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Occurrence Prediction of the Citrus Flatid Planthopper (*Metcalfa pruinosa* (Say, 1830)) in South Korea Using a Random Forest Model

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Abstract: Invasive species cause a severe impact on existing ecosystems. The citrus flatid planthopper (CFP; *Metcalfa pruinosa* (Say, 1830)) is an invasive species in many countries. Predicting potential occurrence areas of the species related to environmental conditions is important for effective forest ecosystem management. In this study, we evaluated the occurrence patterns of the CFP and predicted its potential occurrence areas in South Korea using a random forest model for a hazard rating of forests considering meteorological and landscape variables. We obtained the occurrence data of the CFP in South Korea from literature and government documents and extracted seven environmental variables (altitude, slope, distance to road (geographical), annual mean temperature, minimum temperature in January, maximum temperature in July, and annual precipitation (meteorological)) and the proportion of land cover types across seven categories (urban, agriculture, forest, grassland, wetland, barren, and water) at each occurrence site from digital maps using a Geographic Information System. The CFP occurrence areas were mostly located at low altitudes, near roads and urbanized areas. Our prediction model also supported these results. The CFP has a high potential to be distributed over the whole of South Korea, excluding high mountainous areas. Finally, factors related to human activities, such as roads and urbanization, strongly influence the occurrence and dispersal of the CFP. Therefore, we propose that these factors should be considered carefully in monitoring and surveillance programs for the CFP and other invasive species.

Keywords: hazard rating; invasive species; surveillance; forest ecosystem management; prediction model; species distribution model; random forest

1. Introduction

The occurrence of invasive species has increased worldwide due to global warming and international trade [1–3]. At the beginning of the invasion process, the community containing the invasive species does not have appropriate species interactions, such as prey–predator, host–parasite, and competition between species to stabilize the community dynamics [4–6]. Therefore, they can cause a severe impact on the existing ecosystem, resulting in notorious pests in many countries [7], for example, the gypsy moth (*Lymantria dispar* L.), the Asian long horn beetle (*Anoplophora glabripennis* Motschulsky), the emerald ash borer (*Agrilus planipennis* Fairmaire), found in the USA [8], and the pine wood nematode (*Bursaphelenchus xylophilus* Steiner and Buhrer), which is found in many countries, including Korea and Japan [9,10].

The citrus flatid planthopper (CFP; *Metcalfa pruinosa* Say) (Hemiptera, Auchenorrhyncha: Flatidae) is one invasive species which causes several problems in many countries. This species, originally from North America [11], has spread widely throughout America [12]. In Europe, it was first reported in Italy in 1979 [13] and is now found throughout Europe [14–20]. Meanwhile, in Asia, the presence of this species was first reported in South Korea in 2005 [21] and later in 2009 [22]. Recently, its distribution area has expanded to a nationwide scale [23].

The CFP damages its host plants by feeding on sap and ejecting honeydew, which induces a sooty mold disease [22,24]. The CFP is a polyphagous species feeding on a wide range of host plants in Korea, including woody trees, such as *Robinia pseudoacacia* L., *Castanea crenata* Siebold et Zucc., *Styrax japonicus* Siebold et Zucc., *Diospyros lotus* L., and *Acer palmatum* Thunb., and shrubs and herbaceous plants, such as *Hibiscus syriacus* L., *Rhamnus davurica* Pall., and *Lycium chinense* Mill. [22,23].

The occurrence and dispersal of the CFP are highly related to human activities such as roads, highways, and movement of vehicles on a local scale [25–27]. However, the occurrence and dispersal of invasive species are influenced by various other factors, including meteorological and geographical conditions, landscape, and host plants [28–30]. To effectively manage invasive pests, the evaluation of the occurrence patterns related to environmental conditions and the estimation of the potential occurrence area of the species are essential to provide information to efficiently identify current or future hazardous conditions [28,29,31].

Therefore, various hazard rating systems have been developed for different forest pests. In the early stage of hazard rating, qualitative and statistical methods such as discriminant analysis are used [32–34]. Further, recent machine-learning algorithms, such as self-organizing maps, multi-layer perceptron, classification and regression trees, and random forest models, can been used [28,29,35,36].

