SCIENCE

Potential risk of occurrence of Phytophthora alni in forests of the Czech Republic
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ABSTRACT
Phytophthora alni is an invasive organism that causes root and collar rot in alders, which significantly damages the forest and riparian vegetation of alder trees in Central and Western Europe. In the Czech Republic, this pathogen was first confirmed in 2001, and since then it has been gradually spreading from the west to the east. Here, we applied a model of potential distribution that estimates the level and spatial variability of the pathogen occurrence and spread risk for Czech Republic forests to target the early detection and control the further invasion of \textit{P. alni} in this region. Our predictions are based on a rigorous statistical analysis of data obtained from field survey as well as available geodatabases. We used two sets of predictor variables describing (i) the forest stands and (ii) neighbourhood of the stands, and generalized linear modelling with forward stepwise selection of predictors. The results of statistical analysis showed the significant effect of the area of the forest stand, forest vegetation zone, presence of watercourse and area of alder stands in the neighbourhood on the probability of occurrence of \textit{P. alni} in the study region. The map derived based on the final model shows the potential risk of occurrence and impact of \textit{P. alni} in forests of the Czech Republic as classified on a five-point scale ranging from very low risk for alder stands with a low level of likely invasion to very sensitive alder stands with high probability of pathogen occurrence and high levels of damage. This is a unique output not only for the Czech Republic but also throughout Europe.

1. Introduction

The introduction and subsequent invasion of non-native pathogens of woody plants represent a global challenge for nature and landscape protection, sustainable forestry, rural economics and landscape management (Pautasso, 2013). Moreover, the problem of invasion is increasing in importance due to the emphasis on economic growth, intensification of land use and urbanization, on-going climate change and other phenomena (Anderson, Cunningham, Patel, Epstein, & Daszak, 2004; Brasier, 2008; Desprez-Loustau et al., 2010, 2015; Garbelotto & Pautasso, 2012; Pautasso, 2013; Picco et al., 2011; Stenlid, Oliva, Boberg, & Hopkins, 2011).

Invasive pathogens are becoming a common part of forests and other ecosystems in the Czech Republic (Černý, Strnadová, Fedusiv et al., 2015). The most significant, considered the so-called transformers (Richardson et al., 2000), include \textit{Ophiostoma novo-ulmi} Brasier, \textit{Hymenoscyphus fraxineus} Kowalski, Baral, Queloz, Hosoya and \textit{Phytophthora alni} Brasier and S.A. Kirk (Černý, Strnadová, Fedusiv et al., 2015). The latter is a hydroid-genous organism that causes root and collar rot in alders, which significantly damages the forest and riparian vegetation of alder trees in Central and Western Europe. The pathogen was first confirmed in the Czech Republic in 2001 (Černy et al., 2008). It is especially abundant in the western part of the Czech Republic and is gradually spreading to the east. The pathogen is becoming a permanent component of ecosystems with the presence of alders (mainly alder swamp woods, mixed ash-alder forests, grey alder galleries and riparian vegetation), causing considerable economic damage (Černý & Strnadová, 2010; Černý, Strnadová, Fedusiv et al., 2015).

Given the crucial importance of \textit{P. alni} and other invasive pathogens of woody plants, it is necessary to pay close attention to their dispersal in the landscape and its relationship to environmental conditions (Edmonds, 2013). Modelling of the potential occurrence of the pathogen is an important tool for the management and minimization of its impact (Václavík & Meentemeyer, 2009). Spatial prediction is based on a complex assessment of the relationship between the occurrence of the species and characteristics of the environment in which they occur. When the relationship is found, the probability of occurrence is extrapolated for the whole landscape using the same environmental variables (Elith & Leathwick, 2009; Guisan & Zimmermann, 2000).

The aims of this map were to specify the risk resulting from the invasion of the alien pathogen \textit{P. alni} in forest alder stands in the Czech Republic and to

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identify the areas and stands with high invasion and damage potential (see the Main Map). The map can be used by forest and water authorities and nature conservationists to adjust management approaches appropriately (Cerný & Strnadová, 2011), reduce the risk of pathogen introduction, and predict the possible future degradation of forest ecosystems.

