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Estimating the effect of gypsy moth defoliation using MODIS

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ABSTRACT

The area of North American forests affected by gypsy moth defoliation continues to expand despite efforts to slow the spread. With the increased area of infestation, ecological, environmental and economic concerns about gypsy moth disturbance remain significant, necessitating coordinated, repeatable and comprehensive monitoring of the areas affected. In this study, our primary objective was to estimate the magnitude of defoliation using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery for a gypsy moth outbreak that occurred in the US central Appalachian Mountains in 2000 and 2001. We focused on determining the appropriate spectral MODIS indices and temporal compositing method to best monitor the effects of gypsy moth defoliation. We tested MODIS-based Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Normalized Difference Water Index (NDWI), and two versions of the Normalized Difference Infrared Index (NDIIb6 and NDIIb7, using the channels centered on 1640 nm and 2130 nm respectively) for their capacity to map defoliation as estimated by ground observations. In addition, we evaluated three temporal resolutions: daily, 8-day and 16-day data. We validated the results through quantitative comparison to Landsat based defoliation estimates and traditional sketch maps. Our MODIS based defoliation estimates based on NDIIb6 and NDIIb7 closely matched Landsat defoliation estimates derived from field data as well as sketch maps. We conclude that daily MODIS data can be used with confidence to monitor insect defoliation on an annual time scale, at least for larger patches (>0.63 km^2). Eight-day and 16-day MODIS composites may be of lesser use due to the ephemeral character of disturbance by the gypsy moth.

1. Introduction

Ephemeral forest disturbances are short lived perturbations from which forests often recover quickly, either within the same year or in the following year. Prominent ephemeral disturbances include insect defoliation, the most spatially extensive forest disturbance on an annual basis in North America, as well as ice and windstorm damage and drought stress. While forests often recover after such disturbances with little mortality, long term effects might still be detectable and multiple subsequent disturbances can be fatal.

Insect and pathogen disturbances are the most expensive disturbances in North America (Dale et al., 2001) but are nevertheless difficult to monitor due to their short nature. The most significant defoliator of hardwood trees in the northeastern US is the gypsy moth (*Lymantria dispar* L.) (Joria & Ahearn, 1991), which was introduced to the United States near Boston in 1869 (Williams et al., 1985). Since introduction, the gypsy moth has spread from New England, south through Virginia into North Carolina and west to Wisconsin. It is estimated that more than 30 million hectares have been defoliated since 1970. Since the potential area that is climatically suitable for the gypsy moth is estimated to be 595 million hectares (Gray, 2004), many state and federal programs have been established to both monitor and mitigate possible impacts of gypsy moth (e.g., the United States Department of Agriculture (USDA) funded Slow the Spread Foundation, www.gmsts.org, and US Forest Service (USFS) Forest Health Protection program). The USFS as well as state agencies also closely monitor the gypsy moth defoliation with annual aerial sketch mapping activities.

Sketch mapping in combination with aerial photo interpretation is the most common method used for monitoring extensive forest damage. Sketch maps are created by the manual delineation of affected forests on aerial photographs or topographic maps based on visual cues. In the U.S., aerial sketch mapping efforts are funded in large part by the USFS, although actual sketch mapping is conducted by individual states. As such, sketch mapping methods are not standardized and may be subject to errors resulting from incomplete coverage or overflights at times not optimal for detection of the disturbance. Sketch maps are also prone to subjectivity due to differences in the experience of interpreters. In addition, comprehensive sketch mapping over large areas is time intensive, while the peak time to observe gypsy moth damage is relatively short (~two to three

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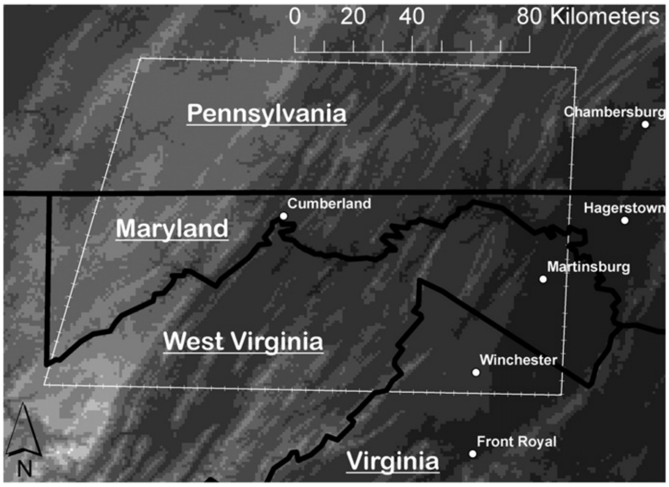

Fig. 1. Overview of the study region, with area having Landsat data outlined. The grayscale background is based on a digital elevation model with the lighter areas representing higher elevations.

weeks) due to subsequent refoliation (Joria & Ahearn, 1991). Finally, sketch mapping is rarely comprehensive, meaning that not all affected areas are monitored every year.

As an alternative, remote sensing techniques have been demonstrated since the mid-1980s to be effective for mapping gypsy moth defoliation using imagery from Landsat and Systeme Probatoire d'Observation de la Terre (SPOT, Williams et al., 1985; Ciesla et al., 1989; Joria & Ahearn, 1991). The resulting maps usually depict degrees of defoliation, e.g. light, moderate and heavy, as well as healthy forests (Williams et al., 1985; Ciesla et al., 1989; Joria & Ahearn, 1991). While the general occurrence of defoliated areas can be identified, the classification of the intensity of defoliation has been less reliable (Ciesla et al., 1989). Only recently have remote sensing techniques advanced to the ability of mapping not only the occurrence of defoliation but also the magnitude of the change (Townsend et al., 2004).

