

Article

Introduction and Spread of the Invasive Alien Species *Ageratina altissima* in a Disturbed Forest Ecosystem

Eunyoung Kim ¹, Jaeyong Choi ² and Wonkyong Song ^{3,*}

¹ Suwon Research Institute 126, Suin-ro, Gwonseon-gu, Suwon 16429, Korea; eykim@suwon.re.kr

² Department of Environment & Forest Resources, Chungnam National University, Daejeon 34134, Korea; jaychoi@cnu.ac.kr

³ Department of Landscape Architecture, Dankook University 119, Dandae-ro, Dongnam-gu, Cheonan 31116, Korea

* Correspondence: wksong@dankook.ac.kr; Tel.: +82-41-550-3636

Abstract: Invasive alien species (IAS) not only displace nearby indigenous plants and lead to habitat simplification but also cause severe economic damage by invading arable lands. IAS invasion processes involve external forces such as species characteristics, IAS assemblage traits, environmental conditions, and inter-species interactions. In this study, we analyzed the invasion processes associated with the introduction and spread of *Ageratina altissima*, a representative invasive plant species in South Korea. We investigated 197 vegetation quadrats (2 × 20 m) in regions bordering 47 forests in southern Seoul and Gyeonggi-do, South Korea. A total of 23 environmental variables were considered, which encompassed vegetation, topography, land use, and landscape ecology indices. The model was divided into an edge and an interior model and analyzed using logistic regression and a decision tree (DT) model. The occurrence of *Ageratina altissima* was confirmed in 61 sites out of a total of 197. According to our analysis, *Ageratina altissima* easily invaded forest edges with low density. The likelihood of its occurrence increased with lower elevation and gentler slope. In contrast, the spread of *Ageratina altissima* in the forest interior, especially based on seed spread and permeability, was favored by a lower elevation and gentler slopes. The analysis of *Ageratina altissima* settlement processes in forest edges coupled with the DT model demonstrated that land characteristics, such as the proximity to urbanized areas and the number of shrub and tree species, play a pivotal role in IAS settlement. In the forest interior, *Ageratina altissima* did not occur in 68 of the 71 sites where the soil drainage was under 2.5%, and it was confirmed that the tree canopy area had a significant impact on forest spread. Based on these results, it can be assumed that *Ageratina altissima* has spread in South Korean forests in much the same way as other naturalized species. Therefore, vegetation management strategies for naturalized species should be developed in parallel with land use management policy in regions surrounding forest edges to successfully manage and control *Ageratina altissima* invasion.

Keywords: decision tree model; forest edge; forest interior; invasive alien species; logistic regression model; vegetation structure



Citation: Kim, E.; Choi, J.; Song, W. Introduction and Spread of the Invasive Alien Species *Ageratina altissima* in a Disturbed Forest Ecosystem. *Sustainability* **2021**, *13*, 6152. <https://doi.org/10.3390/su13116152>

Academic Editor: Jinhyung Chon

Received: 29 January 2021

Accepted: 25 May 2021

Published: 30 May 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Biological invasions have increased drastically over the past few decades, thus posing one of the most serious environmental risks worldwide [1,2]. Invasive species spread leads to the homogenization of urban flora, which worsens as the level of human interference increases [3]. Invasive alien species (IAS) not only lead to socioeconomic and ecological impacts but also pose a threat to human and urban ecosystem health. Therefore, the emergence of new IAS in a growing number of ecosystems poses a serious threat to environmental and even human health. IAS spread easily in urban areas with ongoing land development or forest fragmentation [4]. Additionally, we found that invasive species such as *Ambrosia artemisiifolia* and *Ageratina altissima* not only hinder the photosynthesis of

surrounding plants or inhibit the occurrence of other plants and weeds in Korean forests, but also interfere with biodiversity and adversely affect human, livestock, and farmland wellbeing [5].

The spread of an IAS is known to be influenced by several factors, such as the distance from the source community, the level of disturbance, and other environmental conditions [6]. Most importantly, the proximity between the source community and the recipient community enhances the likelihood of its successful distribution [6]. When the spreading paths are diversified with a high frequency of seed dispersal events or a high species population density, the likelihood of success increases, even if the source community is a great distance from the new recipient community. Therefore, a higher propagule pressure improves the likelihood of successful settlement. Large propagule size in the source community also increases the chances of successful distribution [7], and repeated invasion could increase these odds even in small release events [8]. Such propagule pressure varies according to the adjacent landscape types, and propagule pressure is as important as the physical environment of an alien species [9,10]. Nonetheless, the fundamental mechanisms by which invasive plants succeed remain largely unknown. However, understanding these mechanisms may eventually prove useful for predictive and control efforts [11,12].

