

## Jack Pine Budworm Defoliation Monitoring and Modelling Using Spectral Mixture Analysis

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**Abstract** - Insect defoliation is a key disturbance in many forested ecosystems. Defoliation monitoring is important for both forest managers and scientists. We used 3 Landsat TM images to monitor jack pine budworm (*Choristoneura pinus pinus*) defoliation in a 450,000 ha study area in northwestern Wisconsin during a recent outbreak (1990-95). The images were atmospherically corrected and spectral mixture analysis was employed using spectrometer measurements as endmembers. Heavily defoliated stands exhibited a 5% increase in TM4 reflectance. This increase was smaller than the pre-outbreak range of jack pine TM4 reflectance caused by hardwood mixtures (1987: 17-28%). Hardwood content was negatively correlated with budworm populations ( $r = -0.69$ ) and might be useful to predict future population levels. Defoliation could be identified using spectral mixture analysis. The green needle fraction at the peak of the outbreak was negatively correlated with budworm populations ( $r = -0.94$ ). Spectral mixture analysis allowed reliable jack pine budworm defoliation mapping using Landsat TM imagery and may be applicable in other forested ecosystems as well.

### INTRODUCTION

Ecological disturbances like fires, windthrow and insect defoliation are key ecological processes of many forested ecosystems. Understanding their effect on species composition, ecosystem function and landscape structure is important for both forest managers and scientists.

Remote sensing has been widely used to study forest disturbances both to research past disturbance events and to assist managers in their response to ongoing disturbances. Insect outbreaks have received particular attention, (Nelson 1983, Buchheim et al. 1985, Williams and Nelson 1986, Leckie et al. 1989, Muchoney and Haack 1994).

The objective of our study was to monitor jack pine budworm (*Choristoneura pinus pinus*) defoliation during a recent outbreak (1990-95) in the Pine Barrens region in northwestern Wisconsin (USA). The motivation for our study was to address a management concern as the recent outbreak resulted in salvage cutting on >15,000 ha, and to

increase our understanding of the spatial dynamics of jack pine budworm outbreaks.

Several problems confound satellite monitoring of insect defoliation and resulted in the mixed success of past studies. First, plant-insect interactions are highly dynamic. For example, deciduous trees respond with a second leaf flush to gypsy moth defoliation thus limiting the time window when damage can be detected (Williams and Nelson 1986). Second, the appearance of defoliated trees can change rapidly over time even without the development of new foliage. For example, defoliation by jack pine budworm is marked by heavy chlorosis in the upper part of the crown at the end of July. Dead needles are retained in the crown but subsequently washed to the ground during storms (Weber 1995). Third, plant responses to stress occur at several levels. Reflectance changes of desiccating needles do not always translate to corresponding changes in canopy reflectance because the latter are also determined by crown architecture (Williams 1991). Fourth, cause and effect can be difficult to separate when plant-insect interactions are studied. A correlation between insect populations on the ground and reflectance measured in a satellite image can have two reasons: insects caused defoliation and thus reflectance changes, OR, forest canopy differences, which are revealed in the satellite image, determined the insect population levels. Our study faced each of these four problems.

Our study area is located on a glacial outwash plain and covers approximately 450,000 ha. The soils are extremely nutrient limited and have low water holding capacity. Jack pine (*Pinus banksiana*) is best adapted to these conditions; red pine (*P. resinosa*) and oaks (*Quercus spp.*) occur where soil quality is slightly higher. Current management is dominated by even-aged stands with rotation lengths from 40-60 years for jack pine and 80-120 years for red pine. Jack pine is mainly utilized as pulp-wood, red pine as saw timber.

Jack pine budworm is host specific and well-adapted to jack pine (Weber 1995). Its life cycle is annual, larvae emerge in May and feed on male cones until new foliage is provided in June (Nealis and Lomic 1994). Most of the damage occurs during July. Moths emerge at the end of July, can disperse widely, and lay their eggs in August. Outbreaks are cyclical with return intervals of 6-11 years (Volney and McCullough 1994). Routine spraying against budworm attacks was abolished in Wisconsin during the late 1950's due to environmental concerns and low economic returns.

