MAPPING INSECT DEFOLIATION USING MULTI-TEMPORAL LANDSAT DATA

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ABSTRACT

Insect defoliation is a major natural disturbance to North America's forests, affecting large areas that result in considerable timber losses annually. To address this problem in Canada, a project has been initiated to develop and demonstrate multi-scale Earth Observation-based methods for mapping and monitoring the spatial location, extent and severity of insect defoliation events in a consistent and timely fashion. Reliable and standardized information on insect defoliation and other large-scale forest disturbances will support Canada's capability to meet national and international sustainable development, environmental health and carbon accounting reporting requirements. For this study, a Landsat multi-temporal change detection approach was developed for aspen and spruce budworm defoliation. Within-year spectral variation was mapped for aspen defoliated areas, capturing changes in severity and extent related to the defoliation/refoliation cycle. Multi-year/site analyses demonstrate the natural variability of onset, duration and severity of aspen defoliator infestations. Multi-year spectral variation was mapped for spruce budworm defoliated areas, showing an increase in area and severity of damage to coniferous regions over the duration of the infestation. Mapping results are promising and have shown consistency within and across sites in Alberta and Saskatchewan. Resulting vectors are in general agreement with provincial aerial survey vectors, but with increased spatial precision. Automation procedures have been developed to facilitate integration of the techniques into the National Environmental Disturbances Framework (NEDF). Ongoing work includes developing an approach to model severity of defoliation using ground measurements, adding new sites to increase the robustness of the geo-spatial techniques, and exploring alternate sources of imagery as a substitute to Landsat.

INTRODUCTION

Insect defoliation is an important natural disturbance to North America's forests. In Canada, insects affect more than 10 million ha and account for the loss of 4 million m^3 of wood per year from our sustainable timber supply (Hall et al., 1998; Simpson and Coy, 1999; Canadian Forest Service, 2005). The onset of a changing climate may exacerbate these effects by altering the frequency, severity, duration, and timing of insect disturbances (Dale et al., 2001), and accelerate changes to forest composition and structure (Volney and Hirsch, 2005). Within the framework of the Kyoto Protocol and the United Nations Framework Convention on Climate Change, Canada must quantify carbon stocks and stock changes in forest ecosystems of which information about disturbances are necessary (Wulder et al., 2004; Kurz and Apps, 2006). Detailed temporal and spatial observations are necessary to meet this information need and to improve understanding about the interactions among disturbance types (Bernier and Apps, 2005). Mapping and quantifying both the areal extent and severity of disturbances through space and time will help to derive knowledge about the impact of these events, including their magnitude and dynamics. To derive estimates about insect defoliation, areas of disturbance are currently generated largely from aerial surveys. These surveys lack spatial detail and precision, vary in quality by province, and are largely confined to managed forest areas resulting in many areas of Canada without pest damage information (MacLean and MacKinnon, 1996). In addition, the timing to collate provincial information into a national assessment varies. Satellite imagery, due to its systematic, synoptic and repetitive coverage, has good potential to provide consistent and timely defoliation information to complement provincial aerial surveys. Similar to the work that has been completed to incorporate satellite mapping of forest fires into the Canadian Wildland Fire Information System (CWFIS), this study supports the requirement to map the areal extent and severity of disturbances from defoliation for incorporation into this framework, referred to as the National Environmental Disturbances Framework (NEDF). The framework is being developed to support Canada's national and international reporting requirements on environmental and sustainable development indicators related to Canada's forests, as well as for operational carbon accounting.

This paper addresses the use of fine resolution data, specifically, 30m resolution Landsat data, for consistent mapping and monitoring of insect defoliation, and compares results with provincial aerial surveys. The work builds on previous efforts that have demonstrated the use of pre-defoliation baseline images and defoliation images to map areas of defoliation and monitor changes in leaf area index from defoliation over several years (Hall et al., 2003; 2006). Medium resolution MERIS data (300m resolution) are also being investigated separately for this project as a tool for the planning/selection of higher resolution imagery during the defoliation window for more detailed mapping (e.g., Landsat) (van der Sanden et al., 2006), building on previous work which demonstrated that change metrics applied to coarse resolution satellite data (e.g., SPOT VEGETATION) have proven successful in detecting large areas of disturbances from insect defoliation (Fraser and Latifovic, 2005). Our focus in this project is the two largest damage causing defoliators in Canada – aspen defoliators (forest tent caterpillar (*Malacosoma disstria* Hubner) and large aspen tortrix (*Choristoneura conflictana* Wlk.)), and the eastern spruce budworm (*Choristoneura fumiferana* Clem.).