It has been demonstrated that data from Landsat and other synoptic scale sensors have an appropriate spatial resolution for monitoring many types of insect disturbances to forests. However, due the short window for monitoring and the coarse temporal resolution of Landsat imagery relative to cloud cover, it is not possible to create regional-scale estimates of defoliation in any given year. In contrast, MODIS data have a lower spatial resolution than Landsat or SPOT, and are therefore more appropriate for regional-scale analyses. In addition, MODIS data are available at a significantly higher temporal resolution (~daily) while preserving the spectral bands that are available in the Landsat data. Coarse resolution imagery from MODIS, Advanced Very High Resolution Radiometer (AVHRR), and SPOT VEGETATION have been used in other studies for the detection of insect disturbances (Kharuk et al., 2004; Fraser & Latifovic, 2005; Kovacs et al., 2005). Fraser & Latifovic (2005) found that coarse imagery is very effective in mapping large-scale conifer mortality caused by insects, especially in forest patches larger than 5–10 km^2. They also found that the data could be useful for near-real time monitoring, although with substantial commission errors. Kharuk et al. (2004) used 8-km AVHRR pixels, but suggested that the improved radiometric stability and band width of the MODIS data could increase detection accuracy. Kovacs et al. (2005) evaluated MODIS EVI and Mid Infrared (MIR) data for the detection of insect disturbance. However, none of these coarse resolution studies provided links with finer resolution validation data. In addition, the study by Fraser & Latifovic (2005) did not actually look at an ephemeral disturbance. Instead they focused on mortality and severe defoliation (>90%) in a pine ecosystem that was unlikely to refoliate.

In this study, our primary objective was to estimate the magnitude of defoliation using MODIS imagery for a gypsy moth outbreak that occurred in the US central Appalachian Mountains in 2000 and 2001. We tested five indices for their capacity to map defoliation as estimated by ground observations. In addition, we evaluated three temporal periods (daily, 8-day and 16-day). The results were validated through quantitative comparison to Landsat based defoliation estimates and traditional sketch maps.

2. Datasets

2.1. MODIS dataset

For this study we selected MODIS datasets with three levels of temporal processing from collection 4 for tile h11v5 (Fig. 1). The satellite datasets cover an area of deciduous hardwood forests (largely oaks) in Pennsylvania, West Virginia and Maryland where we have extensive data on defoliation extent and magnitude (Table 1). We tested MOD13Q1 data (MODIS/Terra Vegetation Indices) at a 16-day temporal resolution and 250 meter spatial resolution. This dataset contains NDVI and EVI data, as well as a resampled (from 500 to 250 m) mid-infrared (MIR) band (band 7, 2105–2155 nm). Second, we evaluated the 8-day MODIS/Terra Surface Reflectance data (MOD09Q1 and MOD09A1) with a spatial resolution of 250 m and 500 m, respectively. MOD09Q1 contains 3 data layers, surface reflectance for band 1 (620–670 nm), surface reflectance for band 2 (841–876 nm) and the surface reflectance quality control flags, all three at 250 m resolution. MOD09A1 contains the first seven MODIS reflectance bands as well as surface reflectance state flags, all at 500 m spatial resolution. We specifically used the last three reflectance bands from this dataset and resampled the 500 meter bands to 250 meter resolution with nearest neighborhood resampling. Finally, we used the daily MODIS/Terra Surface Reflectance data at 250 and 500 m resolution (MOD09GQK and MOD09GHK). The data layers are the same as those of the 8-day dataset and the same resampling procedure has been applied. All image analyses employed MODIS data from 2000 and 2001.

Table 1
Overview of dataset evaluated in this study

Code	Days	*m*	Spectral	Index
MOD13Q1	16	250	**NDVI**	NDVI
			EVI	EVI
			620–670 nm	NDIIb7
			841–876 nm	
			459–479 nm	
			2105–2155 nm	
MOD09Q1	8	250	**620–670 nm**	NDVI
			841–876 nm	EVI
MOD09A1	8	500	620–670 nm	NDWI
			841–876 nm	NDIIb6
			459–479 nm	NDIIb7
			545–565 nm	
			1230–1250 nm	
			1628–1652 nm	
			2105–2155 nm	
MOD09GQK	1	250	**620–670 nm**	NDVI
			841–876 nm	EVI
MOD09GHK	1	500	620–670 nm	NDWI
			841–876 nm	NDIIb6
			459–479 nm	NDIIb7
			545–565 nm	
			1230–1250 nm	
			1628–1652 nm	
			2105–2155 nm	

Bold spectral bands are used in the creation of the indices.
NDVI and EVI in MOD13Q1 are accepted without alterations.

2.2. Ground estimates and Landsat measurements

A description of the Landsat based method can be found in Townsend et al. (2004 and in preparation). Briefly, the Landsat method employs change detection between mid-summer imagery from a non-defoliation year (1999) to the defoliation years (2000 and 2001). The difference of the Healy et al. (2005) forest disturbance index for the two years yields a disturbance map that scales directly with ground measures of defoliation. The field measurements of defoliation were derived from caterpillar frass (excrement) collected in litter traps in the field sites during the 2000 and 2001 defoliation events.

