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Potential climate-induced distributions of *Lophodermium* needle cast across central Siberia in the 21 century

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Abstract. Needle cast caused by fungi of the genus *Lophodermium* Chevall. is a common disease in pine trees in Siberia. Regression analyses relating needle cast events to climatic variables in 1997–2010 showed that the disease depended most on precipitation of two successive years. Temperature conditions were important to trigger the disease in wetter years. We used our regional bioclimatic envelope model and IPCC scenarios to model the needle cast distribution and its outbreaks in the 21st century. In a warming climate, the needle cast range would shift northwards. By 2020, needle cast outbreaks would already have damaged the largest forest areas. But outbreak areas would decrease by 2080 because the ranges of modeled pathogen and Scots pine, the disease host, would separate: the host tree progression would be halted by the slower permafrost retreat, which would in turn halt the potential pathogen progression.

1 Introduction

Monitoring of the Russian boreal forest revealed the largest pathogen-damaged area to occur in Siberia, and this area was found to be equivalent to 34.4 % of all dead forests in Russia (Filipchuk and Deryugin, 2008). Needle cast caused by fungi of the genus *Lophodermium* Chevall. is a common disease in the genus *Pinus*. Projected climate change and weather extremes in the 21st century would shift the pathogen ranges to regions where the trees may not be adapted to these new pathogens, and global trade would promote the propagation of invasive pests and pathogens to the interior boreal forests (Gauthier et al., 2015). Our goals were (1) to analyze the relationships between needle cast and climate variables using regression analysis and (2) to construct an envelope bioclimatic model for needle cast, as well as to identify its ranges and outbreaks in central Siberia (53–75° N and 85–105° E) from the baseline (1960–1990) to the future (2020 and 2080) climates by applying the HadCM3 B1 and A2 climate change projections.

2 Materials and methods

Climate and weather provoke a rise in and further a development of tree diseases and determine their bioclimatic ranges. The relationships between the *Lophodermium* needle cast of *Pinus sylvestris* L. and climate variables were analyzed using multiple regression statistics. Needle cast data were collected during 1997–2010 from Scots pine nurseries, provenance trials, and forests across 38 forest management units within 53–60° N in central Siberia. Scots pine is of local forestry interest and is a dominant forest-forming tree species across the plains at midlatitudes. All needle cast events that were registered during 1997–2010 equalled 93. The disease degree was identified in points as follows: first degree – needle damage was <10 % (one point); second degree – 11–25 % (two points); third degree – 26–50 % (three points); and fourth degree (an outbreak) – >50 % (four points). We used two indices to characterize the disease degree in our analyses: (1) one index was a direct estimate of the disease in points from one to four at each forest unit in each year (93 cases); (2) another was a normalized index (%), a ratio of the sum of all disease points which occurred in the study area each year to the maximal sum of points that could occur (4 points $\times$ 38 forest units $=$ 152 points). This index indicated the average picture of the disease across the entire study area in each of the 14 years of the study.

Climate data were collected for the baseline period 1960–1990 and 1997–2010 from reference books on the climate

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of the Krasnoyarsk territory. Three climatic variables were used in the analyses to characterize summer and winter thermal conditions: July, T_7, and January, T_1, temperatures, and annual precipitation (R). A moisture index (MI) – that is, a ratio of T_7 to R – was used to characterize the dryness of the climate. The July temperature is highly correlated to growing degree days, base 5 °C ($R^2 = 0.96$), and may characterize the entire growing season thermal conditions.

We used two climate change scenarios, the HadCM3 A2 and B1, of the Hadley Centre in the UK (www.ipcc-data.org) to characterize the climate at 2020 and 2080. These scenarios represent the highest (A2) and the lowest (B1) projected temperature increases by 2080.

Our regional bioclimatic envelope model of the *Lophodermium* needle cast represented the climatic borders of the disease and its outbreak distributions. To depict these borders, 93 needle cast events in 1997–2010 were ordinated in the climatic space of two pairs of axes: (T_1 and T_7) and (T_7 and MI). Based on pairing these borders with climatic layers in 1960–1990, 2020, and 2080, maps of geographic distributions of the disease and its outbreaks were produced in current and future climates. Comparison of the modeled pathogen map with a real pathogen map (Kuzmina et al., 2014) using the kappa statistics (Monserud and Leemans, 1992) showed that the match between the maps was good (K = 0.54), indicating a high degree of reliability for our model.

3 Results and discussion

Among all needle cast events, 15.4 % were caused by *L. seditiosum*, 1.5 % by *L. conigenum*, and 83.1 % by *L. pinastri*. The maximum number of needle cast events were found in the 2000–2003 and 2008–2010 periods, indicating an increasing trend of disease growth over time (Kuzmina et al., 2014).

A plant disease is a complex process involving many factors favoring the massive reproduction and accumulation of infection and then its spreading to new locations (Krutov, 1989). We found that the more often the disease repeated in a site (> 7 needle cast events), the more severe the disease outbreaks were ($R^2 = 0.5$, $p < 0.1$).

The correlation between needle cast and 2-year rainfall anomalies, averaged over the study area for each year, was the largest ($r = 0.64$, $p < 0.05$, Table 1). The lesser, but significant, correlation ($r = 0.30$, $p < 0.01$, Table 2) was found between needle cast events and July temperature anomalies expressed at each forest unit for each year.

Our analysis of weather conditions found that outbreaks occurred in moister-than-average years. Furthermore, outbreaks were most likely to occur in moist years with warmer-than-average summer (July) temperatures, especially in the moist and warm summers of 2005–2010. Correspondingly, a minimum number of disease events occurred in years that were both cooler and drier than average. In addition, low numbers of outbreaks also occurred (1997–2004) when the departures from average of the temperature and precipitation did not match in sign (positive/negative) for each year. Thus, the disease probability was likely driven by warmer-than-average temperatures on the background of sufficient moisture.

