (de Beurs and Townsend, 2008; Hargrove et al., 2009). Aerial sketch maps of forest defoliation and mortality give only approximate location and are often not accurately georeferenced, which complicates map overlay and GIS analysis (Ciesla, 2000; USFS, 2007). They frequently overestimate the extent of change within a delineated polygon (Hall et al., 2006; Johnson and Ross, 2008) and can also omit spotty or scattered defoliation areas (Johnson and Ross, 2008). Such surveys can also omit extensively defoliated forests, due to monetary constraints and bad weather. Such surveys are often produced without formal, broad area accuracy assessment. Johnson

and Ross (2008) recently assessed the accuracy of ADS sketch maps of insect-induced mortality in a Western US region, comparing ADS results to field survey data. They concluded that the assessed ADS sketch maps of mortality were acceptable for coarse scaled analyses, but lacked spatial specificity for use in fine-scaled applications.

Nonetheless, ADS products are valuable as preliminary reconnaissance tools in forest health monitoring and can be thought of as an initial stage to a multi-phase sampling of forest health conditions (Johnson and Wittwer, 2008). ADS currently represents the only means for collecting and summarizing forest defoliation and mortality survey information at regional and continental United States (CONUS) scales. From 2002 through 2006, the ADS forest survey area averaged 1,800,000 km² across the US (Johnson and Wittwer, 2008).

MODIS-based forest disturbance detection products from this national EWS is not meant to replace ADS sketchmapping and may actually be useful for complementing these activities (Hargrove et al., 2009). As part of the national EWS, aerial sketch mapping will be used with higher spatial resolution data sources (e.g., available satellite, aerial, and in-situ data) to help confirm, validate, and attribute causes of detected forest disturbances. Then, one important objective of the national EWS will be to use coarser scaled regional products from the strategic tier of the EWS to spatially focus the activities of the tactical tier, thus making the two scales of observation (i.e. work activities) complementary and more effective (Hargrove et al., 2009). In particular, near real time MODIS defoliation products will focus aerial sketchmapping efforts on high probability disturbed forests to reduce aerial survey costs and increase efficiencies of the overall ADS monitoring and evaluation capability (Hargrove et al., 2009).

Since the initial deployment of the MODIS sensor on the Terra satellite in 2000, the USFS has increasingly used MODIS data for broad regional forest resource monitoring applications, gradually transitioning from research to an operational basis, as with fire mapping (Quayle et al., 2003). The USFS has also been developing and assessing regional disturbance mapping products from MODIS data, although these products are still considered to be experimental (Ellenwood, 2006; Nielson et al., 2006).

Coarse resolution satellite data from sensors such as Advanced Very High Resolution Radiometer (AVHRR) and SPOT VEGETATION have been used to monitor large regional insect-induced forest disturbance (Kharuk et al., 2004; Breshears et al., 2005; Fraser et al., 2005; Potter et al., 2005); however, most of these studies were conducted in coniferous forest settings and the 1–8 km resolution of these systems is considered too coarse for the national scale EWS described by Hargrove et al. (2009). With all of the recent MODIS products available in different formats and resolutions, it is important to learn from previous research, which MODIS wavebands, vegetation indices, spatial resolutions (0.25 km, 0.50 km), radiometric calibration methods, and temporally processed products (e.g., selective single dates or temporally processed daily to 16 day composites) have been successful in detecting forest canopy disturbance at the regional scale. For example, recent research in remote sensing change detection of forest disturbance (Jin and Sader, 2005a; Hayes and Cohen, 2007; Kharuk et al., 2007; de Beurs and Townsend, 2008; Hayes et al., 2008) and advances in time-series data processing (Chen et al., 2004; McKellip et al., 2005; Bradley et al., 2007; Lunetta et al., 2006) suggest that temporally processed vegetation indices, derived from multitemporal MODIS data, can play a significant role in regional forest disturbance monitoring and threat assessment applications.

Multispectral vegetation indices and transformations have been used extensively as data inputs in forest change detection studies (Coppin and Bauer, 1996; Coppin et al., 2004). The normalized difference vegetation index (NDVI) contrasts the visible red and near infrared (NIR) spectral bands, which are available on most multispectral satellite systems. Other indices that incorporate data from the shortwave infrared (SWIR) waveband, including Tasseled Cap Wetness, have been applied in several studies with forest change

detection results equal to or exceeding those using NDVI (Cohen et al., 2002; Franklin et al., 2001; Jin and Sader, 2005b; Hayes and Cohen, 2007; Hayes et al., 2008). de Beurs and Townsend (2008) assessed gypsy-moth-induced forest defoliation impacts using non-composited daily data sets and temporal composites of MODIS vegetation index products, computed from atmospherically corrected reflectance bands. These researchers concluded that MODIS data are useful for mapping annual gypsy moth defoliation for patches greater than 0.63 km². They reported coefficient of determination (adjusted r^2) values between MODIS (using 250-meter normalized difference infrared index (NDII) data sets, based on NIR and 2150 nm SWIR bands) and Landsat estimates of defoliated foliar biomass of 0.638 and 0.769 for 2000 and 2001, respectively. Though nominally 250 m, these best apparent daily MODIS data products were in part based on 500-meter SWIR reflectance data. The daily products showed higher correlations than the temporal composite products; but significant cloud coverage for the daily products precluded a wall-to-wall survey of the defoliation extent in the study area.

Forest disturbance patterns from insect defoliation can range from dispersed and spotty occurrences to extensive large patches. In many cases, as with gypsy moth defoliation, such disturbance tends to be ephemeral with refoliation usually occurring subsequent to defoliation. This differs from the more severe stand replacement disturbances such as forest harvesting and high burn intensity wildfires that removes all or a significant part of the canopy. A review of available literature indicated few studies of higher resolution MODIS products for mapping deciduous forest insect defoliation have been reported. Recent studies indicate that broad-area forest disturbance (from forest harvest or clearing for agriculture) can be detected using MODIS multispectral time series data with spatial resolutions of 250 to 500 m. Although, these studies were focused on forest harvest or forest conversion to agriculture, they are still informative to the application of MODIS NDVI products and spatial resolutions for regional studies of insect-induced forest defoliation.

In a Northeast U.S. mixed forest environment of deciduous hardwood and coniferous species, Jin and Sader (2005a) reported that 16-day composite 250-meter NDVI data from MOD13 products achieved 69% detection agreement (with Landsat), while single-day 250-meter NDVI data from MOD09 products achieved 76% detection agreement when the disturbed patch size was greater than 20 ha. The detection agreement increased to approximately 90% for both data sources when the patch size exceeded 50 ha. The latter result indicated that selective single day products achieved better results for disturbances within a detectable patch size, which agrees with findings by de Beurs and Townsend (2008) mentioned previously. In another study, Hayes et al. (2008) tested the effect of MODIS product spatial resolution (0.25, 0.50, and 1 km) on forest disturbance detection and model prediction for a tropical deciduous forest region in Guatemala. These authors reported that the normalized difference moisture index (NDMI of the NIR and 1650 nm SWIR bands) calculated from half-kilometer MOD02 calibrated radiance datasets generally showed the best relationships in detecting forest harvest disturbance (tropical forest clearing as a precursor to agriculture) and the lowest model prediction errors at individual study areas and time intervals.

In summary, all three studies (Jin and Sader, 2005a; de Beurs and Townsend, 2008; Hayes et al., 2008) reported better forest disturbance detection results with selective single date MODIS compared to 16 day composite NDVI products. The interpretation of this collective finding is that the 16 day composites, produced before the recent Collection 5 MODIS products and without additional advanced temporal data processing, were noisy due to unmasked, residual contamination from cloud and radiometric processing anomalies, thus reducing their disturbance detection accuracy compared to selective, non-composited single day products. However, the use of temporal composite products increases the odds of obtaining wall to wall cloud-free data products. With better temporal processing, it is

conceivable that the temporal composite product performance would have improved for this forest disturbance detection application. Also these studies suggest that both the 250- and 500-meter resolution MODIS data can be useful for monitoring forest disturbance when it occurs as extensive, large patches. All of these studies were conducted with the intent of monitoring forests on either an annual or event basis. None of these studies addressed the need for monitoring forests on a more frequent interval, as would be required for a forest threat early warning system. The latter will require temporal compositing of daily data as opposed to single date data sets, due to frequent cloud cover of many forested areas in the U.S.