2.3. Sketch map data

Sketch map data were provided by the US Forest Service Forest Health Technology Enterprise Team (FHTET). Even though results are rarely consistent due to surveyor error and subjectivity, sketch maps represent the most spatially comprehensive and widely available maps of insect disturbance for broad scale comparison with remotely sensed data. An important caveat about sketch maps is that polygons mapped as defoliated may not be uniformly disturbed. In fact they may be largely non-defoliated with only patches of defoliation within the sketch-mapped areas. Some sketch maps contain defoliation intensities (light, medium, heavy). In this paper we include all intensities and treat them similarly.

3. Methods

3.1. Vegetation indices

We used the binary MODIS quality flags in the 250 m data to select only cloud-free data of ideal quality and calculated five vegetation indices (VI's) known to correlate strongly with vegetation characteristics (Table 2). NDVI and EVI are surrogate measures for aboveground net primary production, with variation in these linked to temperature, precipitation and atmospheric CO_2 (Dye & Tucker, 2003; Zhou et al., 2003). Insect defoliation is expected to yield a decrease in EVI and NDVI. However, NDVI tends to saturate in areas with significant forest cover, suggesting that a decrease in NDVI due to defoliation may not always occur in forests that start with high (i.e., saturated) NDVI. EVI was developed to optimize the vegetation signal in regions with high biomass and includes a correction for background signal by reducing atmospheric influences with inclusion of the blue (459–479 nm) band. As a result, EVI does not saturate as readily as NDVI (Huete et al., 2002a,b).

It has long been known that water strongly absorbs in the short-wave infrared (SWIR) portion of the electromagnetic spectrum. SWIR reflectance is therefore very sensitive to the amount of water in the vegetation. SWIR reflectance is generally low for high leaf water content, and increases with decreasing water content. The sensitivity of the SWIR channel to water has led to the development of a number of vegetation indices that are responsive to vegetation stress based on SWIR and near infrared (NIR) reflectance. NDWI (Gao, 1996) was developed from hyperspectral data as the difference between NIR reflectance and a SWIR band centered around 1240 nm. NDWI has been adapted for Landsat using band 5 (centered on 1650 nm rather than 1240 nm) or MIR band 7 at 2220 nm (e.g., Jang et al., 2006; Gu et al., 2007; Wang et al., 2007). However the index has been previously proposed as NDII using Landsat band 5 or the SPOT SWIR band (Hardisky et al., 1983; Hunt & Rock, 1989) and as an index using Landsat band 7 (Hunt & Rock, 1989).

Table 2
Overview of MODIS Vegetation Indices evaluated in this study

NDVI	$\frac{Band2-Band1}{Band2+Band1}$	Tucker (1979)
EVI	$2.5\left(\frac{Band2-Band1}{Band2+6Band1-7.5Band3+1}\right)$	Huete et al. (1994, 2002a,b)
NDWI	$\frac{Band2-Band5}{Band2+Band5}$	Gao (1996)
NDII6	$\frac{Band2-Band6}{Band2+Band6}$	Hardisky et al. (1983), Hunt & Rock (1989), Jackson et al. (2004)
NDII7	$\frac{Band2-Band7}{Band2+Band7}$	Hunt & Rock (1989), Chuvieco et al. (2002)

NDVI = Normalized Difference Vegetation Index.
EVI = Enhanced Vegetation Index.
NDWI = Normalized Difference Water Index.
NDII6 = Normalized Difference Infrared Index – band 6.
NDII7 = Normalized Difference Infrared Index – band 7.

Although NDWI as proposed by Gao (1996) cannot be calculated for Landsat due to the absence of the 1650 nm SWIR band, MODIS carries this channel as band 5, thus allowing calculation of all three indices which we will designate here as:

$$\text{NDWI}\left(\frac{\text{Band2}-\text{Band5}}{\text{Band2}+\text{Band5}}\right),\ \text{NDIIb6}\left(\frac{\text{Band2}-\text{Band6}}{\text{Band2}+\text{Band6}}\right)$$
$$\text{and NDIIb7}\left(\frac{\text{Band2}-\text{Band7}}{\text{Band2}+\text{Band7}}\right).$$

Higher NDWI or NDII values are associated with higher water content in the leaves. In case of defoliation, thus removal of leaves, we expect the index to decrease. Several indices incorporating one of the SWIR/MIR bands have been successfully used for the detection of insect defoliation (Vogelmann & Rock, 1989; Fraser & Latifovic, 2005; Kovacs et al., 2005).

3.2. MODIS based defoliation estimates

Existing research has focused on the remote detection of insect defoliation using high resolution Landsat imagery (e.g., Joria and Ahearn, 1991; Muchoney & Haack, 1994; Luther et al., 1997; Chalifoux et al., 1998; Radeloff et al., 1999) often based on the analysis of a base (non-defoliated) image in a year prior to defoliation with respect to an image acquired during or immediately after the defoliation (e.g., Townsend et al., 2004). For a variety of reasons, this approach is not always desirable. First, sometimes suitable pre-defoliation data are not available. In this study, we examine defoliation events that commenced in 2000, the year MODIS was launched aboard TERRA. Following from this, defoliation that occurred in 2000 negated the use of 2000 imagery as basis for mapping 2001 defoliation. Finally, it is unclear the extent to which previous defoliations affect vegetation vigor in the years following defoliation. In a previous paper, we suggested that forests stressed by ephemeral disturbances, although seemingly recovered, were still more susceptible to mortality in the face of subsequent disturbance (McNeil et al., 2007). Thus, it is generally undesirable to use data from previous years in which disturbances may have occurred to detect current disturbance, as the change signal may be related more to the prior disturbance than the current one.