Certain properties make IAS distinguishable from other non-indigenous species [7]. Models of the invasive processes involve external forces such as the species characteristics, the IAS assemblage traits, environmental conditions, and inter-species interactions. McKinney (2001) found that the diversity of non-native plants is closely related to population density [13]. Several plants can be introduced due to high human use, and the settlement of these invasive species can be facilitated by environmental factors. However, the mechanisms by which these factors affect the propagation and settlement process of non-invasive species remains unclear. Specifically, there is a lack of understanding regarding how geographical and spatial dimensions affect the propagation of non-native species, as well as the role of microclimate conditions in this process [14].

There are 427 invasive species in Korea according to data from the Korea National Arboretum (2016) [15]. Given the known adverse effects of these alien species on local ecosystems, many efforts are being made to systematically manage invasive alien species in Korea. South Korea is striving to preserve its biodiversity by establishing a “Foreign organism management plan” based on the “Biodiversity Conservation and Utilization Act” [16]. In particular, the Korean government is currently focused on the management and control of the 12 IAS that are thought to be the most harmful.

The spread of IAS, including *Ageratina altissima*, *Ambrosia artemisiifolia*, and *Ambrosia trifida*, in South Korean natural ecosystems has led to an increased focus on invasive species research. Therefore, more surveys and research have been recently conducted to characterize the distribution and status of plants that negatively affect the ecosystem. However, most current policies focus largely on identifying and preventing the distribution of IAS.

Our research group aims to continuously monitor invasive alien species, develop strategies for their removal, and strengthen local government support to implement them. Therefore, our study sought to analyze the introduction and spread dynamics of *Ageratina altissima*, one of the most representative invasive alien species in South Korea, to enable the development of effective strategies to prevent the further spread of this invasive species in local forests.

2. Materials and Methods

2.1. Study Area

This study was conducted in urbanized areas such as the Gangnam district of Seoul and representative cities including Suwon, Seongnam, Gwacheon, Yongin, and Hwaseong. Much of the nation’s urban development is concentrated in the metropolitan area of Korea. In particular, this region has a high population density (i.e., more than 15 million people) and the forests are extremely fragmented. The forest ecosystem has been greatly disturbed

by the recent urban development around Seoul. Large forests such as Gwanak Mountain, Cheonggye Mountain, and Gwanggyo Mountain are distributed throughout the southern metropolitan area, and fragmented parks and green areas exist around the city (Figure 1a).