Validation of historical MODIS defoliation mapping products is often hindered by the lack of contemporary ground reference data in desired locations over regional study areas. Multiple dates of ground reference data or high resolution aerial and satellite imagery (e.g. IKONOS and QuickBird data) are either not available or too expensive to obtain. One alternative is to use low cost, regional medium resolution imagery (e.g., Landsat, ASTER, or SPOT multispectral data) to support verification or assessment of MODIS-based defoliation detection products.

A review of published research was conducted to determine the suitability of medium resolution imagery as a reference source for comparison of MODIS defoliation products. Earlier studies using Landsat and SPOT imagery demonstrated successful applications in detecting deciduous broad-leaved forest defoliation.

For example, Williams and Nelson (1986) employed multitemporal Landsat Multispectral Scanner (MSS) vegetation index (NIR/red band ratio) products to detect gypsy moth defoliation in Pennsylvania at an approximate overall accuracy of 90%. Ciesla et al. (1989) reported that 20-meter SPOT satellite false color composite imagery showed moderate to heavy gypsy moth defoliation areas and yielded an 86% agreement with comparable products from high-altitude aerial photography. Muchoney and Haack (1994) reported gypsy moth defoliation products from SPOT imagery yielded a 69% overall agreement compared to USFS defoliation sketch maps, but they acknowledged that the reference sketch mapping products also contained classification errors. Vogelmann (1990) compared Landsat Thematic Mapper (TM) NDVI and SWIR/NIR ratio imagery on several forest cover types subjected to biotic or abiotic forest damage. He concluded that 1) the SWIR/NIR ratio was superior in identifying low versus high forest damage in areas with balsam fir mortality; 2) both SWIR/NIR and NDVI distinguished between low and high damage on broad-leaved forest sites; and 3) NDVI was superior in separating medium and low damage within deciduous forest.

Landsat as a reference source for validation of MODIS-based forest defoliation map products is subject to errors, but previous disturbance studies have shown that Landsat has achieved reasonably good accuracy in detecting and mapping harvest disturbances and disturbances caused by defoliating insects.

2. Objectives

MODIS data, available since 2000, provides a rich set of multi-band reflectance and temperature data products available for use in the forest threat EWS being developed by the USFS Forest Threat Assessment Centers. The study described herein assesses MODIS time-series vegetation index data products for their ability to contribute broad, regional geospatial information on gypsy moth defoliation of forest stands. One unique aspect of the methodology is the development of temporally processed time series data to reduce the effect of cloud contamination and to allow a wall-to-wall assessment of defoliation in the study area. The use of temporal compositing is a necessary facet of the EWS's requirement for wall to wall cloud-free observational coverage, as discussed previously herein and also by Hargrove et al. (2009). The EWS was also in need of information on the ability of MODIS products to detect forest

disturbance events across large regions, such as ephemeral forest defoliation from gypsy moths.

In response, a study was conducted with the following objectives: 1) assess agreement of historical, regional MODIS gypsy moth defoliation products with available medium resolution Landsat and ASTER reference data ; and 2) assess results of multiple MODIS NDVI time series defoliation detection products in regard to requirements for a national scale forest threat EWS, especially in regard to spatial resolution and compositing technique (compositing of daily data compared to aggregate compositing of standard pre-existing 16 day

composite products) . Objective 2 was pursued in part to better assess temporal compositing and spatial resolution processing needs of the EWS. The latter objective was addressed to assess if temporal processing of MODIS time series data at desirable spatial resolutions (e.g., 250–500 m) would enable useful regional-scale detections of insect-induced forest defoliation. While the longer term goal was to develop a near real time MODIS-based regional forest disturbance detection capability, this study was done using historical data. The latter enabled meaningful comparisons to higher spatial resolution reference data (primarily Landsat and ASTER satellite data) to be employed.

3. Methods

3.1. Study area

The mid-Appalachian highland region of the Eastern United States was selected for the study area because gypsy moth defoliation had occurred over multiple years during the MODIS operational period (Fig. 1). This area encompasses portions of 4 states (West Virginia, Virginia, Pennsylvania, and Maryland) and a total area of approximately 6.2 million ha. It is largely forested with broad-leaved, hardwood tree species, including an abundance of oak-dominated stands occurring along an extensive network of ridges. Many of the valleys in this region are in agricultural use among residential and small urban communities. During outbreak years, gypsy moth defoliation in this region tended to occur within the oak-dominated forests as large, extensive patches (Fig. 2).

3.2. Satellite data acquisition and preprocessing

Several MODIS Aqua and Terra multitemporal data products were acquired over the study area for all available dates during spring and summer 2000 through 2006, including Collection 4 MOD02 (single-day) and MOD13 (16-day) products. MOD03 and MOD35 products were also acquired to mask out cloud-covered and poor quality data. Additional high-resolution satellite images from Hyperion, Advanced Land Imager, Landsat TM and Enhanced Thematic Mapper Plus (ETM+), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) were acquired for use as reference data in the evaluation of the MODIS-based gypsy moth defoliation detection products.

3.3. Processing MODIS time series data

Cloud-free data is an important requirement for operational monitoring of forest disturbance with electro-optical multispectral sensors. Obtaining optimal single dates of cloud-free, area-wide coverage can be difficult, especially in cloud-prone mountainous forests in the eastern United States. The

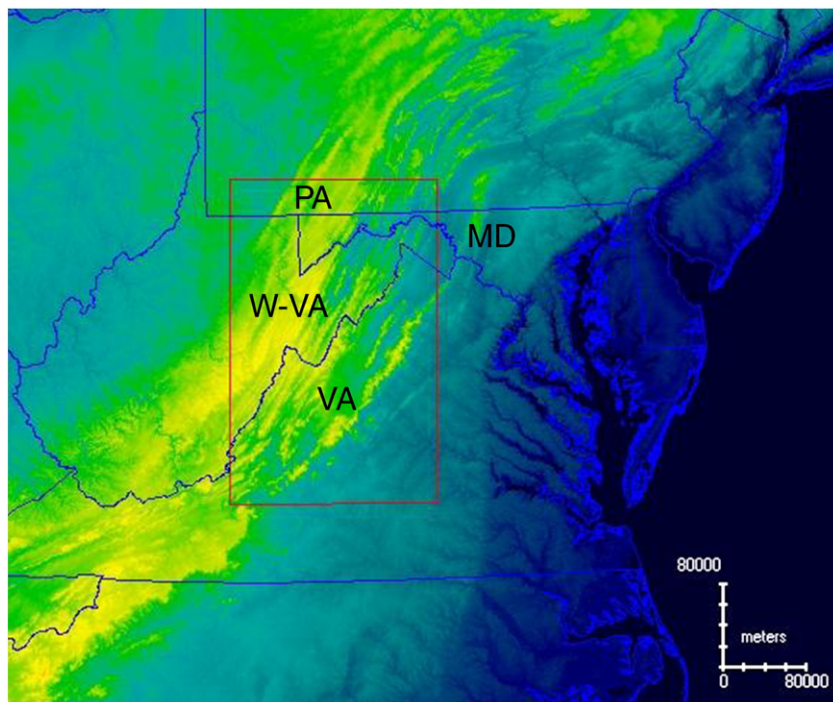


Fig. 1. Location of study area in the Eastern United States (study area extent is outlined in red and overlain onto a digital elevation product acquired from the Shuttle Topography Radar Mission). Ground elevations in the study area range from approximately 34 (dark blue grey tones) to 1483 m (yellow).



