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Forest Site and Stand Structure Affecting the Distribution of Emerald Ash Borer, *Agrilus planipennis* Fairmaire, 1888 (Coleoptera: Buprestidae), in Eastern Ukraine

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Abstract: The Emerald ash borer (EAB), *Agrilus planipennis* Fairmaire, 1888 (Coleoptera: Buprestidae), an invasive phloem-boring beetle, was first detected in the Luhansk Region of Ukraine in 2019. Subsequently, it rapidly expanded its presence to encompass a significant portion of the Kharkiv region and the parks of Kyiv. Previous research has established that the climatic conditions in Luhansk and its neighboring regions are conducive to the EAB, and the absence of a host plant (*Fraxinus* sp.) does not act as a deterrent to the pest's expansion in Ukraine. Recognizing the urgency of identifying infested trees, our current research aimed to identify the most attractive EAB forest subcompartments based on forest site conditions and stand structure. Utilizing the MaxEnt model, we achieved an average performance in predicting the potential distribution of the EAB (AUC = 0.842). The six most impactful variables, contributing to 88.2% of the model, include "age of trees, years", "area of forest subcompartment, ha", "mean height of trees, m", "proportion of *Fraxinus excelsior* in the stand composition, %", "hygrotope index (humidity level), point", and "number of neighboring-non-forest subcompartments". Most likely, EAB occurrence is expected in the driest forest site conditions; the well-lit and warmed-up parts of stands, in particular; small subcompartments surrounded by non-forest landscapes; and forest shelter belts near roads and fields. However, the data obtained can be considered preliminary. To enhance the accuracy of our forecasting, it may be imperative to consider data on road localization, along which the pest can spread passively, as well as dominant wind speed.

Keywords: exotic pest; host range; European ash; *Fraxinus pennsylvanica*; attractive forest stands

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1. Introduction

The emerald ash borer (EAB), *Agrilus planipennis* Fairmaire, 1888 (Coleoptera: Buprestidae), is a phloem-boring beetle, originating from the temperate regions of Northeast Asia [1], that inadvertently found its way into North America and European Russia in the

1990s, likely introduced through infested ash material. The full extent of the catastrophe only became apparent in the early 2000s following the initial widespread outbreaks [2]. On its native range, the EAB colonized *Fraxinus mandshurica* Rupr. And *F. chinensis* Roxb. Without significant damage [3]. EAB displays a broader host range in secondary ranges, infesting all *Fraxinus* species and even a non-ash host, cultivated olive (*Olea europaea* L.) [4,5]. Over the past two decades, the range of EAB has expanded and continues to increase. Numerous kinds of research were devoted to predicting the ecological, economic, and social impacts of EAB, and management efforts based on studies of its host preference, cold tolerance, and many other features are summarized in well-known reviews [3,6]. Despite the diligent efforts of scientists and practitioners, EAB's relentless spread is evident, currently documented in 36 US states, 5 Canadian provinces, and 20 regions of Russia [6].

In 2019, EAB was first identified in Ukraine, specifically in the Luhansk Region [7,8]. However, the various larval instars and exit holes suggest that the pest likely infiltrated the region in 2017, potentially even earlier, potentially originating from the neighboring Voronezh region of Russia.

Within two years, the EAB has expanded its reach over 300 km westward from the initial detection site, colonizing hundreds of trees, both *F. excelsior* and *F. pennsylvanica* [9]. By the end of 2021, the pest was detected in most of the Luhansk region and the neighboring part of the Kharkiv region [9]. In 2022, EAB was identified in the parks of Kyiv [10], and by 2023, it had spread to a significant part of the Kharkiv region [11]. However, field research in 2022–2023 was hindered due to the region's involvement in active hostilities.

Consequently, during these years, investigations focused on the seasonal development of the EAB and climate variables influencing its successful survival. The wide range of bioclimatic variables in EAB regions indicates this pest's high ecological adaptability [9]. The westward spread of EAB from the Luhansk region to the west was predicted using the MaxEnt model, and a comparative analysis of the most significant bioclimatic indicators was conducted between its natural and invasive ranges. Climate favorableness for EAB in Luhansk and neighboring regions further underscores the urgency of addressing this invasive threat [9].

A sufficient number of host trees is a second important condition (besides climate) for EAB spread [12]. In Ukraine, ash forests encompass approximately 150,000 hectares, or 2.4% of the total forested area [13]. Among them, *F. excelsior* stands are dominant, covering nearly 87% or 130,000 hectares, while the remainder are predominantly *F. pennsylvanica*. The majority of ash stands (93.6% or 121,700 hectares) are interspersed with other broadleaved tree species with different proportions of ash. Both ash species are also presented in roadside shelter belts and urban stands in Ukraine [14], although comprehensive data regarding the total area of these plantings are currently unavailable. Consequently, ash as a host tree for EAB is widespread throughout Ukraine.

The primary challenge of effective EAB management is early detection, but this becomes intricate. In young trees, EAB colonizes trunks and branches with a bark thickness ranging from 1.5 to 5 mm [15]. This bark provides sufficient protection for larvae and pupae from desiccation, extreme temperatures, predators, and parasitoids, typically characterizing stems and branches with a diameter of 5–10 cm [15]. Conversely, in large-diameter trees, EAB first inhabits individual branches of high trees, and the crowns of inhabited trees do not differ from uninhabited ones [16–18]. To reveal such trees from the ground (without tree felling) becomes possible only after the woodpeckers begin to peck the galleries [11].

Assessing EAB in the early stages of tree colonization on cut sample branches is labor-intensive [17], prompting the need to identify trees or stands most attractive to the pest, where EAB abundance and outbreak area may rapidly increase [12].

The frequency and intensity of the forest pest outbreaks, as well as the forest damage, vary in different regions and even in the neighboring plots of the same stand [19,20]. It can be explained by a variety of microclimates that depend on forest site conditions and stand structure, as well as on host trees' availability and preferences for given pests [21–23]. To identify the most attractive forest plots for EAB, it is necessary to compare its prevalence in the stands for various parameters of forest site condition and stand structure.

Existing publications suggest that EAB exhibits a preference for trees with open or sparsely populated canopies for mating and egg-laying [24,25]. The density of the population, the speed of development, and the overall survival of individuals are greatly exposed to higher levels of light [15], especially those situated at the edges of forests [1,26].

In the forest management of Ukraine, the territory of each forest unit is divided into compartments (predominantly square or rectangular), delimited by natural (roads, rivers) or man-made boundaries [27]. Within each compartment, subcompartments are identified, in which the stands have similar tree species composition, age, relative density of stocking, and other mensuration parameters. Following this, in the forest management database, all characteristics of the stands are presented by subcompartments, and all measures on forest management, including forest protection, are also planned and executed by subcompartments [27].

Assessment of the distribution of forest subcompartments with different proportions of the preferred host trees, type of forest site conditions, relative density of stocking, tree age, and origin (seed, vegetative) makes it possible to identify the subcompartments with the highest probability in outbreaks of certain species or groups of phytophagous insects, particularly for the defoliators of *Quercus robur* L. and *Pinus sylvestris* L. [23,28], bark beetles in pine forests [29], and some other groups of phytophagous insects [30].

Therefore, our current research aimed to identify the most attractive forest subcompartments for the EAB, considering forest site conditions and forest structure.

