Previous

Estimating the Susceptibility to *Phytophthora alni* Globally Using Both Statistical Analyses and Expert Knowledge

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Abstract

Phytophthora alni subspecies *alni* Brasier and S.A. Kirk is a recently hybridized soil and waterborne pathogen causing root and collar rot of species of the genus *Alnus* spp. (alder). It has quickly spread throughout Europe via planting of infested nursery stock and irrigating fields with infested river water. Once introduced, the pathogen spreads naturally by means of streams, floods, and other drainage water. *Phytophthora alni* can also be passively transported with the bare-root nursery stock, as it is able to adhere to and infect fine roots of visually symptomless plants of alder and other tree species exposed to the pathogen.

We used a classification tree on 434 infested and healthy sample points to determine the required conditions for *P. alni* to successfully infest a nonflooded forest site. Sample points had been collected from 2003 through 2006, and a potential distribution surface was created for forested areas in Bavaria. A tenfold cross-validation accuracy of 78 percent was attained. To understand the potential hazard posed by *P. alni* elsewhere in the world, the rules from the Bavarian classification tree were applied along with additional expert knowledge in a multicriteria model to create a global susceptibility surface for *P. alni*.

Keywords: Alder, *Alnus*, classification tree, hazard, pathogen, *Phytophthora alni*, risk.

Introduction

Phytophthora alni Brasier and S.A. Kirk is a host-specific, highly aggressive soil and waterborne pathogen that causes root and collar rot of *Alnus* (alder) spp. All European alder species (i.e., black alder [*A. glutinosa* (L.) Gaertn.], gray alder [*A. incana* (L.) Moench], Italian alder [*A. cordata* (Loisel.) Duby], and green alder [*A. viridis*] (Chaix) DC.) and the North American red alder (*A. rubra* Bong.) are highly susceptible (Jung and Blaschke 2006, Gibbs and others 2003). The susceptibility of other North and South American and Asian alder species is currently unknown. *Phytophthora alni* was shown to be a recent interspecific hybrid between *P. cambivora* (Petri) Buisman and another species closely related to *P. fragariae* Hickman (Brasier and others 1995, 1999, 2004). There are three subspecies of *Phytophthora alni*, with markedly different aggressiveness to common alder (Brasier and others 2004, Brasier and Kirk 2001). The disease was first detected in 1993 in Southern Britain (Gibbs 1995) and has since been confirmed in 12 other European countries and across the United Kingdom (Figure 1) (Brasier and Jung 2003, 2006; Gibbs and others 1999, 2003; Jung and Blaschke 2004, 2006; Schumacher and others 2005; Streito and others 2002) (Orlikowski, L. Pers. comm., 2006. Pathologist, Research Institute of Pomology and Floriculture, Pomologiczna 18, 96-100 Skierniewice, Poland). Moreover, *P. alni* is likely present in Czech Republic, Spain, and Switzerland because typical symptoms and mortality of alders are reported from these countries. The disease occurs mainly along riverbanks, but also in orchard shelterbelts and forest plantations (Gibbs 1995; Gibbs and others 1999, 2003; Jung and Blaschke 2004; Streito and others 2002). Disease symptoms include abnormally small, sparse, and often yellowish foliage and crown dieback (Figure 2). Other symptoms are early and often excessive fructification and tongue-shaped necroses of the inner bark and cambium. Necroses can extend up to 3 m from the stem base and are marked by tarry or rusty spots on the surface of the outer bark (Figure 3) (Gibbs and