It should be noted that although jack pine budworm causes severe damage to jack pine stands, it may increase the dominance of jack pine in unmanaged landscapes. Jack pine requires crown fires to avoid being outcompeted by red pine and/or oak. Jack pine budworm-related mortality increases the fuel load of jack pine stands and thus the likelihood for stand replacing fires after which jack pine regenerates most effectively. Jack pine budworm is an integral part of the Pine Barrens ecosystem. The context of our study is to increase the understanding of jack pine budworm's role and behavior and thus to foster sustainable management of the Pine Barrens region.

#### METHODS

Our study was based on a set of three Landsat TM images (path/row 26/28) recorded prior to the recent outbreak (14.6.1987), at the beginning of the outbreak (10.5.1992), and at the peak of the outbreak (1.8.1993).

The pre-processing of the satellite data included an atmospheric correction of the 1993 scene so that the satellite data could be compared to spectrometer measurements. The correction algorithm was based on the 5S radiative transfer model (Tanré et al. 1985, Hill 1993). The 1987 and the 1992 scenes were radiometrically matched to the corrected 1993 scene using regression equations based on pseudo-invariant objects (e.g. lakes, urban areas, and airfields). We evaluated the performance of the atmospheric correction by comparing our reflectance values with measurement of jack pine taken from a spectrometer mounted on a helicopter during the BOREAS project (Hall et al. 1996). Errors due to the radiometric matching were tested by examining reflectance changes of independent pseudo-invariant objects and of non-defoliated jack pine stands between 1987 and 1993.

The next step was to examine reflectance changes between 1987 and 1993 in stands that were defoliated. Jack pine budworm population measurement (Percentage of shoots infested by early larvae in late May) conducted by the Wisconsin Department of Natural Resources (WDNR) were available as ground truth. We correlated these with the reflectance of jack pine stands surrounding the sampling point. Correlations were conducted both with

single date TM 4 values and with the TM 4 difference between 1987 and 1993.

The actual defoliation was mapped using linear spectral mixture analysis. We tested various endmember sets selected out of a collection of 13 laboratory spectrometer measurements (2 green jack pine, 2 dry jack needle, 3 aspen leaves, 5 jack pine bark, and 1 shade spectra). The mixture analysis was first applied to the jack pine stands in the vicinity of the jack pine budworm sampling points. Thereby we correlated derived endmember fractions with our ground truth and could select endmember sets which best explained variations in the budworm data.

A species level forest classification derived from Landsat data (Wolter et al. 1995) was used to separate jack pine from other cover types. It became apparent during our analysis that hardwood content within jack pine dominated stands had a strong effect on the defoliation mapping. We separated pure jack pine stands from others using phenological differences of hardwood revealed in increasing TM 4 reflectance between May and June (1992 and 1987 imagery).

The endmember set which explained budworm data best was then applied to the satellite data of all pure jack pine stands resulting in a defoliation map. Using this map, we compared defoliation levels between different soil types to examine if poorer soils exhibit higher defoliation levels, as suggested by Weber (1995). The soil map was derived from the Landtype Association map compiled by the WDNR.

#### RESULTS

The comparison of jack pine reflectance measured in the 1987 and 1993 imagery and during the BOREAS project indicates that our data pre-processing matched all three data sets reliably (Fig. 1). The agreement between BOREAS spectrometer measurements and 1993 data supported the atmospheric correction. The only differences

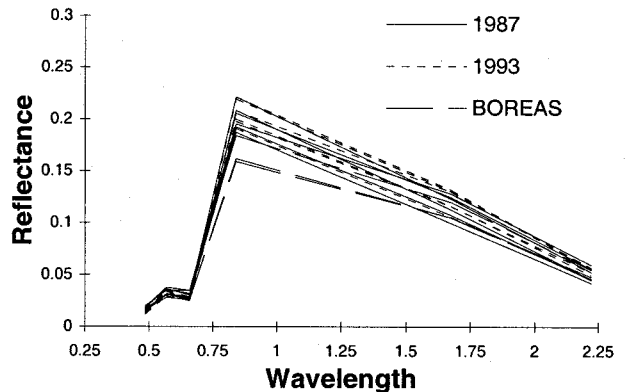


Fig. 1. Reflectance of 6 non-defoliated jack pine stands in 1987 and 1993 plus reflectance of 3 jack pine stands measured during BOREAS.