For this purpose, data analysis from the ground survey for 2020–2021 in the forests in the region of EAB invasion in the Luhansk region of Ukraine and MaxEnt modeling were used. MaxEnt uses the principle of maximum entropy on presence-only data to estimate a set of functions that relate environmental variables and habitat suitability to approximate the species' niche and potential geographic distribution [31]. MaxEnt has been successfully used many times to predict the ecological niches and ranges of plant and animal species [32–34], although not all forecasts regarding the spread of this pest have been realized [9,35].

As EAB continues expanding its range in Ukraine, we consider our data obtained to be preliminary. However, we hope that the data obtained will help the Forest Protection Service in time to detect new outbreaks of EAB.

2. Materials and Methods

2.1. Study Region

The entry point of the emerald ash borer (EAB) into Ukraine was documented in the Luhansk region (Figure 1).

This region is situated within the steppe Atlantic continental climatic region, characterized by the highest continentality and aridity. Geobotanically, the area is classified as diverse feather-grass, fescue-feather-grass, and worm-wood steppes. Based on forest typological zoning, it falls within the Donetsk Bayrak forest region, and according to comprehensive forestry zoning, it belongs to the Forest-Steppe, Left-Bank Dnieper Forest-Steppe District, and Northern (Bayrak) Steppe [36,37]. The region experiences scorching and arid summers marked by drought and hot dry winds, as well as cold and low-snow winters featuring regular thaws, fog, and ice-covered ground; uneven distribution of precipitation in the year and the growing season; dust storms; and snowstorms. The maximum air temperature in July reaches +39 °C (+42 °C on 12 August 2010), while the minimum in January drops to −38 °C (−41.9 °C on 8 January 1935). Frequent thaws occur in winter, with temperatures rising to +15 °C. The annual precipitation is 445 mm, and droughts are recorded on average once every three years. During the growing season, easterly winds prevail [38], contributing to the EAB spreading westward.

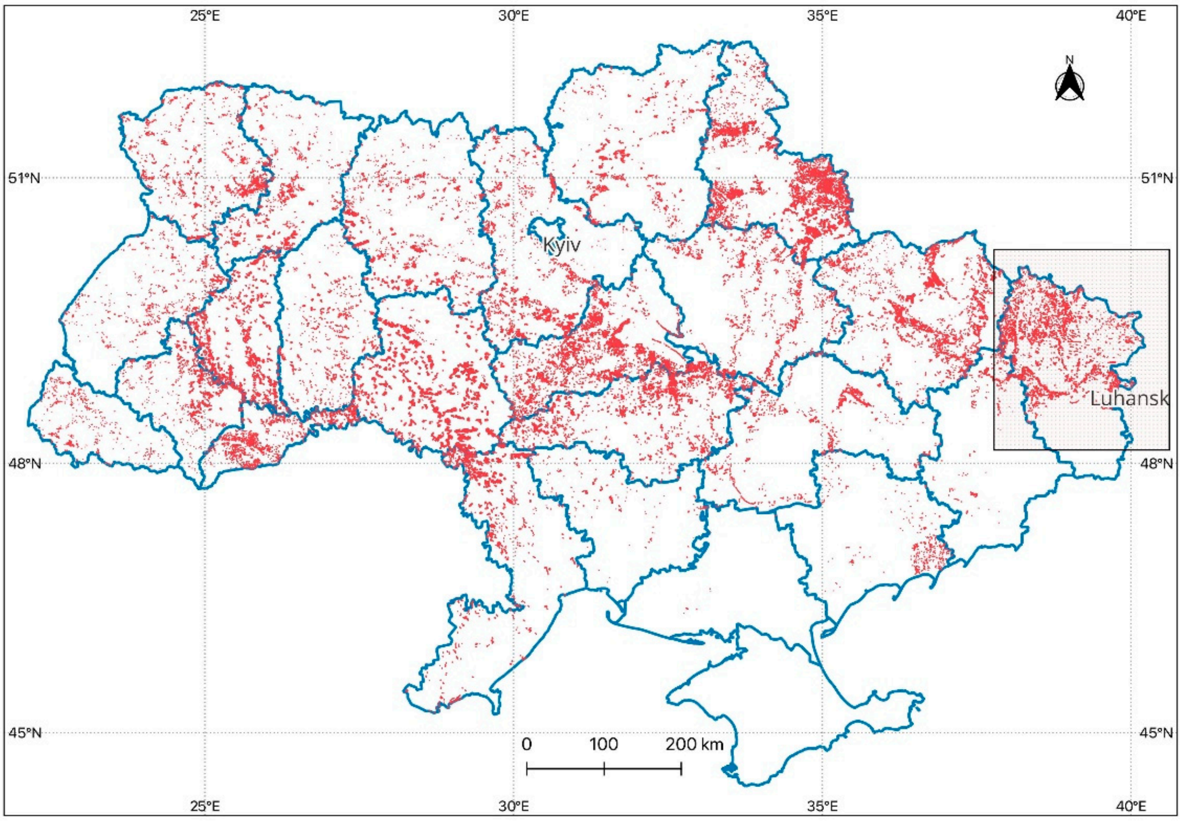

Figure 1. Forest subcompartments (red pixels) containing European ash within the territory of Ukraine (specific emphasis on the Luhansk region—the location where the EAB first entered and underwent field survey).

Forests cover 11.5% of the territory of the Luhansk region, primarily in small areas along rivers, on ravine slopes, and in gullies. More than 70 tree species grow in the forests and forest shelter belts of the Lugansk region; in particular, these include *Quercus robur* L., *Pinus sylvestris* L., *Robinia pseudoacacia* L., *F. excelsior*, and *F. pennsylvanica* [39,40]. The proportion of the area of forests with *F. excelsior* and *F. pennsylvanica* is 5.4% and 3.0%, respectively [40], and in forest shelter belts, 8.0% and 14.7%, respectively [40].

2.2. Field Data

Information regarding the presence of EAB in the Luhansk region was obtained during the ground survey in 2020–2021 (the first years of the pest's invasion into the Lugansk region), covering latitudes from 49°49′03.0″ N to 49°14′03.6″ N and longitudes from 38°51′43.7″ E to 39°21′57.2″ E.

The ground survey covered 300 forest subcompartments with *F. excelsior* or *F. pennsylvanica* in the stand composition with a visual examination of 20 to 100 trees in each subcompartment for signs and symptoms of EAB infestation. The signs and symptoms of an EAB presence were sparse crowns and dieback (Figure 2a), traces of damage by insectivorous birds (Figure 2b), mainly woodpeckers (Picidae), bark splits, as well as D-shaped adult exit holes (Figure 2c) [11,16,41]. If an EAB presence was suspected, the bark was opened and the galleries were examined with insect identification (Figure 2d).

(**a**) (**b**)

(**c**) (**d**)

Figure 2. Symptoms and signs of EAB infestation: (**a**) sparse crowns and dieback; (**b**) traces of damage by insectivorous birds; (**c**) D-shaped adult exit holes; and (**d**) EAB galleries.

Variables representing forest site conditions and stand characteristics (Table 1) were obtained from the Database of Production Association "Ukrderzhlisproekt".

Table 1. Variables representing forest site conditions and stand characteristics.