Our approach to mapping defoliation employs images within a single year that correspond to pre-defoliation and peak defoliation periods. Caterpillar feeding phenology was estimated using the climatically driven insect population model BioSIM (v. 8.3.8, Régnière, 1996), with peak feeding modeled as occurring approximately on day 150 (May 29/30) and the end of feeding close to day 180 (June 28/29) (Fig. 2). VIs may be expected to follow a similar trajectory, in which vegetation greens up, the green-up slows prior to reaching a peak VI, followed by a decrease in VI during peak defoliation (Fig. 3). After defoliation there can be a gradual refoliation; however, the second peak VI is smaller than the initial peak (Fig. 3). Generally trees that are heavily defoliated (60% or more) may refoliate substantially (35–65% of production, see Lovett & Tobiessen (1993) for discussion of compensatory reactions by defoliated trees). As such, heavily defoliated forests may exhibit an increase in VI following the gypsy moth event (Fig. 3 solid line); whereas moderately defoliated forests may not have subsequent refoliation (Fig. 3 dashed line). Based on

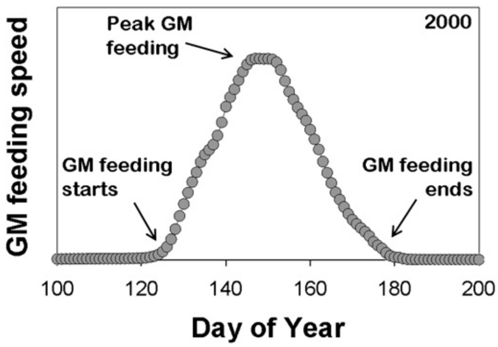

Fig. 2. Feeding start and end dates in 2000 based on simulations from BioSIM.

these two potential responses to defoliation events, we developed a MODIS defoliation index:

$$\text{Defoliation}(\%) = \frac{\text{VI}_{\text{before}} - \text{VI}_{\text{during}}}{\text{VI}_{\text{before}}}, \qquad (1)$$

where $\text{VI}_{\text{before}}$ is the value of a vegetation index at the highest point before defoliation and $\text{VI}_{\text{during}}$ is the value of the vegetation index at the lowest point during the defoliation event.

Our defoliation index is limited by the availability of cloud-free imagery for the period preceding peak defoliation. The year 2001 was especially cloudy in the Appalachian Mountains prior to the defoliation event, and no cloud-free images were available to estimate $\text{VI}_{\text{before}}$ for the study area. We therefore evaluated all cloud-free images (<10% pixels with clouds) and selected the maximum annual VI achieved for the entire 2001 growing season.

Because of easy availability and the somewhat ready-to-use status of MODIS composite data, we also test the capacity of 8-day and 16-day composites with our defoliation index to characterize defoliation. As with the daily data, composite images were selected to correspond to peak greenness and maximum defoliation. Our expectation was that the use of daily images would be superior to composites due to the reduction of cloud contamination and the ability to select images on dates with maximum defoliation (i.e., low VI). It is conceivable that (maximum-value) compositing may obscure the effects of defoliation by employing high VI values during the composite period (rather than a low VI value that may be associated with disturbance).

3.3. Statistical comparison of MODIS derived defoliation estimates with ground/Landsat observed defoliation

MODIS derived estimates of percent defoliation were compared to Landsat measures of biomass defoliated (kg per ha per year) calibrated from field observations (Townsend et al., in preparation). However, a pixel-based comparison between coarse scale MODIS pixels and fine scale Landsat data (30 m) is not straightforward. Confounding factors include forest fragmentation and high spatial variability in forest characteristics across elevation gradients due to steep ridge-and-valley topography. In addition, the MODIS data have been shown to have lower geometric locational precision in the gridded datasets, which could influence the comparison with Landsat (Tan et al., 2006). Our previous research showed that MODIS defoliation estimates as predictors of watershed nutrient export were not influenced by forest fragmentation (McNeil et al., 2007), but for this paper we focus specifically on non-fragmented areas to avoid potential confounding factors associated with non-forest cover types. Therefore, our evaluation concentrated on areas of the MODIS images (i.e., patches) that were at least 0.6 km^2 (10 MODIS pixels) in area, were at least 90% forested (based on the National Land Cover Date (NLCD) 2001 classification data), had no cloud cover, and revealed low spatial variability in defoliation estimates from the Landsat data (coefficient of variation less than 10%). This last restriction was employed to avoid ambiguity resulting from MODIS pixels that were strongly defoliated in one area (per Landsat) and non-defoliated in another area of the pixel. Although it is possible that such areas are accurately mapped, saturation by vegetation in the non-defoliated area of the pixel may obscure mapping of defoliation.

The selection criteria yielded 117 valid patches for 2000 and 40 patches for 2001, ranging from 0.63–23.8 km^2 in area (i.e., patches of 10–381, 250 m MODIS pixels). Without the size requirement, the year 2000 would have included a total of 828 patches incorporating 5588 MODIS size pixels. Thus the size requirement of a patch to be at least 10 MODIS pixels eliminated a total of 711 smaller patches. However, the selected 117 patches incorporated 3956 MODIS pixels or more than 70% of the total number of pixels available for comparison. Note that the included and discarded patches were not necessarily defoliated but rather met the requirements of being at least 90% forested, had no cloud cover as established based on Landsat cloud masks, and revealed low spatial variability in defoliation estimates from the Landsat data. There were far fewer patches in 2001 due to extensive cloud cover in the 2001 Landsat imagery.

