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Landsat TM/ETM+ and tree-ring based assessment of spatiotemporal patterns of the autumnal moth (*Epirrita autumnata*) in northernmost Fennoscandia

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ABSTRACT

We used fine-spatial resolution remotely sensed data combined with tree-ring parameters in order to assess and reconstruct disturbances in mountain birch (*Betula pubescens*) forests caused by *Epirrita autumnata* (autumnal moth). Research was conducted in the area of Lake Torneträsk in northern Sweden where we utilized five proxy parameters to detect insect outbreak events over the 19th and 20th centuries. Digital change detection was applied on three pairs of multi-temporal NDVI images from Landsat TM/ETM+ to detect significant reductions in the photosynthetic activity of forested areas during disturbed growing seasons. An image segmentation gap-fill procedure was developed in order to compensate missing scan lines in Landsat ETM+ "SLC-off" images. To account for a potential dependence of local outbreak levels on elevation, a digital elevation model was included in the defoliation recognition process. The resulting damage distribution map allowed for the assessment of outbreak intensity and distribution at the stand level and was combined with tree-ring data and historical documents to produce a multi-evidence outbreak detection. Defoliation events in the tree-ring data were recognized as significant deviations from temperature related growth.

Our outbreak detection scheme allowed for the reconstruction of nine major insect outbreaks over the past two centuries. The reconstruction proved reliable but only robust for severe defoliation events. Low-intensity incidents were not captured.

1. Introduction

Rejuvenation is crucial for forested ecosystems in order to ensure their continuity and resilience against extreme impacts (e.g. Esper & Schweingruber, 2004). In Fennoscandia, where mountain birch (*Betula pubescens*) is the predominant tree species forming the treeline (Tenow et al., 2004), defoliation caused by geometrids such as *Epirrita autumnata* (autumnal moth) is among the most important ecological disturbances resulting in growth reduction and tree mortality (Tenow, 1972). *Epirrita* has a univoltine life cycle and its larvae hatch at the time of budbreak in the host forests (Bylund, 1997). The potential population growth rate is very high (six to ten fold in one generation) and in northern Scandinavia, the moths tend to reach outbreak numbers every 9–10 years in the middle of each decade (Bylund, 1995). Similar regular outbreak patterns may be found in most forest Lepidoptera species that reach outbreak levels (e.g. gypsy moth, Haynes et al., 2009). Cycles are regional and may become synchronized if conditions are similar. They do not, however, spread from an epicentre but occur simultaneously in different localities (Ruohomäki et al., 2000; Klemola et al., 2006). To reach outbreak level, at least three consecutive years of population growth are needed (Virtanen et al., 1998). Moreover, the population dynamics of *E. autumnata* are strongly dependant on the frequency of lethal minimum winter temperatures. Egg-killing temperatures are below −35.1 to −36.5 °C in high winter and −28.3 to −29.8 °C in early spring (Tenow & Nilssen, 1990). Thus, the distribution and the disturbance regimes in northern Fennoscandia are likely to be altered by regional climate change. Compared to the current state, the forest area protected by cold is predicted to decrease to 1/3 by 2050 and to 1/10 by 2100 (Virtanen et al., 1998).

Over the past two decades, various efforts have been made to assess insect-related disturbances and their consequences in forested ecosystems using remote sensing and related methodologies (e.g. winter moth, Hogda & Tommervik, 1998; jack pine budworm, Radeloff et al., 2000; Leckie et al., 2005; gypsy moth, Townsend et al., 2004; Johnson et al., 2006; pine sawfly, Solberg et al., 2006; Eklundh et al., 2009; mountain pine beetle, Wulder et al., 2006). Early studies commonly determined the spatial properties of population peaks and classified single satellite images to detect outbreak ranges (e.g. Franklin & Raske, 1994). In contrast, recent investigations have

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applied digital change detection techniques such as image differencing, principal component analysis on multi-temporal remote sensing data (see Radeloff et al., 1999 for a summary). Temporal analysis has either focused on changes in the forest distribution (Masek, 2001) or assessed insect outbreaks using time series analysis on annual areal survey information (Johnson et al., 2006).

In the mountain birch forests of northern Fennoscandia, most satellite-based research has focused on tree cover mapping and forest dynamics (e.g. Seppälä & Rastas, 1980; Heiskanen & Kivinen, 2007). Spatiotemporal analyses of *E. autumnata* infestations (Tømmervik et al., 2001) are sparse. Thus, other methodologies such as laboratory experiments (e.g. Hoogesteger & Karlsson, 1992), dendrochronology (e.g. Eckstein et al., 1991) or detailed analyses of climate proxies (Ruohomäki et al., 2000; Jepsen et al., 2008) have been important for the assessment of forest disturbance in this region. These, however, provide no area-wide information about intensity and distribution of defoliation during *Epirrita* population peaks.

In this study, we use fine-spatial resolution remotely sensed satellite data to assess the spatial distribution and intensity of the three most recent *Epirrita* outbreaks in the area of Lake Torneträsk (Swedish Lapland) in 1986, 1994 and 2004 (Karlsson et al., 2004). Digital change detection was applied to determine decreases in photosynthetic activity during *Epirrita* outbreak events. Fine-spatial resolution satellite imagery was then combined with tree-ring data. Dendroecological techniques have often been used in the past to assess the temporal aspects of forest Lepidoptera outbreaks (e.g. *Zeiraphera diniana*, Esper et al., 2007; *E. autumnata*, Eckstein et al., 1991). This multi-evidence approach was used to establish a spatiotemporal link between the area-wide spectral and in-situ tree-ring data. It is, to our knowledge, the first reconstruction of insect outbreak events where satellite-based digital change detection is supported by natural proxy data.

