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Vegetation recovery following extreme winter warming events in the sub-Arctic estimated using NDVI from remote sensing and handheld passive proximal sensors

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ABSTRACT

Extreme winter warming events in the sub-Arctic have caused considerable vegetation damage due to rapid changes in temperature and loss of snow cover. The frequency of extreme weather is expected to increase due to climate change thereby increasing the potential for recurring vegetation damage in Arctic regions. Here we present data on vegetation recovery from one such natural event and multiple experimental simulations in the sub-Arctic using remote sensing, handheld passive proximal sensors and ground surveys.

Normalized difference vegetation index (NDVI) recovered fast (2 years), from the 26% decline following one natural extreme winter warming event. Recovery was associated with declines in dead *Empetrum nigrum* (dominant dwarf shrub) from ground surveys. However, *E. nigrum* healthy leaf NDVI was also reduced (16%) following this winter warming event in experimental plots (both control and treatments), suggesting that non-obvious plant damage (i.e., physiological stress) had occurred in addition to the dead *E. nigrum* shoots that was considered responsible for the regional 26% NDVI decline. Plot and leaf level NDVI provided useful additional information that could not be obtained from vegetation surveys and regional remote sensing (MODIS) alone.

The major damage of an extreme winter warming event appears to be relatively transitory. However, potential knock-on effects on higher trophic levels (e.g., rodents, reindeer, and bear) could be unpredictable and large. Repeated warming events year after year, which can be expected under winter climate warming, could result in damage that may take much longer to recover.

1. Introduction

Extreme weather events are expected to increase in frequency due to climate change (ACIA, 2005; Christensen et al., 2007). Such extreme events can surpass lethal thresholds of species leading to population crashes with knock-on effects throughout the ecosystem (Gaines and Denny, 1993; Jentsch et al., 2007). Increased species mortality following extreme weather is generally the result of the unseasonal weather conditions during the event or changes in the physical environment resulting in extremes of temperature and moisture availability (Barrett et al., 2008). In the Arctic for instance, sudden winter warming events that melt the snow layer have already been implicated in population crashes of soil animals, plants, and their consumers such as voles, reindeer and musk ox (Forchhammer and Boertmann, 1993; Robinson et al., 1998; Coulson et al., 2000; Aanes et al., 2002; Putkonen and Roe, 2003; Bartsch et al., 2010) due to the much lower subnivean temperatures or ice layer formations. Given that Arctic regions are expected to experience the greatest climatic change during winter months and with higher temperatures predicted for winter and early spring (Schwartz et al., 2006; Beniston et al., 2007; Callaghan et al., 2010), these regions will likely experience more extreme weather events with large consequences for ecosystem development.

A recent occurrence of extreme weather in the sub-Arctic was the winter warming event that occurred in northern Scandinavia during December 2007 (Bokhorst et al., 2009). A 12-day period with temperatures between 2 and 10 °C caused snow melt across at least 1400 km^2 exposing the vegetation to at first unseasonally warm, followed by much colder ambient temperatures which vegetation was exposed to due to the lack of snow cover. A large decline (26%) in NDVI (normalized difference vegetation index) was observed due to this event between the summers of 2007 and

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2008 (Bokhorst et al., 2009). The normalized difference vegetation index is a remotely sensed index of the vegetation and provides an indication of amount plant biomass, as such the observed NDVI decline suggests a significant impact on ecosystem structure and function, including primary production and a reduction in carbon sink capacity for the landscape (Street et al., 2007). This NDVI decline was associated with considerable shoot mortality of dwarf shrubs (notably *Empetrum nigrum* L.) as similar mortality was found under experimental simulations of extreme winter warming events (Bokhorst et al., 2009). The experimental simulations showed that a week-long warming event was enough to generate spring-like development in dwarf shrubs making the plants more susceptible to the following cold (Ögren, 1996; Taulavuori et al., 2004; Augspurger, 2009; Bokhorst et al., 2010a). The expected increase in frequency of such damage has relevance for vegetation development in the Arctic region as these events reduce the 'greening of the Arctic' effect resulting from gradual summer warming (Myneni et al., 1997; Jia et al., 2003; Tape et al., 2006). It currently remains unknown the extent to which the vegetation damage and NDVI decline will recover and what the rate and direction of community development during any recovery will be.

Aside from the long-term vegetation dynamics in the Arctic region there are considerable short-term impacts associated with the effects of extreme winter warming events on ecosystem services, particularly for indigenous people who depend on the sub-Arctic for their livelihood (Riseth et al., 2010). Winter foraging for reindeer can be negatively affected by extreme winter weather events (Lee et al., 2000; Aanes et al., 2002; Roturier and Roue, 2009) potentially threatening the survival of reindeer populations (Putkonen and Roe, 2003). The observed reduction in berry production, following a single winter warming event (Bokhorst et al., 2008), can affect food availability for rodents and bears (Dahle et al., 1998; Dahlgren et al., 2007) and commercial harvesting (Wallenius, 1999) and also impact game hunting as most game birds use dwarf shrub leaves and berries as a staple diet (Myrberget, 1979; Spidsö, 1980; Stokkan and Steen, 1980).