Despite the importance of hazard ratings for controlling the CFP, there are limited studies on hazard ratings using the CLIMEX model [37] which is used for the prediction of species distribution [38–41] and for risk assessment of invasive species [42,43]. CLIMEX is a climate-specific model to predict potential distribution and relative abundance of species by considering climatic conditions [44]. However, it does not consider other factors, such as road and landscape conditions. Meanwhile, MaxEnt [45] as a species distribution model is also frequently used to predict the potential distribution of invasive species based on presence-only species records [46]. MaxEnt cannot be applied to abundance data, only to presence data. Recently, studies to predict the distribution of (potential) invasive species, including CFP, using CLIMEX and MaxEnt were reviewed by evaluating their effectiveness [39].

The CFP is one of the quarantine pests listed by the Animal and Plant Quarantine Agency, Republic of Korea (https://www.qia.go.kr/) and its distribution area has been increasing since the first occurrence in Korea. Therefore, it has a high potential as a key insect pest on various plants in agriculture and forests [22]. In this study, we aimed to evaluate the occurrence patterns of the CFP and to predict its potential occurrence area for a hazard rating of forests, considering meteorological and landscape variables in Korea.

2. Materials and Methods

2.1. Data Collection

We obtained occurrence data of the CFP (*Metcalfa pruinosa*) from 105 presence (observed) sites in South Korea from the literature [23,27,47] and government documents from websites of the Gyeonggi-do Agricultural Research Services (https://nongup.gg.go.kr) and the Ministry of Agriculture, Food, and Rural Affairs (http://www.mafra.go.kr) (Figure 1). Our CFP occurrence data included only presence (i.e., observed) sites and we assumed that CFP was in fact absent at the unobserved sites at that moment because the field surveys were extensively conducted to monitor the occurrence of CFP. To evaluate the environmental conditions of the CFP occurrence sites, we selected absence sites with the same number of presence sites randomly with distances over 1.5 km from the presence sites and over 5 km from other selected absence sites to avoid similar environmental conditions. Finally, our dataset comprised 210 sites (105 sites each for presence and absence).

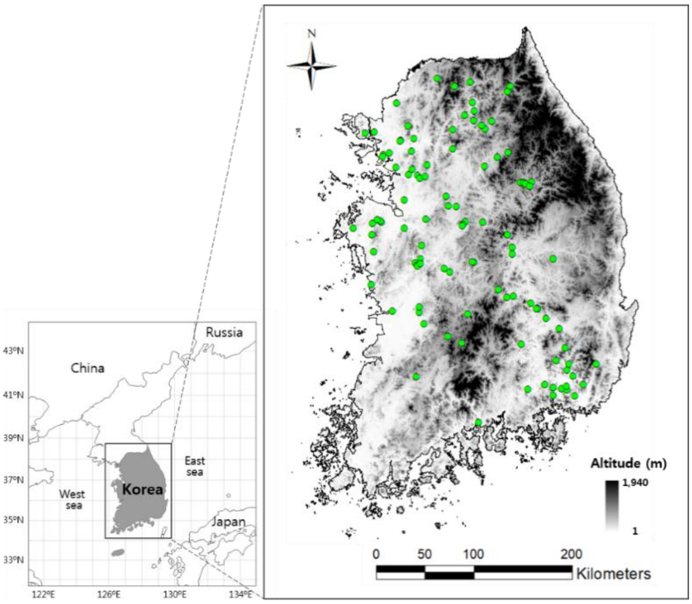

Figure 1. Occurrence (presence) sites of *Metcalfa pruinosa* based on the literature [23,27,47].

At each selected site (for both presence and absence), we extracted seven environmental variables (i.e., altitude, slope, and distance to road as geographical variables and annual mean temperature, minimum temperature in January, maximum temperature in July, and annual precipitation as meteorological variables) and the proportion of land cover types across seven categories (urban, agriculture, forest, grassland, wetland, barren, and water) from digital maps using a Geographic Information System (ArcGIS 10.1, ESRI). Altitude and slope were extracted from the digital elevation model data obtained from the National Geographic Information Institute (http://www.ngii.go.kr). Distance to road indicated a distance from the observation site to a nearest road and it was measured from a road map by combining road data from the National Spatial Data Infrastructure Portal (http://www.nsdi.go.kr) and the Intelligent Transport Systems of Standard Node Link (http://nodelink.its.go.kr). Meteorological variables were extracted from the digital map of Climatological Normals from the Climate Information Portal of the Korea Meteorological Administration (http://www.climate.go.kr) and Applied SERS A1B scenario data from the Digital Agro-climate Map Database for Impact Assessment of Climate Change on Agriculture (http://www.agdcm.kr) of the Rural Development Administration, Korea. The Environmental Geographic Information Service (https://egis.me.go.kr) operated by the Ministry of Environment, Korea, provided the digital land cover map, which was used to extract land cover area. We used raster digital maps with a resolution of 30 m × 30 m cell size.