For each patch, we calculated the total biomass lost to defoliation based on the Landsat/field data, as well as the MODIS defoliation index derived from the five MODIS vegetation indices (Table 2). Linear regression was used to identify the relationships between the MODIS defoliation indices and biomass loss derived from Landsat. For both 2000 and 2001, we assessed a total of 13 versions of our defoliation index (5 indices each using daily data and 8-day composites, and 3 indices for 16-day composites, Tables 2 and 3). We did not assess NDWI (using MODIS band 5) and NDIIb6 for 16-day MOD13Q1 data, because the respective SWIR bands were not a part of this dataset.

3.4. Comparison of 2000 and 2001 predictions

The 2000 and 2001 relationships between the MODIS index and the Landsat based estimates of biomass defoliated were not entirely comparable due to the use of images from different times in 2000 and 2001 for both Landsat and MODIS. The Landsat image in 2000 was recorded on August 22, while the 2001 Landsat image was recorded almost one month earlier on July 24 (Townsend et al., 2004). In addition, defoliation occurred slightly later in 2001 than in 2000. Cloud cover limited the availability of suitable Landsat images, and also prevented the selection of a later, more ideal MODIS image in 2000.

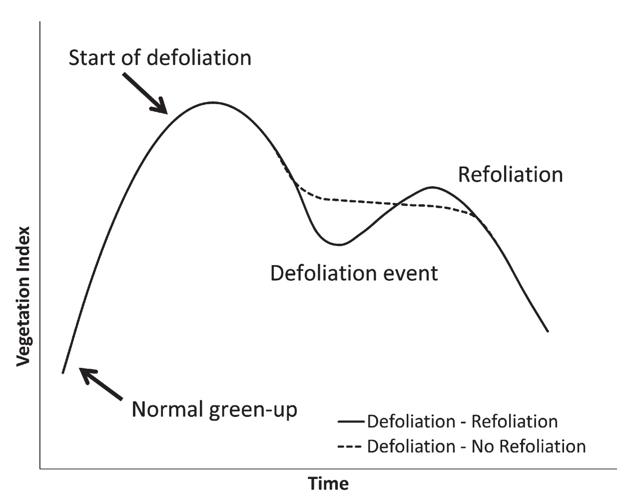

Fig. 3. Potential VI defoliation responses. Severe defoliation is often followed by refoliation as shown by the solid line. The dashed line shows that less severe defoliation is not followed by refoliation.

Table 3
250 meter results for 2000

		Intercept	Slope	R^2_{adj}	RMSE
16-day	NDVI	−141.66	220.59	0.082	1230.72
	EVI	−496.07	100.97	0.119	1226.81
	NDIIb7	187.86	211.89	0.306	1098.62
8-day	NDVI	666.48	296.22	0.398	1016.99
	EVI	−531.25	184.73	0.452	948.90
	NDWI	152.26	32.15	0.442	965.65
	NDIIb6	892.30	247.50	0.466	980.89
	NDIIb7	81.24	142.02	0.596	826.71
Daily	NDVI	−340.63	115.28	0.453	949.84
	EVI	242.42	149.53	0.588	834.46
	NDWI	818.74	22.12	0.536	890.94
	NDIIb6	650.76	260.35	0.643	782.94
	NDIIb7	426.41	115.85	0.638	788.91

All slopes are divided by 100.

The primary concern in the comparison of 2000 and 2001 is the possibility that the Landsat estimates may contain some signal of refoliation, even if the refoliation was modest compared to the overall defoliation (Hurley et al., 2004). To understand the effect of refoliation in the 2000 Landsat data, we tested the use of an even later MODIS image (during the presumed period of refoliation) in order to adjust the 2000 defoliation for refoliation. This analysis was only performed for daily data and not evaluated for composites. We used a slightly different index compiled from the same bands as the methods we have presented. For 2000, a refoliation-adjusted index can be calculated as:

$$\frac{\text{day135}}{\text{day162}} \times \frac{\text{day135}}{\text{day235}} - 1, \quad (2)$$

where day 135 is the MODIS VI right before defoliation and assumed to be close to the maximum of the growing season. Day162 is the MODIS VI during the defoliation event, while day235 is the MODIS VI during refoliation and corresponds to the day that the Landsat image was recorded. The 2000 refoliation-adjusted index was compared to a 2001 index that does not include the refoliation term in Eq. (2), since refoliation was not an issue in the ancillary Landsat data for 2001:

$$\frac{\max \text{Index}}{\text{day161}} - 1 \quad (3)$$

As noted previously, in 2001 cloudiness prevented the selection of a within-year pre-defoliation image. As such, day135 (pre-defoliation VI in Eq. (2)) is replaced with the maximum VI on any available image from 2001 (max*Index* in Eq. (3)). Although this highlights the issue of persistent clouds in satellite imagery of the eastern U.S., the objective for calculating the indices in Eqs. (2) and (3) is to provide an image-based evaluation that accounts for vegetation effects resulting from the use of different dates to map defoliation.

4. Results

4.1. 16-day composites

In 2000 and 2001, composite number 162 (from day 162, included days June 9–June 24) and 161 (from day 161, included days June 10–June 14) provided the best MODIS defoliation estimates (Tables 3 and 4). The results for the 16-day composites for both years were quite variable. In 2000, the results were generally poor and only significant for NDIIb7 (R^2_{adj}=0.306), while in 2001 the results were much better and the best relationship was found for NDVI (R^2_{adj}=0.706). In both cases EVI did not perform as well as at least one of the other indices. The R^2_{adj} for NDVI increased from non-significant (R^2_{adj}=0.082) in 2000 to very significant (R^2_{adj}=0.706) in 2001.