Fig. 2. Oblique view of gypsy moth defoliation. Photograph acquired by Mark Robinson, USDA Forest Service. Source: <http://www.forestryimages.org/browse/detail.cfm?imgnum=2912081> (accessed March 31, 2009).

scarcity of cloud-free data on single dates may be mitigated when temporal composites of cloud-free data encompass the time during which tree damage symptoms are evident. In this study, analysts applied each MODIS time series data product as input into the MATLAB-based Time Series Product Tool (TSPT) to generate cloud-free time-series datasets (McKellip et al., 2005; Prados et al., 2006; McKellip et al., 2008). The TSPT software identifies and removes user-defined, suspected poor-quality data degraded by atmospheric contamination and poor viewing geometry. Replacement of the “contaminated” data was a necessary step in producing essentially cloud-free temporal image composites of the study area during the gypsy moth defoliation period for each year in the time series.

The procedure for generating the MOD02 NDVI time series in this study was initiated by inputting daily MODIS Terra MOD02 data files over the entire 2000–2006 time frame into the TSPT. The TSPT initially called upon the MRTSwath (USGS, 2006) software to reproject the needed co-registered NIR and red reflectance data to the UTM map projection. The NDVI was calculated from relevant NIR and red reflectance bands, cloud masked with the MOD35 product, and further masked to exclude reflectance data collected with sensor zenith angles greater than 47° , and to eliminate aberrant spikes in NDVI (that were either much higher or lower than can be reasonably expected compared to adjacent NDVI values in the time series). The data voids in the cleaned dataset were then subjected to temporal interpolation, followed by temporal filtering with the Savitzky–Golay algorithm (Savitzky and Golay, 1964). This algorithm includes parameter settings for 1) temporal frame size; 2) polynomial order; and 3) Full Width Half Maximum (FWHM) in regard to the temporal distance from a given date. These settings were determined by trial and error and are somewhat dependent on the satellite data product and on scene-dependent parameters, such as cloud frequency. For example, in this study, the MOD02-based daily product generation uses a temporal frame size of 15 days, a polynomial order of 1, and an FWHM of 8 days. In some cases, the Savitzky–Golay filtering did not return an NDVI value because of clouds on several contiguous dates of data. In such instances, additional data void interpolation was performed, using the nearest cloud-free NDVI data points on each side of the void (for a given date) followed by cubic spline curve fitting of the date and pixel in question. This multi-step time series data procedure was run to compute temporally filtered daily NDVI products for the defoliation period of each year during 2000–2006.

The TSPT produces intermediate files so that the effect of each processing step can be assessed. It also stacks output from each day into a multitemporal data stack for each year. The final filtered output contains NDVI pixels gridded at 250-meter Ground Sampling Distance (GSD). TSPT was also used to temporally process and refine the 16-day MOD13 NDVI products into 48-day temporal composites of the same defoliation period as with the MOD02 products.

3.4. Detection of gypsy moth defoliation from MODIS time series data

For each year during 2000–2006, MODIS time series were computed for the period when peak gypsy moth defoliation tended to occur in the study area (June 10–July 27). This time frame was determined using available documentation on the phenology of gypsy moth defoliation (e.g., McManus et al., 1989) and on the scheduling of gypsy moth sketch mapping surveys (e.g., USFS, 2007). This approach differs from that of de Beurs and Townsend (2008), who used the BioSIM model in conjunction with field data to estimate the period of peak defoliation. We also used Landsat and ASTER imagery in conjunction with published, regionally specific gypsy moth insect development chronology (e.g., McManus et al., 1989) and sketch mapping metadata (e.g., USFS, 2007) to help determine the June 10–July 27 defoliation time frame. For the Northeast and Great Lakes region of the United States, Ciesla (2000) reported that the optimal bio-window for aerial sketch mapping of gypsy moth defoliation is from June 20 to July 20. In general, gypsy moth defoliation in early June has not yet reached its peak extent. By early August, partial re-foliation can be evident, though the re-foliation level varies according to multiple factors, such as site, weather, and defoliation intensity (Gottschalk, 1993). Gypsy moth defoliation can occur over consecutive years depending on these conditions and others influencing pest insect population dynamics, such as the impacts of pathogens on the defoliating insects. McManus et al. (1989) indicate that larval (i.e., caterpillar) development ceases in early July, which also marks the end of defoliation progression. We defined the defoliation time frame or bio-window as a 48-day period to aid

production of cloud-free temporal composites of NDVI levels during evident gypsy moth defoliation. This 48-day time frame includes 3 dates of 16-day composites from the MOD13 data and 48 days of daily MOD02 data from the MODIS Terra sensor.

ERDAS IMAGINE® (Leica GeoSystems, 2005) and ENVI® (Research Systems, Inc, 2003) software were used to compute and assess MODIS gypsy moth defoliation mapping products. For each MODIS time-series product during the targeted defoliation period, the maximum NDVI value was computed on a per-pixel basis for all 7 years. A multi-channel image data stack was used to compute the maximum NDVI during each defoliation season of 2000–2006 and of the maximum NDVI during the defoliation periods for all 7 years combined. In most cases, the latter records forest NDVI values during non-defoliated states over the defoliation time frame. Fig. 3 depicts the maximum NDVI during the defoliation season for all years assigned to the red color and the maximum NDVI for the defoliation season of 2001 assigned to the blue and green colors. The RGB display shows the defoliation areas in red tones, indicating a drop in NDVI for the 2001 defoliation period compared to the maximum NDVI during the defoliation time frame across the entire 2000–2006 era. This form of change detection visualization employs an additive color theory approach to multi-date color compositing discussed by Sader and Winne (1992). Defoliation detection maps were first developed using unsupervised classification of one date of maximum NDVI during a defoliation season of a given year and of the maximum NDVI during the defoliation time frame across all 7 years. MODIS data sets for 2001 were selected for developing and validating detection products because relevant, cloud-free Landsat and ASTER imagery were also available for this year (Fig. 4). Unsupervised classifications were produced for MOD02 and MOD13 data products using ISODATA unsupervised clustering and 20 cluster classes per dataset. Initially, the 20 classes were initially recoded into 3 land cover categories: 1) non-forest; 2) non-defoliated forest; and 3) defoliated forest. Recoding was aided by visual comparisons with Landsat, ASTER, and Hyperion images, and reference to USFS gypsy moth sketch maps and National Land Cover Database 2001 data products. Compared to higher resolution remotely sensed data, commission error was noted for smaller patches on the 250-meter and 500-meter products. To reduce such commission error in the MODIS 250-meter products, homogenous single-class patches in the recoded image were aggregated (“clumped”) to dissolve small patches of less than 4 pixels into the dominant class of the surrounding area. For MODIS 500-meter products, homogenous single-class patches in the recoded image were aggregated to dissolve regions of less than 2 pixels into the dominant class of the surrounding area. This aggregation resulted in an effective minimum area mapping unit of 0.25 and 0.50 km² for the 250- and 500-meter products, respectively. Final classifications were created by recoding from 3 into 2 classes (defoliated forest versus “other”). Fig. 5 depicts defoliation maps computed from the MOD02 250-meter NDVI data.

Image thresholding techniques were applied to compute an additional defoliation detection product from the 250-meter MOD02 time series data. MOD02 NDVI products were used to compute a percent change in NDVI for the 2001 defoliation season compared to the maximum NDVI for same time frame across the entire 2000–2006 period, using the following formula:

$$\% \text{Change in Maximum NDVI} = \frac{(\text{Maximum NDVI Peak Defoliation YearX}) - (\text{Maximum NDVI Peak Defoliation All Years})}{(\text{Maximum NDVI Peak Defoliation All Years})} * 100$$

The output image was thresholded into 2 classes (defoliated versus non-defoliated) based on visual comparison with MOD02 and Landsat NDVI RGB displays (Fig. 4). This detection product was thresholded so that anomalously high drops in NDVI, indicative of forest defoliation, were defined as pixels with 4% change or greater. As with the MOD02 unsupervised classification result, we applied clump aggregation techniques on the image thresholded defoliation product to reduce visual indications of commission error due to small patches. Homogenous single-class patches in the recoded image were “clumped” to dissolve small patches of 4 pixels or less into the dominant class of the surrounding area. The total area of detected forest defoliation was enumerated for each MODIS defoliation detection product (Table 1).