2.2. Analysis of Occurrence Patterns

The number of occurrence regions, such as districts (i.e., "si", "gun", or "gu" level in Korea) and the area damaged by the CFP were evaluated for different years (Figure 2). The Mann–Whitney U test was used to evaluate the statistically significant differences between the presence and absence sites for environment and land cover conditions. The Mann–Whitney U test was performed with a "stats" package in R [48].

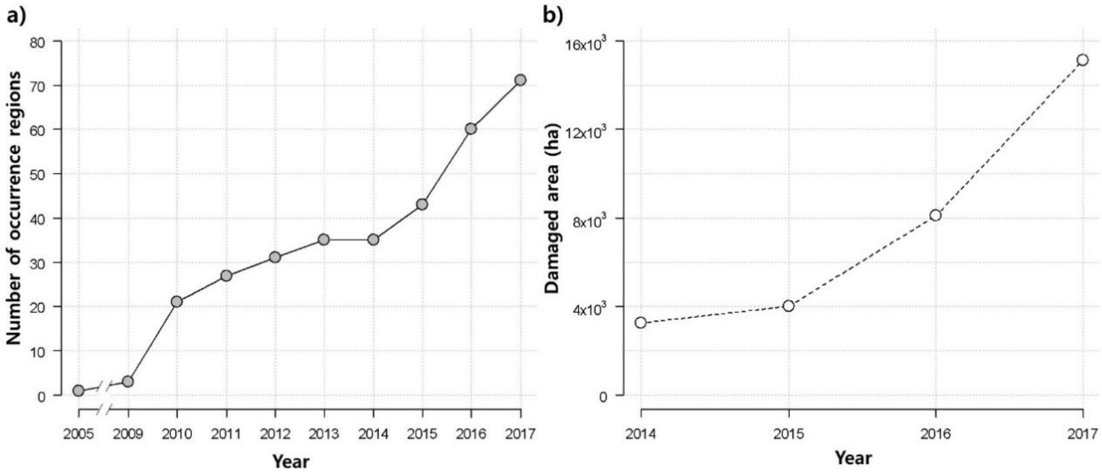

Figure 2. Change in (**a**) the number of occurrence regions and (**b**) area damaged by *Metcalfa pruinosa* in South Korea. Data were from databases (Gyeonggi-do Agricultural Research Services (https://nongup.gg.go.kr) and the Ministry of Agriculture, Food, and Rural Affairs (http://www.mafra.go.kr)). Damaged area data in Figure 2b were only available from 2014.

2.3. Prediction of Potential Occurrence

To estimate the occurrence risk of the CFP in the forests on a nationwide scale in Korea, we predicted the potential occurrence area (presence: 1; absence: 0) of the CFP based on the environmental conditions at the occurrence sites using a random forest (RF) model. The RF is an ensemble machine-learning model and it is a non-parametric method of predicting and assessing the relationships among a large number of potential predictor variables and a response variable [49]. In the RF model, we used five environmental variables (altitude, slope, and distance to road (geographical) and minimum temperature in January and maximum temperature in July). We excluded annual mean temperature to avoid collinearity among variables (Figure 3) and annual precipitation, which was not significantly different ($p < 0.05$) between the presence and absence sites. Although altitude and minimum temperature had high correlation coefficients, we included them as predictors because altitude strongly influences the distribution and abundance of insects [50] and the minimum temperature in January greatly affects the mortality of insects during the winter [6]. We calculated a mean decrease in node impurity by the residual sum of squares to evaluate the relative importance of each variable to determine the presence or absence status of CFP occurrence in the RF model.