DEFOLIATOR CHARACTERISTICS

The forest tent caterpillar and large aspen tortrix are the most serious defoliators of aspen and a chronic problem in the prairie/boreal forest ecozone in Central Canada (Ives and Wong, 1988). Both of these defoliators emerge in the spring coincident with bud flush and feed on developing buds and shoots in early spring (Volney and Hirsch, 2005). Foliage is consumed during larval feeding that is completed in the middle of June for large aspen tortrix and end of June or early July for the forest tent caterpillar. Defoliation results in the physical loss of foliage that is best detected near the culmination of larval feeding that occurs approximately between the middle of June to early July. By mid to late July, trembling aspen with sufficient vigor will produce a second flush of foliage and thus remote sensing images acquired after this date are no longer suitable for assessing defoliation.

The spruce budworm reportedly causes more damage than any other insect in North America's boreal forest (Volney and Fleming, 2000). Larval emergence and feeding begins during the early spring, and during latter stages of larval feeding, visible signs of damage become obvious when residual portions of needles and frass turn the tree to a reddish brown color. Principle hosts include white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.)), and black spruce (*Picea mariana* (Mill.) BSP). Defoliation damage results in reduced photosynthetic capacity from loss of foliage, growth loss, and top kill (MacLean, 1990). Spruce budworm outbreaks typically last 5 to 15 years, and several consecutive years of severe defoliation can result in large areas of mortality and subsequent stand replacement (Fleming, 2000). The time window for detecting current defoliation during the reddish-brown color stage is extremely narrow, consisting of only two to three weeks as the residual needles then fall off, and detection is difficult because only the remains of the damaged foliage turns red-brown (Ahern et al., 1986). As a result, remote sensing studies typically focus on detection of cumulative defoliation (Leckie et al., 1992; Franklin and Raske, 1994).

STUDY AREAS

The study areas include two sites in Alberta and one site in Saskatchewan that have been subjected to multi-year outbreaks of aspen defoliators (forest tent caterpillar/large aspen tortrix) and the spruce budworm respectively (Figure 1).

Figure 1. Location map showing study areas.

The Alberta study area is centered at about 57º40'N, 118º00'W and roughly corresponds to the Northwest forest region of the province. The first site is located near the town of High Level; the second site near the town of Grande Prairie. Topographically the study area can be characterized as nearly level to gently undulating. The tree species comprise pure and mixed stands of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce (*Picea glauca* (Moench) Voss). Aspen defoliator outbreaks have caused severe defoliation to many trembling aspen stands in this region. At the High Level site, the currently active aspen defoliator outbreak began in 1999. Peak defoliation occurred in 2003 with 5.4 million hectares of forest defoliated; in 2007 the outbreak nearly collapsed. The infestation at Clear River, north of Grande Prairie, began in 1997 and by 2004 had collapsed.

The Saskatchewan study area consists primarily of Prince Albert National Park and forested lands directly north of the park. The park is situated on the southern edge of Canada's boreal forest, forming a transition zone between the southern parkland and northern forest. The southwestern portion of the park is dominated by aspen parkland. Bordering this parkland is a zone of mixed wood forest consisting of coniferous and deciduous species that occur throughout the park. In the northern reaches of the park, the boreal forest is dominated by black spruce muskeg and tamarack. The spruce budworm outbreak in Saskatchewan began in the early 1980's and increased significantly to peak during the early 2000's, at which time mortality had become visible from aerial surveys. Based on information collected from provincial aerial surveys, 5,097,850 ha of spruce and fir forests had sustained moderate to severe defoliation by the 2003 spray season. Cool, wet weather during the spring of 2004 and 2005 significantly reduced the population of spruce budworm in the park, thus limiting active defoliation. Defoliation in the park has occurred in both pure coniferous and mixed stands containing balsam fir and white spruce.