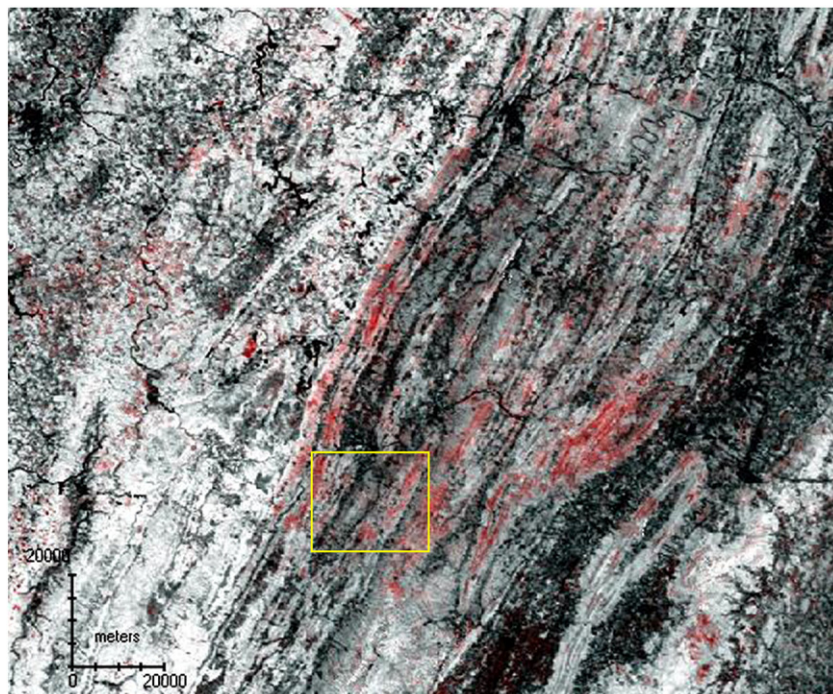


Fig. 3. Synoptic view of 2001 gypsy moth defoliation using RGB color composite image based on MOD02 maximum NDVI during the defoliation seasons across 2000–2006 era loaded in red plus maximum NDVI during the defoliation for 2001 assigned to the blue and green color guns. The deep red tones indicate defoliation. The yellow box shows the location of Figs. 4 and 5.

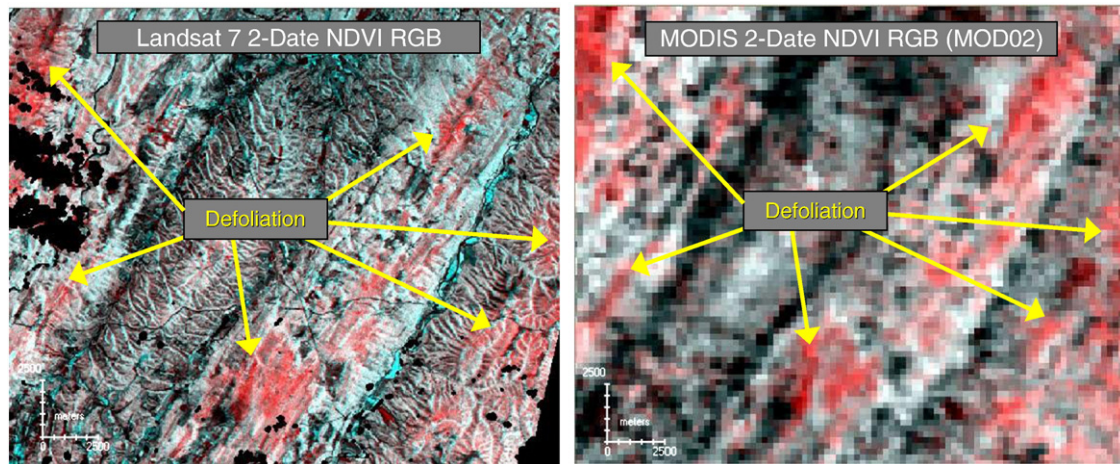


Fig. 4. Visual comparison of 2001 gypsy moth defoliation evident on Landsat (left) versus MODIS (right) 2-date NDVI color composite imagery. The Landsat RGB includes NDVI from June 10, 2000, loaded in the red and NDVI from July 15, 2001, loaded into the blue and green color guns. The MODIS RGB is from MOD02 data and composed as discussed in the caption for Fig. 3.

3.5. Validation of gypsy moth defoliation detection products

A stratified random sample of pixels was selected using the MODIS 250-meter classification (MOD02 NDVI) so that each of 3 classes (non-forest, non-defoliated forest, and defoliated forest) was represented by at least 50 random sample locations. Each random sample pertained to a single MODIS 250-meter pixel area consisting of a single class. The sample selection algorithm collects samples that occurred within 3×3 pixel windows of single class values to aid assessment of polygonal surface cover patch features as opposed to the edges of such features. An analyst viewed each randomly sampled location on either Landsat or ASTER imagery recorded during the 2001 defoliation time frame. The primary 2001 scenes included path 17 row 34 Landsat data from July 7 (Landsat 5) and July 15 (Landsat 7). We also utilized July 15, 2001 Landsat 7 data from path 17 row 33. The primary ASTER data sets were from July 24, 2001. This analysis also employed Landsat 7 data of largely non-defoliated forest within the study area from June 10, 2000 for path 17 rows 33 and 34. Landsat 5 data from path 17 rows 33 and 34 acquired September 17, 2001 was also used for comparative purposes, though some gypsy moth defoliation was still evident. In addition, NDVI products were computed from Landsat imagery and then copied into a two channel data stack that was used to visually interpret the defoliation status of randomly sample locations. This stack was used to compute 2 date RGB screen displays in which the predominantly non-defoliated early summer 2000 Landsat NDVI channel was loaded into the red color gun and a corresponding 2001 Landsat NDVI was loaded into the blue and green color gun (Fig. 4). This RGB showed defoliated forests in red tones, enabling an additional enhanced view of forest defoliation, not evident when only viewing single date Landsat false and true color composite RGBs.

The visual interpretation of Landsat color composite imagery as a reference source to support accuracy assessment of historical MODIS regional forest change detection has been applied and reported in previous studies (Jin and Sader, 2005a; Hayes and Cohen, 2007; Hayes et al., 2008). The use of Landsat TM and ETM+ as reference data is also supported by work from Williams and Nelson (1986) in which Landsat MSS defoliation detection products yielded 90% overall accuracy. In assessing MODIS-based defoliation detection products, the Landsat and ASTER data interpretation of randomly sampled areas were made by a trained, experienced geospatial image analyst. In doing so, the expectation was that this product validation method would enable a reasonably good assessment of MODIS defoliation detection product performance, even though the interpretation of defoliation on Landsat and ASTER image data are also subject to some error.