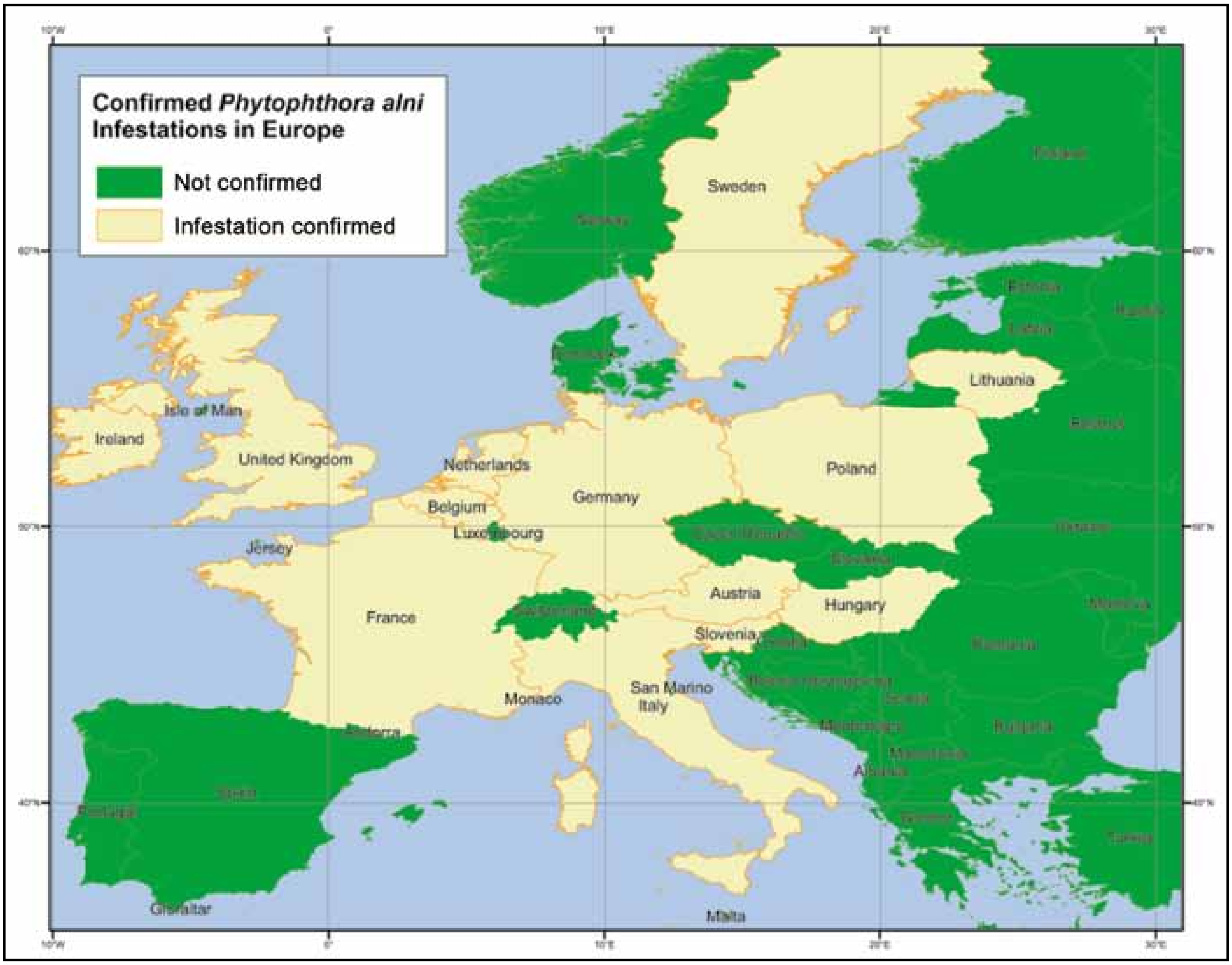

Figure 1—Current distribution of *Phytophthora alni* (yellow).

others 1999, 2003; Jung and Blaschke 2001, 2004) (http://www.baumkrankheiten.com/gallery/docs-en/alder_dieback/index.html). On riparian sites, *P. alni* has caused mortality as high as 70 percent in some locations. Disease incidences of 50 percent and high mortality rates were common (Gibbs and others 2003, Jung and Blaschke 2004, Streito and others 2002). The pathogen was shown to be widespread in alder nursery fields (Jung and Blaschke 2004, Schumacher and others 2005). Infected plants seldom showed symptoms, which made control efforts difficult.

A thorough investigation of disease pathways in Bavaria demonstrated that in most infested river systems, *P. alni* was introduced via infested young alder plantations established on the riverbanks or on forest sites that drain into the rivers (Jung and Blaschke 2004). Once introduced, *P. alni* spreads downhill with water runoff and downstream with streams and floods. Many infected alders were planted in afforestations of former agricultural land and also on wet sites in woodlands to stabilize steep slopes and banks of white water rivers (Jung and Blaschke 2004). These plantings increased the risk of infestation of riparian sites with the increased length of the river and upstream tributaries.

The rapid proliferation of *P. alni* throughout Europe probably resulted from the increased importance of alders in afforestation activities on wet sites and on former agricultural lands. The combined anthropogenic impacts of

▲ Figure 2—Mature riparian stand of common alder (*Alnus glutinosa*) with sparse, chlorotic and small foliage and crown dieback owing to *Phytophthora alni* root and collar rot.

◄ Figure 3—Mature grey alder (*Alnus incana*), with collar rot caused by *Phytophthora alni*; typical tarry spots at the outer bark and tongue-shaped orange-brown necrosis of the inner bark.

outplanting infected nursery stock and utilizing contaminated river water to irrigate nursery fields were contributing factors (Brasier and Jung 2003, Gibbs and others 2003, Jung and Blaschke 2004). *Phytophthora alni* may also be passively transported on bare-root nursery stock because it is able to adhere to and infect the fine roots of alders as well as adhere to other nonhost tree species exposed to the pathogen.

As short-time control measures, coppicing of infected alder trees and stools is recommended along water courses (Gibbs 2003), but not in infested forest plantations (Jung and Blaschke 2006). Some survivors in highly infested common alder stands were shown to be less susceptible

