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The recent northward expansion of *Lymantria monacha* in relation to realised changes in temperatures of different seasons

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ABSTRACT

The northern regions are warming more rapidly than the global mean. This may cause problems in boreal forests if pest insects expand their ranges north. In Finland, the Nun moth (*Lymantria monacha* (Linnaeus)) is a potential forest defoliator that has earlier occurred sparsely along the southern coast of the country, but that might become a significant pest as it is in Central Europe. In this study we describe the changes in distribution and abundance of *L. monacha* in Finland, analyze these in relation to changing climate, and discuss management implications for the situation of a potentially serious pest expanding its range rapidly to new areas.

We used data from two long-term databases, the open access Insect Database (1960–2013), and Nocturna (1993–2013), the national monitoring scheme for night-flying moths. A trend of rising *L. monacha* abundances in Southern Finland since the 1990s was discernible in both datasets. Furthermore we found that the species has expanded its range from the southern coast northwards to approx. 63 °N, i.e. about 200 km, during two decades.

To compare the development of the *L. monacha* population with climatic variables we calculated three temperature parameters, EminT – the minimum temperature during the egg stage of *L. monacha* in winter, LT – the average temperature for the larval stage, and PAT – the average temperature for the pupal and adult stage. Model selection methods using information criteria ranked highest models where *L. monacha* abundance was related to EminT and PAT. This indicates that the recent success of *L. monacha* in Finland may be related to higher winter survival of eggs or improved dispersal and reproduction success of adult moths. The experimentally confirmed median freezing temperature of *L. monacha* eggs is −29.5 °C. Minimum winter temperatures on the southwestern coast of Finland have not dropped below this lethal limit since 1987. This corresponds temporally well the *L. monacha* upswing starting in the 1990s. Furthermore, it was notable that the temperature during the larval period (May – June) did not increase during the last decades, which suggests that high early summer temperatures have not been necessary for the northward expansion of *L. monacha*.

L. monacha is a major pest in coniferous forests in Central Europe, and may become a threat throughout its expanded range. We outline a multilevel monitoring programme that has proven efficient in *L. monacha* outbreak areas, and advocate risk reduction through forest conversion to mixed and ecologically stable stands.

1. Introduction

Poleward range shifts due to climate change have been observed in numerous organisms worldwide, with changes being particularly pronounced at high latitudes (Chen et al., 2011; Parmesan, 2006; Pöyry et al., 2009). Especially range expansion of potential pest species has

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raised much concern, unfortunately not without foundation: invasive pests have been repeatedly reported to cause great environmental and economic losses (Lodge, 1993; Pimentel et al., 2000). However, there are few documented examples of range expansions of forest pests where the actual role of climate change is well understood (Battisti and Larsson, 2015).

Several research papers address problems created by alien invasive insect pests (e.g. Lowe et al., 2000; McNeely, 2001; Vitousek et al., 1997), but there are much fewer studies documenting the northward range shifts of "native" insect pests. A noteworthy exception is the northward spread of Pine processionary moth (*Thaumatopoea pityocampa*), which is attributed to increasing winter temperatures and hence feeding and food digestion of overwintering larvae (eg. Battisti et al., 2005; Battisti and Larsson 2015; Netherer and Schopf, 2010).

Finland is a northern country with 72% of the area covered by forests. Two conifer species account for the majority of the forest resources: Scots pine (*Pinus sylvesrtris* L.) (50%) and Norway spruce (*Picea abies* (L.) H. Karsten) (30%). Modeling studies have revealed that the growth of these species generally increases in a warming climate (Briceño-Elizondo et al., 2006), although spruce may suffer from prolonged drought periods, especially in southern Finland (Ge et al., 2013; Kellomäki et al., 2008; Zubizarreta-Gerendiain et al., 2016). However, none of these models consider the potential effects of possibly increasing biotic damage (Niemelä et al., 2001).

While pine forests in Finland have suffered from defoliation by pine sawflies, defoliation of spruce by insects has been rare (Christiansen, 1970; Harding et al., 1998; Neuvonen and Viiri, 2017; Nevalainen et al., 2010, 2015). However, this situation may, however, change due to the northward advance of a serious pest of conifers, the Nun moth (*Lymantria monacha* (Linnaeus), Erebidae: Lymantriinae, also known as Black arches) (Karolewski et al., 2007; Vanhanen et al., 2007; Vapaavuori et al., 2010).