Table 1. Correlation coefficients ($^* p < 0.05$, $^{**} p < 0.2$) between the normalized index of needle cast and climate anomalies (Δ) averaged over the study area in each year.

Climate variable			
Δ January temperature	Δ July temperature	Δ Rainfall for current year	Δ Rainfall for two successive years
−0.04	0.14	0.35**	0.64*

Table 2. Correlation coefficients ($^* p < 0.01$) between the direct index of needle cast and climate anomalies (Δ) estimated in each year at each forest unit.

Climate variable			
Δ January temperature	Δ July temperature	Δ Rainfall for current year	Δ Rainfall for two successive years
0.01	0.30*	0.15	0.14

Lophodermium needle cast also damages Siberian pine (*Pinus sibirica* Du Tour). In a warming future climate, this pathogen may harm extensive Siberian pine forests that occupy the moist windward slopes in the Altai-Sayan mountains south of 53° N bordering our study area.

The bioclimatic model of needle cast predicted its potential distributions and outbreaks when paired with current climate and climate change projections of HadCM3 B1 and A2 at 2020 and 2080 across central Siberia (Fig. 1, upper). The needle cast range would shift northwards in a warming climate to regions where the disease had not yet been registered. In both 2020 B1 and A2 climates, there was prediction of the largest areas of needle cast range and outbreaks. In the 2080 climate, the potential range of needle cast would shift far north up to 70° N, but the realized range of outbreaks (Fig. 1, middle) would be limited by the Scots pine range (Fig. 1, lower, Tchebakova and Parfenova, 2012), the major host of needle cast, which in turn would be limited by the slow permafrost retreat.

4 Conclusions

By the end of the century, under climate warming and extreme weather, pathogen invasions may shift to new regions where they have not previously been registered. The climatic factors of the rainfall of previous and current years and the July temperature explained 40 and 10 % of the variation of needle cast occurrence, respectively. Accumulated infection at a site explained about 50 % of the variation. Other fac-

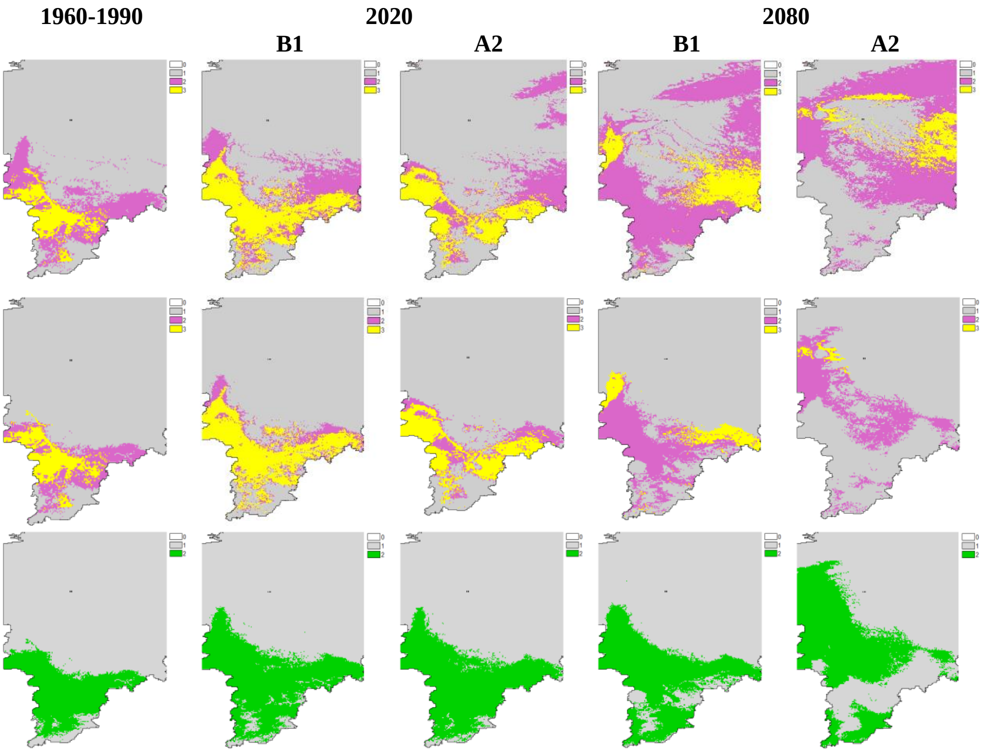

Figure 1. Potential (upper) and realized (corrected with regard of the *Pinus sylvestris* range, middle) ranges of *Lophodermium* needle cast and the *Pinus sylvestris* range (Tchebakova and Parfenova, 2012, lower) in the baseline 1960–1990 and HadCM3 B1 and A2 warmed climates at 2020 and 2080. 1 – no needle cast; 2 + 3 – needle cast range; 3 – needle cast outbreak.

tors not considered in the study (genetics, soils, phytosociology, etc.) explained 10–40 % of the variation. Predictions of the largest areas of needle cast range and outbreaks were in the near 2020 B1 climate. The realized disease outbreak (high needle damage > 50 %) area would decrease by 2080 because the Scots pine (the host) range would be limited by the slower permafrost retreat. Thus, this finding may be considered as a positive outcome of climate change. Moreover, predicted drier climates at 2080 would not favor needle cast outbreaks either. However areas with lesser needle damage (< 50 %) would be noteworthy.

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