Variable Short Name	Variable Description	Limits
Var_1	Hygrotope index (humidity level)	0, 1, 2, 3, 4, 5
Var_2	Trophotope index (A, B, C, D)	1, 2, 3, 4
Var_3	The proportion of *F. excelsior* in the stand composition, %	10–100
Var_4	The presence of any *Fraxinus* species in the stand composition	1/0
Var_5	Age of trees, years	30–110
Var_6	Mean height of trees, m	6–25
Var_7	Mean diameter of trees, cm (DBH)	4–36
Var_8	Relative density of stocking	0.5–0.9
Var_9	Site index class	1–5
Var_10	Area of forest subcompartment	0.5–59.5
Var_11	Number of non-forested lands neighboring subcompartment	0–8

A combination of soil richness levels (trophotope—nutritional richness for trees) (A, B, C, and D), and humidity levels (hygrotope) (0, 1, 2, 3, 4, and 5) characterize each forest subcompartment, aligning with the Ukrainian forest typology [36]. Group A ("bor") is characterized by sandy soils, as well as oligotrophic (nutrient-poor) vegetation (*Pinus* spp., *Betula* spp.). At the same time, group B ("subor") features sandy clay soils and mesotrophic (moderately fertile) vegetation (*Quercus* spp., *Populus* spp., *Picea* spp.). Clay loam soils together with megatrophic flora (*Acer* spp., *Tilia* spp., *Alnus* sp., and *Fraxinus* spp.) define group C ("sugrud"), and clay soils, conducive to the optimal development of mesotrophic and megatrophic (highly fertile) vegetation and the lack of oligotrophic are characteristic for group D ("grud"). Six soil moisture regimes (potential hygrotope) are identified: 0—very xeric, 1—xeric, 2—submesic, 3—mesic, 4—subhygric, and 5—hygric (wetland) [36].

The distribution of subcompartments with an EAB presence or absence was evaluated by each variable characterizing the forest site and stand structure. Such distributions for EAB presence and EAB absence were analyzed using a χ^2-text comparing observed χ^2 values with χ^2 values at $p = 0.05$ or $p = 0.01$ [42,43].

2.3. Modeling the Spread of the Emerald Ash Borer

The spread of *A. planipennis* was projected using a niche model generated in MaxEnt software, version 3.4.4 [44,45]. This software was chosen due to its capability to handle presence-only data and accommodate a limited number of presence points [34].

In preparation for MaxEnt, all parameters were used as real. Trophotope classes A, B, C, and D were converted to 1, 2, 3, and 4, respectively (Table 1). Several consecutive operations were executed using QGIS 3.3.2 [46]:

- Attributive data (variables for each subcompartment as an XLSS file) and subcompartment geometry (Esri shp format) were joined in one vector layer for the whole Luhansk region;
- Subcompartments with a *Fraxinus* sp. presence were selected;
- Vector layer projection was converted to EPSG:3856 (Pseudo-Mercator);
- Values of each variable (columns or fields) in the attribute table (see Table 1) were converted to raster images in the GeoTIFF format;
- All raster images obtained were converted to ASC files for further use in MaxEnt 3.4.4.

For forest plots inspected with unknown coordinates, we used the centroids of respective compartments and then exported them in a CSV file for further use in MaxEnt 3.4.4.

The variables listed in Table 1 served as predictors, and the algorithm identified the most important variables based on the preset regularization parameters. The default setting of "cross-validation" was selected for replicates of the Species Distribution Models

(SDMs), as it effectively utilized all available data and maximized the utility of the limited dataset [47]. The forest layer for the map (ESA WorldCover 10m v200) was sourced from the dataset Google Earth Engine [48]. QGIS 3.3.2 was utilized for map creation [46].

To assess model performance, the area under the curve (AUC) parameter of the ROC (receiver operating characteristic) was employed [47]. AUC reflects the probability of accurately predicting the existence of emerald ash borer in forest subcompartments. If the AUC value approached 0.5 for the experimental data, the model demonstrated performance equivalent to a random model; $0.5 \leq$ AUC < 0.7 denotes poor performance, $0.7 \leq$ AUC < 0.9 denotes average results, and $0.9 \leq$ AUC < 1 denotes high performance [31,45,47].

The impact of variables on the obtained model was assessed through both contribution and permutation coefficients. For verification, the jack-knife test is included in the MaxEnt software [45]. It generates three various models for each variable. The first model is without any variable, while the second and third comprise one and all the variables, respectively (Table S1). This test enables us to determine the significance of each independent variable in the creation of the model.

The frequency of EAB presence in different grades of studied variables was estimated as the proportion of the number of subcompartments with EAB presence from all surveyed subcompartments (observed probability of pest existence (POP)) and used for comparison with probability predicted by MaxEnt (predicted probability of pest existence).

3. Results

3.1. Field Data

A ground survey in 300 forest subcompartments confirmed EAB presence in 194 subcompartments (64.7%) and EAB absence in 106 subcompartments (35.3%). The distribution of subcompartments with EAB presence and EAB absence by *Fraxinus* sp. tree age (Figure 3a) differed significantly (χ^2 = 15.2; $\chi^2_{\ 0.05}$ = 9.5; $\chi^2_{\ 0.01}$ = 13.3). The stands of less than 20 years grow in 5.2 and 1.9% of surveyed subcompartments with EAB presence and EAB absence, respectively. However, ash trees in 81–100 years grow in 5.2 and 17% of surveyed subcompartments with EAB presence and EAB absence, respectively.

The proportion of subcompartments in an area less than 20 ha with EAB presence exceeds 80% (Figure 3b). The proportion of subcompartments in the smallest area with EAB absence is 1.4 times less. Subcompartments with an area of more than 20 hectares are more represented among forest stands where EAB was not found. The distribution of subcompartments with EAB presence and EAB absence by subcompartment area (Figure 3b) differed significantly (χ^2 = 16.1; $\chi^2_{\ 0.05}$ = 6.0; $\chi^2_{\ 0.01}$ = 9.2).

The distribution of subcompartments with EAB presence and EAB absence by ash tree height (Figure 3c) differed significantly (χ^2 = 8.7; $\chi^2_{\ 0.05}$ = 6.0; $\chi^2_{\ 0.01}$ = 9.2). The greatest differences in the proportion of EAB present and EAB absent were found for ash trees up to 10 m high.

Despite the tendency for the EAB presence growth with ash tree proportion (r = 0.5), the distribution of subcompartments with EAB presence and EAB absence by ash proportion in the stand composition (Figure 3d) did not differ significantly (χ^2 = 5.6; $\chi^2_{\ 0.05}$ = 16.9).

EAB presence decreased with the growth of site humidity (hygrotope level) (Figure 3e). The distribution of subcompartments with EAB presence and EAB absence by hygrotope level differed significantly (χ^2 = 6.8; $\chi^2_{\ 0.05}$ = 6.0; $\chi^2_{\ 0.01}$ = 9.2).

The distribution of subcompartments with EAB presence and EAB absence by the number of neighboring non-forest compartments (Figure 3f) did not differ significantly (χ^2 = 1.3; $\chi^2_{\ 0.05}$ = 6.0).

