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Monitoring the spatio-temporal dynamics of geometrid moth outbreaks in birch forest using MODIS-NDVI data

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ABSTRACT

Defoliation caused by repeated outbreaks of cyclic geometrid moths is the most prominent natural disturbance factor in the northern-boreal birch forest. Evidence suggests that recent changes in outbreak distribution and duration can be attributed to climate warming. There is hence an immediate need for methods that can be applied to characterize the geographical distribution of outbreaks. Here we assess the reliability of MODIS (Moderate Resolution Imaging Spectroradiometer) 16-day NDVI data for generating time series of the distribution of defoliation caused by moths attacking birch forest in Fennoscandia. We do so by first establishing the relationship between ground measures of moth larval density and a defoliation score based on MODIS-NDVI. We then calibrate and validate a model with the MODIS-NDVI defoliation score as a classifier to discriminate between areas with and without visible defoliation as identified from orthophotos and provide two examples of application of the model. We found the MODIS defoliation score to be a valid proxy for larval density ($R^2 = 0.88–0.93$) above a certain, low threshold (a defoliation score of ~5%). Areas with and without visible defoliation could be discriminated based on defoliation score with a substantial strength of agreement (max kappa = 0.736), and the resulting model was able to predict the proportion of area with visible defoliation in independent test areas with good reliability across the range of proportions. We conclude that satellite-derived defoliation patterns can be an invaluable tool for generating indirect population dynamical data that permits the development of targeted monitoring on relevant regional scales.

1. Introduction

Defoliation and tree mortality caused by outbreaks of pest insects is one of the most prominent disturbance factors in forests around the globe. The ecological and economic impacts of pest insects, in particular species that exhibit eruptive population dynamics, are massive (Dale et al., 2001; Wulder et al., 2006a). A continuing effort is invested in developing and refining tools for monitoring the effects and predicting the spatial dynamics of forest pest insects. One important rationale for this investment is a growing concern that recent, rapid changes in distribution ranges mediated by climatic warming and changing seasonality documented for several important forest pests (Battisti et al., 2005; Jepsen et al., 2008; Parmesan et al., 1999; Tenow et al., 1999) may lead to increased spatial extent and severity of outbreaks in forest (Fleming & Candau, 1998; Logan et al., 2007; Volney & Fleming, 2000; Williams & Liebhold, 1995).

To understand how the consequences of climate-mediated changes in geographical distribution and outbreak severity can be mitigated using appropriate management decisions, there is a need for developing targeted monitoring programmes (Nichols & Williams, 2006; Yoccoz et al., 2001) that can provide information on pest outbreak distribution and dynamics and permit hypotheses to be tested at relevant large spatial scales. Studies of complex spatio-temporal dynamics, such as large-scale synchrony and travelling waves (Bjørnstad et al., 1999; Johnson et al., 2004; Koenig, 1999; Ranta et al., 1998) have significantly improved our predictions of the spatial dynamics of outbreaks (Bjørnstad et al., 2002; Cooke & Roland, 2000; Johnson et al., 2004; Liebhold et al., 2006; Peltonen et al., 2002). However, availability of adequate data to assess the predictions on regional scales has become a major obstacle to continued progress (Bjørnstad et al., 1999).

Many studies have shown that forest discoloration, including defoliation caused by insects, can be successfully identified using satellite-derived vegetation reflectance data of varying spatial resolution. Fine resolution satellite imagery, such as Landsat (30 m resolution), has been used to study forest discoloration caused for instance by gypsy moth, *Lymantria dispar*, (Hurley et al., 2004; Townsend et al., 2004), jack pine budworm, *Choristoneura pinus pinus*, (Radeloff et al., 1999), Siberian silk moth, *Dendrolinus superans sibiricus* (Kharuk et al., 2003; Ranson et al., 2003), mountain pine beetle, *Dentroctonus ponderosa* (Skakun et al., 2003) and autumnal

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and winter moth, *Epirrita autumnata* and *Operophtera brumata* (Tømmervik et al., 2001). However, Landsat sensors have a limited temporal resolution; i.e. rarely more than one or at best a few images can be obtained during a growing season. While this represents no problem in detecting forest discoloration resulting from forest death (Skakun et al., 2003; Wulder et al., 2006b), it severely limits the applicability of Landsat imagery in detecting the seasonally ephemeral outbreaks by forest defoliators (de Beurs & Townsend, 2008). Commercial fine resolution sensors are now available with relevant high temporal resolutions (such as Formosat and Quickbird). However, the costs of obtaining and individually processing and calibrating large numbers of fine resolution images has prevented any practical use of fine resolution imagery for monitoring insect outbreaks on a regional scale. Very coarse resolution imagery, in particular SPOT_VEGETATION and NOAA AVHRR (>1 km resolution), have been put to use in identifying and mapping forest defoliation on regional scales (Fraser et al., 2005; Fraser & Latifovic, 2005; Kharuk et al., 2004). While evaluations of coarse resolution imagery generally confirm that forest change patterns can be identified with a good accuracy, the coarse resolution limits the applicability of this type of imagery in detailed monitoring. Coarse resolution imagery has however been successfully applied in identifying major forest change areas which could subsequently be the target of more detailed analysis in order to establish the cause of the change (Fraser et al., 2005). Very promising results have been obtained using MODIS which provide global moderate resolution (~250–500 m) reflectance data on a daily basis, and hence allow mapping both of relative changes in reflectance patterns between years and of short term changes occurring within a single growing season. 16-day composite MODIS-NDVI and pre- and post-outbreak Landsat data has been used to quantify the extent of an outbreak by Siberian silk moth (Kharuk et al., 2007). In a more comprehensive study de Beurs and Townsend (2008) evaluated a number of vegetation indices derived from both daily, 8-day and 16-day MODIS composite data, in estimating the extent and magnitude of gypsy moth defoliation.