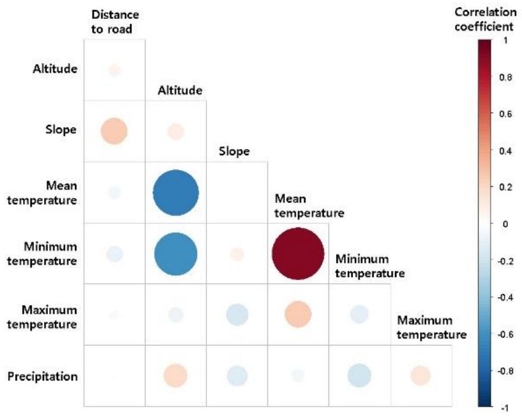

Figure 3. Correlation coefficient between environmental variables measured at 210 presence or absence sites.

We standardized all environmental variables a priori the modeling procedure. We divided our dataset in two parts with a ratio of 8:2 with respect to training and testing the models. We repeated the procedure for the RF model 10 times and averaged the calculated values. The RF models were performed using the package "randomForest" [51] in R. Partial dependence plot function (partialPlot) in "randomForest" and generalized additive model (GAM) in the "mgcv" package [52] were used to present the marginal effect of environmental variables in our model. The model performance was evaluated by accuracy and area under the receiver operating characteristic (AUROC) curve value using the "ROCR" package [53] in R.

3. Results

3.1. Occurrence Patterns of CFP

The number of occurrence regions (districts as "si", "gun", or "gu" in Korea) increased as a function of year after the first occurrence. It was less than five districts in 2009, but increased greatly to over 20 districts in 2010. From 2010 to 2015, the rate of increase was relatively low. However, in 2016, the number of occurrence regions abruptly increased from 43 to 60 districts, showing an exponential growth pattern. The damaged area displayed similar patterns regarding the number of occurrence regions from 2014 to 2017 ($r = 0.95$, $p < 0.05$) when the data were available.

Geographical and meteorological conditions were significantly different between the presence and absence sites (Mann–Whitney U test, $p < 0.05$) (Figure 4). The CFP was mostly observed in areas with low altitude (103.2 m ± 8.9 standard error (SE)), low slope (5.0° ± 0.6 SE), and short distance to the road (24.2 m ± 4.0 SE). Annual mean temperature and maximum temperature in July were higher at the presence sites than at the absence sites (Mann–Whitney U test, $p < 0.01$), while the minimum temperature in January was lower at the presence sites (Mann–Whitney U test, $p < 0.01$). Annual precipitation was not significantly different between the presence and absence sites.