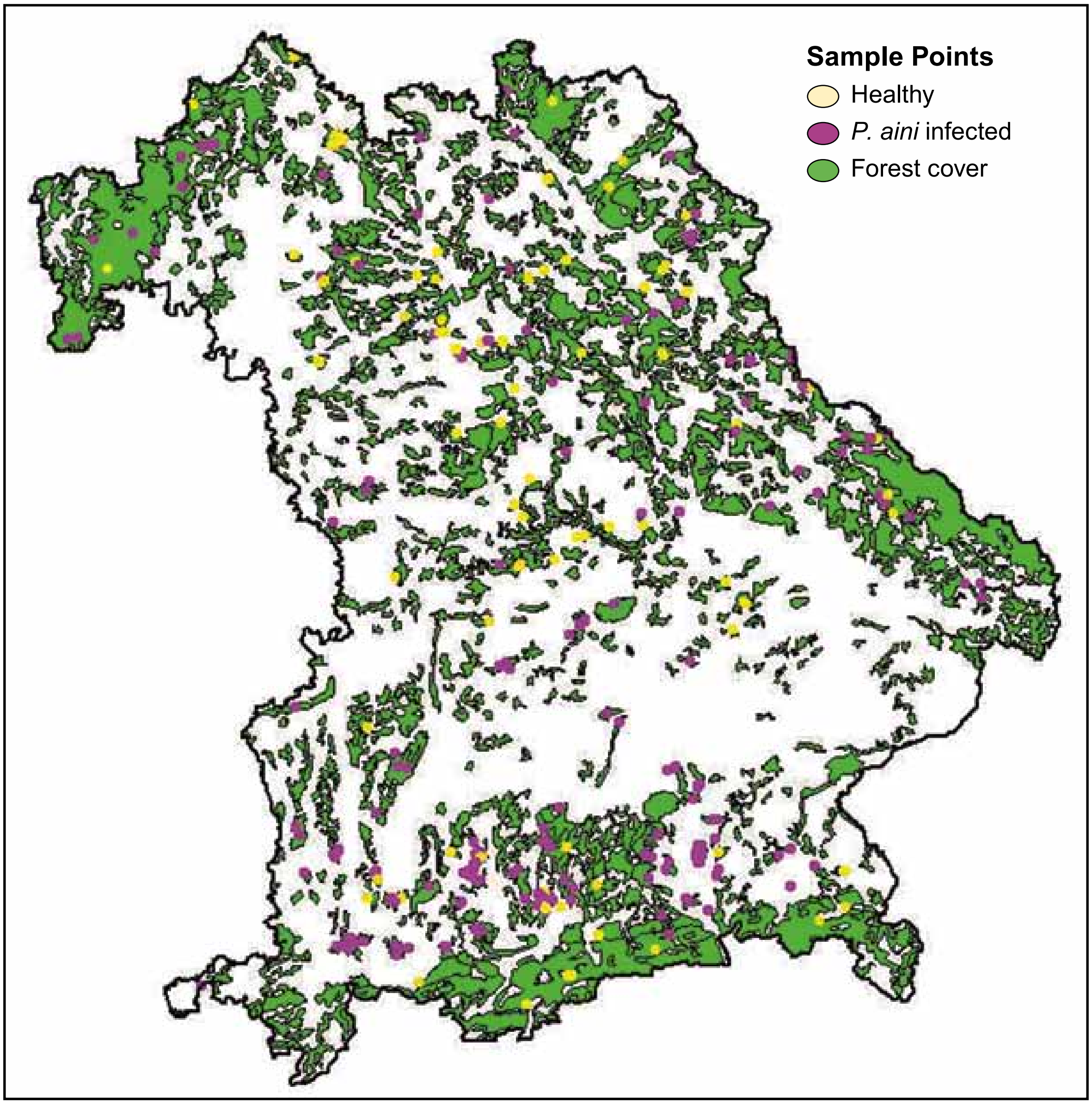

Figure 4—Study area of forested land cover (green) in Bavaria with *Phytophthora alni* infested (pink) and healthy (yellow) sample locations overlain.

to *P. alni* than declining trees, and in the long term, a resistance screening program may help to sustain alders as major components of riparian and swamp forests (Jung and Blaschke 2006).

The Exotic Forest Pest Web site, which is sponsored by the North American Forest Commission (NAFC 2006) lists *P. alni* as a high risk pest to North American forests for its potential to (1) adversely affect the economic trade of alder trees and (2) affect the environment; specifically by changing forest composition, reducing wildlife food and habitat, increasing soil erosion, and changing soil composition owing to alder's nitrogen-fixing capabilities (Cree 1999).

An investigation of the conditions present at 434 sample locations in forested areas in Bavaria (Figure 4) was conducted using classification tree analyses and a tenfold cross validation to estimate the error. Classification and regression trees are a nonparametric iterative approach to compare all possible splits among the independent