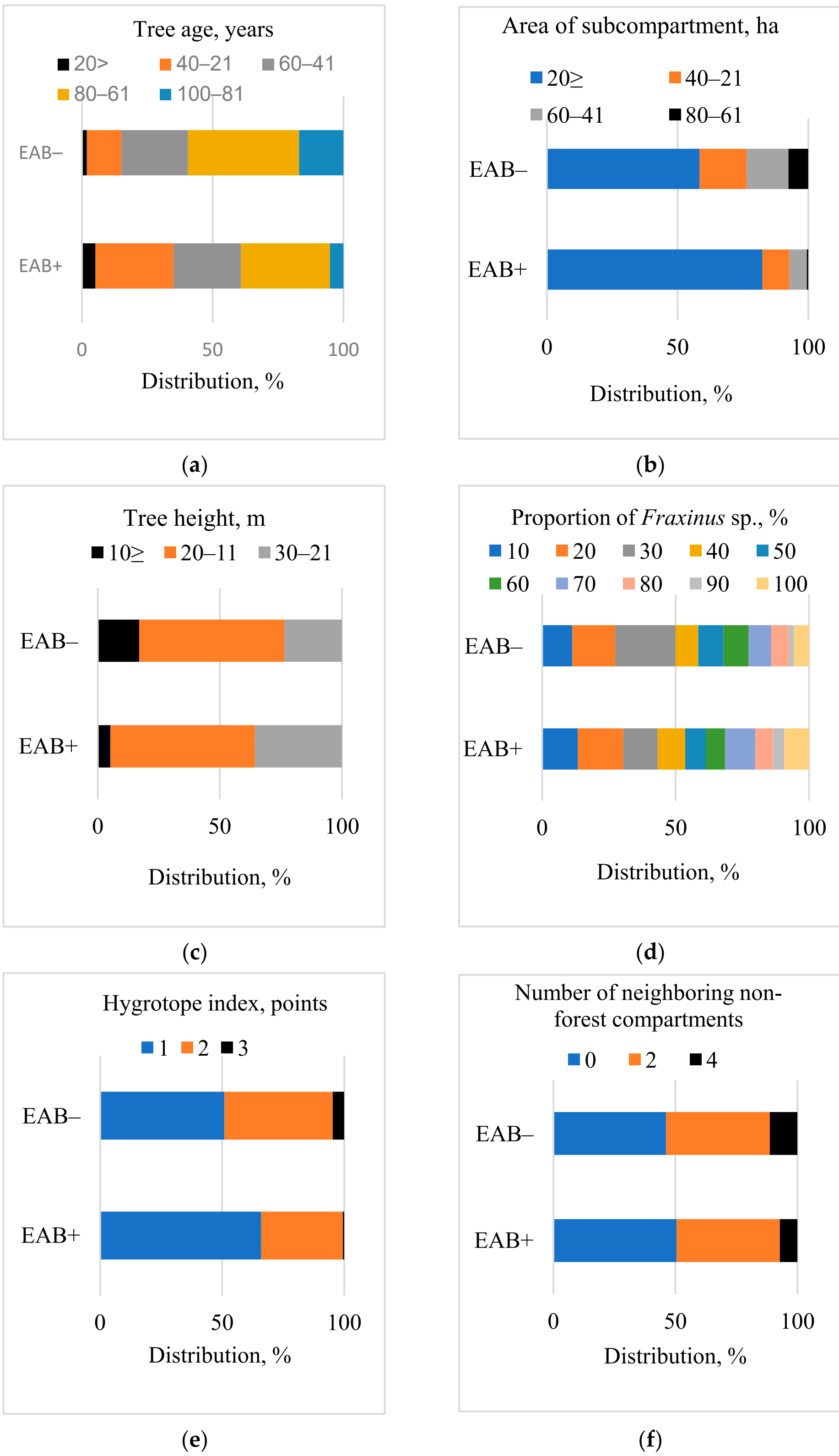

Figure 3. Distribution of variables in the compartments with EAB presence and absence: (**a**) by *Fraxinus* tree age; (**b**) by the area of subcompartment; (**c**) by *Fraxinus* tree height; (**d**) by the proportion of *Fraxinus* sp. in the stand composition; (**e**) by hygrotope index; and (**f**) by the number of neighboring non-forest subcompartments.

3.2. Modeling the Spread of the Emerald Ash Borer

MaxEnt accurately forecasted the potential distribution of the emerald ash borer, yielding a commendable test under the curve (AUC) value of 0.842 accompanied by a standard deviation of 0.018 (Figure 4).

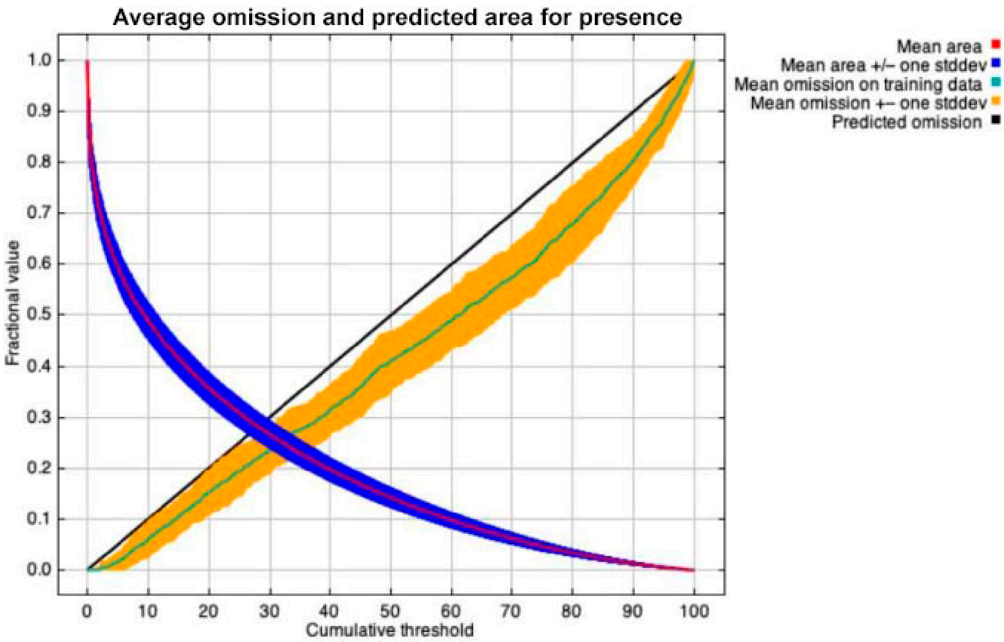

Figure 4. Average omission and predicted area (generated by MaxEnt).

The receiver operating characteristic (ROC) curve confirmed that the performance of the model was sensitive (Figure 5).