4.2. 8-day composites

The results for the 8-day composites were more consistent between 2000 and 2001. NDIIb7 provided the best fit with R^2_{adj} 0.596 and 0.617 for 2000 and 2001, respectively (Tables 3 and 4). The traditional VIs – NDVI and EVI – did not perform as well as the 'water' indices, NDWI, NDII6 and NDII7.

4.3. Daily data

The daily data generated the most consistent results despite the limitation of very few daily images that were cloud free over the majority of the study region (Tables 3 and 4). In the year 2000, we identified the following six cloud-free dates: 121 (April 30), 132 (May 11), 135 (May 14), 155 (June 3), 162 (June 10) and 235 (August 22). Only day 162 was close to the peak of the defoliation, the earlier days were deemed too early and day 235 was during refoliation. In the year 2001, we found more cloud-free days (11 days): 120 (April 30), 121 (May 1), 127 (May 7), 161 (June 10), 162 (June 11), 187 (July 6), 202 (July 21), 203 (July 22), 205 (July 23), 214 (August 1) and 219 (August 6). Although the same day (161/June 10) was cloud free in both 2000 and 2001, we achieved better results in 2001 for day 187 (July 6), immediately after the end of the defoliation event. We did not have a later day available in 2000 (except the August date, during refoliation); thus we could not test whether the later date would have also improved our fits in 2000. In both 2000 and 2001 we identified NDIIb6 and NDIIb7 as the best performing VIs (R^2_{adj} of 0.643 and 0.638 in 2000 and 0.741 and 0.769 in 2001, Tables 3 and 4).

4.4. Sketch map data

Maps of the MODIS defoliation index are continuous for the study area and are not restricted to the areas used in the Landsat validation (Fig. 4). Overlaid are the defoliated areas as indicated by sketch mapping. MODIS-mapped defoliation closely matched sketch-mapped polygons of defoliated areas in 2000, while the MODIS index slightly overestimated defoliation in 2001. Despite the fact that sketch maps cannot be considered absolute "truth", the sketch map data confirm that the MODIS index was capable of the detection of gypsy moth defoliation in our study region. Since we masked all the MODIS pixels that are less than 90% forested (based on the NLCD 2001) or had any cloud cover, some of the sketch mapped areas shown on Fig. 4 did not have corresponding MODIS data. Some general issues with sketch map data were also apparent, such as sketch mapped polygons for defoliation were observed to end at state boundaries in both 2000 (Fig. 4b) and 2001 (Fig. 4c), even though defoliation from MODIS appeared to cross state lines. In other instances the sketch map

Table 4
250 meter results for 2001

		Intercept	Slope	R^2_{adj}	RMSE
16-day	NDVI	−1157.58	282.93	0.706	335.58
	EVI	−342.12	50.15	0.450	461.84
	NDIIb7	−678.05	140.79	0.664	359.28
8-day	NDVI	−1093.07	176.68	0.561	410.25
	EVI	−684.59	65.73	0.525	419.09
	NDWI	−8479.3	102.26	0.519	407.72
	NDIIb6	−474.98	106.96	0.570	388.08
	NDIIb7	−1454.94	67.84	0.617	391.97
Daily	NDVI	75.85	310.38	0.716	317.41
	EVI	−160.88	60.04	0.493	396.46
	NDWI	−7545.73	91.27	0.548	416.66
	NDIIb6	−126.77	142.88	0.741	309.96
	NDIIb7	−463.31	66.85	0.769	292.72

All slopes are divided by 100.

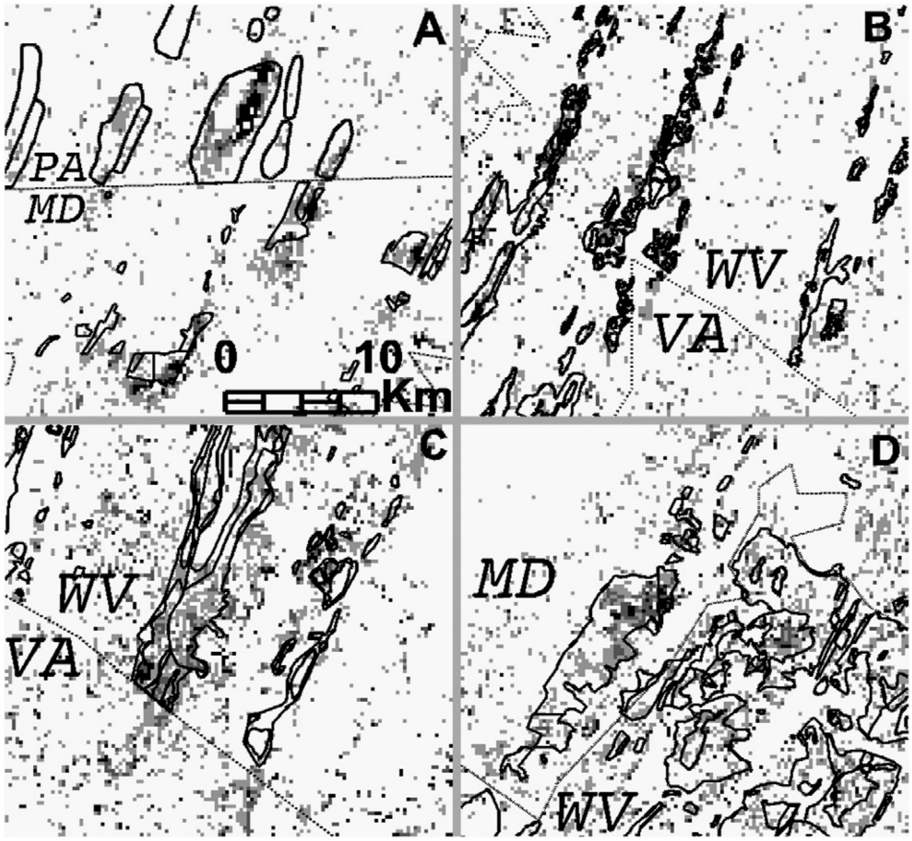

Fig. 4. A and B: two zoomed images of defoliation as detected by MODIS data in 2000 with the sketch map vectors overlaid. **C and D**: defoliation as detected by MODIS data in 2001. Darker grey areas indicate higher defoliation amounts and lighter areas indicate lower defoliation amounts.

data appear to be wrongly positioned (one ridgeline east or west of mapped defoliation from MODIS) or missing altogether.

