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Modeling spatial distribution of bark beetle susceptibility using the maximum entropy approach

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Abstract

Bark beetles cause significant damage to forests, which are valuable natural resources. The creation of susceptibility maps for bark beetles is a significant stage in the management and reduction of bark beetle-related harm. The present investigation involved the development of a susceptibility map for bark beetles, utilizing the Maximum Entropy (MaxEnt) model, a machine learning technique, and incorporating 19 different bioclimatic climate variables. The model's accuracy was evaluated through receiver operating characteristic (ROC) analysis, and the area under the curve (AUC) was computed to be 0.705. The MaxEnt model indicated that the annual mean temperature (BIO 1) had the greatest impact on the susceptibility of bark beetles. Categorization of bark beetles' susceptibility was delineated into four different categories, namely low, moderate, high, and extreme. Based on the results, approximately 58% of the study area included areas that exhibit vulnerability to bark beetle infestation. The accuracy of the bark beetle susceptibility map, which was developed based on these results, was found to be high and consistent with the observed bark beetle damage.

1. Introduction

Epidemics of bark beetles (Coleoptera: Curculionidae, Scolytinae), which have affected the global region and caused tree deaths, have increased considerably in recent years all over the world (Hlásny et al. 2019; Hlásny 2021; Sommerfeld et al. 2021). Current projections indicate that these outbreaks will increasingly continue (Evagelista et al. 2011; Seidl et al. 2014). 16 species of the genus Ips, one of the taxonomically defined bark beetles in the world, are distributed in Eurasian forests (Cognato and Felizet 2000). One of these species, Ips sexdentatus Boerner (Coleoptera: Curculionidae: Scolytinae), is a natural species of Turkey's forests and causes damage in pine, fir, and spruce forests (Bernard 1935; Oymen 1992; Ozcan et al. 2011). In such endemic populations, this species prefers to colonize weakened, stressed, and recently dead trees (Gil and Pajares 1986). However, when the presence of suitable hosts increases, it can also attack healthy trees and cause an epidemic level infestation (Raffa and Berryman 1983).

The prevalence of aggressive bark beetle species is influenced by certain stand and climatic factors (Fttig et al. 2007; Mezei et al. 2012; Salinas Moreno et al. 2004; Sivrikaya et al. 2023; Sproull et al. 2017; Stadelmann et al. 2013; Özcan et al. 2022). Extreme temperatures and droughts due to climate change will increase insect outbreaks and thus increase tree deaths (García de la Serrana et al. 2015; Raffa et al. 2008). The life cycles of bark beetles are also regulated by climate (Evangelista et al. 2011). Of course, the climate tends to favor bark beetle populations, which will cause infestations to occur in previously unrecorded forests (Buotte et al. 2017). Therefore, accurately modeling the spatial distributions of species is of greatest significance (González-Hernández et al. 2020; Phillips and Dudik 2008). These models are important for forestry activities (Graham et al. 2004).

Various modeling methods are used to predict suitable habitat based on future conditions (Smith et al., 2013). The MaxEnt performs better than other methods, and the software is relatively easy to use (Elith et al. 2006; Merow et al. 2013). It stands out with its high estimation accuracy and good results with smaller sample sizes compared to other methods (Phillips and Dudik 2008). There are studies that determine the potential distribution of different bark beetle species with the MaxEnt approach (Dowling 2015; Evangelista et al. 2011; González-Hernández et al. 2020; Li et al. 2021; Sarıkaya et al. 2018; Sivrikaya et al. 2023; Şen et al. 2020). Presently, there is currently a scarcity of

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research that demonstrates the sensitivity of forests to Ips sexdentatus utilizing this specific modeling approach. The aim of this study is to reveal the susceptibility map of Ips sexdentatus according to bioclimatic variables with MaxEnt, which is a machine learning approach.

2. Materials and Method

2.1. Study area

This study was conducted in the Sarıçam planning unit in Kastamonu, which is located in the north of Türkiye. The study area is 10272 ha, of which 7672 ha are forested. 87% of the forest area is productive, and 13% is degraded forest. The most common tree species in the study area are Crimean pine, Calabrian pine, oak, and fir. The climate of the area is continental. The winter months are usually snowy, and the spring and autumn are cold. Summers are hot and mostly dry.