2. Methods

Modelling of the potential occurrence and risk of damage caused by P. alni consisted of several phases. First, a field survey was carried out to determine the occurrence of the pathogen in forests. This included the detection of the presence of typical symptoms of the disease, the rate of forest infestation and description of basic silvicultural characteristics that are assumed to play an important role in the establishment and spread of the pathogen. The data were obtained in cooperation with State Forest of the Czech Republic from a total of 854 alder stands throughout heterogeneous habitat conditions in the Czech Republic. A spatial database of all alder stands in the Czech Republic containing about 191,000 individual polygons was then developed. The database contained two sets of variables derived for each stand using a geographical information system (GIS): (i) variables characterizing the alder stand, its topography and climate conditions (Table 1) and (ii) variables describing landscape, topography and climate conditions in the neighbourhood of the forest stand (Table 2). To examine all factors possibly influencing the spatial distribution of invasion of P. alni, these two spatial levels were considered because the occurrence and spread of the pathogen was assumed to be influenced not only by the characteristics of the stand and its environmental conditions but also by factors of the neighbourhood.

The factors of the wider environment of the forest stand are important for the spread of the pathogen. A buffer zone 500 m wide was created around each stand and used in the analyses of the neighbourhood level.

The effect of the characteristics describing the forest stands (Table 1) and their neighbourhood (Table 2) on the occurrence of P. alni was analysed using generalized linear modelling (GLM) with a binomial distribution of the response variable and Logit link function. The model was developed based on 854 field plots of pathogen occurrence (presence/absence). We used the presence and absence of the species as a response variable, which was binary coded as 1 and 0. The predictor variables were logarithmic or square root transformed if needed to match a normal distribution. The potential predictor variables of interest were first assessed for significance in univariate analyses, and then a model selection procedure with forward stepwise selection of predictors was used to create a final multivariate model. Mean altitude was excluded from the model before stepwise selection because it is by definition correlated with the factor of forest vegetation zone. We preferred this ordinal variable because we expected nonlinear dependence of the P. alni occurrence on altitude. No other predictor had to be excluded because of strong inter-correlation (Pearson, r < 0.75). The goodness-of-fit of the regression was assessed using the Hosmer–Lemeshow test. The statistical analyses were carried out with Statistica 9 (StatSoft Inc., Tulsa, OK, USA).

The final model describing the probability of the occurrence of P. alni and its dependence on the predictor variables was used to predict the potential distribution of the species in all forest alder stands of the Czech Republic. Final values were assigned to individual stands according to unique codes and spatially expressed in the GIS environment to identify the areas at potential risk of the establishment and spread of P. alni in the Czech Republic. They were subsequently classified using quantiles into five spread risk categories (from very low to very high risk) to describe the potential level of invasion of forest stands with alders.

3. Results

Results of the statistical analysis showed the significant effect of the following environmental characteristics on the occurrence of P. alni in the study region: area of the

Table 1. Variables describing the forest stand.

| Abbreviation | Description of the variable       |
|--------------|-----------------------------------|
| S_ALT        | Mean altitude                     |
| S_FVZ        | Forest vegetation zone (0th pine, 1st oak, 2nd beech-oak, 3rd oak-beech, 4th beech, 5th fir-beech, 6th spruce-beech, 7th beech-spruce, 8th spruce) |
| S_ES         | Ecological series (nutrient-rich, acidic, wet, gleyed, enriched, peat) |
| S_W          | Presence of water course          |
| S_AGE        | Age of forest stand               |
| S_bp         | Biomass pool                      |
| S_AL_PERC    | Percentage of alder trees in forest stand |
| S_area       | Area of forest stand              |

Notes: DTM 4 g, pixel 5 m. ©CUZK 2015; DIBAVOD© VUV 2015; Database of The Forest Management Institute – ©UHUL.

Table 2. Variables describing the neighborhood of the forest stand (buffer zone 500 m).

| Abbreviation | Description of the variable       |
|--------------|-----------------------------------|
| B_area       | Area of all alder stands in buffer zone |
| B_AREA*PROP  | Area of alder stands * proportion of alder trees in forest stands within the buffer zone |
| B_EDGE       | Total length of edges of alder stands within buffer zone |
| B_FOREST     | Proportion of forest areas within buffer zone |
| B_LINVEG     | Total length of linear vegetation within the buffer zone |
| B_SFFHE    | Vertical heterogeneity within the buffer zone |
| B_TEMANN     | Mean annual temperature within the buffer zone |
| b_TEMPJAN    | Mean temperature in January within the buffer zone |
| bPREC        | Mean annual precipitation within the buffer zone |