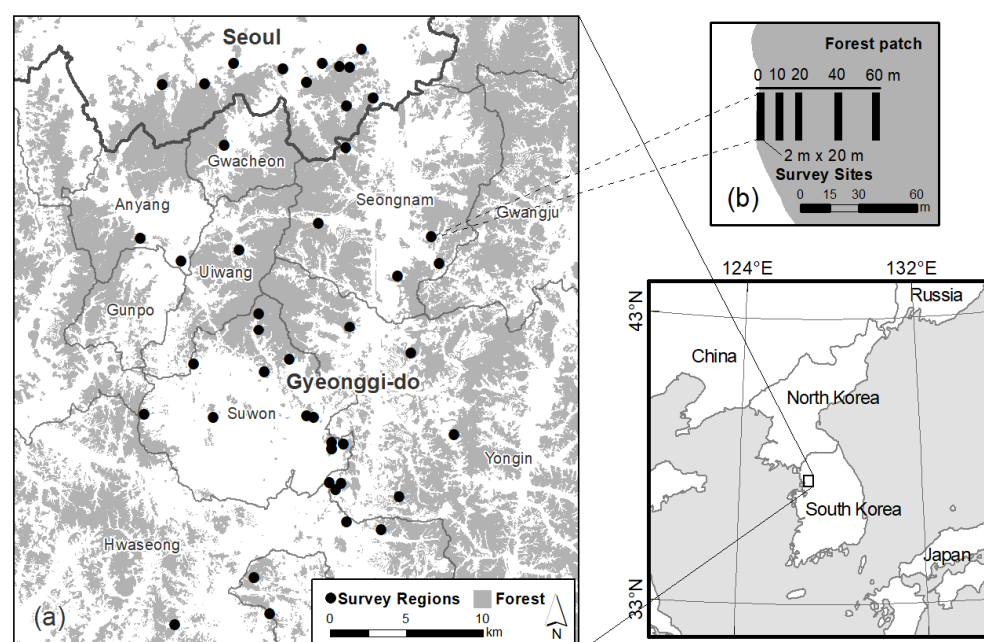


Figure 1. Study area. The research sites were located in southern Seoul and Gyeonggi-do, which share similar forest ecosystems. (a) The black dots represent the 47 forest survey points studied herein, (b) each survey region included survey sites that were 10, 20, 40, and 60 m away from the forest edge. Vegetation surveys were conducted for 3–5 sites per region.

We evaluated 47 regions, including regions that have relatively larger forest coverage rates, as well as fragmented forest parks within the cities (Figure 1a). The occurrence of *Ageratina altissima* was analyzed and its habitat characteristics were evaluated according to each vegetation structure. In particular, the size of the forest patches, the distance from urbanized areas, and the land use status were considered when selecting the study sites to accurately characterize the habitats and ecological niches of *Ageratina altissima*. We examined and analyzed the invasion processes of *Ageratina altissima* from forest edge to forest interior (i.e., 0, 10, 20, 40, 60, and >60 m from the forest edge) using the belt transect method. A 2 × 20 m survey area was established to quantitatively capture the variations in vegetation as a function of the forest edge distance (Figure 1b) [9,17]. Depending on the size of the forest in the survey area, vegetation surveys were conducted for 3–5 sites per region. The field survey was conducted at 197 sites in 47 regions. “Cover” is defined as the area of the quadrat occupied by the above-ground parts of a species when viewed from above. The plants inside the quadrat were then identified and their abundance was estimated.

2.2. Study Species

Ageratina altissima is a plant commonly found in the midwestern and eastern United States that causes trembles in livestock and milk sickness in humans that consume contaminated milk [18]. *Ageratina altissima* is a native perennial herb species that belongs to the Asteraceae family and can grow to a height of 1.5 m with a short rhizome at the bottom. This species exhibits opposite ovate leaves, which are 2–10 cm long and 1.5–6 cm wide, with serrated margins and an acute tip. White flowers bloom in August and September [19]. *Ageratina altissima* is known to invade gap areas; however, limited information is available on its dispersal mechanisms in different regions [19]. Due to a lack of removal and management strategies, *Ageratina altissima* is spreading quickly in urban green areas.

The successful distribution of an IAS depends on the level of invasion and the suitability of the invaded habitat. Until now, research on *Ageratina altissima* in Korea has focused on the physiological and geographic aspects of its distribution in specific regions [20,21]. Importantly, these previous studies reported that *Ageratina altissima* was mainly distributed in cities. This distribution is presumably attributable to the high volume of freight and traffic in cities, which may further disseminate invasive plant seeds. However, few attempts have been made to model invasion processes as a function of the distance from forest edges by considering both factors separately.

2.3. Variable Description and Statistical Analysis

In Korea, the spread of *Ageratina altissima* is thought to occur in two stages (Table 1). The first stage entails the propagation and growth of the IAS, which comprises seed deposition and establishment in forest edges [22]. Several factors may influence this first stage, including the surrounding lands, landscape, and ecological factors, as well as the location's land use characteristics (e.g., urban versus agricultural) and proximity to roads [9,23–25]. Additionally, for forest edge analyses, we included variables to identify the relationship between the forest edges and the adjacent urbanized/agricultural areas but excluded the variables from the forest interior analyses.

Table 1. Environmental variables.