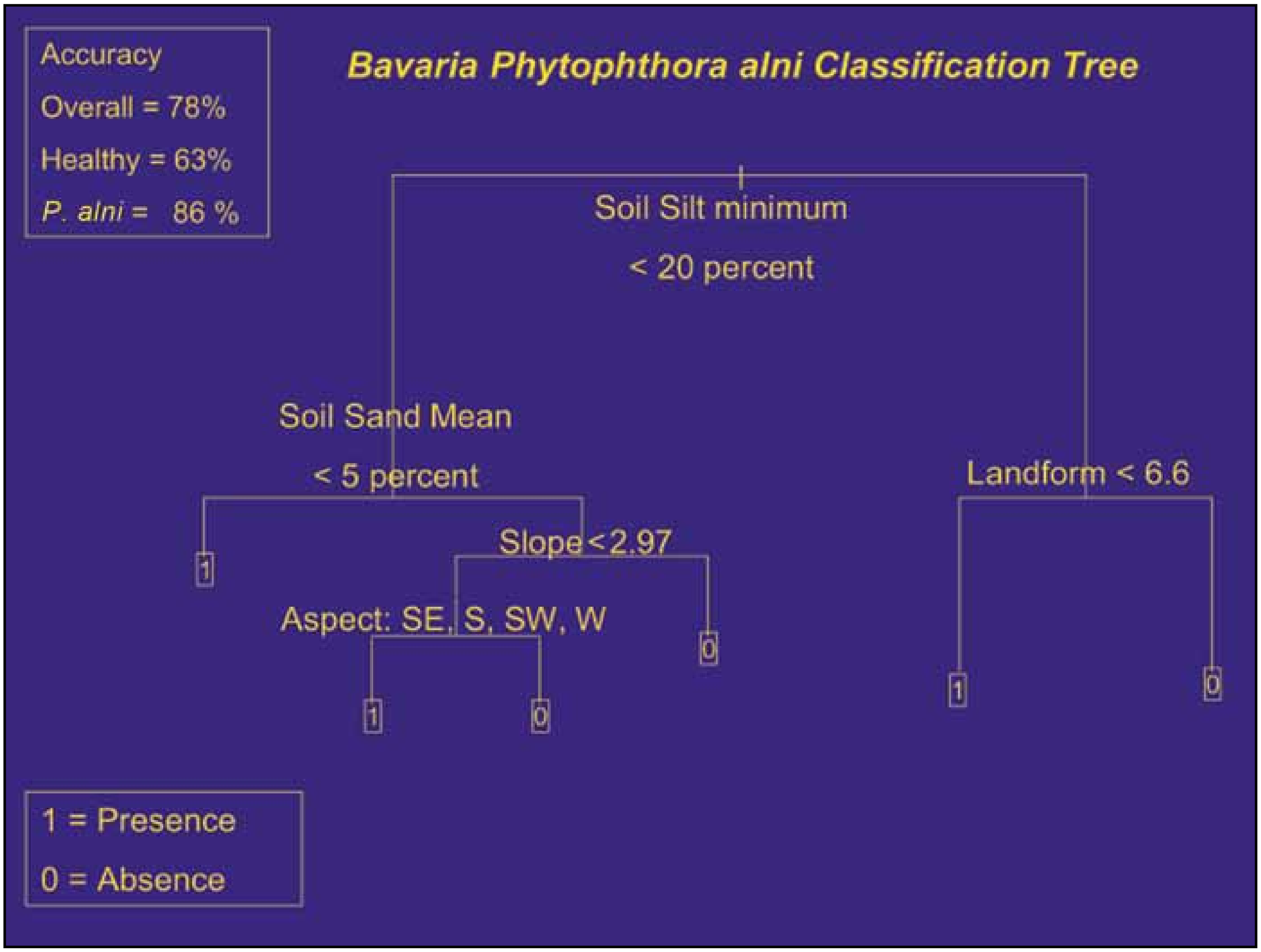

Figure 5—Classification tree model for presence and absence of *Phytophthora alni* in forested areas in Bavaria.

variables using a partitioning algorithm that maximizes the dissimilarities among groups. Classification trees are best used with binary data and regression trees with continuous data. Advantages of using decision trees such as classification and regression trees include the nonparametric nature of the model, ease of interpretation, and the robustness of the test (De'ath and Fabricius 2000). Decision trees have been successfully developed recently for (1) modeling landscape dynamics of the spread of *P. ramorum* (Kelly and Meentemeyer 2002), (2) mapping hemlocks via tree-based classification of satellite imagery and environmental data (Koch and others 2005), (3) predicting the presence and absence of lichen and past fires in Jalisco, Mexico (Reich and others 2005), (4) developing a spatial model for estimating fuel loads in the Black Hills, South Dakota (Reich and others 2004), and 6) developing a methodology to predict oak wilt distribution in Minnesota and Texas (Downing and others 2007).

In this study, rules from the classification tree were used to create the potential distribution surface for Bavaria. Another potential distribution model, a Multicriteria model (Eastman 2001, Eastman and others 1995), was created for the globe using both the rules from the Bavarian classification tree, and additional parameters established with expert knowledge. Global susceptibility surfaces, such as the *P. alni* surface, may be used to illustrate the need for a pathway approach to regulate nursery stock and for host species resistance testing. Multicriteria models have been helpful to produce pest-risk maps for forested land in the United States (Krist and others, this volume).

Table 1—Bavarian independent variables used to produce a potential distribution for *Phytopthora alni* in Bavarian forested areas

A. Aspect: was derived via the DEM surface. **(DEM: Digital Elevation Model) surface.** The DEM surface was used to create ancillary data: slope, aspect, and landform. The DEM was created from the Shuttle Radar Topography Mission (SRTM) in February 2000. SRTM was a joint project between the National Geospatial-Intelligence Agency and the National Aeronautics and Space Administration. The DEM surface was obtained and distributed by the U.S. Geological Survey Earth Resources Observation and Science (EROS) Seamless Data Distribution System (http://seamless.usgs.gov)]. The cell values of zero slope (flat) are assigned an aspect of -1. Therefore, the continuous aspect grid was reclassed to eight basic cardinal directions. Plus another class for zero slope.

B. Soil Fraction/Texture Percent: Soil fraction data were obtained as a soil polygon shapefile from the German **Federal Institute for Geosciences and Natural Resources**. Soil fraction percentage pertains to the volume amount by soil type (sand, silt, and clay) found in the soil sample. The percentage of all three soil fractions sums to 100 percent. To capture the variance of each soil type, three categories of soil fraction percentage were created for each soil type: (1) the minimum soil fraction value for each soil type, (2) the mean soil fraction value, and (3) the maximum soil fraction value. With three data sets included for each of the three soil types, there were a total of nine soil data sets used in the analysis.

C. Landform Index: Landform was derived via the DEM. Landform is independent of slope and created using a custom ArcView Avenue application. The application uses an irregular 3 by 3 kernel, where positive landform values indicate concavity, negative values indicate convexity, and a zero value indicates flat terrain (McNab 1989).

D. Normalized Difference Vegetation Index (NDVI): The NDVI was created from 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. The MODIS data was obtained from the Remote Sensing Applications Center (RSAC) in Salt Lake City, Utah. Personnel at RSAC downloaded an archived Bavarian MODIS image and performed the NDVI model. The values of NDVI relate to the relative greenness of the vegetation.