Notes: DTM 4 g, pixel 5 m. ©CUZK 2015; ZABAGED©CUZK 2015; DIBAVOD©VUV 2015; Database of The Forest Management Institute – ©UHUL; Database of Czech Hydrological Institute – ©CHMI 2015.
forest stand, presence of watercourse, forest vegetation zone and acreage of alder stands in the buffer zone (see Appendix 1). The Hosmer-Lemeshow test indicated that the final model was a good fit (Hosmer-Lemeshow = 7.9814, p = .5360). The probability of pathogen occurrence increased with the increasing area of the forest stand, with the increasing area of alder stands in nearby vegetation and with the presence of streams. Stands in the first forest vegetation zone were found to have significantly higher probability of *P. alni* occurrence, whereas stands in the eighth forest vegetation zone were less likely to be invaded by this pathogen (see Appendix 1). The alder stands in the fourth and the seventh forest vegetation zones also tended to have a higher risk of infestation, but this relationship was not significant at the 5% significance level (Appendix 1). These forest stands are probably larger plantations on waterlogged sites in highlands and mountains with a wet climate.

Among others, the alder biomass pool, vertical heterogeneity and the edge density of alder stands were found to be statistically significant variables in models with a single predictor (Appendix 2). However, these variables were not included in the final model using the stepwise selection procedure.

Based on the relationships identified using GLM, the probability of the *P. alni* occurrence was predicted for all alder stands throughout the Czech Republic. The final values range from 0 to 0.88 and are classified into five spread risk categories using the Natural Breaks method according to the number of alder stands. Categories presented on the map clearly show the spatial pattern and frequency distribution of the individual spread risk categories of *P. alni* and the damage caused to alder stands in the Czech Republic.

Nearly 49% of the total area of alder stands in the Czech Republic (255,476 ha) are predicted to be at very high risk of pathogen spread. These highly susceptible stands have an average area of 3.9 ha and are usually nested within larger forested areas with alders present. The final map suggests that the most endangered forests in the country occur in two different types of environments: (i) floodplain forests at lower altitudes with a high density river network and large watershed area, that is, a potential source area of *P. alni* spread and (ii) mainly upland or mountain forest areas with a high density of streams and drainage channels, with high rainfall and a high proportion of waterlogged positions. In contrast, only 9054 ha (4%) of all alder forests in the Czech Republic were mapped with very low risk. Habitats with a very low risk of the *P. alni* occurrence are generally small in area (~0.2 ha), isolated, that is, have low connectivity to other stands with alders and are scattered across all vegetation zones. Compared with higher risk habitats, these stands tend to have a relatively high proportion of alder trees (almost 50%). The lowest likelihood of infection was localized to small local plantations that are limited to specific microsite conditions different from their surroundings, such as small springheads.

Other risk categories represent a continuum between the two described extremes. Low risk stands (category 2) cover an area of almost 19,000 ha, that is, 7% of all alder stands in the Czech Republic, medium risk stands (category 3) occupy more than 36,800 ha (14%) and 66,325 ha (26%) were mapped to be at high risk of *P. alni* occurrence and damage (category 4).

### 4. Conclusion

Predictive spatial tools that help to identify the current geographic extent of biological invasions and habitats at potential risk of spread are essential for the implementation of effective management strategies to minimize the impact of invasive species and diseases in natural ecosystems. The invasive species often extensively affect the landscape due to the slow discovery of invasion outbreaks, and models of potential distribution of the pathogen in the study region could help to identify locations for the early detection of invasion and enhance the efficacy of invasion control and eradication treatments. In this study, we developed a predictive model of the potential distribution of *P. alni* in forests with alders in the Czech Republic based on geostatistical analysis of the occurrence of the pathogen depending on the underlying environmental characteristics for approximately 850 forest stands within the country. Our predictions were based on the following variables included in the final model: area of forest stand, area of all alder stands in the buffer zone, the presence of a watercourse and forest vegetation zone. The results can be summarized and interpreted as follows:

- *P. alni* has a broad ecological tolerance and could potentially affect alder stands in all types of vegetation and forests throughout the country.
- Almost half of the total area of all alder stands in the Czech Republic are predicted to belong to the very high spread risk category and an additional 26% to the high-risk category. In contrast, the lowest spread risk was predicted over only 4% of the alder stand area.
- Alder stands with the highest likelihood of infection can be divided into two types: (i) floodplain and wetland alder forests at lower elevations with a high density of river networks and a large catchment area as the potential source area of the pathogen and (ii) alder stands in hilly or mountainous landscapes with a high density of streams and drainage channels, with high rainfall and a significant proportion of waterlogged locations. In contrast, small
plantations of alder trees with a high percentage of host species may not be affected when they are well isolated.

