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Sanitary felling of Norway spruce due to spruce bark beetles in Slovenia: A model and projections for various climate change scenarios

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ABSTRACT

A model is presented to predict sanitary felling of Norway spruce (*Picea abies*) due to spruce bark beetles (*Ips typographus*, *Pityogenes chalcographus*) in Slovenia according to different climate change scenarios. The model incorporates 21 variables that are directly or indirectly related to the dependent variable, and that can be arranged into five groups: climate, forest, landscape, topography, and soil. The soil properties are represented by 8 variables, 4 variables define the topography, 4 describe the climate, 4 define the landscape, and one additional variable provides the quantity of Norway spruce present in the model cell. The model was developed using the M5′ model tree. The basic spatial unit of the model is 1 km^2, and the time resolution is 1 year. The model evaluation was performed by three different measures: (1) the correlation coefficient (51.9%), (2) the Theil's inequality coefficient (0.49) and (3) the modelling efficiency (0.32). Validation of the model was carried out by 10-fold cross-validation. The model tree consists of 28 linear models, and model was calculated for three different climate change scenarios extending over a period until 2100, in 10-year intervals. The model is valid for the entire area of Slovenia; however, climate change projections were made only for the Maribor region (596 km^2). The model assumes that relationships among the incorporated factors will remain unchanged under climate change, and the influence of humans was not taken into account. The structure of the model reveals the great importance of landscape variables, which proved to be positively correlated with the dependent variable. Variables that describe the water regime in the model cell were also highly correlated with the dependent variable, with evapotranspiration and parent material being of particular importance. The results of the model support the hypothesis that bark beetles do greater damage to Norway spruce artificially planted out of its native range in Slovenia, i.e., lowlands and soils rich in N, P, and K. The model calculation for climate change scenarios in the Maribor region shows an increase in sanitary felling of Norway spruce due to spruce bark beetles, for all scenarios. The model provides a path towards better understanding of the complex ecological interactions involved in bark beetle outbreaks. Potential application of the results in forest management and planning is discussed.

1. Introduction

Some species of spruce bark beetles (e.g., *Ips typographus* L. and *Pityogenes chalcographus* L.) can break out under favourable ecological and trophic conditions. The outbreaks of spruce bark beetles can have devastating consequences on forests. This has been confirmed by data regarding the sanitary felling of conifers in Slovenia during the period from 1995 to 2006. In 2005, for example, around 747,000 m^3 of wood were felled due to bark beetles, which is 22.9% of the total felled wood, or 9.9% of the total yield in Slovenia (ZGS, 2006). Such episodes allow us to define spruce bark beetles according to the classification of disturbance described by Anko (1993), as a complex, natural, and chronic disturbance (sometimes even as an acute disturbance). A natural disturbance of the forest ecosystem means a swing between succession and dynamic equilibrium (Anko, 1993). In light of climate change, spruce bark beetles can be treated as a disturbance that affects the dynamics of the forest ecosystem, and also as a factor that is affected by such climate changes (Berryman, 1986; Malström and Raffa, 2000).

Studies have shown that the behaviour of spruce bark beetles will likely change due to climate change. For example, researchers are expecting a drastic increase in damages caused by *Ips typographus* in Scandinavia over the next decade, because higher temperatures will allow this species to produce two complete generations per year instead of the single generation they currently produce (Lange et al., 2006). In Slovenia, *I. typographus* reproduction is developing towards two complete and one sister generation per year (Jurc, 2008). In Scandinavia, the border for sur-

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vival of *I. typographus* may move 600 km north (Lange et al., 2006). Apart from these changes in the speed of bark beetle development, changes in the resistance of Norway spruce (*Picea abies* (L.) Karst.), and consequently in the physiological interaction between the Norway spruce and this pest, are also expected (e.g., Berryman, 1986; Rolland and Lempérière, 2004; Wermelinger, 2004). Another likely consequence of climate change is a probable shift in the geographical distribution of the Norway spruce and its pests (e.g., Williams and Liebhold, 2002; Lange et al., 2006). Consequently, there will also be a change in the intensity of damages caused by such pests.

The dynamics of spruce bark beetles is a complex phenomenon. Risk evaluation at the individual tree level due to *I. typographus* is usually connected to exposure, age, trophic capacity, and water. The dynamics of *I. typographus* outbreaks are generally dependent on population density, tree susceptibility, weather conditions, and human activities. Outbreaks are difficult to predict due to the complexity of their dynamics (Wermelinger, 2004). A model for short-term forecasting of the numbers of spruce bark beetles was created for the Dinaric Mountains region in Slovenia (Jurc et al., 2006). The model was developed using linear regression and model tree induction. The model calculates the number of spruce bark beetles for next month or week based on the known exposition, age of pheromones in traps, number of days since the bark beetles in traps were last counted, average monthly temperature, monthly rainfall, month of the year, and previous number of bark beetles in the trap. A similar model was developed for the Alps in Italy (Faccoli and Stergulc, 2006). This model can forecast short-term trends in the *I. typographus* population density for the next year and, consequently, can evaluate the risk of an outbreak. The model relies on the rules determined using data obtained from bark beetles caught in pheromone traps during the period from 1996 to 2004. A comparison of the models for Slovenia and Italy shows that both models use number of bark beetles caught in traps as the input for the model; however, there are several differences in methods and time scale of the models predictions. The model for Slovenia was developed using induction of decision trees and the model for Italy is based on two different indexes. The model for Slovenia predicts the abundance of *I. typographus* and *P. chalcographus* for next week or month which depends on frequency of beetle counting caught in traps. But the model for Italy can predict the abundance of *I. typographus* for the following year.