With this study, we aimed to determine for how long vegetation damage would remain, measured through regional NDVI values, following the natural winter warming event of 2007. In addition, we wanted to elucidate whether the observed NDVI decline was solely caused by the increase in dead *E. nigrum* shoots (i.e., reducing high NDVI values; green leaves, and increasing lower ones; litter) or if species-specific leaf NDVI levels were affected. We therefore further examined the impact of the winter warming events on the ground by measuring NDVI values at plot and leaf levels. This was done in the plots that were associated with the natural event damage (Bokhorst et al., 2009) and in the experimental plots where extreme winter warming events were run for three consecutive years (Bokhorst et al., 2011). Given the generally slow growth and recovery in this sub-Arctic ecosystem (Callaghan and Emanuelsson, 1985; Callaghan and Karlsson, 1996; Aerts, 2010), we hypothesized that regional and plot level NDVI values would not return to pre-event values within this short time span. We further hypothesized that NDVI values at plot and species levels were reduced in the experimental plots.

Species composition is an important factor for local NDVI values (Riedel et al., 2005), suggesting that the sum of the individual components (i.e., species and their abundance) should reflect the average NDVI. This hypothesis was tested by reconstructing plot NDVI from species-specific leaf NDVI and their relative abundance and comparing those to plot values. Further correlations from leaf level NDVI to plot (m) and regional (km) levels were made to determine if a quick-and-easy species level approach would provide additional information on the measured NDVI through remote sensing.

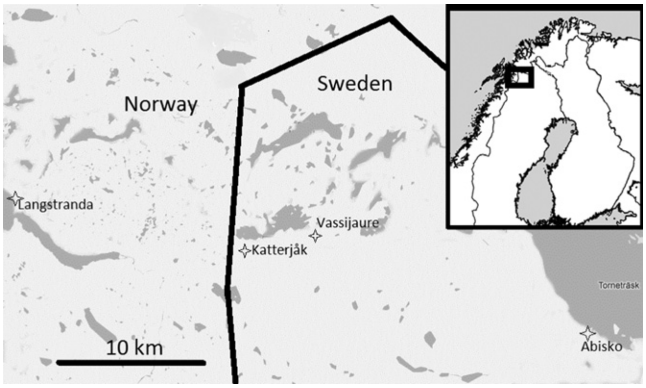

Fig. 1. Study area in northern Scandinavia. The local NDVI values for Vassijaure, Katterjåk and Langstranda were obtained through MODIS while at these respective sites plot NDVI values were obtained using a multispectral camera (Maxmax). The experimental plots, exposed to extreme winter warming event manipulations, were near the Abisko Scientific Research Station where plot and leaf NDVI values were obtained in the field using multispectral cameras (ADC and Maxmax).

2. Materials and methods

2.1. Regional NDVI

Our study area for satellite-derived (i.e., regional) NDVI measurements is a 1425 km^2 large area in northern Scandinavia ranging from Abisko in northern Sweden (68°21′N, 18°49′E) westwards to Narvik (68°25′N, 17°33′E) on the Norwegian coast (Fig. 1). This area was severely affected by a winter warming event in 2007–2008, which led to a 26% decline in NDVI (Bokhorst et al., 2009). The study region is dominated by sub-Arctic dwarf shrub heathland, birch forest, alpine meadow and mire (see Bokhorst et al., 2009 for details). The mean leaf area indices (LAI) for birch forests, snow-protected heaths and wind-exposed heaths in the study area were estimated to 2.06, 0.52 and 0.09, respectively, meaning that the vegetation is not dense (Dahlberg et al., 2004). Although this region includes different vegetation types, dwarf shrub heathland is the major component of this region and therefore, the focus of our work lies on this vegetation type and its components. Since satellite data with high spatial resolution (SPOT, IRS-P6 and Landsat TM/ETM+) do not exist for the peak summer season annually due to extensive cloud cover (Karlsen et al., 2008), regional NDVI values were acquired using NDVI data covering periods of 16 days (centred on mid-July) from the MODerate-resolution Imaging Spectroradiometer (MODIS) sensors on NASA's Terra satellites for 2006–2010 (the MOD3A1 and MOD13Q1 products (Huete et al., 2002)). The 16-day NDVI data product was found to be the most optimal product in this part of the world under conditions of frequent cloudy weather during summer (Karlsen et al., 2008). The MODIS imagery covering the study area consists of 6642 pixels. NDVI was calculated as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} - \mathrm{RED}}$$

with the reflectance values of NIR (near-infrared 0.73–1.10 mm) and RED (red 0.58–0.68 mm). NDVI measurements made by SPOT-5, Landsat-5 TM, Landsat-7 ETM+ and IRSPS6 LISS-3 in July 2007 and 2008, respectively, were consistent with the MODIS-based measurements supporting the validity of the latter (Bokhorst et al., 2009). For example Landsat 7 ETM+ showed a significant reduction of NDVI for the alpine heathland in Katterjåk from 0.39 ± 0.14 in July 2007 to 0.05 ± 0.16 in July 2008 and back to 0.43 ± 0.10 in 2009. The same area for Katterjåk based on MODIS was 0.70 ± 0.01 in 2007, 0.54 ± 0.03 in 2008 and 0.65 ± 0.03, respectively. Using the Landsat image from July 2008 for the accuracy assessment for 20