2. Materials and methods

2.1. Study area

To guarantee the comparability with previous research on *E. autumnata* population peaks (e.g. Tenow, 1972; Eckstein et al., 1991; Bylund, 1995; Karlsson et al., 2004), this study was carried out in the area of Lake Torneträsk (68°19′6″N, 19°16′44″E; 341 m a.s.l.) and the Abisko National Park in Swedish Lapland (Fig. 1). The region of interest is situated in a mountainous area on the eastern slope of the Scandes Range, which retains moisture that is brought from the Atlantic Ocean by cyclones following the main westerly air-flow (Tenow, 1972). As a consequence of this lee situation, average precipitation is only 304 mm per year of which 124 fall during summer. Nevertheless, water is not a limiting factor for tree growth as transpiration is low due to the cold temperatures. The average annual air temperature is −0.6 °C and mean summer temperature (JJA) is 10 °C allowing tree growth up to an elevation of about 650 m a.s.l. Climate data used in this is study derived from the Abisko Scientific Research Station (ANS), which is situated at the southern margin of Lake Torneträsk at an elevation of 385 m a.s.l. Its consistent time series reaches back until 1913.

The productivity of the forest mainly depends on temperature during the main growing season, which lasts from the beginning of June to the end of August (Eckstein et al., 1991). The lower areas are covered by a monocultural mountain birch forest of the heath-type. At most slopes above the lake, the denser meadow birch forest prevails (Vegetationskarta, 1981). Field observations showed that where drier ecological conditions prevail locally, particularly on hills, the area-wide birch forest is occasionally interrupted by coniferous trees, mainly Scots Pine (*Pinus sylvestris*). Scots Pine is not affected by the leaf-eating caterpillars of *E. autumnata* (Ruohomäki & Haukioja, 1992).

Artificial surface structures may directly affect the dispersal of the poor-flying moths (Ruohomäki et al., 2000). There are no major settlements around Lake Torneträsk or the adjacent areas which had to be taken into account during the georeferencing process. Small villages are concentrated on the south side of the main lake along the road and the railroad from Kiruna (SWE) to Narvik (NOR). Summer and winter tourism in the Abisko National Park is limited to the main trails and a small skiing resort. The north shore is mainly unsettled.

2.2. Digital change detection

Fine-spatial resolution satellite imagery is useful for studying changes in land cover and in the magnitude of peak greenness over time (e.g. Stow et al., 2004; Fraser et al., 2005). Many previous studies

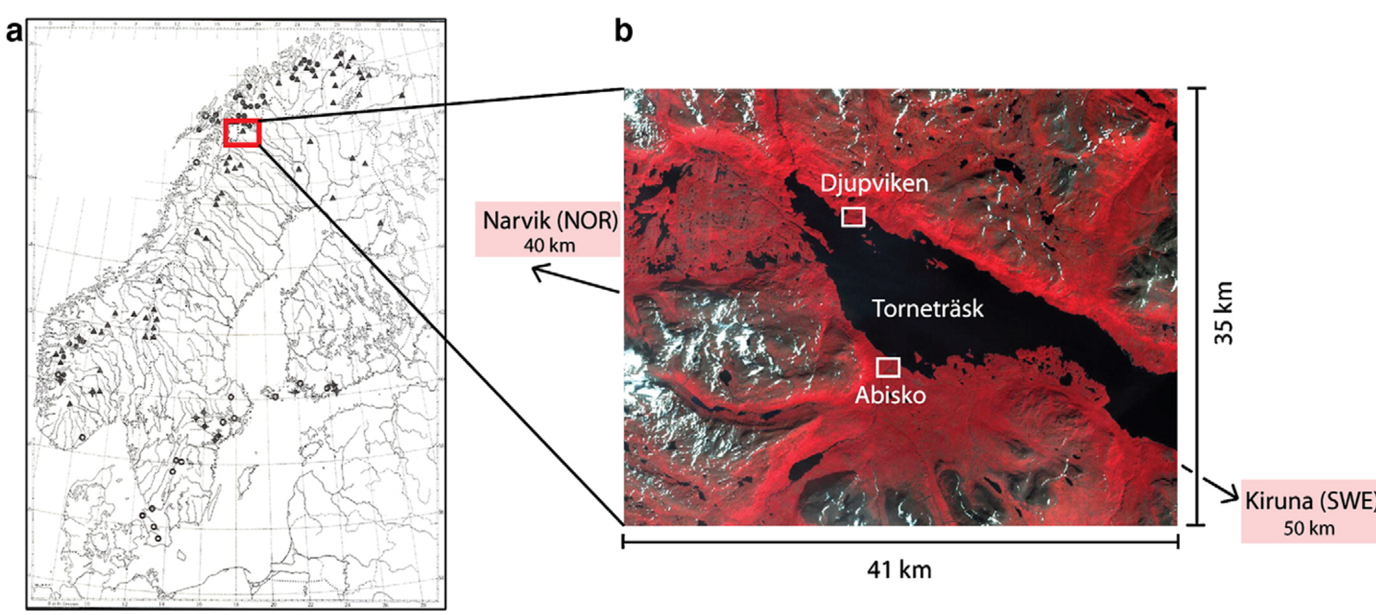

Fig. 1. Location of the research area: (a) distribution of documented insect outbreaks along the Scandes (*O. brumata*, *O. fagata*, *O. autumnata*; Tenow, 1972); (b) false-colour infrared composite of the spatial subset that has been used for all satellite-based investigations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)