E. Slope: Slope was created using the “Derive Slope” function in the ArcView 3.3 Spatial Analyst extension coupled with the DEM surface. Slope units were degrees.

Methods

Between the spring of 2003 and the winter of 2006, a total of 307 *P. alni* infested and 127 healthy/noninfested alder tree locations were sampled in forested areas in Bavaria (Figure 4). Among the 307 infested sites, there were 232 points where alder trees had been planted, and 75 points where alders were naturally occurring. Of the 127 healthy sample points, 38 were planted and 89 had natural alder growth. A geographic information system sample point theme of the dependent variable was created containing all 434 sample point locations for analysis in the classification tree.

Thirteen independent variable raster data sets were used in the Bavarian classification tree analysis (Table 1). Specifically, these were twelve 93-m physiographic data sets including nine soil texture components (minimum, mean, and maximum percentage values for sand, silt, and clay polygons), aspect, slope, and landform an index of concavity and convexity. The 13^{th} data set was the Normalized Difference Vegetation Index (NDVI) calculated from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery at 250 m. Numerical values were extracted from each of the independent variable grids at each of the sample locations from the sample point theme. These values were then used to compose the spatial information database that was exported to S-PLUS© statistical software (S-PLUS©, Statistical Sciences 2000) for analysis. The independent variables selected by the classification tree were silt, sand, slope, aspects that were Southeast, South, Southwest, and West, and the landform index.

The default S-PLUS© validation technique, tenfold cross validation, was used to prune the tree to avoid overfitting the classification tree model to the Spatial Information Database. The tenfold cross validation was used, as it does not rely on an independent data set and can identify the optimum tree size for minimizing prediction errors.

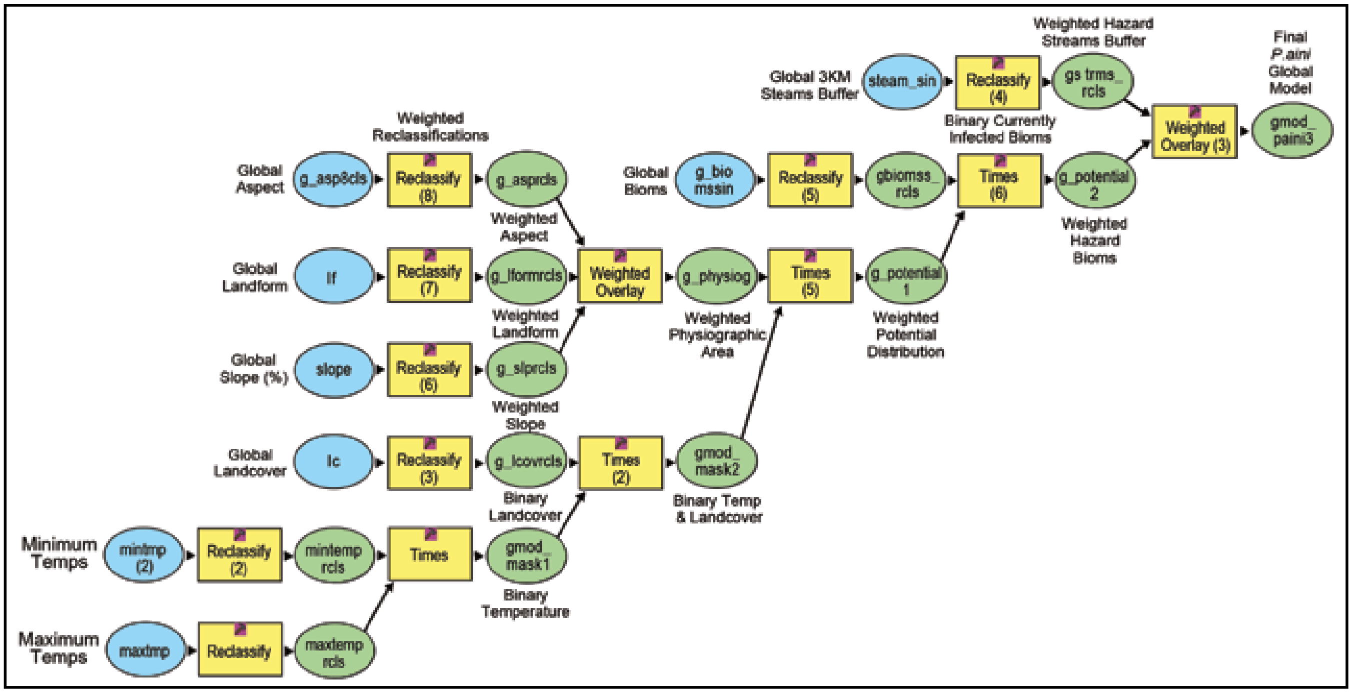

Figure 6—*Phytophthora alni* multicriteria model for the globe.

Based on the results of the classification tree analysis (Figure 5), conditional statements (CON statements; ESRI ArcView, 2000) were used to create a binary *P. alni* potential distribution (i.e., presence and absence) surface for the forested areas in Bavaria. The significant independent variables selected by the classification tree, as well as the decision tree rules (e.g., threshold values taken at the tree nodes), were the input for the CON statements.