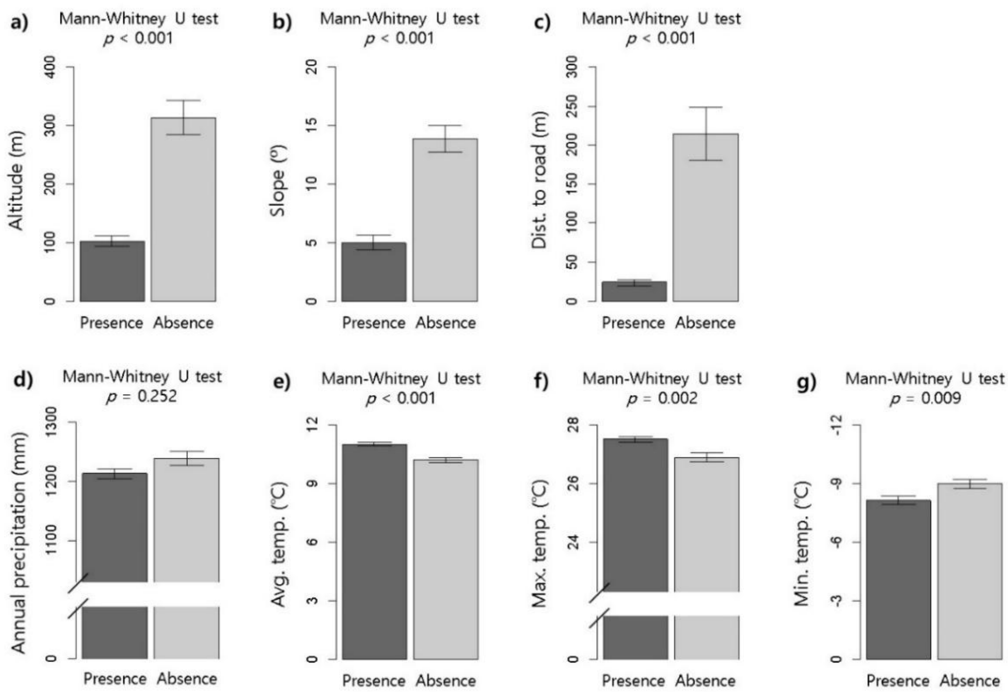

Figure 4. Differences in environmental conditions between the presence and absence sites of *Metcalfa pruinosa*. Bars denote averages and standard errors. The *p*-value (p) was calculated based on the Mann–Whitney U test. (**a**) Altitude, (**b**) slope, (**c**) distance to road, (**d**) annual precipitation, (**e**) annual average temperature, (**f**) maximum temperature in July, and (**g**) minimum temperature in January.

The ratios of all land cover types, except wetland, were significantly different between the presence and absence sites (Mann–Whitney U test, $p < 0.01$) (Figure 5). The presence sites were mostly observed in forests (33.8% ± 2.2 SE), agricultural land (31.6% ± 2.3 SE), and urban areas (19.5% ± 1.5 SE). The proportion of presence in forests was lower than that of absence, whereas the proportion of urban and agricultural areas of presence sites were higher than those of the absence sites.

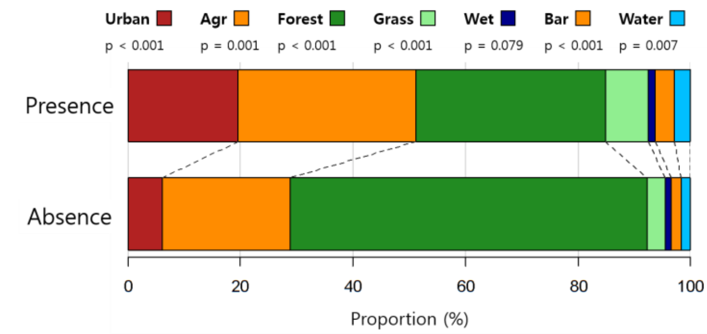

Figure 5. Differences in land cover types between presence and absence sites of *Metcalfa pruinosa*. The *p*-value (*p*) was calculated based on the Mann–Whitney U test. Urban: Urban area; Agr: Agricultural land; Wet: Wetland; and Bar: Barren.

3.2. Prediction of Potential Occurrence Area

The RF model predicted the potential occurrence areas of the CFP based on the geographical and meteorological conditions. The model showed high predictability: 0.78 (±0.01 SE) accuracy and 0.80 (±0.01 SE) AUROC curve value (Figure 6a). The model displayed that the occurrence probability was mostly high in lowland and urban areas (Figures 1 and 6b).

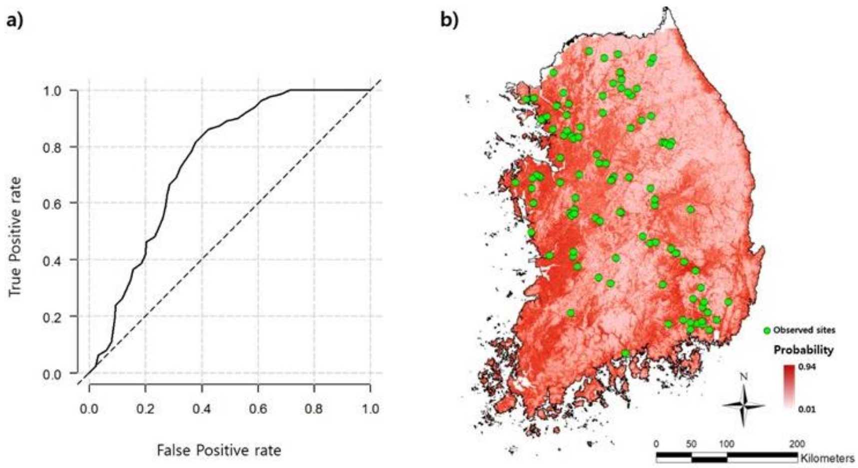

Figure 6. Prediction of potential distribution area of *Metcalfa pruinosa* with the random forest (RF) model. (**a**) Mean receiver operating characteristic (ROC) curve of the random forest (RF) model with 10 replications and (**b**) predicted potential distribution with different occurrence probability and actual observed sites with green circles.

