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Using a remotely sensed optimized Disturbance Index to detect insect defoliation in the Apostle Islands, Wisconsin, USA

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ABSTRACT

The Disturbance Index (DI) proposed by Healey et al. (2005) has been used successfully to locate and monitor disturbances by various researchers and in many locations. Here, a modification of the DI is presented that adapts it to local conditions by weighting each of its input components to maximize the difference between disturbed and undisturbed forest canopy. The weights reduce the effects of background variation while emphasizing the variation caused by disturbance. The weighted DI was applied to the severe insect defoliation of 2006 in the Apostle Island National Lakeshore with promising results. A supervised maximum likelihood thematic map based on the unweighted DI was 59% accurate and one based on the weighted DI was 62%. A classification with only two classes, defoliated and not defoliated, was also more accurate when based upon the weighted DI (77% verses 69%). In nearly all instances, the user's and producer's accuracies were significantly higher for the weighted DI image, suggesting that weighting the DI to fit local conditions is a superior approach, at least for small-area studies.

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1. Introduction

Detecting and monitoring forest disturbances are important for understanding global biogeochemical cycles and forests' response to perturbation and climate change. To more easily detect forest disturbance, Healey et al. (2005) introduced a Disturbance Index (DI) based on the brightness, greenness and wetness components of a Kauth-Thomas tasseled cap transformation (TCT; Crist & Cicone, 1984; Kauth & Thomas, 1976) of Landsat imagery:

$$DI = B_r - (G_r + W_r) \quad (1)$$

where B_r is the brightness component, G_r is the greenness component, and W_r is the wetness component, all of which have been rescaled by converting them to z-scores using the mean and standard deviation of healthy, undisturbed forest vegetation. The underlying theory is that disturbed forest will have higher brightness values and lower greenness and wetness values than undisturbed forest (Healey et al., 2005). The DI is essentially the distance in tasseled cap space between healthy forest and disturbed forest. DI values larger than zero indicate that the pixel has been disturbed, DI values less than zero indicate a recent flush of vegetation (possibly recovery), and DI values near zero indicate no change in canopy cover (DeRose et al., 2011). The simplicity and effectiveness of the DI has encouraged its use. As of this writing, the Healey et al. (2005) paper has been cited nearly 130 times — for example, see Healey et al. (2006), Masek et al. (2008), Hayes et al. (2008), Hilker et al. (2009), and Deel et al. (2012). The DI is a SWIR-dominated vegetation index and is highly correlated with the wetness component of the TCT in many datasets (Hais et al., 2009; Healey et al., 2006; Masek et al., 2008).

The equation for the DI implies that each of the three TCT input components; brightness, greenness, and wetness; are equally important predictors of forest disturbance. While the DI has been very useful in many scenarios, it is likely that the importance of the contribution of each TCT component varies by location and disturbance. Healey et al. (2005) suggests that the contrast of DI values between disturbed and undisturbed forests is likely different between ecosystems and that the DI might be improved by adapting it to local conditions by giving higher weights to the TCT components that are most useful, thus maximizing its sensitivity to specific disturbances of interest. The DI as calculated with equation one is likely the best option for detecting general disturbance in study areas with various environmental conditions; however, adding weights to fit the DI to specific disturbances could improve results at local scales.

In the current paper, a weighting scheme is introduced, where the TCT components (B_r, G_r, and W_r) in equation one are weighted by coefficients indicative of their contribution to mapping the disturbance of interest. The weights are derived by optimizing the difference between disturbed and undisturbed areas, making it an optimized Disturbance Index (DIopt). The severe gypsy moth (*Lymantria dispar* L.) defoliation of 2006 in the Apostle Islands National Lakeshore (AINL) in northern Wisconsin is used as a case study to achieve the following objectives: 1) derive an optimized DI and assess its utility in detecting

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various severity levels of gypsy moth defoliation, and 2) use the weights from the optimized DI to better understand how the individual TCT components contribute to detecting gypsy moth defoliation. Not only could this advance understanding of the biophysical effects of gypsy moth defoliation, it may also lead to the establishment and use of a more effective disturbance index.

2. Background

2.1. Gypsy Moths in Northern Wisconsin

The gypsy moth was accidentally released in 1868 or 1869 in Medford, Massachusetts by Étienne Léopoldo Trouvelot, who was trying to breed a robust silk-producing moth for North America (Liebhold et al., 1989). The moths have spread to become the most detrimental insect defoliator in the northeastern US (Joria & Ahearn, 1991), costing the U.S. Government $11 million annually in control and prevention programs (Pimentel et al., 2005). The problem will worsen since gypsy moths currently occupy only one-fourth of their potential range in North America (Liebhold et al., 2000).

A tree defoliated by gypsy moths will usually recover (Joria & Ahearn, 1991), although it will produce 10–20% less foliage the following year (Hurley et al., 2004). The probability of tree mortality increases with the number of consecutive infestations (Campbell & Sloan, 1977; Eisenbies et al., 2007; Wilson & McComb, 2005). Ten years or more may be required for complete recovery (Campbell & Sloan, 1977). Predation by small mammals, primarily mice, of larvae is the most significant control of gypsy moth population (Liebhold et al., 2000 and the papers cited therein). In years of general mast failure, when fewer acorns are produced, these small mammals do not have sufficient food reserves to overwinter and small mammal mortality increases, reducing predation pressure on gypsy moth larvae during the following spring (Jones et al., 1998; Liebhold et al., 2000). The result are episodic and spatially synchronous one to two year outbreaks of large gypsy moth populations that cause severe defoliation, the last of which occurred in the AINL in 2006–2007.