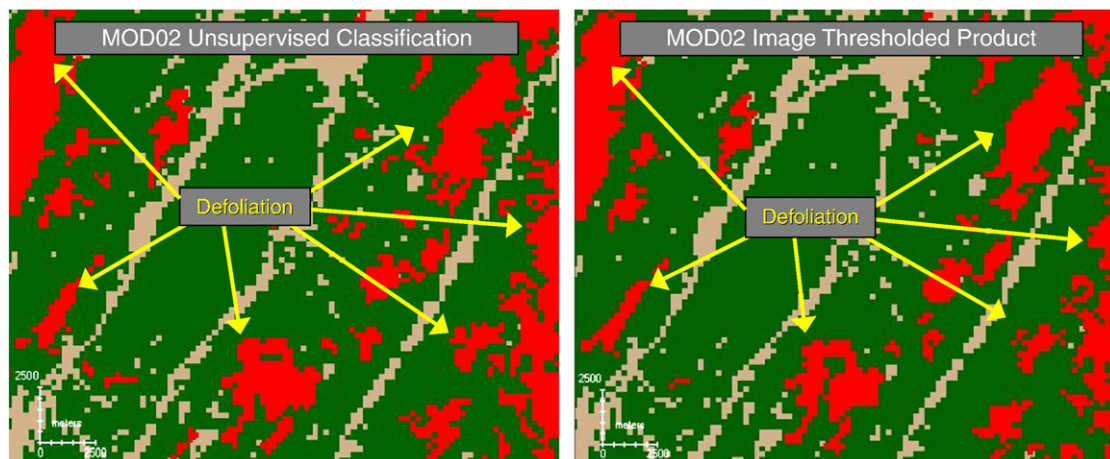


Fig. 5. Example of defoliation detection products computed from MODIS MOD02 time-series data. The area shown here is identical to Fig. 4. The mapped defoliation shown in red is draped onto a forest mask derived from NLCD 2001 data in which forest is shown in green and non-forest is displayed in tan.

Based on interpretation of the Landsat or ASTER false color composite RGB displays at a fixed high-resolution viewing scale (1:17,500), the analyst interpreted and categorized each selected 250×250 m sample location as being either predominantly non-forest, non-defoliated forest, or defoliated forest. In doing so, the 250 by 250 m area of each random sample location was clearly defined on the applicable Landsat or ASTER screen displays. An error matrix was then prepared to compute estimates of percent overall agreement with available reference data as well as omission and commission error on a per-class basis. Kappa statistics were generated to assess overall classification agreement adjusted for random chance effects (Congalton, 1991). Kappa statistics were also computed on a per-class basis. In addition, an assessment of agreement was performed on 2-class classification products depicting defoliated forest versus “other” by grouping samples from non-defoliated and non-forest to “other.”

4. Results and discussion

4.1. Agreement assessment of unsupervised classification of gypsy moth forest defoliation

Unsupervised classification agreement results of defoliated forest versus “other” land cover for the MOD02 250-meter NDVI, MOD13 250-meter NDVI, and MOD02 500-meter NDVI are presented in Table 2. The table also includes agreement metrics for the image thresholded defoliation detection product.

The MOD02 250-meter NDVI classification product and the image thresholded product yielded very similar overall classification agreement with the reference data (88.4% versus 87.3%), overall Kappa values (0.75 versus 0.72), defoliation class omission error rates (0.09 versus 0.16), and defoliation class Kappa values (0.67 versus 0.68). The MOD13 250-meter NDVI classification had a lower overall agreement (79.1%) and a much lower overall Kappa (0.46). The MOD13 250-meter NDVI classification of defoliation yielded high omission error rate (0.56) but the lowest commission error rate (0.14) and highest defoliation class Kappa (0.79), suggesting that the classification usually omitted defoliation areas but did not substantially over-classify (i.e., cause excessive commission error) defoliation areas. Non-defoliation agreements are also reported in Table 2.

Compared to 250-meter data products, the overall agreement was similar, but slightly lower, using the 500-meter data products. The MOD02 500-meter NDVI classification had an overall agreement of 85.0% and Kappa of 0.65. For defoliation detection, the 500-meter NDVI had higher omission rate (0.30) but slightly lower commission error rate (0.18) and higher defoliation class Kappa (0.73) compared to the MODIS 250-meter defoliation mapping products.

4.2. Temporal datasets created from time series product tool

Williams and Nelson (1986) reported that the Eastern United States is often 50+ percent cloudy during the summer months. Based on available Collection 4 MODIS MOD35 cloud mask products, the study area's cloud frequency during the gypsy moth defoliation time frame (June 10–July 27) approached 80% for 2000–2006 (Table 3). This cloud frequency significantly hinders effective use of Landsat data for annual region-wide detection of gypsy moth defoliation, particularly where several Landsat scenes are required to cover the study area. For large study areas, it is also difficult to find single dates of MODIS data with low cloud coverage for the study area during the defoliation season. In contrast to previous studies of gypsy moth defoliation, our study employed a novel approach to reduce cloud contamination problems by employing temporal processing techniques (e.g., TSPT discussed in

Table 1

Summary area estimates of 2001 gypsy moth defoliated forest and “non-defoliated other” for assessed MODIS NDVI sketch mapping products (areas expressed in square kilometers).

2001 gypsy moth defoliation detection product	Defoliation	Other	Total
MOD02 250 m NDVI unsupervised classification	2427	59,572	61,999
MOD02 250 m NDVI image thresholded classification	2290	59,710	61,999
MOD13 250 m NDVI classification	1228	59,622	60,847
MOD02 500 m NDVI classification	1694	60,305	61,999

Methods) to allow a wall-to-wall assessment of defoliation patterns across the entire study area. This study successfully applied available pest phenology information in defining the period over which temporal compositing was done, using available scheduling information on aerial gypsy moth defoliation surveys (Ciesla, 2000; Sellers, 2001; USFS, 2007) and regional gypsy moth life cycle trends (McManus et al., 1989). Doing so enabled a broad regional assessment of defoliation, an important requirement for the forest threat EWS.

Temporal processing of the MODIS data using the TSPT resulted in the detection of large defoliation patches, rather than producing products including defoliation patterns interrupted by scene-dependent cloud contamination. In 2001, the cloud cover in the study area was at a low enough frequency to be mitigated through temporal processing (e.g., compositing and filtering). The fact that cloud-free temporal composites for the main defoliation period of 48 contiguous days could be developed within the cloud-prone mid-Appalachian highlands study area is encouraging. Also, these results are promising given that only available MODIS Terra data was used and that no data were collected from June 15 through July 2, 2001, because of a sensor issue. Despite time-series data processing, residual atmospheric contamination from clouds and from cloud shadows lowered detection ability, although less so for the MOD02 products. Producing comparable defoliation classification agreement results with Landsat or ASTER, using single-day MODIS imagery without temporal processing would be unlikely given the cloud statistics and the variability of average sensor zenith angle for the MODIS imagery. Many of the better single-date MODIS scenes across the time series were collected at high sensor zenith angles, which effectively increased the Point Spread Function and decreased the spatial resolution.

The temporal compositing can be complicated by use of data bands generated at different spatial sampling scales (e.g., 250 versus 500 m)

Table 2

Agreement of MODIS-based defoliation detection products for 2001 compared to interpretation of randomly sampled locations on Landsat and ASTER RGB displays.

Product	Defoliated forest			Other			Overall	
	OER	CER	Kappa	OER	CER	Kappa	OA	OK
MOD02 NDVI 250-m unsupervised classification	0.09	0.22	0.67	0.13	0.05	0.86	88.4 (153/173)	0.75
MOD02 NDVI 250-m image thresholded classification	0.16	0.21	0.68	0.11	0.08	0.76	87.3 (151/173)	0.72
MOD13 NDVI 250-m unsupervised classification	0.56	0.14	0.79	0.03	0.22	0.33	79.1 (137/173)	0.46
MOD02 NDVI 500-m unsupervised classification	0.30	0.18	0.73	0.08	0.14	0.48	85.0 (147/173)	0.65

OER = Omission Error Rate (1-Producer's Agreement), CER = Commission Error Rate (1-User's Agreement), Kappa = Kappa Statistic, OA = % Overall Agreement (# correct/total), and OK = Overall Kappa.

Table 3

Estimated frequency of cloud coverage during the gypsy moth defoliation time frame of June 10–July 27 for 2000–2006, based on analysis of Collection 4 MODIS MOD35 daily cloud mask products.