METHODS

A summary of the general procedure developed for mapping insect defoliation from Landsat data is presented in Figure 2. Future steps in this on-going study are also identified. As the methods will ultimately be implemented into the NEDF, the ability to automate and operationalize the techniques is a key consideration in the development process.

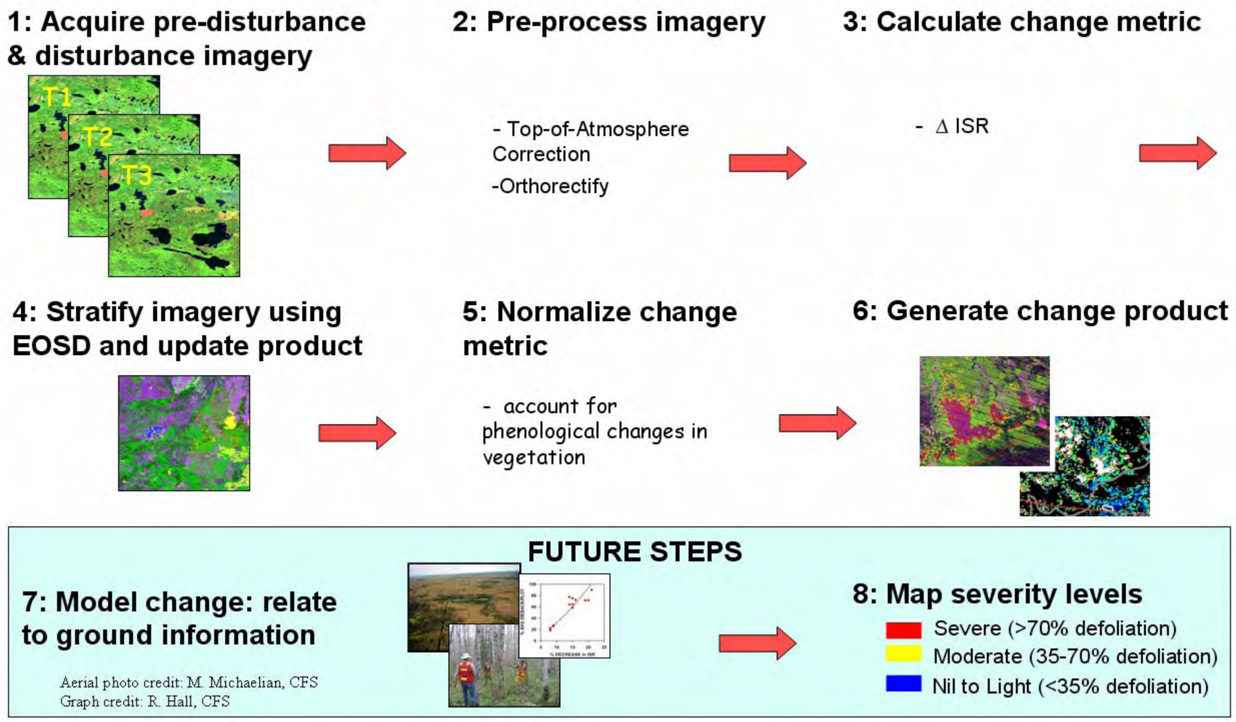

Figure 2. Remote sensing methods development and future steps.

A time-series of Landsat images was acquired over Clear River, High Level, and Prince Albert National Park during the respective defoliation periods. All images and image bands were corrected to Top-of-Atmosphere Reflectance (TOAR) using a freely distributed program developed at the Canada Centre for Remote Sensing (pers. comm. R. Landry). This correction accounts for differences in sensor variation and solar illumination but does not correct for variations in absolute atmospheric conditions between images. The method assumes a uniform atmosphere within the image and the same atmospheric characteristics between images. Since our application makes use of cloud and haze free imagery where possible, these assumptions are acceptable. All images were then orthorectified to a UTM projection using orthorectified Landsat imagery downloaded from Geogratis (http://geogratis.cgdi.gc.ca/frames.html) and the 1:250 000 Canadian Digital Elevation Data (CDED).