Classification	Variables	Sub-Variables
Forest edges	Vegetation (10)	Rate of broadleaf trees (RBT), rate of broadleaf subtrees (RBST), rate of broadleaf shrubs (RBS), tree canopy (TC), subtree canopy (STC), shrub canopy (SC), number of tree species (NTS), number of subtree species (NSTS), number of shrub species (NSS), herbaceous ground cover (HGC)
	Topography (5)	Elevation (ELE), slope (SLO), soil drainage (SD), soil hardness (SH), solar radiation (SR)
	Land use and landscape ecology (7)	Size of forested areas (SFA), shape index (SI), edge density (ED), distance from urbanized areas (DUA), distance from roads (DR), rate of urbanized areas within a 500-m radius (RU500), rate of agricultural areas within a 500-m radius (RA500)
Forest interior	Vegetation (10)	Rate of broadleaf trees (RBT), rate of broadleaf subtrees (RBST), rate of broadleaf shrubs (RBS), tree canopy (TC), subtree canopy (STC), shrub canopy (SC), number of tree species (NTS), number of subtree species (NSTS), number of shrub species (NSS), herbaceous ground cover (HGC)
	Topography (6)	Distance from forest edges (DFE), Elevation (ELE), slope (SLO), soil drainage (SD), soil hardness (SH), solar radiation (SR)
	Land use and landscape ecology (5)	Size of forested areas (SFA), shape index (SI), edge density (ED), distance from urbanized areas (DUA), distance from roads (DR)

The second stage entails the spread of *Ageratina altissima* to the forest interior, which is affected by vegetation and topographical conditions [22]. The persistence of the IAS is determined at this stage. Even if its seeds are dispersed at the forest edges, overstory vegetation and topographical conditions affect the formation of the plant community and the spread of its population [6,22,26]. Therefore, our study divided forest stratification into four categories (tree layer (over 6 m), subtree layer (2–6 m), shrub layer (under 2 m), and herbaceous layer) and measured the canopy coverage rates, the number of species, and the broadleaf population accordingly. Given that canopy coverage is an important factor that directly affects the amount of sunlight that reaches the herbaceous layer, the canopy spectra were divided into three categories (tree canopy, subtree canopy, and shrub canopy) to measure the sunlight amount, and the herbaceous ground cover was estimated [6,26]. Additionally, the number of species of tree, subtree, and shrub were also measured. Given that the studied forests were comprised of both deciduous broadleaf and coniferous trees, the rate at which the broadleaf population would affect the amount of solar radiation during winter and early spring was also included as a variable. Elevation and slope were included among the environmental variables due to the undulating topography of South

Korea, as well as the effect of orientation on the amount of solar radiation. Soil drainage and soil hardness were included to represent soil quality [27,28]. Additionally, the distance from the forest edge was considered for the forest interior analyses.

Vegetation-related variables were characterized via field surveys, whereas elevation, slope, and the amount of solar radiation were calculated using a 30-m resolution DEM (digital elevation model) provided by the Ministry of Environment of South Korea. The average soil hardness was measured by conducting on-site assessments on five locations using a SHM-1 soil hardness tester. Moreover, the size of the forested areas, shape index, edge density, distance data, and proportion of land cover type (%) were extracted from a land cover map and analyzed using ArcGIS 10.5 (see Appendix A).

Statistical models were constructed to analyze the likelihood of *Ageratina altissima* habitation based on the above-described environmental variables. Student's *t*-tests were conducted to identify differences in the environmental variables depending on whether *Ageratina altissima* was present or absent at a given site. Logistic regression analysis was performed with the environmental variables, and both forward and backward selection were used to achieve an optimal model. Logistic regression is a regression analysis method employed when the dependent variable is binary [29]. This procedure is used to describe data and explain the relationship between one dependent binary variable and one or more nominal, ordinal, interval, or ratio-level independent variables.

Decision tree (DT) analysis was conducted using the same environmental variables implemented for the statistical analyses. DT analysis is a commonly used data mining approach to establish classification systems based on multiple covariates or for the development of prediction algorithms for a target variable [30]. One of the strengths of DT models is that they produce results that are easily interpretable in the context of predictor and target variables. The DT model was therefore used to identify the variables and conditions with the strongest effects on IAS dissemination. All of the statistical analyses were performed using the R language for statistical computing version 4.0.2 [31], and the DT analyses were conducted using the "rpart" package.

3. Results

3.1. Distribution of *Ageratina Altissima*

Ageratina altissima was found at 61 sites out of a total of 197. Although *Ageratina altissima* appeared in multiple sites in areas up to 20 m from the forest edges, population analyses showed that its numbers gradually decreased from the forest edge to the forest interior (Figure 2). Regarding the distribution of *Ageratina altissima* in the study sites, this species tended to occur in groups, with areas of the forest interior adjacent to hiking trails exhibiting considerably higher numbers of *Ageratina altissima*.