The value of mean decrease in node impurity presented the distance to road as the most important variable for the prediction of the CFP occurrence sites in the RF model, followed by altitude and slope (Figure 7). This was reflected in the partial dependence plot of occurrence probability responding to the changes in the dependent variables (Figure 8). The occurrence probability of the CFP mostly changed as a function of distance to road and altitude, in particular, at low values of distance to road (mostly <50 m) and altitude (mostly <200 m), which displayed high occurrence probability. The probability was not highly influenced at high altitude and long distance to road.

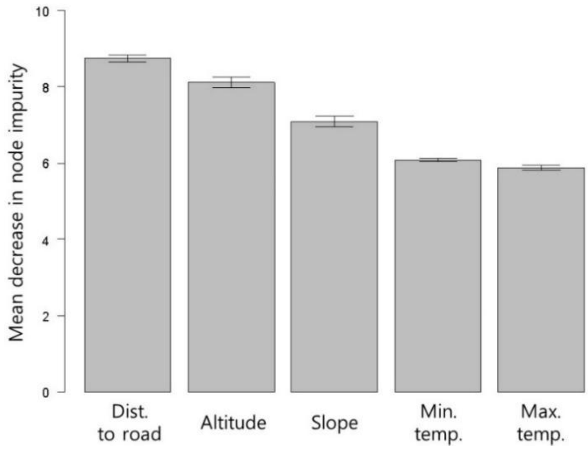

Figure 7. Relative importance of independent variables in the RF model for projecting presence or absence of *Metcalfa pruinosa*. Importance was calculated using node impurity in the RF model. Error bars indicate averages and standard errors. Dist. to road: distance to road, Min. temp.: minimum temperature in January, and Max. temp.: maximum temperature in July.

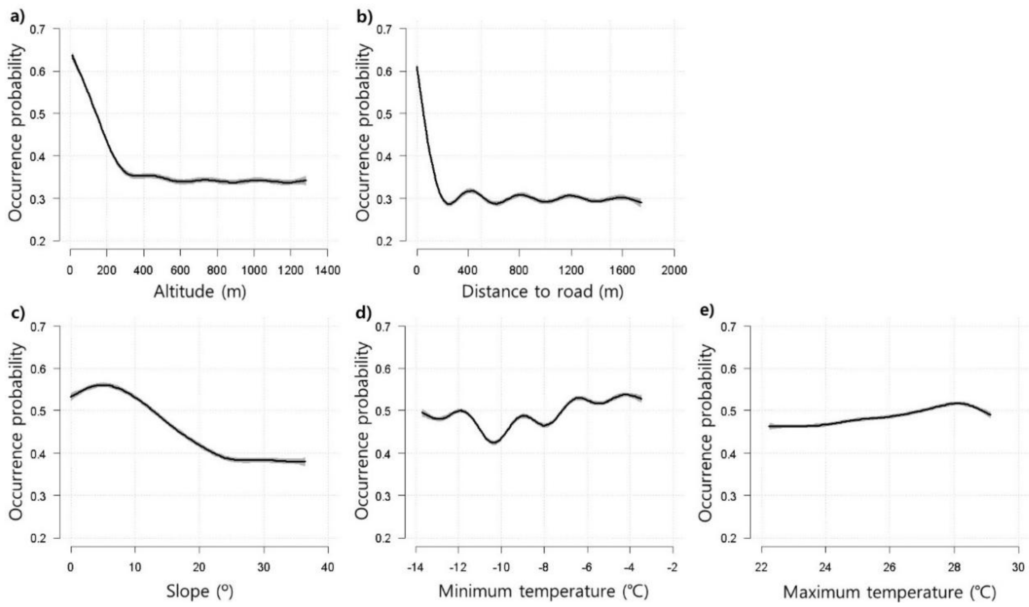

Figure 8. Partial dependence of occurrence probability of *Metcalfa pruinosa* against the changes of each environmental variable in the RF model. (**a**) Altitude, (**b**) distance to road, (**c**) slope, (**d**) minimum temperature in January, and (**e**) maximum temperature in July. Solid lines represent averages and gray areas display the 95% confidence interval.