Images were automatically or manually cleaned to remove clouds, cloud shadows, water bodies, border pixels and Landsat-7 Scan Line Corrector (SLC) data gap lines. Land cover products created by the Canadian Forest Service in the framework of the Earth Observation for Sustainable Development of Forest (EOSD) project were used to stratify the imagery and focus the analysis on the desired land cover type. EOSD mapsheets, which represent forest conditions circa 2000, were downloaded from the SAFORAH website (http://www.saforah.org/), merged, filtered, and resampled to the 30m Landsat imagery resolution. Because the EOSD products pre-date many of the Landsat images analyzed for this work, it was necessary to update the products for forestland disturbances such as harvesting and fire. Thresholding methods have been developed for excluding potential false-alarms such as recent and regenerating clearcuts, and an assessment into using the CWFIS national burn area composite vectors for excluding recent fires from the products is underway.

Image normalization procedures have been investigated to ensure sensitivity for detecting defoliation severity. The normalization approach under development accounts for phenological changes in vegetation within a season and between years. Since the seasonal and inter-annual variation in reflectance due to phenological changes in vegetation differs by tree vegetation class, normalization is based on either deciduous or coniferous species depending on the defoliator of interest. Our algorithm automatically selects healthy deciduous or coniferous pixels based on reflectance values in Landsat bands 4 and 5 for each image. These values were used to normalize the change metric images.

Defoliated areas within pure regions of the vegetation class of interest were identified and mapped by means of a multi-temporal change detection approach using the infrared simple ratio (ISR) change metric and a pre-defoliation image as a baseline. The Landsat infrared simple ratio, band 4/band 5, was calculated for each image in the time-series. Change images were calculated by subtracting the ISR values between pre-defoliation and defoliation images, and normalized based on differences in healthy pixel statistics between the two images. The results were then segmented based on manually determined thresholds into two preliminary severity classes of defoliation and converted to vector format.

RESULTS

Aspen Defoliation

Figure 3 compares NEDF defoliation vectors extracted for pure aspen regions for a Landsat image acquired June 18, 2005, with the 2005 provincial aerial survey sketch map for the High Level site. The NEDF vectors compare favorably with the provincial aerial sketch map. NEDF defoliation vectors, however, have increased spatial precision over provincial vectors and exclude non-host areas which are often included in the provincial vectors, resulting in a more realistic assessment of the extent and severity of defoliated areas. This was consistently observed for NEDF vectors extracted from Landsat time-series imagery acquired during defoliation events spanning 1999-2006 for both Alberta sites. This finding agrees with results from previous work focused on relating Landsat-derived LAI to defoliation (Hall et al., 2006).

The results are consistent within a year, between years, between sites and with general insect defoliation patterns (Figure 4). Within-year spectral variation was mapped for Clear River and High Level using a time-series of imagery spanning from early June to late August. The time series captures the defoliation period in June with high values of ISR normalized difference (ISRND), while in mid-July during refoliation the ISRND values decrease gradually until the second flush of leaves appear. Consistency between the Landsat TM and ETM+ sensors is also observed. Figure 5 compares the NEDF vectors extracted from a Landsat-7 ETM+ image acquired June 13, 2006 with that from a Landsat-5 TM image acquired June 14, 2006. The NEDF vector distribution and severity appear to be consistent between the two sensors.

Spruce Budworm Defoliation

A total of six defoliation images spanning 1996-2005 and one baseline image, where defoliation was negligible, were processed for the Prince Albert National Park study site. Figure 6 shows that NEDF cumulative defoliation vectors extracted for pure coniferous regions for a Landsat-5 TM image acquired July 16, 2003, are in general agreement with the 2003 provincial aerial sketch map. The NEDF vectors are within the defoliated regions as mapped by the provincial aerial vector product. However, similar to aspen defoliation, the NEDF defoliation vectors tend to have increased spatial precision and exclude non-host areas which are often included in the provincial vectors, resulting in smaller areas of defoliation mapped and a more realistic assessment of the extent of defoliation. This trend was observed for images acquired from 1996 to 2003. In 2004 and 2005, areas of cumulative defoliation lying outside provincial defoliation vectors were mapped. This was to be expected as the provincial sketch maps are limited to current year defoliation and the infestation essentially collapsed in 2004 and 2005. For these years, the ongoing effects of severe cumulative defoliation from previous years were detected by Landsat data, confirming that satellite remote sensing can be used to map these effects after an infestation has collapsed. In general, the multi-year mapping results show both an increase in cumulative defoliation area and severity in coniferous regions over the duration of the infestation.

