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

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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 km^2 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.

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).

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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 overflown 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 km^2 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