3.2. Distribution Model in Forest Edges

Among the land use and landscape ecology variables, the distance from roads, the distance from urbanized areas, the edge density, and the rates of urbanized/agricultural areas were significantly different in areas with *Ageratina altissima* compared to areas where this species was not present, as demonstrated by our *t*-test analyses. Among the vegetation-related variables, the proportion of broadleaf populations in tree and subtree layers, the number of shrub species, and herbaceous ground cover were found to be significantly different in regions with and without *Ageratina altissima*. Moreover, among the topographic variables, elevation, slope, soil hardness, and soil drainage also exhibited significant differences (Figure 3).

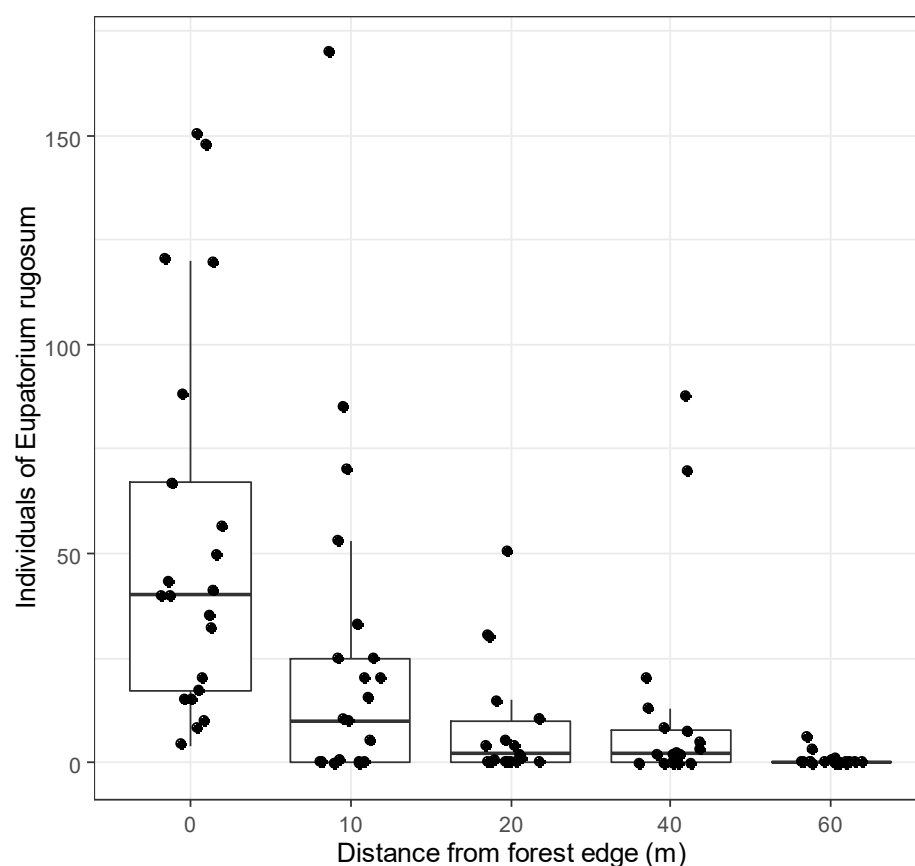


Figure 2. *Ageratina altissima* populations as a function of the distance from forest edges. The black dots represent each point of appearance. Distances of more than 60 m were also considered and were grouped with the 60 m classification.

According to our logistic regression analyses, SC was among the vegetation-associated variables that was substantially affecting the occurrence of *Ageratina altissima*, whereas ELE and SH were among the topographic variables, and SI and RA500 were among the land use and landscape ecology variables (Table 2). This model had a McFadden's pseudo R^2 of 0.593. *Ageratina altissima* tends to occur less when the proportion of agricultural area around the forest is high. Therefore, croplands may lower the likelihood of *Ageratina altissima* propagation, as this plant species favors semi-shaded forests [32]. Linear forests have more invasive species due to the increased likelihood of contact at the forest boundaries. Moreover, lower altitudes and softer soils also increase the probability of *Ageratina altissima* occurrence [20]. These characteristics are similar to those that promote grass settlement in the forest edge. Shrub cover is a factor that affects the canopy at the edge of the forest during the open season and determines whether *Ageratina altissima* can settle at the edge or not [33].

Table 2. *Ageratina altissima* distribution model using the logistic regression results in the forest edges (see Table 1 for the definitions of environmental variables SC, ELE, SH, SI, and RA500).