2.2. Dataset

Between 2008 and 2018, the Kastamonu Regional Directorate of Forestry (RDF) conducted a field study to assess the extent of damage caused by *I. sexdentatus*. 120 beetle damaged points in Sarıçam planning unit were obtained from the Kastamonu RDF as point layers. Bioclimatic variables were obtained from the WorldClim website in raster format (WorldClim, 2023) (Table 1). The presence of a strong correlation between variables may result in overfitting of the model, thereby impacting the accuracy of the predictions (Méndez-Encina et al. 2021). The Pearson correlation coefficient (r) was employed as a means of assessing the correlation between variables. The Band Collection Statistics tool in ArcGIS 10.6 was utilized to exclude one of the two associated variables that exhibited a correlation exceeding 0.90 from the model (Yusup et al. 2018). The preparation of bark beetles' susceptibility map was carried out through the utilization of MaxEnt 3.4.4. The training dataset consisted of 70% of beetle damage points, and the rest was used for model validation. The susceptibility map of the bark beetle was classified into four distinct categories, namely low, moderate, high, and extreme, using the natural break method within the ArcGIS 10.6 software.

3. Results and Discussion

In order to minimize the risk of overfitting, a correlation analysis was conducted. The analysis revealed that 11 variables exhibited a strong correlation (>0.90) with other variables. The MaxEnt model utilized eight distinct and uncorrelated variables to predict the vulnerability of bark beetles. The modeling procedure comprised of the variables BIO 1, BIO 4, BIO 7, BIO 12, BIO 14, BIO 17, BIO 18, and BIO 19.

The accuracy of the bark beetle susceptibility map generated using the MaxEnt model was evaluated through ROC analysis. Based on the analysis results, the training data showed an AUC value of 0.742, while the test data revealed an AUC value of 0.705. The results indicate that the model that was created shows a high level of accuracy and suitability for practical use (Fig. 1). According to González-Hernández et al. (2020), temperature, which is considered, one of the bioclimatic variables, played a crucial role in determining the potential areas of the bark beetle Dendroctonus mexicanus as determined by MaxEnt. The potential distribution models generated AUC values that were in close proximity to 1. A recent investigation employed MaxEnt to generate susceptibility maps of Pityokteines curvidens in fir forests, revealing that NDVI, elevation, and stand structure were the most critical parameters. The AUC metric was calculated for the susceptibility maps pertaining to this particular species, yielding a value of 0.739 (Sivrikaya et al. 2023).

Table 1. The bioclimatic variables

Variables	Code	Unit
Annual mean temperature	BIO 1	°C
Mean diurnal range	BIO 2	°C
Isothermality	BIO 3	%
Temperature seasonality	BIO 4	°C
Max temperature of warmest month	BIO 5	°C
Min temperature of coldest month	BIO 6	°C
Temperature annual range	BIO 7	°C
Mean temperature of wettest quarter	BIO 8	°C
Mean temperature of driest quarter	BIO 9	°C
Mean temperature of warmest quarter	BIO 10	°C
Mean temperature of coldest quarter	BIO 11	°C
Annual precipitation	BIO 12	mm
Precipitation of wettest month	BIO 13	mm
Precipitation of driest month	BIO 14	mm
Precipitation seasonality	BIO 15	%
Precipitation of wettest quarter	BIO 16	mm
Precipitation of driest quarter	BIO17	mm
Precipitation of warmest quarter	BIO18	mm
Precipitation of coldest quarter	BIO19	mm

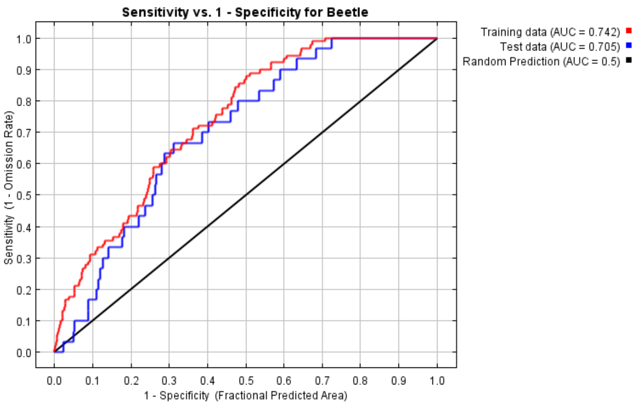

Figure 1. AUC values in ROC curve for bark beetle susceptibility map based on the MaxEnt

The bark beetle susceptibility map was found to be primarily influenced by the BIO 1 and BIO 19 variables, as indicated by the MaxEnt model output. These variables accounted for 35.8% and 35.3% of the overall contribution, respectively. Furthermore, it can be observed from Table 2 that the variables BIO 1, BIO 19, and BIO 14 collectively account for approximately 82% of the model. The variables BIO 17, BIO 19, BIO 18, and BIO1 were identified as the top four variables with the highest permutation importance for bark beetle susceptibility when analyzed independently. These variables accounted for 27.2%, 24.6%, 11.2%, and 10.9% of the permutation importance, respectively. The results indicate that the model developed exhibits a high degree of accuracy and applicability. The potential distribution of *Ips amitinus* was predicted using MaxEnt models under both current and future climate conditions. The species is likely to expand its range in Central, Southeastern, and Southern Europe. The MaxEnt estimate was primarily influenced by temperature, which accounted for 70.8% of the variation in the climate parameter (Økland et al. 2019). According to a study conducted by Méndez-Encina et al. (2021), the process of developing ecological niche models for the three primary Pinus species of *Dendroctonus mexicanus* revealed that a solitary variable (BIO 1) accounted for 93.9% of the model.