4. Discussion

4.1. Occurrence Patterns of CFP

In South Korea, CFPs were first observed as adults only in Hanrim of Gimhae-si in the southern part of South Korea in 2005. The nymphs and adults were observed in Jinyoung of Gimhae-si, which is the town next to Hanrim, in 2008 [21,22]. Meanwhile, the CFP was discovered at several locations in the southern to central regions of the Korean Peninsula, including Seoul and Suwon in 2009 [22], and its occurrence and damage area increased greatly from 2010 (Figure 2). Currently, the CFP is widely distributed in South Korea. Thus, considering the distribution area of the CFP over time, the dispersal of the CFP was limited, with a small dispersal area, at the early stage of the invasion process from the first occurrence in 2005 until 2009. This phenomenon is commonly observed in the dispersal of invasive species [4,54]. During the early stage of invasion, the species might colonize and increase its population size, then disperse to the neighboring areas [8].

Regarding the increase in occurrence area, we have to note that there was a big difference between 2009 and 2010 (Figure 2). We infer that the actual distribution of the CFP in 2009 was wider than that displayed by the recorded data. The observed number of locations in 2009 might be smaller than that of the actual ones because the CFP was not well recognized as an invasive species and a pest insect by entomologists and policy decision-makers in South Korea until 2009. Meanwhile, the distribution area of the CFP increased exponentially after 2015, showing a stepwise dispersal pattern in the number of occurrence areas. This pattern was also reported in the dispersal of invasive species such as pine wilt disease in both Korea [9] and Japan [10]. This may be related to the increase in exponential population growth. However, the mechanism of this dispersal pattern was not clear. Therefore, further study is needed to understand the dispersal patterns of invasive species to effectively manage them.

4.2. Invasion Route and Factors Promoting Dispersals

Two possible routes were proposed for the CFP invasion into South Korea: From North America, which is the origin of the CFP, or from European countries [22], which would imply that the CFP arrived in South Korea through the imports of horticultural nursery stock. Similarly, the possible means of the CFP invasion were mostly by passive transport of the CFP adults or eggs with infested plants of many countries, including the Czech Republic and Romania [55,56]. Guillemaud, et al. [57] reported two main factors promoting biological invasion: Human activities and the biological adaptation of species. Human activities, including international trade and movement of vehicles among local regions, are highly responsible for recent biological invasions by moving invasive species and causing long distance dispersal [4,5,9,14,25,27,58–62]. Human activities also promote the dispersal of invasive species by modifying and disturbing natural habitats and providing the possibility of the introduction of new species into ecosystems [63].

Our results also revealed that human activities are the main influencing factors for the occurrence and dispersal of the CFP in South Korea. The CFP was observed mostly in areas close to the road with low altitude and slopes (Figure 4). This was also supported by the difference in occurrence patterns in different land use types. The occurrence of the CFP was observed mainly in urban and agricultural areas (Figure 5), which are highly influenced by human activities. Meanwhile, the proportion of presence sites in forest areas was smaller than that of absence sites. However, the occurrence proportion in forest areas was still the highest (over 33.8%) among land use types. This indicates that the occurrence areas in the forest are mostly in lowland areas which are close to the road and urban and agricultural areas.

Meanwhile, flight activities of the CFP adults contribute to local dispersal [14,56]. The annual dispersal distance of the CFP was estimated at 0.2–0.5 km in Austria [64]. The dispersal distance in natural conditions can be variable depending on various environmental conditions, such as temperature, precipitation, landscape, geology, and distribution of host plants [4,5,8,14,58–60], although human activities play a substantial role in their dispersal. Therefore, an integrated approach for the evaluation of the dispersal of invasive species is recommended with the consideration of environmental factors in several different categories, if data are available.

4.3. Host Plants

The high values of CFP occurrence in urban, agricultural, and forest areas reflect the diversity of both their habitats and host plants. The CFP is polyphagous; it has a variety of host plants and can inhabit very different environmental conditions. Therefore, the CFP can damage various types of plants, including ornamental or agricultural plants and herbaceous or woody plants [22,23,56]. It has a high probability of dispersing to new areas with commercial trade and transportation. Meanwhile, in this study, we did not include the distribution of host plants in the analysis and in the model for the potential occurrence prediction of the CFP because of its polyphagous nature and the difficulty in characterizing the distribution of host plants on the digital map. From another aspect, polyphagous species have a wide distribution of host plants. Therefore, our results would not be influenced by the exclusion of host plants distribution.