Only three of the independent variables that were selected by the Bavarian classification tree were available globally. These were slope, aspect, and the landform index. To see how the rules would change given only the three independent variables, a second classification tree was developed for Bavaria using only those three data sets. This second model had limited utility as it overpredicted the presence of *P. alni*, predicting more than 90 percent of the study area to have *P. alni* present. Still, the rules from the second model did provide some additional insight regarding the broader range of conditions within which *P. alni* might be present. Therefore, the rules from both the original as well as from the second model were combined, along with additional expert knowledge, in a final multicriteria model to create a global susceptibility surface for *P. alni*.

To develop the multicriteria susceptibility model for the globe (Figure 6), the unique numerical values from each criterion had to be standardized. Therefore, each data set was reclassified using a hazard ranking of 0 to 10. The decision rules from both classification trees as well as additional expert knowledge were used as a guide in setting the hazard rankings.

Areas where alder and *P. alni* could not grow were eliminated from the global analysis by creating masks from climate and landcover data. To determine temperature thresholds for the climate mask, an investigation of *Alnus* species was conducted. It was determined from frost hardiness and heat/drought hardiness zones for all alder species that alder does not survive temperatures +/- 40 degrees Celsius.

In addition, lab results performed by Dr. Jung indicated that soil temperatures greater than 32 degrees Celsius prevent the survival of *P. alni*. Although soil temperature data is not available, a regression formula (Temperature MAX threshold value = (Soil Temperature MAX threshold value - intercept estimate)/Regression Coefficient Estimate), was applied to determine that 32 degrees Celsius equates to air temperatures of 34 degrees Celsius.

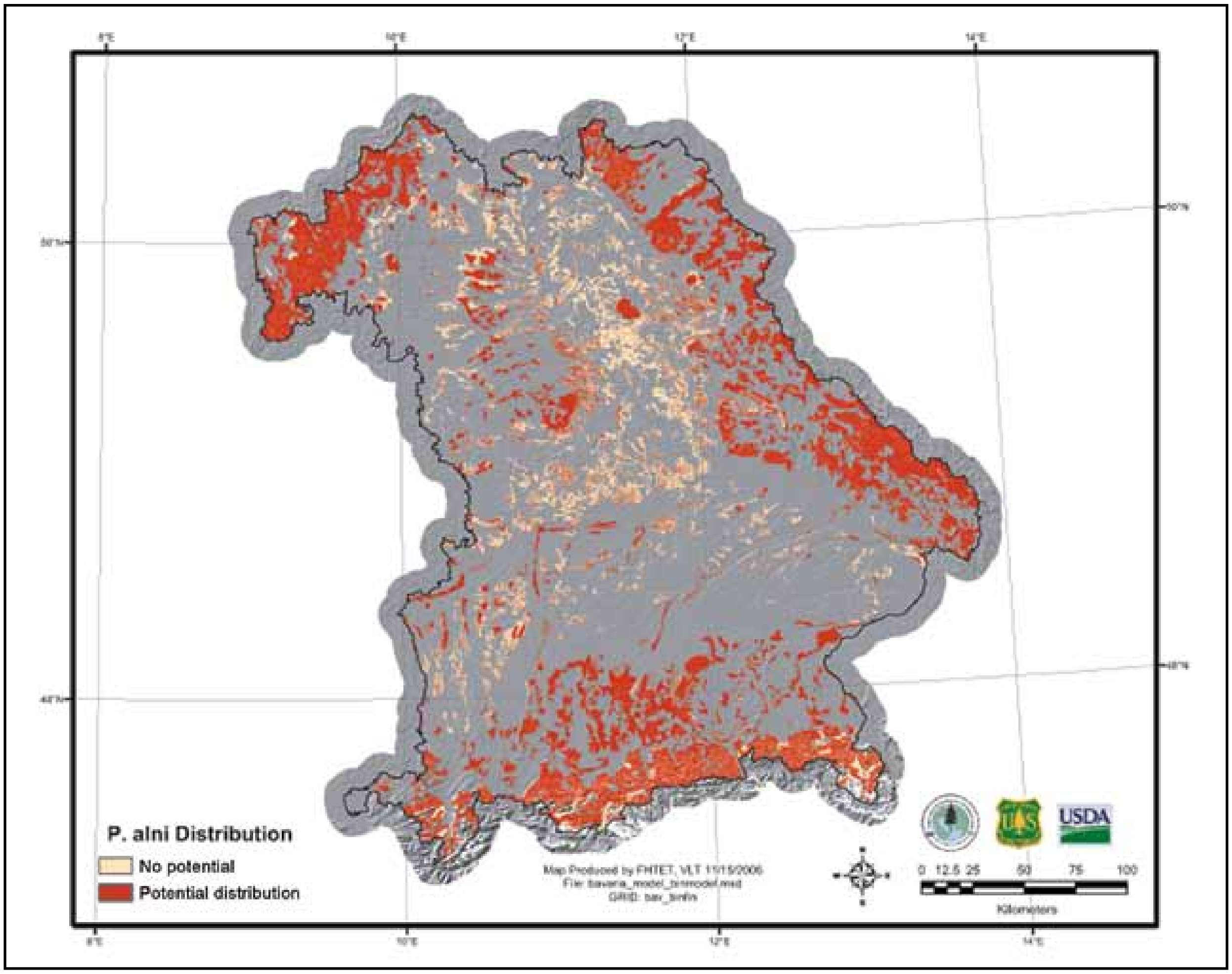

Figure 7—Potential distribution of *Phytophthora alni* (presence and absence) for all forested areas in Bavaria.