4.5. Comparison between 2000 and 2001

Using the refoliation-corrected index, both 2000 and 2001 MODIS predictions were compared to the Townsend et al. (in preparation) Landsat estimates (Fig. 5). The relationships for 2000 and 2001 with Landsat estimates did not differ significantly. Note that estimates of negative "defoliation" in the Landsat data indicated growth in the vegetation compared to the base year 1999 (Townsend et al., in preparation). Negative values in the MODIS indices were pixels that showed healthy growth over the course of the season rather than declines in VI due to disturbance.

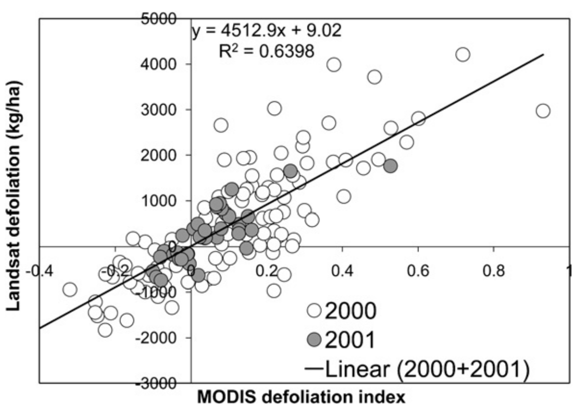

Fig. 5. MODIS defoliation index corrected for refoliation for 2000 but not for 2001 show the same relationship with the Landsat based defoliation estimates of biomass defoliated, regardless of year. The Landsat estimates are based on imagery exhibiting both defoliation and refoliation in 2000 but defoliation only in 2001.

5. Discussion

5.1. Vegetation indices

Defoliation of deciduous hardwood forests is more readily detected using MODIS NDII than the more traditional vegetation indices EVI and NDVI. In both 2000 and 2001, the best results were found based on either NDII using band 6 (NDIIb6, uses 1640 nm channel) or band 7 (NDIIb7, uses 2130 nm channel). NDWI (using the 1240 nm band) did not compare well to the NDII indices, while EVI generally performed worse than all other indices. The results for NDVI were highly variable, with better results in 2001 than in 2000. We speculate that NDVI is more sensitive to the timing of the imagery during peak defoliation as a result of saturation effects. Even though it remains unclear why NDVI appeared to work better in 2001, it is clear that the results for the SWIR bands are more consistent. These results confirm other observations in the literature that have shown SWIR data to be superior to visible and near infrared indices for detecting forest changes. Hayes et al. (2008) demonstrated that NDMI (NDIIb6 in this paper) was superior in the detection of tropical forest changes compared to NDVI and MODIS Tasseled Cap Indices, they did not test NDIIb7. Using SPOT VEGETATION, Fraser & Latifovic (2005) found the best results using a simple infrared ratio (NIR/SWIR), while Vogelmann & Rock (1989) found that the SWIR band (Landsat band 5) was very important in monitoring the effects of insect defoliation. Joria & Ahearn (1991) found that the Landsat bands 5 and 7 had the highest ability to separate among defoliation levels. Also, Kovacs et al. (2005) found MODIS band 7 to be very important for mapping silk moth damage in Siberia.

5.2. Composite data versus daily data

Individual cloud free days work better for estimating defoliation than composite data. We hypothesize that the degraded performance of composite data results from three interacting factors. First, the composites are based on a large number of days and may exhibit spatial variability that obscures the relationships between the MODIS defoliation index and the ancillary Landsat estimates. Second, local spatial properties of the MODIS imagery are influenced by gridding artifacts and diminished spatial precision is likely compounded in composited datasets (Tan et al., 2006). Finally, the compositing process may have resulted in the selection of data from dates that are further away from the optimal timing of defoliation effects based on peak insect activity. Others have also found that single date MODIS NDVI data have significantly higher detection accuracy than 16-day NDVI composites for forest disturbances (Jin & Sader, 2005).

In 2000, the 16-day MODIS composite 161 was based on observations collected between June 9 and June 24. Metadata indicate that information from the full range of 16 days was incorporated in this composite. Because this is during the peak of defoliation, with cumulative defoliation increasing daily, it is likely that VI values were highly variable during this time frame. Only one day (June 10) was cloud-free over our study region during that compositing period. In 2001, the 16-day composite 161 was based on observations *only* collected between June 10 and June 14. During this time, we also found that only four of the 16 days provided enough cloud-free information to be incorporated in the final composite. The decrease in temporal variability may have contributed to the improved detection provided by the 2001 16-day composites. We conclude that analyses of defoliation based on 16-day composites are subject to large potential errors due to timing and cloud contamination that was not adequately screened during composition.