4.4. Hazard Rating with the CFP

The hazard rating of forests regarding susceptibility to insect pests and diseases provides information to efficiently identify current and future hazardous conditions in the concerned forests [28]. Therefore, it is very important in forest ecosystem management [29]. In this study, we evaluated the hazard rate of forests on a nationwide scale in Korea through the prediction of the potential occurrence of the CFP, showing that most areas in the South Korean territory, excluding high mountain areas, have a high occurrence probability of the CFP (Figure 5). Distance to road displayed the highest contribution regarding predicting the occurrence of CFP, followed by altitude and slope (Figure 7). The marginal effect of each variable to the model output displayed the influence of each variable to the hazard rating (Figure 8). The occurrence probability of the CFP showed a wide variation according to the distance to road, altitude, and slope. The occurrence probability was high at low values of these variables, while it remained at low values above certain values of each variable (300 m, 300 m, and 20° for the distance to road, altitude, and slope, respectively). The importance of roads in the invasion of species was supported by previous studies [25–27], showing that roads that allow human activities contribute highly to the early invasion and dispersal of species, because sites near roads are more likely to receive invasive species. These results indicate that these variables greatly affect the dispersal and occurrence of the CFP. Therefore, we propose that these factors should be considered carefully in the monitoring and surveillance programs for the CFP and other invasive species.

Meanwhile, minimum and maximum temperatures in January and July induced little variation in the occurrence probability. However, both temperature and occurrence probability displayed a positive relationship. This indicates that most areas in South Korea have a suitable temperature for the CFP. Although temperature is a fundamental factor for the development and distribution of species, it did not display an influential impact on the model output. This might be due to the relatively small differences among study sites where the South Korean territory was not big enough to display temperature differences. Therefore, if this was applied in a much larger area, temperature factors could have been influential on the distribution of the species. In this regard, the CLIMEX model has been frequently used for the prediction of the potential distribution area based on temperature conditions. Strauss [26] predicted the CFP's potential geographical distribution and identified areas at risk in Austria using CLIMEX®. The potential distribution of CFP and its dispersal were evaluated in South Korea using CLIMEX according to the climate change scenario [38]. Similar to our study, their results showed that CFP has spread in all regions of South Korea under the current climate. Both CLIMEX and MaxEnt are frequently used for the prediction of potential distribution of various species with different objectives, such as conservation of endangered species, control of invasive species, etc. However, there are some limitations in their applications. CLIMEX is based on climate-oriented data, whereas MaxEnt is not applicable to abundance data, only presence/absence data. Meanwhile, the RF model used in this study can be applied to presence/absence data as well as abundance data with various types of predictors, although presence/absence data were used in this study.

Although our models predicted the occurrence probability and potential distribution areas based on various environmental factors, the actual occurrence probability and hazard rating could be influenced by the adaptation ability of invasive species, which was not considered in our study. Species have a great ability to adapt to new environments, including changes in temperature and habitats, and this promotes the colonization of invasive species and dispersal to new regions. Therefore, further study is needed on the influence of biological adaptation of invasive species on dispersal and settlement.

5. Conclusions

The CFP occurrence areas were mostly located at low altitudes and near roads and urbanized areas. The RF model predicted the potential distribution areas of CFP with five environmental variables, showing that the CFP has a great potential to be distributed over the whole of South Korea, excluding high mountainous areas. Finally, factors related to human activities, such as roads and urbanization, strongly influenced the occurrence and dispersal of the CFP. Therefore, these variables should be considered carefully in monitoring and surveillance programs for the CFP and other invasive species to effectively control the CFP.

Author Contributions: Conceptualization, D.-S.L. and Y.-S.P.; data curation, D.-S.L., Y.-S.B., B.-K.B., S.L., and J.K.P.; methodology, D.-S.L. and Y.-S.P.; writing—original draft preparation, D.-S.L. and Y.-S.P.; writing—review and editing, D.-S.L., Y.-S.B., B.-K.B., S.L., J.K.P., and Y.-S.P.

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