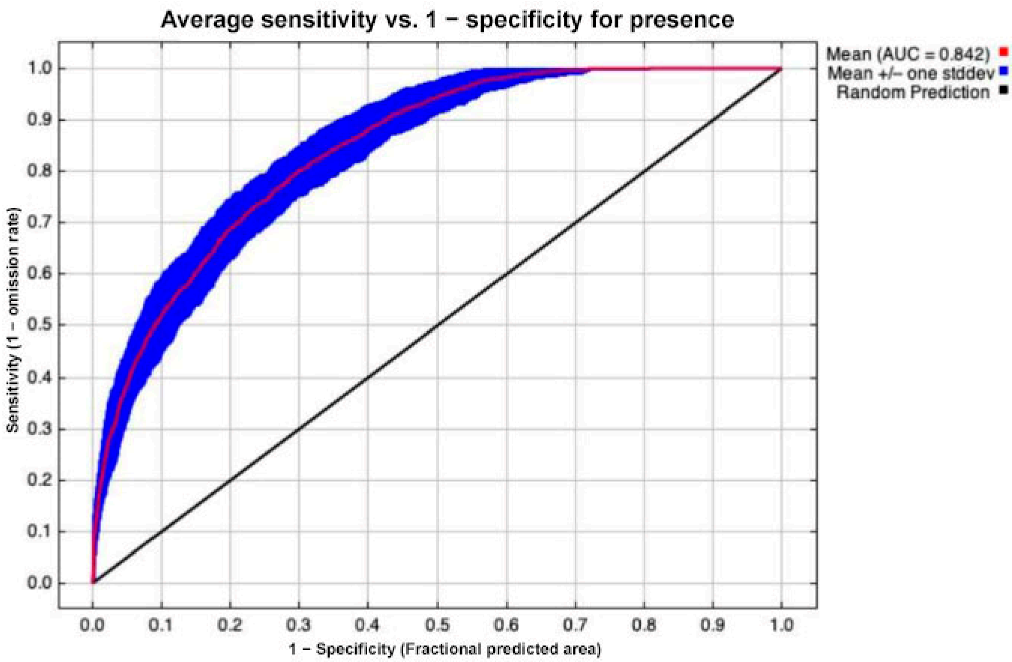

Figure 5. Reliability of the prediction (generated by MaxEnt).

Additionally, the jack-knife test option in the MaxEnt modeling program revealed that the variable "age" gave the most information (Figure 6).

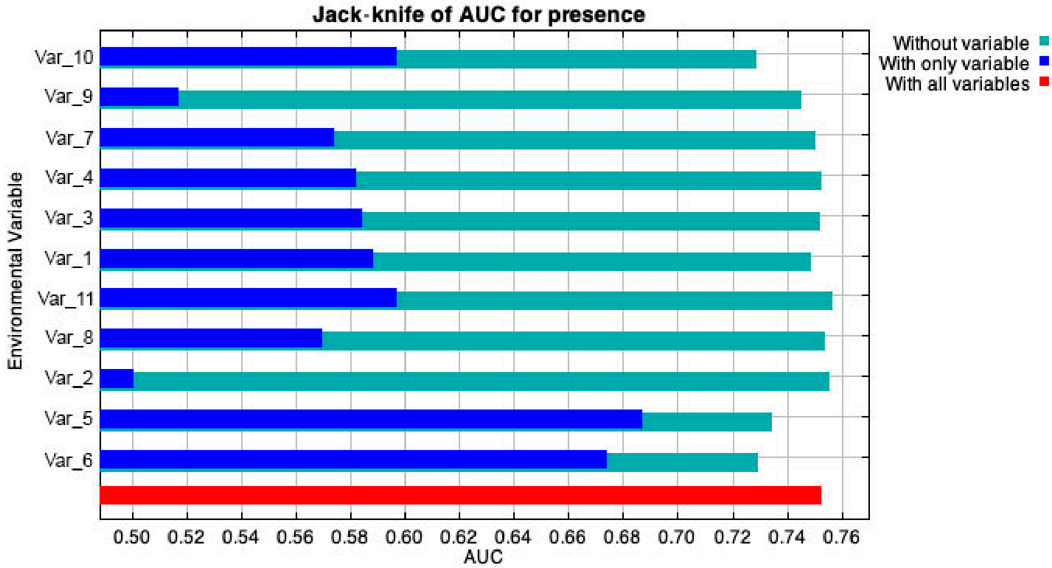

Figure 6. Jack-knife test of variable importance (green: without variable, blue: with only variable, red: with all variables) (generated by MaxEnt) and reliability of the prediction (generated by MaxEnt; values shown are averages over replicate runs).

Based on the calculations, the age of trees exhibited the highest significance in constructing the EAB range model, accounting for 38.9% of the model's influence (Table 2).

The highest permutation of the variable "age of trees" is estimated in young age categories (Table 2; Figure 7a).

Table 2. The MaxEnt probability of EAB existence is primarily influenced by variables, which are presented in descending order of significance.

Variables	AUC	Contribution, %	Permutation, %	Aggregated Contribution, %
Age of trees, years (Var_5)	0.7	38.9	31.4	38.9
Area of forest subcompartment, ha (Var_10)	0.6	13.9	11.2	52.8
Mean height of trees, m (Var_6)	0.7	11.2	17.1	64.0
The proportion of *F. excelsior* in the stand composition, % (Var_3)	0.6	10.6	4.3	74.6
Hygrotope index (humidity level), points (Var_1)	0.6	8.3	13.5	82.9
Number of non-forested lands neighboring subcompartment, point (Var_11)	0.6	5.3	3.6	88.2
Site index class, point (Var_9)	0.5	5.8	8.3	94.0
Relative density of stocking, unit fraction (Var_8)	0.6	2.1	2.6	96.1
Mean diameter of trees, cm (DBH) (Var_7)	0.6	1.7	5.5	97.8
Trophotope index (soil richness level), points (Var_2)	0.5	1.3	1.0	99.1
The presence of any *Fraxinus* species in the stand composition, 1/0 (Var_4)	0.6	0.9	1.4	100.0

Note: AUC (area under the curve) is calculated for each variable, serving as a metric to assess the model's performance.

The variable "area of forest subcompartment" takes second place in terms of contributing to the model (Table 2). Pest foci are found more often in the subcompartments of a low area (Figure 7b), which are characteristic of the sparsely forested Luhansk region.

The variable "mean height of trees, m" takes the third place in terms of contributing to the model (Table 2). The probability of colonization by EAB increases with tree height; however, the observed probability of EAB presence in low trees exceeds the predicted one (Figure 7c).