- Although the spread of the pathogen with alder seedlings is a highly effective pathway of the infection of forest stands (Jung & Blaschke, 2004), it is still marginal in the Czech Republic (Černý, Strnadová, Romportl et al., 2015), and it is necessary to pay attention to the future measures required to eliminate it in forest nurseries. This is one important way to prevent extensive damage to alder forests, especially those in middle and high altitudes that have not yet been invaded.

**Software**

All analyses of the input variables, visualization and map preparation were performed in Esri ArcGIS 10.3. Statistical analyses were processed using STATISTICA 9.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.

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Appendix 1. Results of the final multivariate model describing the probability of Phytophthora × alni occurrence in dependence on the characteristics describing the forest stands (Table 1) and their neighborhood (Table 2). GLM with forward stepwise selection of predictors was used to create the model.

| Predictor variable | Category (in categorical variable) | Coefficient estimate | Wald stat. | p     |
|-------------------|------------------------------------|----------------------|-----------|-------|
| Intercept         |                                    | −1.1038              | 6.5292    | 0.0106|
| Ln(S_AREA)        |                                    | 0.2314               | 11.5583   | 0.0007|
| Ln(B_AREA)        |                                    | 0.0820               | 5.5037    | 0.0190|
| S_W               | Yes                                | 0.2841               | 11.6408   | 0.0006|
|                   | No                                 | −0.2841              | 11.6408   | 0.0006|
| S_FVZ             | 0th Pine                           | 0.1515               | 0.0277    | 0.8677|
|                   | 1st Oak                            | 0.8278               | 9.6831    | 0.0019|
|                   | 2nd Beech-oak                      | 0.2549               | 0.8904    | 0.3454|
|                   | 3rd Oak-beech                      | −0.0880              | 0.1747    | 0.6759|
|                   | 4th Beech                          | 0.4130               | 2.7078    | 0.0999|
|                   | 5th Fir-beech                      | 0.0106               | 0.0021    | 0.9636|
|                   | 6th Spruce-beech                   | −0.1587              | 0.3418    | 0.5588|
|                   | 7th Beech-spruce                   | 0.6318               | 2.4434    | 0.1180|
|                   | 8th Spruce                         | −2.0429              | 4.4487    | 0.0349|

Appendix 2. Characteristics describing the forest stands (Table 1) and their neighborhood (Table 2) that had significant effect on the occurrence of Phytophthora × alni in the study field plots. Results of GLM with a single predictor variable.

| Predictor variable | Category (in categorical variable) | Coefficient estimate | Wald stat. | p     |
|-------------------|------------------------------------|----------------------|-----------|-------|
| S_ALT             |                                    | −0.0009              | 4.6940    | 0.0303|
| S_FVZ             | 0th Pine                           | 0.0578               | 0.0041    | 0.9488|
|                   | 1st Oak                            | 0.7202               | 7.7487    | 0.0054|
|                   | 2nd Beech-oak                      | 0.2081               | 0.6158    | 0.4326|
|                   | 3rd Oak-beech                      | −0.1099              | 0.2832    | 0.5946|
|                   | 4th Beech                          | 0.3943               | 2.5551    | 0.1099|
|                   | 5th Fir-beech                      | 0.0981               | 0.1846    | 0.6674|
|                   | 6th Spruce-beech                   | −0.0689              | 0.0672    | 0.7955|
|                   | 7th Beech-spruce                   | 0.5884               | 2.2376    | 0.1347|
|                   | 8th Spruce                         | −1.8881              | 3.8745    | 0.0490|
| S_W               | Yes                                | 0.2362               | 8.9711    | 0.0027|
|                   | No                                 | −0.2362              | 8.9711    | 0.0027|
| S_BP              |                                    | 0.0011               | 8.5798    | 0.0034|
| Ln(B_AREA)        |                                    | 0.0958               | 8.0802    | 0.0045|
| Ln(B_AREA*PROP)   |                                    | 0.2557               | 15.3809   | 0.0001|
| Sqrt(B_EDGE)      |                                    | 0.0086               | 9.4703    | 0.0017|
| Sqrt(B_VERTHET)   |                                    | −0.1040              | 6.7159    | 0.0096|