Long-term predictions of damage due to spruce bark beetles and the influence of climate change in Slovenia have not yet been carried out. Due to the complex population dynamics of bark beetles, even short-term predictions are difficult. Therefore, we justifiably expect lower reliability of long-term, compared to short-term, forecasts.

In the present paper, we present a model designed to predict potential sanitary felling of Norway spruce due to bark beetles attack in Slovenia under various climate change scenarios. This model can be defined within the class of correlation models (Malström and Raffa, 2000). The correlation model attempts to determine the causes and consequences of bark beetle outbreaks over a large area, with the help of research on the relationships between variables describing the environment and the intensity of damage caused by bark beetles. An example correlation model is found in Williams and Liebhold (2002). Their model examines potential shifts in outbreaks of the southern pine beetle (*Dendroctonus frontalis* Zimm. and *D. ponderosae* Hopk.) in North America due to climate change. They used a discriminant function model, which includes climate variables, forest type groups, and damage due to southern pine beetles. When making predictions using the climate change model, they considered changes in the range of the forest and changes in climatic variables. This procedure can yield important results, but such results are still based on the assumption that the relationships between variables do not change under the new conditions which are conditioned by climate change. This assumption, and the limitations it imposes, also applies to the model described in this paper.

2. Methods

2.1. Model

2.1.1. Purpose of the model and definition of the system

The purpose of the model was to predict the potential sanitary felling of Norway spruce due to bark beetles under various climate change scenarios in Slovenia. The spatial framework was the entire territory of Slovenia, with a resolution of 1 km^2. There were 20,376 model cells, and the time resolution was 1 year. The model was developed using a M5′ model tree. The M5′ algorithm builds tree-based models with top-down induction of decision trees where the leaf is represented by multivariate linear model. The original algorithm M5 was developed by Quinlan (1992), Wang and Witten (1997) made improvements and created M5′. The model described in this paper was developed using Weka 3.4 software (Witten and Frank, 2005) where the M5′ parameters were set to default values (minNumInstances = 4, unpruned = false, useUnsmoothed = false), except where described otherwise in the text.

2.1.2. Variables

Sanitary felling in Slovenia is recorded by the Slovenian Forestry Service (SFS) in 11 causal classes: insects, disease, game, wind, snow, ice, landslides, fire, pollution, harvesting, and other (TIMBER, 2007). In addition to the cause, other data is also recorded: location (at the level of the smallest forest unit), tree species, number of trees, volume of trees, and the 5-cm thickness class of the trees. The TIMBER database has been available for the entire area of Slovenia since 1995.

The average yearly sanitary felling of Norway spruce due to bark beetles was the dependent variable in the model. The learning datasets for the dependent variable encompassed the period spanning 1995–2006. The data source for the dependent variable was the database on the felling of trees in Slovenia (TIMBER, 2007), which is run by the SFS. The dependent variable was measured in cubic meters.

The structure of the model developed herein provides greater insight regarding the effects of bark beetle outbreaks. The structure of the model itself confirms important known factors, assesses how the multiple factors interact, and calculates definitive values for these factors, which influence bark beetle outbreaks. The ecology of spruce bark beetles has been well studied (e.g., Dutilleul et al., 2000; Wermelinger, 2004). Based on the results of these studies, we included a number of variables in the model that influence the ecology of bark beetles and for which data was both available and of sufficiently high quality.

The M5′ algorithm included 45 independent variables, which can be divided into 5 groups: those describing the climate, the soil, the forest, the topography, and the landscape (Table 1). In the model cell, 7 variables describe the climate, 25 variables describe the soil, 3 variables describe the forest, 5 variables describe characteristics of the topography, and 5 variables describe the landscape. During the learning process, the algorithm M5′ selects the variables that best describe the variability of the dependent variable. Therefore, the model used to predict the sanitary felling of Norway spruce due to bark beetles includes 21 out of the 45 variables provided. Of these 21 variables, the majority concern the soil (8), 4 deal with the topography, 4 describe the climate, 4 describe the landscape, and 1 describes the forest (Table 1).

Descriptions of the variables and their data sources are given in Table 1. Summary statistics for the variables are provided in Table 2. The quality of the variables is defined by ReliefF, which is provided