are lower BOREAS values in TM 4 which are probably due to the lower LAI of jack pine in Canada compared with Wisconsin. The agreement between 1987 and 1993 satellite data showed that the radiometric matching did not result in a shift of reflectance values between these two dates. The standard deviation of the reflectance changes observed on the pseudo-invariant objects was <1%.

Strong differences in reflectance values occur when 1993 reflectance of heavily defoliated stands are compared with 1987 values (Fig. 2). Most notably was an increase in TM 4 reflectance of about 5% and in TM 5 of about 4%.

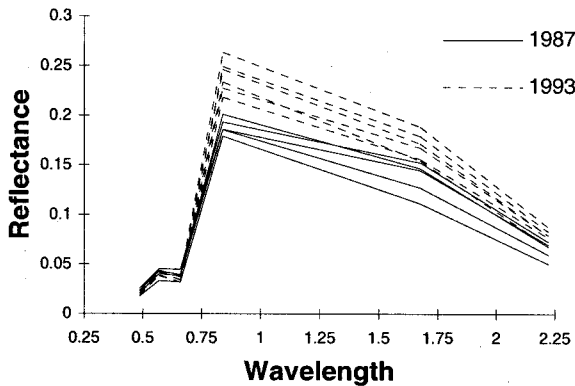


Fig. 2. Reflectance of 6 heavily defoliated jack pine stands in 1987 and 1993.

This increase in NIR reflectance seems to contradict the negative correlation ( $r = -0.47$ ) between NIR reflectance and budworm populations (Fig. 3). Highest TM 4 reflectance values exhibit lowest budworm populations. The reason for this is the varying amount of hardwood content, which resulted in a range of TM 4 reflectance from 17 to 28% already in the pre-outbreak 1987 imagery. Hardwood content limits budworm population and correspondingly we found a stronger negative correlation between 1987 satellite reflectance and 1993 budworm data ( $r = -0.69$ , Fig. 3.). TM 4 increase between 1987 and 1993 were positively correlated with budworm data, but the correlation is weak ( $r = 0.48$ ).

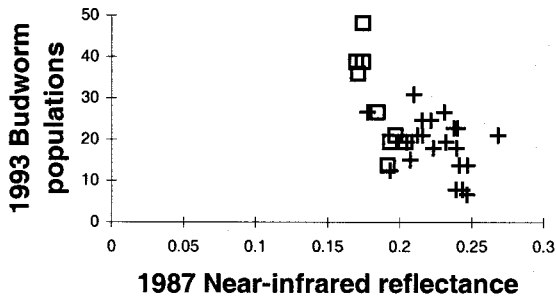


Fig. 3. 1987 TM 4 Reflectance versus 1993 jack pine budworm population data for 33 sampling points (Squares: pure jack pine stands; crosses: mixed jack pine stands).

Our separation of pure and mixed stands was based on the difference between TM 4 reflectance in our May and June imagery (1992 and 1987). The May 1992 image does not exhibit strong defoliation, because budworm populations were still low in summer of 1991. Mean TM 4 reflectance increase was 0.051 (st.dev.: 0.02) in the mixed stands and 0.016 (st.dev.: 0.013) in the pure stands. We defined a 0.03 threshold above which we assumed a stand to be mixed. Using this threshold, 80% of all jack pine identified in the species level forest classification of our study area (Wolter et al. 1995) remained as pure jack pine.