Table 2. Contribution and importance percentage of variables for MaxEnt

Variable	Contribution (%)	Permutation Importance (%)
BIO 1	35.8	10.9
BIO 19	35.3	24.6
BIO 14	11.0	10.0
BIO 17	4.2	27.2
BIO 4	4.0	4.2
BIO 12	3.3	4.4
BIO 18	3.3	11.2
BIO 7	1.1	7.5

Comparable outcomes were likewise noted in the jackknife analysis utilizing the training dataset. As per the Jackknife method, it was observed that BIO 1, BIO 19 and BIO 12 variables demonstrated the maximum level of influence among the variables present in the model (Fig. 2). At the same time, the jackknife test results indicate that the environmental variable exhibiting the highest gain in isolation is BIO 1, implying that it possesses the most valuable information independently. The variable that exhibits the most substantial reduction in gain upon its exclusion from the model is BIO 19.

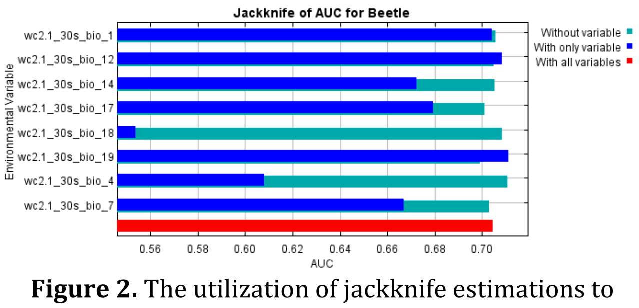

Figure 2. The utilization of jackknife estimations to determine variable importance in MaxEnt

The susceptibility of bark beetles can be classified into four distinct categories, namely low, moderate, high, and extreme, as illustrated in Figure 3. According to Table 3, the study area can be categorized into four sensitivity levels, with 30.5% classified as being in the extreme sensitivity category, 27.7% in the high sensitivity category, 21.3% in the medium sensitivity category, and 20.5% in the low sensitivity category. To clarify, it can be stated that around 58% of the study area comprises regions that are susceptible to bark beetle infestation.

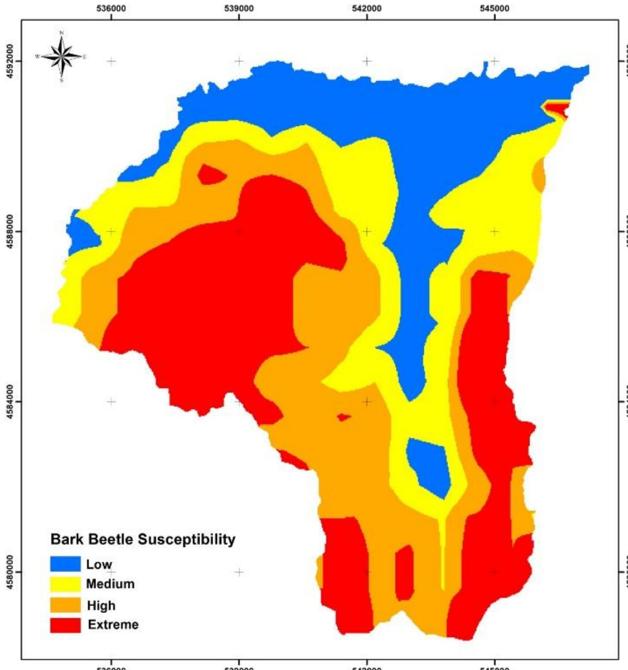

Figure 3. Bark beetle susceptibility map

Table 3. The area of bark beetle susceptibility classes

Bark Beetle Susceptibility Class	Area	
	ha	%
Low	2115.1	20.5
Moderate	2190.6	21.3
High	2837.2	27.7
Extreme	3129.2	30.5
Total	10272.1	100.0

4. Conclusion

Accurately and reliably predicting the potential distributions of harmful species holds significant importance in the sustainable planning of forests. MaxEnt, which utilizes data from prediction models, has gained significant popularity in recent times. The MaxEnt model utilized nineteen bioclimatic variables to forecast the sensitivity of *Ips sexdentatus*. The two most significant contributors were the BIO 1 and BIO 19 variables, which had values of 35.8% and 35.3%, respectively. Thus, it was determined that around 58% of the study area was susceptible to the detrimental effects caused by *I. sexdentatus*. The results of this investigation possess the potential to facilitate the monitoring of *I. sexdentatus* and similar species of bark beetles.

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