Year	% Cloudy	# Sampled days	Mean # cloudy days	Mean # sunny days
2000	82.51	47.00	38.78	8.22
2001	73.28	30.00	21.98	8.02
2002	76.01	48.00	36.49	11.51
2003	77.26	48.00	37.08	10.92
2004	83.77	48.00	40.21	7.79
2005	81.13	48.00	38.94	9.06
2006	73.55	48.00	35.30	12.70
Average all years	78.48	45.29	35.54	9.75

and by different sensor subsystems (e.g., visible and NIR versus SWIR). Noise mitigation of temporal composites can also be problematic even when the utilized bands have the same resolution and are from the same sensor subsystem. Consequently, noise mitigation of vegetation index products based on both NIR and SWIR bands may need to be applied to raw bands independently prior to computing higher order vegetation index products. The results presented here focus on the use of NDVI time series for monitoring forest disturbance, primarily due to the higher inherent spatial resolution of the MODIS NDVI products generated from 250-meter red and NIR bands.

4.3. Data gaps and recommended future work

Atmospheric correction of reflectance is highly desirable for detection and depiction of vegetation anomalies from NDVI time series, although for a given current season the products need to be as near real time as possible for fullest use in the USFS EWS. While atmospherically corrected products may be desirable, the most useful results for this experiment were from MOD02 products that were not atmospherically corrected. It is not completely clear as to why the temporally composited daily MOD02 products performed better than the atmospherically corrected, temporally composited MOD13 products, although other authors have reported similar findings favoring selective dates of daily MODIS over MOD13 temporal composites in forest disturbance detection studies (Jin and Sader, 2005a; Hayes et al., 2008; de Beurs and Townsend, 2008). The MOD02 temporal composites in this study appeared to be less noisy and visually depicted the defoliation more consistently. Another factor is that the 2001 defoliation season was only covered by MODIS Terra and that there was a multi-day stretch (June 15–July 2) during the surveyed June 10–July 27 defoliation period in which no MODIS data was collected due to a sensor issue. This could have created an advantage in using daily data to mitigate data voids prior to temporal compositing. It is conceivable that the computation of 48 day composites from the temporally processed 16 day MOD13 NDVI data was a less effective strategy than computing 48 day composites from the daily, temporally processed MOD02 data. The MOD13 defoliation products were computed from the best available pre-processed MODIS data at the time: the Collection 4 products. The use of Collection 5 MODIS products may improve the MOD13 results for this application by providing data with improved atmospheric correction and reduced residual noise.

An effort was also made to use Collection 4 MODIS MOD09 atmospherically corrected ground reflectance data for this application, but this was abandoned because of the noise from residual atmospheric contamination evident in the MOD09 raw data displays. This noise caused significant omission for classification of defoliation areas. Because of these problems, further evaluation (e.g., agreement assessment) of MOD09 products for this application was delayed until a better determination could be made on the nature of the MOD09

noise artifacts and an optimal approach for noise reduction. Views of non-temporally filtered MOD09 data products indicate that the noise problem is evident before TSPT processing, suggesting that residual atmospheric contamination was a factor. A modification of the atmospheric correction procedure may be needed to make MOD09 products more useful for this forest threat EWS application. For areas prone to clouds during defoliation, atmospheric correction may increase noisiness of vegetation index products compared to results from MOD02 planetary reflectance. Collection 5 MOD09 atmospherically corrected data should enable an improved application product and may therefore help improve defoliation detection results for cloud-prone areas, such as the mid-Appalachian Highlands.

Alternative indices to NDVI should be explored using MODIS data for mapping forest defoliation. In particular, we recommend that MODIS NDVI defoliation maps be compared to those from NDMI (Jin and Sader, 2005b; Hayes et al., 2008) or NDIb7 obtained from the NIR and 2150 nm SWIR band (de Beurs and Townsend, 2008) time series products (or comparable vegetation index products involving SWIR and NIR bands). NDMI-based defoliation analysis was initiated in this study but was not fully pursued because of noise evident in the TSPT-processed NDMI products that was not evident in the corresponding NDVI products. The noise problem is apparently due to running the TSPT noise reduction routines on the vegetation index product versus the individual bands used to compute the vegetation index. It appears that noise reduction may need to be applied separately to the 250-meter NIR and 500-meter SWIR bands prior to computing daily NDMI images and producing subsequent temporal composites. In addition, the fusion of MODIS Aqua and Terra data products may also improve quality of NIR- and SWIR-based vegetation indices used to compute forest defoliation detection products. The application of fused MODIS Aqua and Terra data products should be advantageous to decrease data voids from clouds and to decrease the noise from atmospheric contamination in general.

Although not an objective of this study or an absolute requirement of the forest threat EWS described by Hargrove et al. (2009), future research is recommended to determine if more than one defoliation severity class can be accurately detected from 250 or 500 m MODIS data. Additional defoliation severity classes would be useful if obtainable at sufficiently high accuracies. While this study did not yield multiple defoliation classes, the determination might be attempted using a fractional abundance classification approach (e.g., Hansen et al., 2003) to compute percent forest overstory defoliation on a per-pixel basis. Accuracy of gypsy moth defoliation detection products as a function of patch size should also be explored and compared to results from work by de Beurs and Townsend (2008). Their study concluded that defoliation patches greater than 0.63 km² can be accurately detected with daily non-composited MODIS data. In comparison, all of defoliation detection products from our study were derived using a minimum patch size of 0.25 km² (2 pixels) for the 250 m products and 0.5 km² (4 pixels) for the 500 m product.

In comparing results across the different years of the time series, the MODIS defoliation mapping products were most effective for years when defoliation was extensive, such as 2001. While results indicated that defoliation maps for 2001 produced from MODIS data showed general agreement with reference data, accuracy assessment is needed for other years to confirm consistency of the detection techniques and suitability of the data for the application.

This investigation considered one extensive study area (mid-Appalachian Highlands) that is not completely representative of all forest landscapes and U.S. regions with extensive forest. Other forest types and landscape conditions vulnerable to major insect threats should be examined using similar datasets and techniques, because the USFS forest threat EWS will be implemented on a national scale. This study provided some evidence that MODIS time series NDVI data can provide geospatial information on gypsy moth defoliation in near real time, although more testing is needed to demonstrate and

validate the potential for supplying this information in near real time to the EWS. Some of this testing was recently performed for 2009 using MOD13 NDVI data in conjunction with near real time MODIS NDVI from the USGS eMODIS data stream (Hargrove et al., 2009).

Gypsy moth defoliation phenology is an important component of the approach for region-wide defoliation detection from daily MODIS time series data. The bio-temporal window used in this study appeared to be appropriate based on the 2001 gypsy moth case study discussed here. However, other biotic and abiotic factors can also cause defoliation, so care must be taken when defining the bio-temporal windows of observation and interpreting detection results. For example, forest tent caterpillar (*Malacosoma disstria*) peak defoliation in this region tends to occur earlier than gypsy moth defoliation, though there is some overlap in the defoliation phenology of these two pests. Abiotic agents, such as ice storm damage, also produce ephemeral forest defoliation. The most definitive assignment of a causal agent requires field validation in a statistically valid manner to represent the region at large.