2.2. The Disturbance Index

The DI has been especially useful for mapping forest canopy damage caused by insect defoliation. Wulder et al. (2006) used several spectral vegetation indices (the DI among them), elevation, slope, and solar irradiance to predict mountain pine beetle damage with 86% accuracy. DeRose et al. (2011) used the DI to map Engelmann spruce mortality caused by spruce beetle outbreaks in southern Utah with accuracy as high as 79%. DeRose and his coauthors noted that the utility of the DI in discerning insect-caused tree mortality increased as the infestation progressed and canopy damage and tree mortality increased. This is in line with other researchers' observation that the DI is especially sensitive to severe disturbances (Hais et al., 2009; Healey et al., 2005; Kuemmerle et al., 2007; Masek et al., 2008).

2.3. The Nelder–Mead Optimization

Determining the weighting coefficients for the DIopt requires an optimization function. The Nelder–Mead method is a widely popular nonlinear optimization technique used for multidimensional unconstrained minimization (Bélisle, 1992; Lagarias et al., 1998). The method uses an iterative downhill simplex approach to find a local optimum of a multivariate problem where the function is unimodal. It is particularly useful when applied to functions with multiple interdependent variables (Nelder & Mead, 1965), like the brightness, greenness, and wetness TCT bands. The Nelder–Mead method can be converted to a maximizing optimization by applying a negative overall scaling. In geography, the Nelder–Mead method has been used to automate the projection of aerial photographs (Gede, 2010), optimize cell tower placement (Akella et al., 2010), improve estimates of forest biomass (Bortolot & Wynne, 2005), calculate the effects of the ionosphere on GPS satellites (Strangeways & Ioannides, 2002), and optimize forest stand management (Pukkala, 2009).

3. Methodology

3.1. Study Area

The Apostle Islands are an archipelago of 22 islands extending from northern Wisconsin into Lake Superior. Twenty-one of the islands and about 18 km of shoreline on the mainland (a total of 42,500 acres), were designated as the Apostle Island National Lakeshore (AINL) in 1970. The islands are sandstone, and the park contains several abandoned quarries that once supplied material for brownstone construction in Chicago. Precipitation averages about 75 cm annually, including about 200 cm of snow. The growing season is about 120 days (Judziewicz & Koch, 1993). The mean July temperate is around 65 °F (Beals, 1960) and the mean January temperature is about 7 °F (Judziewicz & Koch, 1993).

Pre-settlement hemlock (*Tsuga canadensis*) and white pine forests (*Pinus strobus*) have been replaced by trembling aspen (*Populus tremuloides*) and white birch (*Betula papyrifera*), especially in places that were logged or burned (Judziewicz & Koch, 1993). Sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*) have also increased (Beals, 1960). Red oak (*Quercus rubra*) may appear at higher elevations (Beals, 1960). Aspen, maple, and oak are among the gypsy moths' preferred species (Campbell & Sloan, 1977; Foss & Rieske, 2003).

3.2. Data

The most critical element of choosing satellite imagery for studying gypsy moth defoliation is finding a cloud-free image that closely corresponds to the peak of defoliation while ensuring that the image was not collected after refoliation had begun (de Beurs & Townsend, 2008). Using imagery with shorter revisit periods, like MODIS, would make this easier, unfortunately the concomitant loss of spatial resolution would mean that important areas of defoliation in this small study site would not be detected. Problems with the timing of image collection could also be mitigated by using imagery from Landsat 5 and from Landsat 7 (Hurley et al., 2004). Unfortunately, the scan line correction failure of Landsat 7 dramatically reduces image quality over the Apostle Islands. The analysis focused on 2006, the year of the last episode of severe defoliation in the Apostle Islands. Fortunately, two Landsat 5 images were collected at appropriate times: the pre-defoliation image is from June 2, 2006, and the peak-defoliation image is from August 12, 2006. Landsat imagery was also used since the DI relies on the TCT, which was initially prepared for the Thematic Mapper family of sensors.

A sketch map of defoliation drawn during an aerial survey performed on August 8, 2006, was generously provided by the resource managers at the AINL (Fig. 1). The map shows the severity of defoliation by labeling each location as severely, moderately, slightly, or not defoliated. These severity classes were used to create different samples for performing the optimization and for assessing the accuracy of the results (Table 1). In both cases, stratified random sampling was used to ensure that equal numbers of points were generated for each of the defoliation severity classes. The points for calculating the z-scores of the TCT bands were all selected from the non-defoliated class, so that the z-scores of each pixel represent the distance from each pixel to non-defoliated forest in z-score TCT space. For the optimization, 100 points were randomly generated from each severity class, for a total of 400 points. These data are z-scores, so the means should be close to zero and the standard deviations should be close to one; notice, however, that the means increase with increasing defoliation, i.e., these points are further from the mean of the non-defoliated pixels.

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