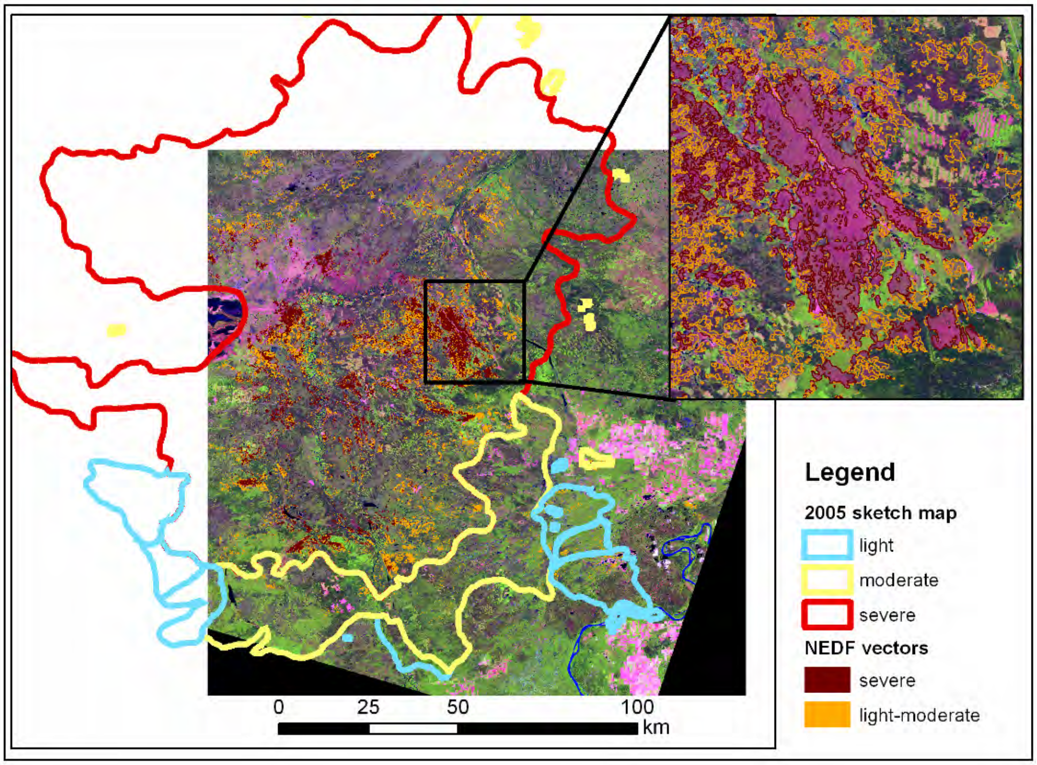

Figure 3. Comparison of 2005 provincial sketch map and NEDF vectors for aspen defoliation, High Level. Subset of Landsat-5 TM image (5,4,3 composite) acquired on 18 June 2005.