Until recently, *L. monacha* has not received much attention in Finland. The species has mainly occurred locally in the southernmost areas in low densities or as occasional vagrants from adjacent regions, and has not been considered a pest yet (Marttila et al., 1996). During the past few years it has, however, spread northwards (Leinonen et al., 2016), and together with other insect pests contributed to significant defoliation on at least two islands in the southwestern archipelago of Finland (Heino and Pouttu, 2014; Jaakko Kullberg, personal communication) and on islands of western Estonia (Nilson et al., 2014; Õunap, 2012; Voolma et al., 2014). In southern Sweden *L. monacha* is an established pest species with historical records of sporadic outbreaks since late 19th century (Hydén et al., 2006).

Understanding the impacts of climatic change on different life stages of insects is necessary for developing better mechanistic models for predicting the speed and extent of range shifts of forest pests (Kingsolver et al., 2011; Neuvonen and Virtanen, 2015). This study aims at increasing this knowledge by: (a) describing a recent range expansion and population increase of *L. monacha* in Finland using two different entomological datasets ranging from 1961 to 2013, (b) analyzing moth data together with temperature data to reveal possible relationships between climatic variables and *L. monacha* populations, and (c) using model selection methods based on information criteria to determine which seasonal temperatures best explain *L. monacha* abundance the best. Furthermore, we also discuss management implications of increased forest damage risks associated with the northward spread of *L. monacha*.

2. Materials and methods

2.1. The study system

Lymantria monacha occurs in temperate forests in most parts of Europe and Asia. It frequently reaches outbreak densities in southern and central Europe, although without regular cycles (Bejer, 1988). It is a medium sized, polyphagous, and univoltine moth that overwinters as small, fully developed larvae diapausing in eggs (Bejer, 1988; Majunke et al., 2004). The egg stage lasts from late summer to the following spring, followed by the larval stage, which normally occurs during May – June in Finland. Early-instar larvae of *L. monacha* are capable of ballooning, i.e. using thin silk strands to float with the airflow to a new location (Bejer, 1988). However, this form of short-distance dispersal is unlikely to have any large effects on the distribution range of the species. The duration of the pupal stage (July) is short, and the adults fly mainly in August (Huldén et al., 2000; Marttila et al., 1996).

From the end of the 1960s onwards, mean daily temperatures in Finland have increased on average by about 0.3 °C per decade (Aalto et al., 2016; Finnish Meteorological Institute 2016). The warming has not been seasonally even. Winter temperatures have increased most. Spring (March–May) temperatures have also increased more than the annual average, however, during the summer months the increase has been below average (Mikkonen et al., 2015).

2.2. Observations of Lymantria monacha abundance and distribution

To create reliable models and predictions for the future range of an organism, it is crucial that the current distribution of a species is accurately known, preferably from multiple sources (Björklund et al., 2016). We used occurrence data from both a public open database – the Insect Database – and one systematic monitoring scheme, Nocturna.

2.2.1. Insect database

Observations of Finnish Lepidoptera have been compiled into the Insect Database ("Hyönteistietokanta"), maintained by *Luomus*, the Finnish Museum of Natural History at the University of Helsinki (Insect Database, 2017). We extracted observations of *L. monacha* as well as other lymantriins, erebids and noctuids from the database on 23 January 2014. These observations include, at the very least, the following details: species, date (or collecting period), biogeographic province (Heikinheimo and Raatikainen, 1971), and coordinates in the Finnish national grid system (YKJ) (Heikinheimo and Raatikainen, 1981).

Typical for this kind of observational data is the variation (both temporal and spatial) in observation and reporting intensity. We aimed at reducing or controlling for these potential biases by:

- Focusing on the period from 1961 onwards. The most efficient method for catching night-flying moths, i.e. light-trapping, was introduced into Finland around 1950, and it was well established among Finnish lepidopterologists ten years later (Mikkola, 1997).
- When analyzing temporal changes in *L. monacha* abundance we restricted our analyses to the three southernmost biogeographical provinces (Regio Aboënsis, Ab; Nylandia, N; Karelia australis, Ka) in continental Finland (see Heikinheimo and Raatikainen, 1971), these provinces with the highest human population density in Finland. The archipelago province Åland (Al, Alandia) was excluded because light-trapping has been restricted there (Somerma, 1994).

We used 2-tailed Pearson's correlation tests in IBM SPSS Statistics 23 to describe temporal trends in *L. monacha* abundance. Further, we analyzed changes in the northern distribution limit of the species, using observation data from the entire continental Finland. For comparison we extracted Swedish species observations data of *L. monacha* from ArtPortalen, a species observation database maintained by ArtDatabanken, Swedish Agricultural University, in February 2014. As the geographical coordinates of species observations in ArtPortalen are given using the WGS84 coordinate system, we transformed the Finnish data from the Insect Database to match this coordinate system.

We calculated the northern distribution limit of *L. monacha*, separately for Finland (Insect Database, 2017), and Sweden (ArtPortalen, 2017), for five-year periods covering the years 1961–2013 (the length of the first and last periods was only four years). The limit was defined