Satellite-based monitoring of insect damage has yet to find its way into operational pest monitoring and management programmes. Yet, time series of satellite-derived defoliation estimates may yield important insight not only into annual defoliation patterns, as demonstrated in many of the case studies referenced above, but also into the spatio-temporal dynamics of forest pest insects such as regional population synchrony and travelling waves (Bjørnstad et al., 2002). Among the most important criteria for success is an appropriate matching of sensor temporal resolution to the temporal manifestation of the damage as well as verification that the satellite-derived measure of damage is a valid proxy for the variation in population density of the pest insect on the ground.

The goal of the work reported here was to assess the reliability of MODIS-NDVI data for generating time series of the distribution of severe defoliation caused by geometrid moths attacking northern-boreal mountain birch forest in Fennoscandia. Since defoliation of birch by geometrids in this region is of a seasonal character (little or no re-foliation in the same growing season), we base our analysis on 16-day NDVI composite data obtained during June–August for the years 2000–2008. We evaluate the validity of the MODIS-NDVI defoliation score as a proxy for moth larval density using ground data from 3 separate study regions, differing with respect to local climate and topography. In addition we calibrate and validate a model with the MODIS-NDVI defoliation score as a classifier to discriminate between areas with and without visible defoliation as identified from orthophotos. Finally we provide two examples of applications of the model. In one we reconstruct the outbreak history in an altitudinal gradient at a fairly local scale while in the other we generate time series (2000–2008) of the predicted distribution of defoliated areas for the entire birch forest region in northern Fennoscandia.

2. Methods

2.1. Study system

Northern Fennoscandia lies in the arctic/alpine–boreal transition zone and includes the northern parts of Norway, Sweden and Finland. The Scandinavian mountain chain (the Scandes) divides the area into a humid oceanic region along the western coast (Tromsø, 69°38′N, 18°57′E: mean July: 11.8 °C, mean January: −3.8 °C, annual precipitation: 1000 mm), and a dry continental region to the southeast (Karasjok, 69°28′N, 25°30′E: mean July: 13.1 °C, mean January: −17.1 °C, annual precipitation: 366 mm). Birch (*Betula pubescens*, Ehrh.) forests dominate the lowland, except in the southeast where dominance gradually shifts to conifers. In the western region, wind-protected areas are characterized by tall birch forest types where herbs and ferns dominate the ground cover. In contrast, the continental east is characterized by low-growing and open, multi-stemmed birch forest types where lichen and crowberry dominate the ground cover. Throughout the whole region, intermediate bilberry birch forest types cover large areas (Hämet-Ahti, 1963; Johansen & Karlsen, 2005; Väre, 2001). The growing season lasts from late May–early June until early September (Karlsen et al., 2008).

In the northern-boreal birch forests of Fennoscandia, two geometrid species, winter moth and autumnal moth (the names reflect a difference in the timing of emergence of adults in autumn), are the most important cause of disturbance. Both species exhibit cyclic population outbreaks at approx. 10-year intervals in this region (Bylund, 1999; Hogstad, 1997; Neuvonen et al., 1999; Tenow, 1972). The cyclicity of the outbreaks is documented in qualitative historical records as far back as the 1860s (Nilssen et al., 2007; Tenow, 1972). Individual outbreaks vary greatly in amplitude, duration, spatial extent as well as the degree of spatial synchronicity (Klemola et al., 2006; Ruohomäki et al., 2000; Tenow, 1972; Tenow et al., 2007). Where the two species occur sympatrically within their outbreak range, there is a partial interspecific synchrony in the timing of the outbreaks, but with winter moth often lagging 1–2 years behind autumnal moth (Klemola et al., 2008; Tenow et al., 2007). The outbreaks can be massive and usually have dramatic effects, with severe defoliation over vast areas and occasionally death of the forest (Lehtonen & Heikkinen, 1995; Tenow, 1972; Tenow & Bylund, 2000). Defoliation of birch by geometrids in this region is of a seasonal character. The larvae of both species hatch in approximate synchrony with budburst (late May–early June) and the feeding periods last for 4–8 weeks depending on temperature and forage quality (Ruohomäki et al., 2000). At high larval densities a large proportion of birch leaves are consumed at the bud stage and never unfold. Although the occurrence of some re-foliation in heavily defoliated birch has been reported from Fennoscandia (Kaitaniemi et al., 1997), the degree to which this occurs is in our experience very limited. The short growing season and the rapidly decreasing temperatures during August and early September do not allow a crown layer of any substance to develop. The total extent and distribution of forest damage caused by geometrids in the Fennoscandian birch forest is not known, as no systematic monitoring is in place.

In the present study we considered Fennoscandia north of 68°N (Fig. 1). We delineated the study region to the east by the approximate birch/mixed birch–coniferous forest limit, a total area of about 106,700 km^2 of which roughly 30% are forested.

2.2. Satellite imagery and NDVI change analysis

The Normalized Difference Vegetation Index (NDVI) is a commonly used vegetation index defined as NDVI = (Rnir − Rred) / (Rnir + Rred), where Rnir and Rred are the reflectance measured in the near infrared and red channel, respectively. For this study we used the MODIS TERRA NDVI data product with a 16-day temporal resolution