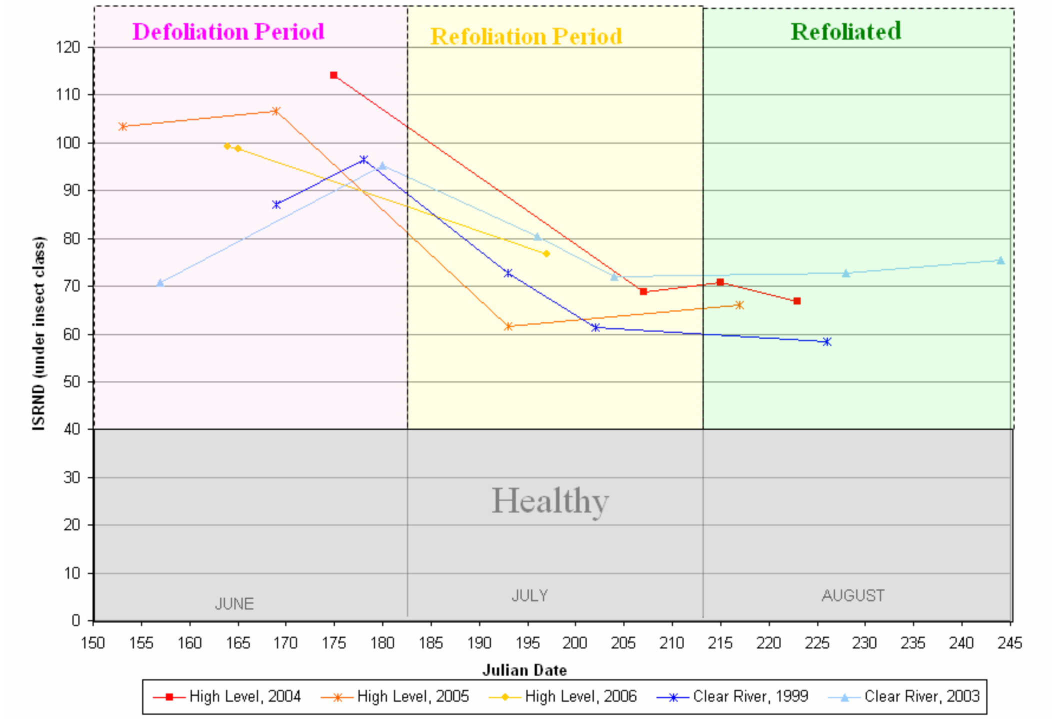

Figure 4. Aspen defoliation time series showing the within-year cycle and between year variability at the two northern Alberta sites.

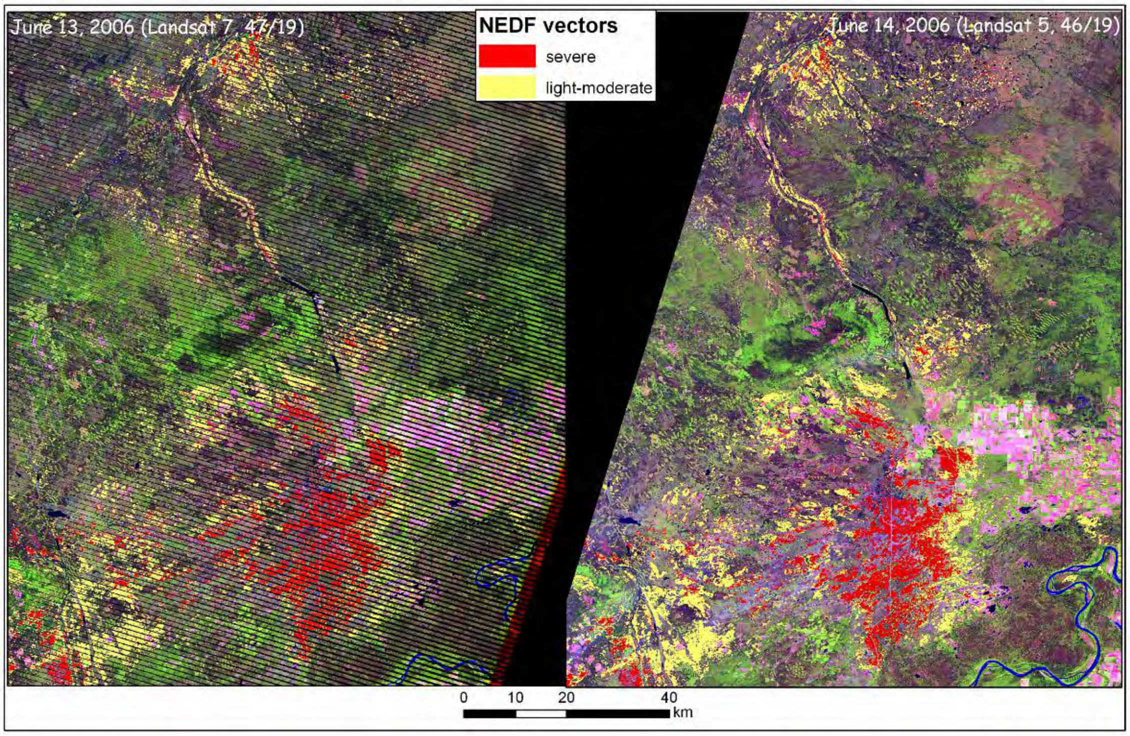

Figure 5. Comparison of NEDF vectors extracted from Landsat-7 ETM+ image acquired 13 June 2006 and Landsat-5 TM image acquired 14 June 2006.