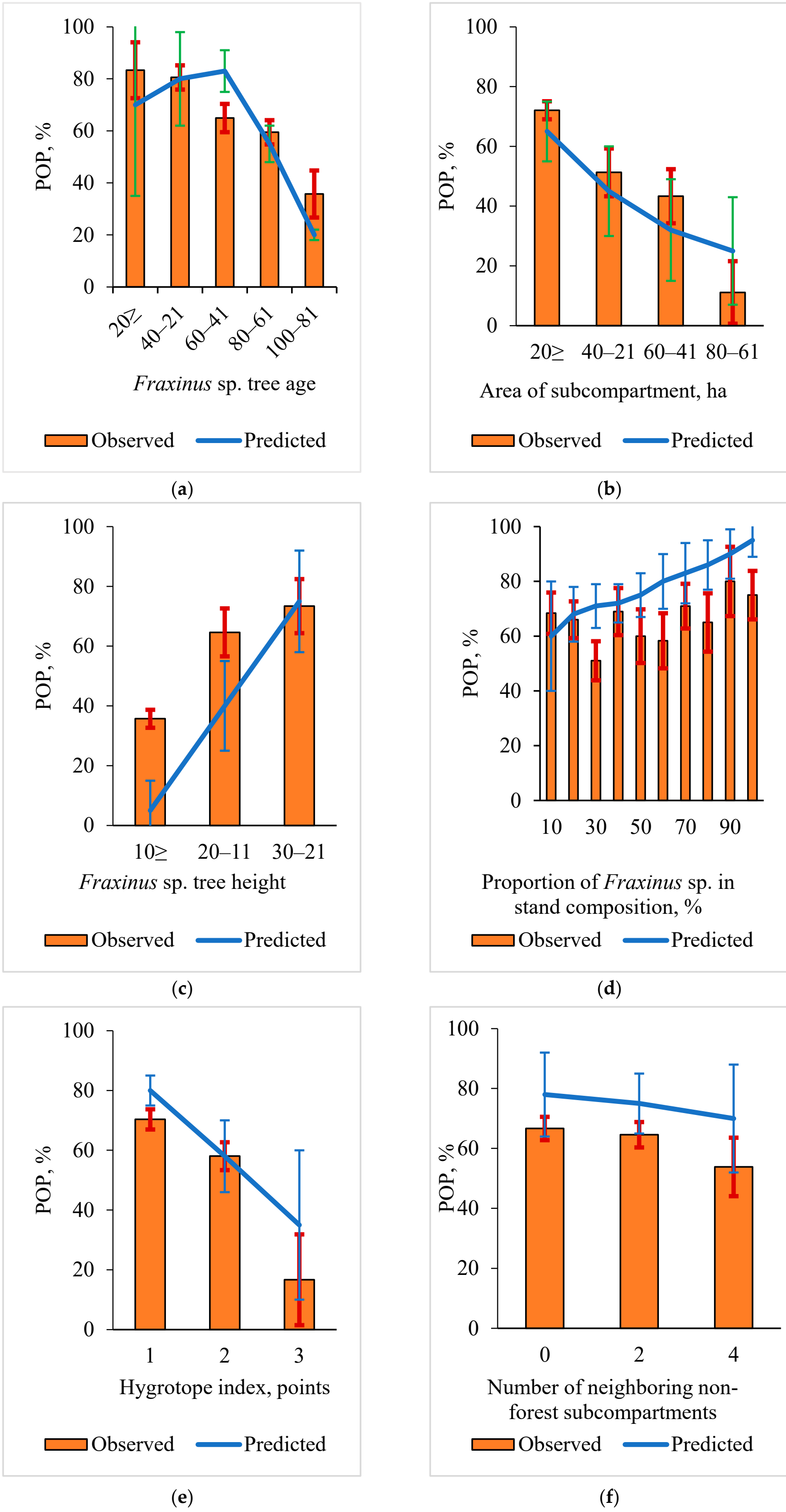

Figure 7. Observed and predicted dependences in the probability of pest existence (POP) on certain variables characterizing site and stand structure in forest subcompartments. Variables: (**a**) *Fraxinus* sp. tree age; (**b**) area of subcompartment; (**c**) *Fraxinus* sp. tree height; (**d**) proportion of *Fraxinus* sp. in the stand composition; (**e**) hygrotope index; and (**f**) number of neighboring non-forest subcompartments. Bars represent standard deviation for the observed data (red bars) and the permutation for predicted data (blue bars).

The percentage of *F. excelsior* in the stand composition contributes 10.6% to the EAB prediction model with a rather low permutation (Table 2). With an increase in the proportion of *F. excelsior* in the stand composition, the probability of colonization by EAB rises (Figure 7d).

"Hygrotope index (humidity level)" contributes 8.3% to the model of EAB spread, but has a rather high permutation,13.5% (see Table 2). The probability of colonization by EAB increases in drier conditions (Figure 7e).

The mentioned six variables describe 88.2% of the contribution to the modeling of the probability in EAB presence (see Table 2). The trend in the observed proportion of subcompartments with the presence of EAB coincides with the POP predicted by the model for each of these variables.

The model revealed a possibility of EAB spread in all forest compartments with *Fraxinus* sp. in the stand composition in the Luhansk region. We used four thresholds to create potential distribution maps: ≤30% POP means low suitable, 31%–60% means moderately suitable, 61%–90% means suitable, and >90% means highly suitable territory (Figure 8).

Distribution in the number of subcompartments and their area were calculated for subcompartments with EAB present (at ground survey), with EAB absent (at ground survey), and for subcompartments that were not surveyed (Figure 9).

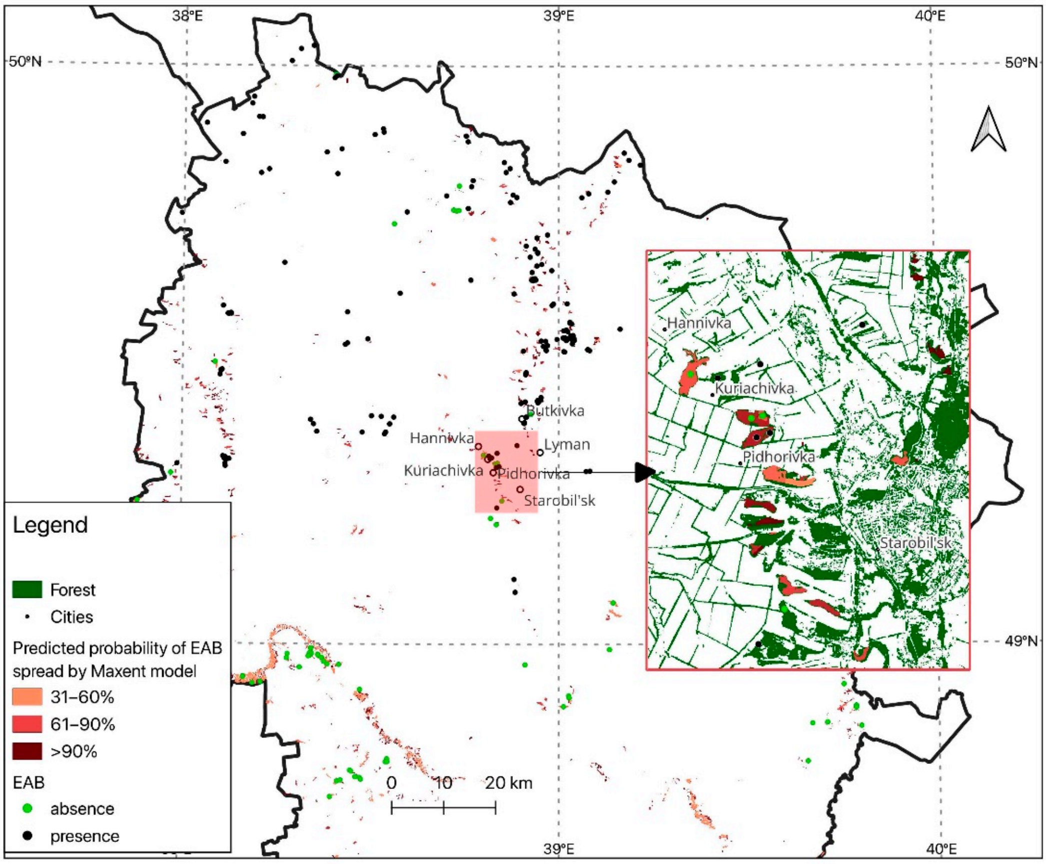

Figure 8. The expected spreading area for the emerald ash borer (EAB) was estimated through MaxEnt modeling. The segment with the maximum probability of EAB infestation is enlarged. Dark dots denote points where the beetle was registered, while light dots indicate points where EAB was absent in 2021. The color of forest fragments corresponds to the predicted likelihood of EAB distribution in each forest subcompartment (see the legend).