Consequently, areas with temperatures less than -40 degrees Celsius and greater than +34 degrees Celsius, as well as areas that could not support alder such as tundra, bare ground, and bodies of water, were removed from further analysis. The binary climate and landcover masks were combined by multiplying both surfaces together to create a combined binary temperature and landcover mask. The resulting mask was combined again in a weighted overlay with the reclassified criteria to produce a potential global distribution.

Because slope predicted most of the variability in the classification tree, it was weighted at 50 percent; aspect and the landform index were both weighted at 25 percent.

To produce the final global susceptibility surface, areas that were identified in the global distribution as having a potential for a *P. alni* infestation were classified according to hazard. Biome and stream data were combined in an equal weighted overlay to assign a hazard ranking. The hazard ranking was based on each pixel's occurrence within ecological biomes similar to the biomes where *P. alni* presently occurs, as well as its proximity to streams. Thus, pixels within the selected biomes were assigned hazard rankings based on their proximity to streams. A set of three global stream buffers at distances of 1km were used to assign the hazard rankings. Pixels that had the potential for infestation were given a high hazard ranking if they fell within 1 km of the stream. Those pixels between 1 and 2 km were assigned a medium potential hazard, and pixels between 2 and 3 km from the stream were assigned a low potential hazard. Pixels that were found greater than 3 km

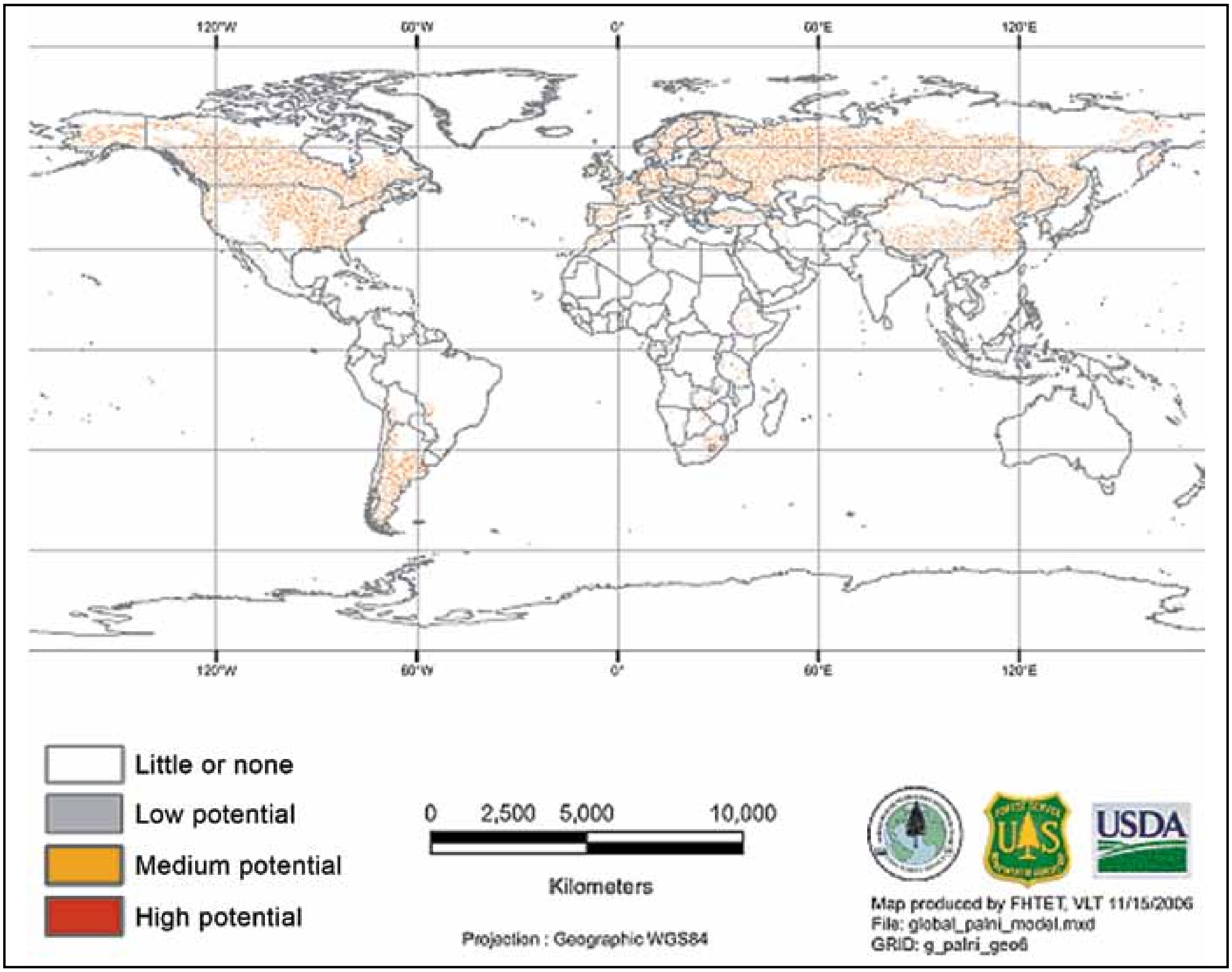

Figure 8—The final global susceptibility surface had 27, 835, 766 km^2 of suitable area where alder and *P. alni* could survive.

from a stream or outside the selected biomes were given a hazard ranking of little or no potential hazard.