For the 8-day data, the best predictions were generated for both years by composite 161 (data selected from June 9–June 16 in 2000 and June 10–June 14 in 2001). By our evaluation, this resulted in the same cloud-free days incorporated in the eight-day composite as the 16-day composite in 2001. For NDVI in 2001, composite 201, including observations from July 20 to July 27 (at the end of the defoliation event) performed much better than composite 161. It is unclear why this is only true for the NDVI data and not for the other indices. However, we also saw increased performance for all indices in the daily data for a later date in 2001 (day 187).

The goal of image compositing is to select the best available observation for each pixel during a given time period. Multiple compositing algorithms have been developed, and these do not necessarily deliver identical results (Dennison et al., 2007). Although our objectives were not to evaluate or suggest improvements to the compositing methods, we have determined that the compositing methods used to create the 16-day VI data and the 8-day surface reflectance data do not provide comparable data. The 16-day VI composites are created with a constraint–view angle–maximum value composite (CV-MVC) method. In contrast, the 8-day surface reflectance data are created using minimum view zenith angle criterion (collection 4, Tan et al., 2006).

Only in 2001 are the same days used in the 16-day and the 8-day composite but the difference in results clearly demonstrates that it does make a difference which data set is applied when analyzing for defoliation.

5.3. Sketch map data

Although sketch maps and aerial surveys contain substantial inherent errors, in many instances these data provide the only large regional or national scale estimates of insect defoliation (Gray & MacKinnon, 2006). As we have noted, sketch mapping tends to be subjective because observer experience and abilities vary greatly (Hurley et al., 2004). In addition, some observers tend to be very precise in identifying defoliation, resulting in detailed polygons, while others combine defoliated areas into larger polygons (e.g. compare Fig. 4a and b for 2000). It has also been shown that light and weather conditions can have a strong influence on detection accuracy (MacLean & MacKinnon, 1996). In particular, low levels of defoliation are often omitted, since it is difficult to observe small amounts of defoliation from fast flying aircrafts (MacLean & MacKinnon, 1996). Overestimation of defoliation is generally a lesser issue. For the mapping of gypsy moth defoliation, an additional constraint is that mapping generally starts before defoliation is completed to avoid interpretation errors in refoliated areas. As a consequence, the first areas mapped during an aerial campaign may underestimate total defoliation, with light or moderate defoliation not distinct enough to be delimited. Finally, few studies have evaluated the accuracy of both defoliation estimation errors and positioning errors in aerial sketch-mapping. However, one extensive study considering spruce budworm defoliation spanning 10 years found that 56% of the defoliated areas were correctly identified by aerial sketch mapping with 37% of the plots underestimated (MacLean & MacKinnon, 1996).

5.4. Other disturbances

Our methods are targeted primarily toward monitoring the effect of gypsy moth defoliation, which is a major recurring disturbance to deciduous hardwood (oak) forests of the Northeastern and Mid-Atlantic U.S., including the Appalachian Mountains. As such, the timing of images we used corresponded to insect phenology and related patterns of feeding and defoliation. The correspondence between VI signals and insect phenology during periods in which defoliation typically occurs can be used to label the areas as defoliated (rather than some other disturbance). However, without additional information, it is not possible to distinguish between the effects of gypsy moth and other disturbances with similar VI responses occurring at the same time (wind damage, selective logging). Nonetheless, ancillary datasets (e.g., the MODIS fire product) can be used to rule out some other types of disturbances. Likewise, spatial pattern analysis can provide additional information to distinguish other types of disturbances. For example, patches resulting from forest clearance usually exhibit more regular shapes (lower edge to area ratio) and sizes than defoliation patches. Also, in case of fire and clear-cuts, the within-year temporal pattern of refoliation that is observed for severely defoliated forests does not occur.

6. Conclusions

Despite efforts to prevent the ongoing spread of the gypsy moth, the affected area of North American forests continues to expand. With the increased area of infestation, ecological, environmental and economic concerns about gypsy moth disturbance remain significant. As such, the pressure on current monitoring tools is greater than ever, and it becomes more likely that sketch-mapping and similar observer-based programs may become less able to comprehensively quantify the areas of disturbance in any given year. Regional monitoring based on MODIS data represents an important tool for broad-scale detection.

Our MODIS-derived defoliation estimates closely match Landsat defoliation estimates derived from field data for patches larger than 0.6 km^2, as well as sketch maps (not limited to the larger patches). Based on the validation of the MODIS data with the Landsat data, we conclude that daily MODIS data can be used with confidence to monitor insect defoliation on an annual time scale for larger patches (>0.6 km^2). Eight-day and 16-day MODIS composites show promise, but are likely of lesser use due to the ephemeral character of the gypsy moth disturbance. One important conclusion from this study is that the indices provided in the standard MODIS products (NDVI and EVI) are not necessarily optimal for the detection of ephemeral forest disturbances. We found that "alternative" indices that include SWIR bands, such as NDIIb6 and NDIIb7, perform significantly better. Clouds remain the primary issue interfering with straightforward monitoring of gypsy moth defoliation in this area of North America. Clouds are especially abundant during the peak of the growing season, which also coincides with the prime defoliation period. Nevertheless, we found a small but sufficient number of images in both 2000 and 2001 to allow for a quantification of defoliation.

We focused on determining the appropriate spectral MODIS index and temporal compositing method to best monitor the effects of gypsy moth defoliation. Further testing of these defoliation indices for other temperate forests in the Eastern U.S. and elsewhere is needed to expand and reinforce our conclusions. In subsequent work we are also evaluating whether similar spectral indices can be used to detect defoliation by different insects (jack pine and spruce budworms) in different types of forests (conifer forests of the Upper Midwest).

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