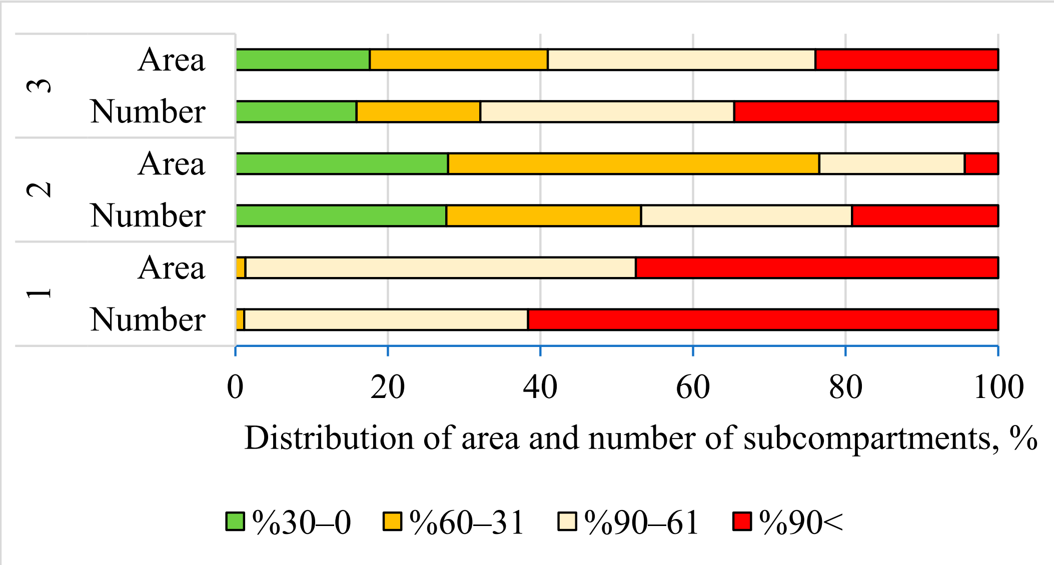

Figure 9. Distribution of area with *Fraxinus* sp. and the number of respective subcompartments predicted by MaxEnt modeling: 1—subcompartments where EAB was absent at the ground survey; 2—subcompartments where EAB was present at the ground survey; 3—subcompartments which were not surveyed.

Distribution in the number of subcompartments and their area was calculated for subcompartments with EAB present (at ground survey), with EAB absent (at ground survey), and for subcompartments that were not surveyed (Figure 9). According to the MaxEnt forecast, in the forests where EAB was detected during the ground survey, there were no low suitable stands for this pest, and highly suitable stands account for 61.6% of the subcompartments and 47.5% of the area. In forests where EAB was not detected during the ground survey, low suitable stands account for 27.7% and 27.9% of the number of subcompartments and area, respectively, and highly suitable stands account for 19.1% and 4.4% by the number of sub-compartments and area. In forests not surveyed in 2020–2021, low suitable and moderately suitable stands for EAB infestation together account for 32.1% of the subcompartments and 40.9% of the area, and suitable and highly suitable stands for this pest together comprise 67.9% of the subcompartments and 59.1% of the area.

4. Discussion

The survival success of a non-indigenous species in establishing itself in a new region is contingent upon favorable climatic conditions [49,50], a sufficient number of host trees [51], and a minimum in competitors or entomophagous [52,53]. Therefore, various approaches to predicting the EAB spread have considered climatic conditions favorable for pest survival and propagation [33,49,54,55], the spread of a host plant [12,56], landscape and stand characteristics [57], the possibility of active adult migration along the roads and the passive spread of larvae with wood chips [32], other trunk fragments with bark, and various combinations [6].

It has been demonstrated that EAB is well-adapted to temperature variations [6]. Particularly in Ukraine, using the MaxEnt model and 19 bioclimatic variables [9] resulted in high accuracy (AUC = 0.988) in predicting EAB invasion for 87% (Luhansk), 48% (Kharkiv), and 32% (Donetsk). Field inspection confirmed that EAB spread in 2020–2021 in most of the Luhansk region and the southeast of the Kharkiv region [14]. In 2022, EAB was discovered in the parks of Kyiv [10], and, in 2023, in shelter belts of a significant part of the Kharkiv region, including urban plantings of Kharkiv [11].

An analysis shows that *Fraxinus* sp. is rather abundant in the forest (see Figure 1), as well as in the shelter belts and urban plantings of Ukraine [13,39], suggesting that the lack of a host plant does not hinder the expansion of EAB in Ukraine. At the same time, in the

Luhansk region, *Fraxinus* sp. in the forest is represented on 12.3 thousand hectares, in the Kharkiv region on 7 thousand hectares, in the Kyiv region on 6.1 thousand hectares, and in the Sumy region on 12.8 thousand hectares [13]. However, there are regional variations, such as EAB's absence in the Sumy region [14], but it is present in Kyiv [10]. Non-published information about the mass decline of *F. pennsylvanica* marshall in the shelter belts along the Kharkiv–Kyiv highway suggests that the pest spreads mainly in this way.

A ground survey of EAB-infested and neighboring stands began in 2020 and continued in 2021. In February 2022, Russia started military actions, and as a result, part of the territory of Ukraine is under occupation, and the rest of the territory is subjected to shelling and partial mining, which limits the possibility of access to the forest and routine surveys and pest assessment. However, the results of forest surveys in 2020–2021 allow us to identify some features of EAB distribution depending on forest site conditions and the structure of stands. The primary analysis of these features is presented in this paper, and the data obtained are used to predict the combination of conditions in which new EAB outbreaks may occur.

All information on forest site conditions and forest structure is confined to the subcompartments and concentrated in the forestry databases [27]. During a ground survey of 300 forest subcompartments, we found ash trees infested with EAB in 194 subcompartments.

The choice of trees for infestation depends on certain ecological conditions that allow EAB to infest the tree and to complete development under the bark: the position of the tree on the edge or inside the stand, the greater height of the tree compared to adjacent trees provide sun exposure, and increasing bark temperatures that are favorable for larval growth [1,58–62].

Among the parameters that characterize forest site conditions and stand structure, 11 variables were selected that were used both for direct survey data analysis and for modeling the EAB distribution using MaxEnt. When implementing MaxEnt, 11 variables that characterize the forest stands of the Luhansk region populated with EAB in 2020–2021 were used. The reliability of the EAB spread prediction model was statistically confirmed (AUC = 0.842), and the contribution of individual variables was evaluated (see Table 2). The most significant six variables explained 88.2% of the model, particularly «age of trees, years», «area of forest subcompartment, ha», «mean height of trees, m», «the proportion of *F. excelsior* in the stand composition, %», and «hygrotope index (humidity level), point». The distribution of subcompartments with EAB presence and EAB absence were estimated according to the gradations of these six variables.