Results

For the original Bavarian model: of the 19 620 forested km^2 assessed in Bavaria, approximately 14 015 km^2 (71.43 percent) were modeled to have a high potential for *P. alni* root and collar rot, and 5604 km^2 (28.56 percent were modeled to have a high potential to remain healthy (Figure 7). Seven terminal end nodes were used and accounted for 78.34 percent of the variability. The tenfold cross validation gave a higher accuracy for predicting the 307 *P. alni* infested sites at 86 percent, and showed 63 percent accuracy in predicting the 127 healthy sites. The independent variables important in predicting the presence or absence of *P. alni* were minimum silt fraction values less than 20 percent (range = 0 to 80 percent), mean sand fraction values less than 5 percent (range = 0 to 93 percent), slope less than 2.97 degrees (range = 0 to 30.74 degrees), aspects that were Southeast, South, Southwest, and West, and the landform index less than 6.6 (range = - 15.20 to + 21.60; < 0 = concave; 0 = totally flat; > 0 = convex) (Figure 5).

For the second Bavarian model, with only the three independent variable data sets that are available globally being used, 14 terminal end nodes accounted for 77.19 percent of the variability. The tenfold cross validation still showed a higher accuracy for predicting the 307 infested sites at 92.51 percent, but only 40.16 percent accuracy in predicting the 127 healthy sites. As expected, all three of the independent variables were used to predict the presence or absence of *P. alni*, but, in this model, slopes less than 19.57 degrees had a higher probability for infestation, and the East aspect was selected in addition to the four aspects that had originally been selected. Also, landform indexes less than 6.2 had a higher probability of infestation.

The final global susceptibility surface had 27,835,766 km^2 of suitable area where alder and *P. alni* could survive (Figure 8). Of that area 1,482,487 km^2 (5.33 percent) were highly susceptible to *P. alni*; 3,930,660 km^2 (14.12 percent) had a medium susceptibility; 5,721,467 km^2 (20.55 percent) had a low susceptibility; and 16,701,152 km^2 (60.00 percent) had little or no susceptibility.

Discussion

The original Bavarian classification tree identified five ecological factors important in the distribution of *P. alni*. Where these factors occur together in the environment, the likelihood of infection is increased. Specifically, where silt minimum values are less than 20 percent, and sand mean values are less than 5 percent, the probability of a *P. alni* infection is high. When silt minimum values are less than 20 percent, and sand means are greater than 5 percent, the site is more likely to have *P. alni* infections if slopes are less than 2.97 degrees and have warmer aspects. Sites with a landform index measure of less than 6.6 (concave, flat or slightly convex) also have an increased probability of a *P. alni* infestation. These results make biological sense. Areas with poor drainage and warmer aspects provide an optimal environment for the pathogen to flourish, as will sites with fairly flat or concave physical structure. Conversely, areas with less clay and more silt or sand will drain better, as will sites with steeper slopes and convex landform. These types of sites will not provide a wet environment for this water-borne pathogen to form sporangia and release zoospores that are essential for the spread and infection of *P. alni*.

Not all of the five ecological factors identified as being important by the first Bavarian model for predicting the distribution of *P. alni* were available for the global model. A second model for Bavaria, which utilized only the three data sets that were available globally, demonstrated the limitations of modeling invasive species at a global scale without appropriate data. The limitation most notable was the soil texture data because it was selected by the first Bavarian model as the most important variable for predicting the presence and absence of the soil-borne pathogen *P. alni*. In addition, data was not available for (1) forest species type (i.e., distribution of the individual alder species), and (2) susceptibility of North and South American and Asian alder species to *P. alni*. We addressed forest species type by keeping our analysis near and around streams and flood plains where most alders tend to grow. We also looked at the temperature range, eliminating areas with temperatures that were too cold or hot for alder and *P. alni* survival. Although we made compromises to work within the data limitations, this work emphasizes the need for quality spatial environmental data at the global scale.

Since planting infected nursery stock is one of the primary pathways by which *P. alni* has been spread, we were careful to consider the social or cultural habits in association with outplanting alder trees. Of particular concern was the outplanting of infected alder trees in respect to elevation. At higher elevations, alder trees are planted much less frequently than at lower elevations. Yet, it has been observed by the Jung that where *P. alni*-infected alder was planted at higher elevations, those sites have become infested and further contribute to infections downhill and downstream. Because alder was rarely planted at higher elevations, *P. alni* was much less prevalent on higher elevation sites. We therefore assumed that the model would be biased toward selecting elevation as an important variable for predicting presence and absence. Consequently, elevation was not used in the model.

A higher accuracy was attained for predicting the *P. alni*-infested sites than for predicting healthy sites. This is likely an outcome of having three times more infested than healthy sample locations. Had we sampled a greater number of locations for the healthy condition, it is likely that the accuracy for predicting healthy sites would improve.

Of the 127 healthy alder tree locations collected between 2003 and 2006, some sites may have changed in status. Some of the sites that were not infested by 2006 may become infested in the future. These are problems one would expect in attempting to model a species that is unlikely to have been in existence before the 1980s (Gibbs and others 2003, Jung and Blaschke 2004) and has not yet completely expanded into its potential range. With no complete range map for *P. alni*, the Bavarian model provides managers worldwide with useful decision rules and a data mining tool for estimating the susceptibility of their resources to *P. alni*.

Because all of the applicable variables from the first Bavarian model are available in data sets for the United States, the extrapolation of the Bavarian model to forests in the United States should demonstrate the specific improvement that can be gained by applying the appropriate data sets identified by the Bavarian model.

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