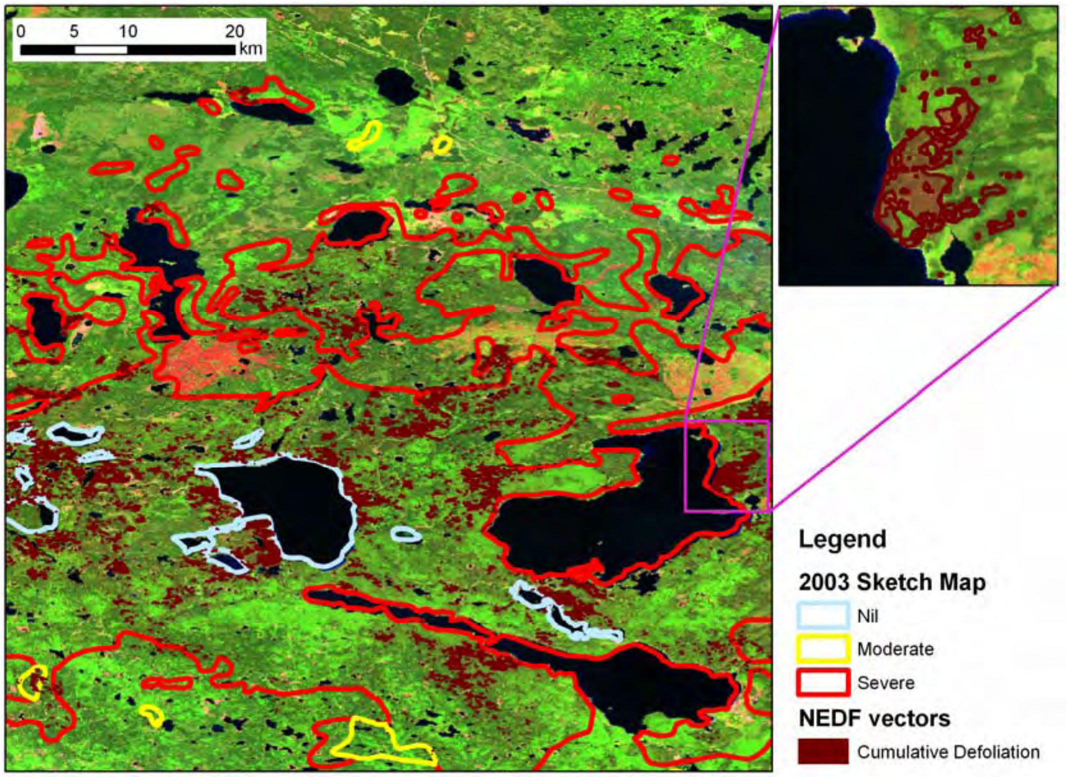

Figure 6. Comparison of 2003 provincial sketch map and NEDF vectors for spruce budworm defoliation, Prince Albert National Park. Subset of Landsat-5 TM image (5,4,3 composite) acquired 16 July 2003.

Figure 7 shows 2-class defoliation products for two Landsat-5 TM images, acquired July 21, 1999 and July 16, 2003. In the July 21, 1999 image, defoliation vectors show mainly light to moderate cumulative defoliation. In comparison, provincial sketch maps indicate defoliation in this area began in 1998, with moderate-to-severe current-year defoliation in 1998 and severe current-year defoliation in 1999. By July 2003, after an additional four years of severe defoliation in the area as recorded by the provincial sketch maps, mainly severe cumulative defoliation was detected by our methodology. Preliminary fieldwork was conducted in this area from June 27-29, 2005, confirming the presence of severe cumulative defoliation, topkill, and a mortality rate of 33% for balsam fir and white spruce. Provincial sketch maps recorded no current-year defoliation in the area in 2005. Therefore, Landsat data were successful in detecting the effects of cumulative defoliation one year after the collapse of the infestation.