The largest differences in the distribution of such subcompartment groups (significant at $p = 0.01$) were found for the variables "*Fraxinus* sp. tree age" (Figure 3a) and "subcompartment area" (Figure 3b). The variable "age of trees, years" (38.9%) has the largest contribution to the model (see Table 2) because EAB colonizes trees of all ages, but favors parts of the trunk and branches with thin bark [59,63]. Hence, colonization in the upper trunks and crowns of trees over 60 years old is often impossible to see from the ground. It is for this reason that the contribution of the variable "mean diameter of trees" ranks one of the last among the considered indicators (see Table 2). However, it usually correlates with the age of trees [36]. Thus, there were more EAB-infested than EAB-non-infested subcompartments in ash up to 20 years old, and more EAB-non-infested subcompartments after 60 years of age. A decrease in the proportion of infested subcompartments with increasing age of stands was observed in the direct analysis of the field data (Figure 3a) and in modeling with MaxEnt (Figure 7a).

Many studies in different regions have investigated the role of host spatial distribution, tree diameter, and bark roughness in EAB distribution [63–67]. EAB was found to infest trunk sections with bark thicknesses ranging from 1.5 to 5.5 mm, with a maximum density of 2.1 galleries/sq dm at a bark thickness of 3.5–4 mm, corresponding to a tree diameter of approximately 10 cm [15]. Higher EAB mortality was observed in trees with a rougher bark. However, the diameter of branches in the canopy of large trees approximates the size of smaller trees with optimal bark thickness [63].

Our ground surveys in the Lugansk region showed that EAB occurrence decreased as the subcompartment area increased (Figures 3b and 7b). The more frequent EAB spread in forest subcompartments of smaller areas can be explained by the fact that the study region belongs to the steppe zone, the size of forest subcompartments is often quite small, and they are surrounded on different sides by non-forest landscapes and have illuminated edges for a sufficient length. In addition, it is easier for adults to fly between such areas. In such subcompartments, the trees are better lit and heated, which benefits EAB for oviposition; larvae develop faster in them [1,2,15]. Such conditions are typical for forest edges [41,59–61]. The presence of EAB in urban plantings is consistent with information from other regions about its preference for more illuminated trees [15], particularly at the forest edges [1,26], and sparse crowns for mating and laying eggs [18,25], as well as with EAB detection in the parks of St. Petersburg [68], Moscow [69], Kyiv [10] and Kharkiv [11]. However, a significant increase in EAB presence as the number of neighboring non-forest subcompartments increases (Figures 3f and 7f) was not detected. This indicator may be considered in combination with the size of the subcompartment and the characteristics of the stand. Thus, the probability of outbreaks in bark beetles in pine forests significantly increased in stands that were adjacent to fresh clear-cuts [29].

Differences in the distribution of subcompartments with EAB presence and EAB absence, significant at $p = 0.05$, were found for the variables "ash tree height" (Figure 3c) and "hygrotope level" (Figure 3e). Variable "mean height of trees" takes the third place in terms of contribution to the MaxEnt model after "*Fraxinus* sp. tree age" and "subcompartment area" (see Table 2). The proportion of EAB-inhabited subcompartments increases with tree height (Figures 3c and 7c). It can be explained by the dependency of the available bark surface of the trunk and branches for colonization by EAB on the tree height. The tops of tall trees are better lit, making it easier for females to penetrate to lay eggs. However, the observed probability of EAB presence in low trees exceeds the predicted one (Figure 7c). It is possible that in this region, it is necessary to separately consider the crown structure, particularly the presence of branches accessible for EAB colonization.

The higher probability of EAB spread in drier conditions (hygrotope 1–xeric) (Figures 3e and 7e) is consistent with the fact that submesic and mesic forest site conditions (hygrotopes 2 and 3, respectively) [36] are more favorable for ash, and in less favorable conditions, the trees are more weakened and susceptible to pest infestation [70]. This is shown for different species of trees and phytophagous insects [23,29,71–73]. Thus, it has been found that EAB prefers to colonize trees with sparse crowns, and its larvae develop more slowly in healthy trees [18,25]. In more lightened trees, EAB has a higher population density, development rates, and survival [15], particularly at the forest edges [1,26].

An increase in EAB presence with an increasing proportion of ash in the stand was expected, as mixed stands are usually more resistant to pests [74,75]. However, only a weak trend was identified (Figures 3d and 7d). EAB even colonized subcompartments where ash was present only singly. In the region of our research, EAB colonizes *F. excelsior* and *F. pennsylvanica* [14]. The first species grows mainly in forests, and the second mainly in forest shelter belts and urban plantings, which are quite large in the east of Ukraine [39,40]. Through these plantings, EAB spreads quite quickly to the west [11]. The contribution of the remaining analyzed variables to the MaxEnt model for predicting EAB spread was 17.3%.

An analysis of MaxEnt results showed that the probability of EAB spread is higher where it has already been detected. Considering the trends of the most significant variables, which were assessed in two-year ground surveys of the forest, MaxEnt showed that in the Lugansk region, all plantings with the presence of *Fraxinus* sp. can be populated by EAB (Figures 8 and 9).

Similarly, our use of MaxEnt to predict the EAB spread to the east based on climatic variables [9] showed the greatest probability of pest outbreaks in the neighboring Kharkiv and Sumy regions. However, according to a survey at the end of 2021, EAB was not found in the Sumy region [14], but it was found in the parks of Kyiv [10], where it could get actively through road shelter belts or passively with transported wood materials. As is known, EAB females tend to oviposit either on trees from which they emerged or on those nearby [24]. Some EAB beetles are capable of flying up to 20 km in a single day, with a median daily flight capability of approximately 3 km [76]. However, a significant EAB range expansion is human-mediated transport [77–79].

The swift penetration of EAB into Kyiv within such a brief timeframe indicates an increased threat in the further spread of the pest to the West. Improving the forecasting accuracy may involve considering data on road localization along where EAB can disperse passively, as well as dominant wind speed. Leveraging pairwise distances among places where EAB is present, as indicated in [35], could prove to be a beneficial method for determining the likelihood of EAB spread.

5. Conclusions

The MaxEnt model for predicting the spread of the emerald ash borer (EAB) in the forest stands of the Luhansk region, populated with EAB in 2020–2021, demonstrated average performance (AUC = 0.842). The most impactful five variables provided 88.2% to the model, particularly «age of trees, years», «area of forest subcompartment, ha», «mean height of trees, m», «the proportion of *F. excelsior* in the stand composition, %», «hygrotope index (humidity level), point», and "number of neighboring-non-forest subcompartments".

To identify the places of EAB presence, first of all, it is necessary to inspect forest subcompartments in the driest forest site conditions, well-lit and warmed up, in particular; small subcompartments surrounded by non-forest landscapes; and forest shelter belts near roads and fields. Unfortunately, access to many of them in the region is limited due to military operations.

Considering the trends of the most significant variables, which were assessed in two-year ground surveys of the forest, Maxent showed that in the Lugansk region, all plantings with the presence of *Fraxinus* sp. can be populated by EAB. However, the data obtained can be considered preliminary.

To enhance forecasting accuracy, it is recommended to consider data on road localization, which serves as a passive pathway for pest spread, along with an evaluation of dominant wind speed.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15030511/s1, Table S1: Results of MaxEnt modeling of EAB spread.

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