The spectral mixture analysis was performed with various sets of 3 or 4 endmembers, larger endmember sets were not feasible due to the limited spectral dimensionality of Landsat TM. The best correlation between resulting fraction values and budworm data was found for a set of 3 endmember (Jack pine bark, green jack pine needle, and shade). The green needle fraction exhibited the strongest correlation ( $r = -0.94$ , Fig. 4), and the bark fraction was positively correlated ( $r = 0.41$ ). Correlations between green needle fraction and budworm data was higher for 1993 than for 1987 ( $r = -0.74$ ).

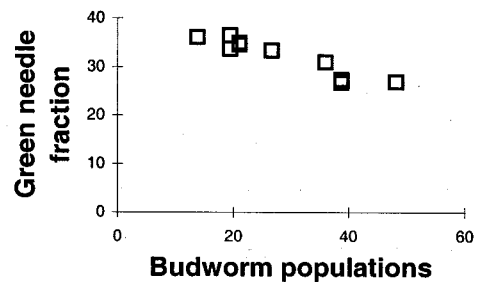


Fig. 4. 1993 budworm populations versus 1993 green needle fractions in pure jack pine stands.

When we employed the same endmember set to demix pure jack pine stands on soils of varying quality, we found no significant differences between the fraction values for three soil classes (Fig. 5). Standard deviations of the fraction images within each soil class are high (4.2-12.2), indicating that other environmental factors (e.g. stand age) determined budworm population levels and jack pine defoliation.

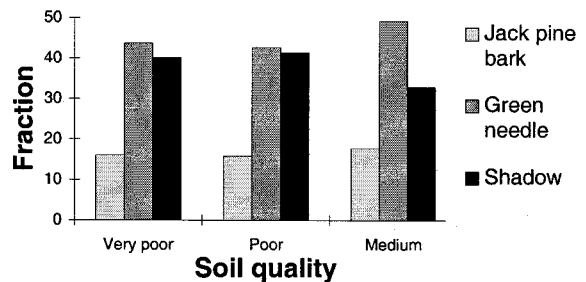


Fig. 5. Mean fraction values of jack pine on different soil classes.

## DISCUSSION AND CONCLUSION

We outlined in the introduction four problems that occur when insect defoliation is monitored with remotely sensed data. First, the optimal time window to identify insect attacks is often small. The peak of jack pine chlorosis occurs at the end of July. Cloud-free Landsat TM data taken in July or August were available only for one year during the outbreak (1993). We could not monitor chlorosis annually.

Second, reflectance changes due to defoliation vary over time. The 1993 satellite data exhibit two types of defoliation: 1993 defoliation with dry needles remaining in the crowns, and 1992 defoliation characterized by a higher amount of bark in the upper crown but without remaining dry needles. Spectral mixture analysis was necessary to identify both defoliation phases.

Third, reflectance changes occur at different scales. Our spectrometer measurements showed lower NIR reflectance for dry needles than for green needles. However, the NIR reflectance of the canopy increased with defoliation. The same increase in TM 4 reflectance was found in damaged scots pine (Herrmann et al. 1988). However, the physiological reasons for this increase are not completely understood and more research in this area is strongly suggested.

Fourth, cause and effect can be difficult to separate when satellite measurements and insect populations are correlated. The strong negative correlation between the 1987 satellite data and the 1993 budworm data is not due to defoliation but to the influence of mixed stands which exhibit lower budworm populations and higher TM 4 reflectance.

Common remote sensing techniques, like vegetation indices, were not capable of detecting defoliation due to the increasing NIR reflectance. Only by using spectral mixture analysis were we able to correlate 1993 satellite data with 1993 budworm population data and thus mapping defoliation. This allowed us to compare defoliation on three different soil types, and found no significant differences between them.

There are many possible uses of defoliation maps derived via spectral mixture analysis. Defoliation maps can be derived quickly and used as support for managers in their response to an occurring outbreak. We used - and will continue to use - our mapping to study the determining factors of population levels of jack pine budworm in the Pine Barrens region.

Insect disturbance is an integral part and a key ecological process, especially in coniferous forests. Using remotely sensed data and advanced image processing methods we can monitor defoliation, study outbreak dynamics, and thus

provide the knowledge required to manage forest ecosystems sustainably.

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