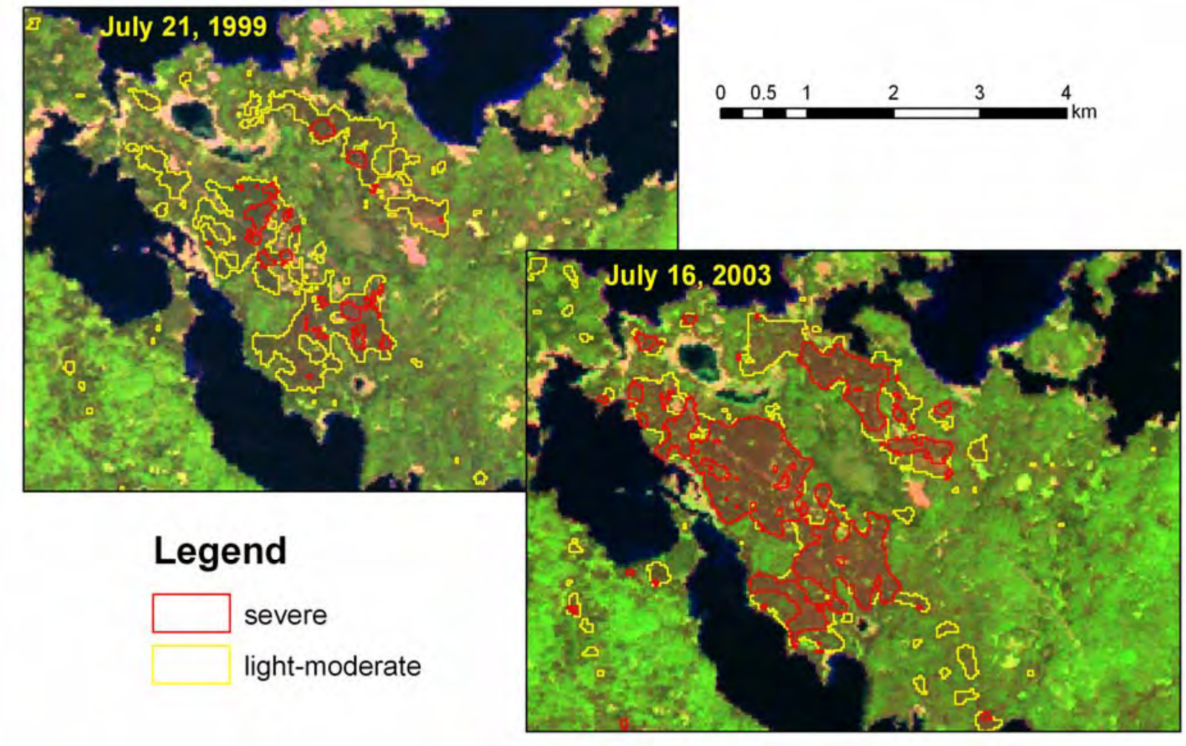

Figure 7. 2-class cumulative defoliation vectors derived from Landsat-5 TM imagery acquired 21 July 1999 and 16 July 2003, Prince Albert National Park.

CONCLUSIONS AND FUTURE WORK

The study results show that NEDF defoliation vectors extracted from time-series Landsat images acquired during the peak defoliation period for aspen defoliators and during the summer months for spruce budworm defoliation are in general agreement with the provincial aerial sketch maps. NEDF defoliation vectors, however, have increased spatial precision and show spatial variability in defoliation severity that is not captured by the sketch maps. In the mapping of aspen defoliation, images acquired during the peak defoliation period provide the best estimate for extent and severity of defoliation and compare best with the provincial vectors. However, images acquired “off-peak” can also provide valuable information if no other images are available due to cloud cover. Results are consistent for the within-year defoliation/refoliation cycle, between years, between sites, and between Landsat-5 TM & Landsat-7 ETM+ sensors. In mapping cumulative spruce budworm defoliation with Landsat imagery, results show both an increase in cumulative defoliation area and severity in coniferous regions over the duration of the infestation. The effects of severe cumulative defoliation have been detected after infestation collapse. Future work will concentrate on sampling a more complete range of defoliation conditions for validation of multi-scale remote sensing information products and severity assessment/model development, investigating additional sites to increase the robustness of the geo-spatial techniques, characterizing defoliation in mixed wood stands, and exploring the utility of alternate sources of imagery as a substitute for Landsat data (e.g., Spot, IRS).

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