	Estimate	Std. Error	t Value	Pr (> t)
(Intercept)	18.544	7.414	2.501	0.012 **
SC	−0.056	0.047	−1.196	0.232
ELE	−0.106	0.048	−2.211	0.027 *
SH	−1.066	0.470	−2.269	0.023 *
SI	0.587	0.241	2.439	0.015 *
RA500	−18.741	12.664	−1.480	0.139

Significance codes: *** 0.01, ** 0.05.

The DT model can more briefly explain the process of settling at the edge of the forest (Figure 4). The emergence of *Ageratina altissima* was found to be largely associated with the distance from urbanized areas, number of shrub species, and number of tree species. This species appeared in 12 of the 13 areas located within 3.5 m of an urbanized area. Therefore, *Ageratina altissima* settlement is highly likely in forests that surround cities. When the urbanized areas were distant and the number of shrub species exceeded 10, the target species appeared in only one of the 17 survey sites. When the number of shrub species was less than 10 and the number of tree species was 1.5 or more, the target species appeared in 8 out of 11 areas.

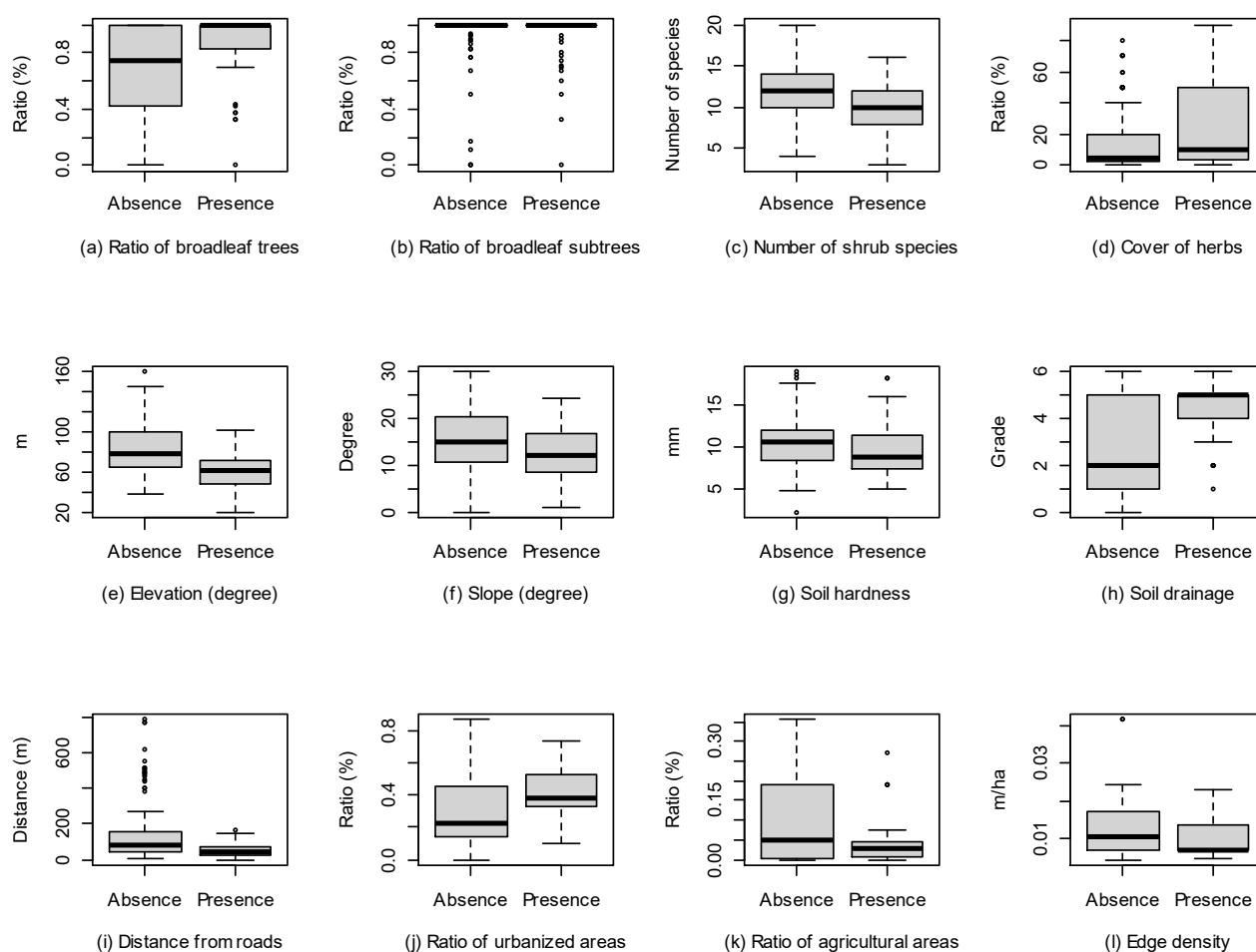


Figure 3. Environmental variables that were significantly related to the establishment of *Ageratina altissima* at the forest edge. “Presence” and “Absence” refer to the presence or absence of the target species at the study site. These twelve variables were significantly different in regions with and without *Ageratina altissima* (p -value < 0.05).

3.3. Distribution Model in Forest Interior