5. Conclusions

This study produced MODIS-based gypsy moth defoliation maps for 2001 that showed reasonable agreement compared to available reference data. Effective defoliation detection products were obtained, using temporally filtered and composited MOD02 and MOD13 NDVI data. Accuracy assessments of these products employed visual interpretation of random sample locations on higher resolution Landsat and ASTER imagery; previous studies have shown this technique (of using moderate resolution satellite data for assessing MODIS-based forest change detection accuracy) to be valid. The MOD02 250-meter defoliation detection products yielded the highest agreement with the reference data. The MOD02 500-meter unsupervised classification overall classification and Kappa agreements with reference data were slightly lower than for the MOD02 250-meter products; however, the Kappa agreement of MOD02 500-meter defoliation classification with Landsat and ASTER reference data was slightly higher. The MOD02 products outperformed the MOD13 products, although the MOD13 product still provided a means to visualize defoliation patches and conservatively estimate gypsy moth defoliation across the landscape. These results suggest that MODIS-based gypsy moth defoliation detection products provides complementary information on the location and extent of heavy defoliation areas, compared to that obtained from aerial sketch map products and may be helpful for adjusting end-of-year estimates of defoliation currently based on aerial sketch maps. When produced in near real time, such MODIS products should be useful for aiding planning and implementation of ADS surveys. The MODIS results required that multitemporal data be processed over the entire MODIS time series during 2000–2006 to establish a cloud-free baseline of the non-defoliated NDVI values during the time of defoliation. The success of the techniques employed in this study requires sufficient cloud-free data across the defoliation time frame to enable cloud-free temporal composites. It also requires that noise reduction of residual atmospheric contamination be sufficiently effective to provide useable imagery for defoliation detection. The success depends in part on use of an appropriate bio-temporal window for a given biotic threat (e.g., gypsy moth defoliation) and locale. Single dates of non-composited MODIS data can also be effective for monitoring gypsy moth defoliation when suitable region-wide, cloud-free data are available at acceptable viewing geometries during both defoliated and non-defoliated states of the same time frame.

The USFS is considering using 500-meter MODIS reflectance data products for inclusion into a near-real-time EWS. Our results suggest that this sampling scale can be effective for monitoring regional gypsy moth defoliation, providing that defoliation tends to occur as large, extensive patches. In terms of latency, the MOD02 products are more

amenable to the EWS near-real-time requirement than the MOD13 products. However, efforts are underway by the USFS and NASA that may enable near-real-time processing of MOD02 data into the products that are atmospherically corrected and also mitigated for Bidirectional Reflectance Distribution Function (BRDF) effects. These NRT products would be created at a 250 or 500-meter GSD and would be similar to MOD43B4 products. These products would be then processed into gypsy moth defoliation products. However, until such near-real-time BRDF corrected reflectance data products are available and validated, the results of this study indicate that MOD02 and MOD13 products have potential for contributing useful gypsy moth defoliation maps needed for the EWS. The MOD13 products also showed less potential for this application, though this potential should increase using Collection 5 Terra and Aqua data. The MOD13 products are also more suitable for integrating with USGS eMODIS expedited CONUS MODIS NDVI products (latter described by Jenkinson and Schmidt, 2008). Collection 5 MOD13 and eMODIS products were employed to generate 2009 gypsy moth defoliation detection products for the Eastern U.S. in near real time (Hargrove et al., 2009).

This study has demonstrated that useful regional gypsy moth defoliation detection products can be obtained from temporally processed MODIS NDVI time series data. Such products will be a useful component of the eventual nationwide forest threat EWS that will provide information on forest disturbances periodically throughout each year (Hargrove et al., 2009). Utilizing available information on appropriate bio-windows and historical reference data on pest occurrence will enable MODIS-disturbance detection products to be assessed according to potential damage agent. Such information will be available in GIS formats to aid planning, implementation, and analysis of aerial sketchmapping surveys and to assist other facets of natural resource management.

Acknowledgments

Participation in this research by Science Systems and Applications, Inc. and Computer Sciences Corporation was supported by NASA at the John C. Stennis Space Center, Mississippi, under Task Order NNS04AB54T. We thank Slawomir Blonski and two anonymous reviewers for providing constructive comments on the manuscript.

References

- Bosworth, D. (2006). Statement of Dale Bosworth, Chief, U.S. Forest Service, United States Department of Agriculture Before the United States Senate. *Committee on Energy and Natural Resources, Subcommittee on Public Lands and Forests Concerning Healthy Forests Restoration Act Implementation*, July 19, 2006 URL: <http://www.fs.fed.us/congress/109/senate/oversight/bosworth/071906.html> (last date accessed: 6 April 2009).
- Bradley, B. A., Jacob, R. W., Hermance, J. F., & Mustard, J. F. (2007). A curve fitting procedure to derive inter-annual phenologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment*, 106, 137–145.
- Breshears, D. D., Cobb, N. S., Rich, P. M., Price, K. P., Allen, C. D., Balice, R. G., et al. (2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences U.S.A.*, 102, 15144–15148.
- Chen, J., Jönsson, P., Tamura, M., Gu, Z., Matsushita, B., & Eklundh, L. (2004). A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter. *Remote Sensing of Environment*, 91, 332–344.
- Ciesla, W. M., Dull, C. W., & Acciavatti, R. E. (1989). Interpretation of SPOT-1 color composites for mapping of defoliation of hardwood forests by gypsy moth. *Photogrammetric Engineering and Remote Sensing*, 55, 1465–1470.
- Ciesla, W. M. (2000). *Remote Sensing in Forest Health Protection*. FHET Report No. 00-03. U. S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Remote Sensing Applications Center 266 p., URL: http://www.fs.fed.us/foresthealth/technology/pdfs/RemoteSensingForestHealth00_03.pdf (last date accessed: 9 April 2009).
- Cohen, W. B., Spies, T. A., Alig, R. J., Oetter, D. R., Maersperger, T. K., & Fiorella, M. (2002). Characterizing 23 years (1972–95) of stand replacement disturbance in Western Oregon forests with Landsat imagery. *Ecosystems*, 5, 122–137.
- Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37, 35–46.
- Coppin, P. R., & Bauer, M. E. (1996). Digital change detection in forest ecosystems with remote sensing imagery. *Remote Sensing Reviews*, 13, 207–234.

- Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., & Lambin, E. (2004). Digital change detection methods in ecosystem monitoring: A review. *International Journal of Remote Sensing*, 25, 1565–1596.
- Dale, V. H., Joyce, L. A., McNulty, S., Neilson, R. P., Ayres, M. P., Flannigan, M. D., et al. (2001). Climate change and forest disturbance. *Bioscience*, 51, 723–734.
- de Beurs, K. M., & Townsend, P. A. (2008). Estimating the effect of gypsy moth defoliation using MODIS. *Remote Sensing of Environment*, 112, 3983–3990.
- Ellenwood, J. (2006). Forest health monitoring—Enhancing detection monitoring. *US Forest Service Forest Disturbance Mapping Workshop*, 29 November 2006, Salt Lake City, Utah.
- Franklin, S. E., Lavigne, M. B., Moskal, L. M., Wulder, M. A., & McCaffrey, T. M. (2001). Interpretation of forest harvest conditions in New Brunswick using Landsat TM enhanced wetness difference imagery (EWDI). *Canadian Journal of Remote Sensing*, 27, 118–128.
- Fraser, R. H., Abuelgasim, A., & Latifovic, R. (2005). A method for detecting large-scale forest cover change using coarse spatial resolution imagery. *Remote Sensing of Environment*, 95, 414–427.
- Gottschalk, K. W. (1993). Silvicultural guidelines for forest stands threatened by the gypsy moth. *Gen. Tech. Rep. NE-171*, Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.
- Hall, R. J., Skakun, R. S., & Arsenault, E. J. (2006). Remotely sensed data in the mapping of insect defoliation. In M. A. Mulder, & S. E. Franklin (Eds.), *Understanding forest disturbance and spatial pattern: Remote sensing and GIS approaches* (pp. 85–111). Boca Raton, Florida, USA: Taylor and Francis, CRC Press.
- Hansen, M., DeFries, R. S., Townshend, J. R. G., Carroll, M., Dimiceli, C., & Sohlberg, R. A. (2003). Global percent tree cover at a spatial resolution of 500 meters: First results of the MODIS vegetation continuous fields algorithm. *Earth Interactions*, 7, 1–15.
- Hargrove, William W., Spruce, Joseph P., Gasser, Gerald E., & Hoffman, Forrest M. (2009). Toward a national early warning system for forest disturbances using remotely sensed canopy phenology. *Photogrammetric Engineering and Remote Sensing*, 75, 1150–1156.
- Hayes, D. J., Cohen, W., Sader, S. A., & Irwin, D. E. (2008). Estimating proportional change in forest cover as a continuous variable from multi-year MODIS data. *Remote Sensing of Environment*, 112, 735–749.
- Hayes, D. J., & Cohen, W. B. (2007). Spatial, spectral and temporal patterns of tropical forest cover change as observed with multiple scales of optical satellite data. *Remote Sensing of Environment*, 106, 1–16.
- Jenkerson, C. B., & Schmidt, G. (2008). eMODIS product access for large scale monitoring. *Proceedings of the 17th William T. Pecora Memorial Symposium on Remote Sensing*, Denver, CO. Bethesda, MD: American Society for Photogrammetry and Remote Sensing.
- Johnson, E. W., & Ross, J. (2008). Quantifying error in aerial survey data. *Australian Forestry*, 71, 216–222.
- Johnson, E. W., & Wittwer, D. (2008). Aerial detection surveys in the United States. *Australian Forestry*, 71, 212–215.
- Jin, S., & Sader, S. A. (2005a). MODIS time-series imagery for forest disturbance detection and quantification of patch size effects. *Remote Sensing of Environment*, 99, 462–470.
- Jin, S., & Sader, S. A. (2005b). Comparison of time-series tasseled cap wetness and the normalized difference moisture index in detecting forest disturbances. *Remote Sensing of Environment*, 94, 364–372.
- Kharuk, V. I., Ranson, K. J., Kozuhovskaya, A. G., Kondakov, Y. P., & Pestunov, L. A. (2004). NOAA/AVHRR satellite detection of Siberian silkmouth outbreaks in eastern Siberia. *International Journal of Remote Sensing*, 25, 5543–5555.
- Kharuk, V. I., Ranson, K. J., & Fedotova, E. V. (2007). Spatial pattern of Siberian silkmouth outbreak and taiga mortality. *Scandinavian Journal of Forest Research*, 22, 531–536.
- GeoSystems, Leica (2005). *ERDAS field guide*. LLC, Norcross, Georgia: Leica Geosystems Geospatial Imaging.
- Lunetta, R. L., Knight, F. K., Ediriwickrema, J., Lyon, J. G., & Worthy, L. D. (2006). Landcover change detection using multi-temporal MODIS NDVI data. *Remote Sensing of Environment*, 105, 142–154.
- McConnell, T., Johnson, E., & Burns, B. (2000). A guide to conducting aerial sketchmap surveys. *USDA Forest Service, Forest Health Technology Enterprise Team, Fort Collins, Colo., FHET 00-01* 88pp.
- McKellip, R., Ryan, R. E., Prados, D., & Blonski, S. (2005). Crop surveillance demonstration using a near-daily MODIS vegetation index time series. *Proceedings of the 2005 International Workshop on the Analysis of Multi-Temporal Remote Sensing Images*. New York, New York: IEEE.
- McKellip, R., Prados, D., Ryan, R., Ross, K., Spruce, J., Gasser, G., et al. (2008). Remote-sensing time series analysis, a vegetation monitoring tool. *NASA Tech Briefs*, 32, 63–64.
- McManus, M., Schneeberger, N., Reardon, R., & Mason, G. (1989). *Gypsy Moth*. USDA Forest Service Forest Insect and Disease Leaflet 162, Radnor, PA: Northeastern Forest Experiment Station, Forest Service URL: <http://www.na.fs.fed.us/spfo/pubs/fidls/gypsymoth/gypsy.htm> (last date accessed: 9 April 2009).
- Muchoney, D. M., & Haack, B. N. (1994). Change detection for monitoring forest defoliation. *Photogrammetric Engineering and Remote Sensing*, 60, 1243–1251.
- Nielson, E., Quayle, B., & Johnson, J. (2006). USFS RSAC work in broad-scale forest change detection. *2006 USDA Forest Service Workshop on Forest Disturbance Mapping*.
- Pimentel, D., Lach, L., Zuniga, R., & Morrison, D. (2000). Environmental and economic costs associated with non-indigenous species in the United States. *Bioscience*, 50, 53–65.
- Potter, C., Pang-Ning, T., Kumar, V., Kucharik, C., Klooster, S., Genovese, V., et al. (2005). Recent history of large-scale ecosystem disturbances in North America derived from the AVHRR satellite record. *Ecosystems*, 8, 808–824.
- Prados, D., Ryan, R. E., & Ross, K. W. (2006). *Remote Sensing Time Series Product Tool 2006 AGU Fall Meeting*, abstract URL: http://www.agu.org/meetings/fm06/fm06-sessions/fm06_IN33B.html (last date accessed: 9 April 2009).
- Tobin, P. C., & Blackburn, L. M. (2007). Slow the spread: A national program to manage the gypsy moth. *Gen. Tech. Rep. NRS-6*. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.
- Quayle, B., Lannom, K., Finco, M., Norton, J., & Warnick, R. (2003). Monitoring wildland fire activity on a national-scale with MODIS imagery. *2nd International Wildland Fire Ecology and Fire Management Congress, 5th Symposium on Fire and Forest Meteorology*, abstract URL: http://ams.confex.com/ams/FIRE2003/techprogram/paper_66050.htm (last date accessed: 9 April 2009).
- Research Systems, Inc. (2003). *ENVI Field Guide*. ENVI version 4.0, September 2003 Edition. : Research Systems, Inc.
- Sader, S. A., & Winne, J. C. (1992). RGB-NDVI color composites for visualizing forest change dynamics. *International Journal of Remote Sensing*, 13, 3055–3067.
- Savitzky, A., & Golay, M. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, 36, 1627–1639.
- Schrader-Patton, C. (2003). Digital aerial sketchmapping. *USDA Forest Service—Engineering, Forest Health Technology Enterprise Team—Fort Collins, Remote Sensing Applications Center, Report No. RSAC-1202-RPT2*.
- Sellers, P. (2001). Forest Health Protection Evaluation of the Gypsy Moth on the Deerfield, Dry River, Glenwood-Pedlar, James River, Lee, and Warm Springs Ranger Districts of the George Washington and Jefferson National Forests, Fiscal Year 2002. *USDA Forest Service, Forest Health Protection, Report #01-01-15, November 2001*.
- Spruce, J. P., Ryan, R. E., Smoot, J. C., Prados, D., McKellip, R., Sader, S. A., et al. (2007). Potential of VIIRS data for regional monitoring of gypsy moth defoliation: Implications for forest threat early warning system. *American Geophysical Union 2007 Winter Meeting, presentation, 10–14 Dec. 2007, San Francisco, CA, USA*.
- USFS USDA Forest Service. (2004). *Center Charter. Western Wildland Environmental Threat Assessment Center* URL: <http://www.fs.fed.us/pnw/wwetac/Charter.pdf> (last date accessed: 9 April 2009).
- USFS (2005). *Center Charter. Eastern Forest Environmental Threat Assessment Center*.
- USFS (2007). *Annual gypsy moth defoliation. Metadata documentation on aerial sketch mapping geospatial datasets*.
- USFS (2009). *Gypsy moth digest—Defoliation* URL: <http://www.na.fs.fed.us/fhp/gm/defoliation/index.shtm> (last date accessed: 9 April 2009).
- U.S. Geological Survey. (2006). *MODIS Reprojection Tool Swath User's Manual*. Release 2.1, January 2006. USGS EROS Data Center Land Processes DAAC.
- Vogelmann, J. E. (1990). Comparison between two vegetation indices for measuring different types of forest damage in the Northeastern United States. *International Journal of Remote Sensing*, 11, 2281–2297.
- Williams, D. L., & Nelson, R. F. (1986). Use of remotely sensed data for assessing forest stand conditions in the Eastern United States. *IEEE Transactions on Geoscience and Remote Sensing*, GE-24, 130–138.