According to the results of the environmental variable t -tests, which were conducted in 21 sites that exhibited *Ageratina altissima*, the distance from roads and distance from urbanized areas were among the land use and landscape ecology variables that were significantly different in the areas with and without *Ageratina altissima*. Among the vegetation-related variables, the rate of broadleaf population in the tree and subtree layers, the number of trees and subtrees, and the herbaceous ground cover were found to be significantly different. Among the topographic variables, elevation and distance from forest edges were also found to be significantly different (Figure 5).

According to our logistic regression analyses, the environmental variables affecting the occurrence of *Ageratina altissima* were RBT, TC, and STC among the vegetation variables; ELE, SD, and SR among the topographic variables; and SI and ED among the land use and

landscape ecology variables (Table 3). This model has a McFadden's pseudo R^2 of 0.724. Interestingly, *Ageratina altissima* easily invaded areas where the forest boundary shape was simple (e.g., square-shaped). Moreover, low tree canopy and subtree canopy coverage were identified as the minimum conditions for herbaceous vegetation settlement in the forest.

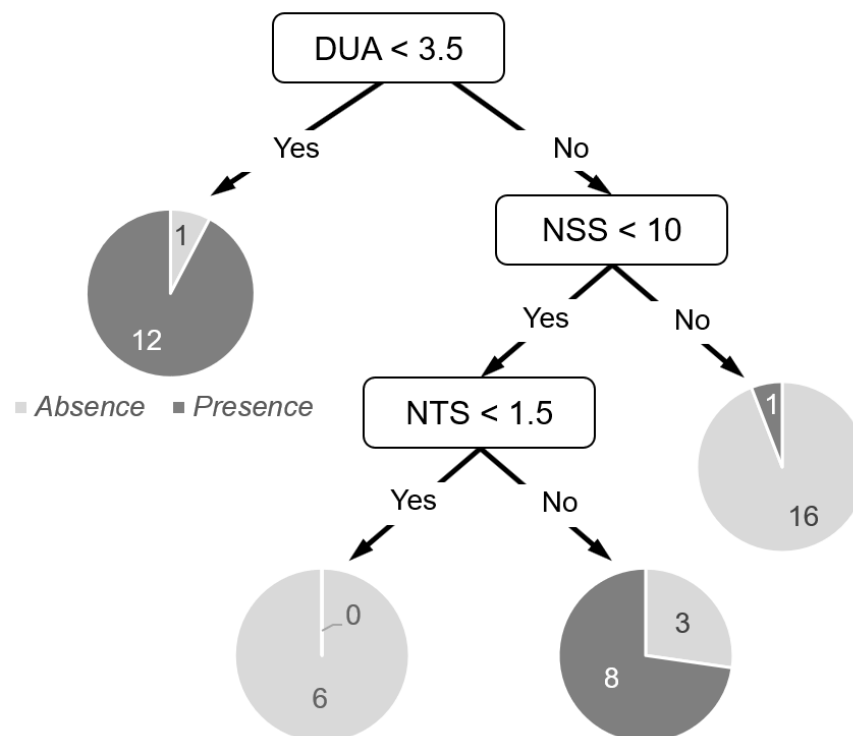


Figure 4. DT model for the forest edge. *Ageratina altissima* appeared within a 3.5 m radius of urbanized areas (DUA). Even if the site is off the road, the probability of this invasive species occurring increased at the edge of the forest where the number of shrub species (NSS) was less than 10 and the number of tree species (NTS) exceeded 1.5.

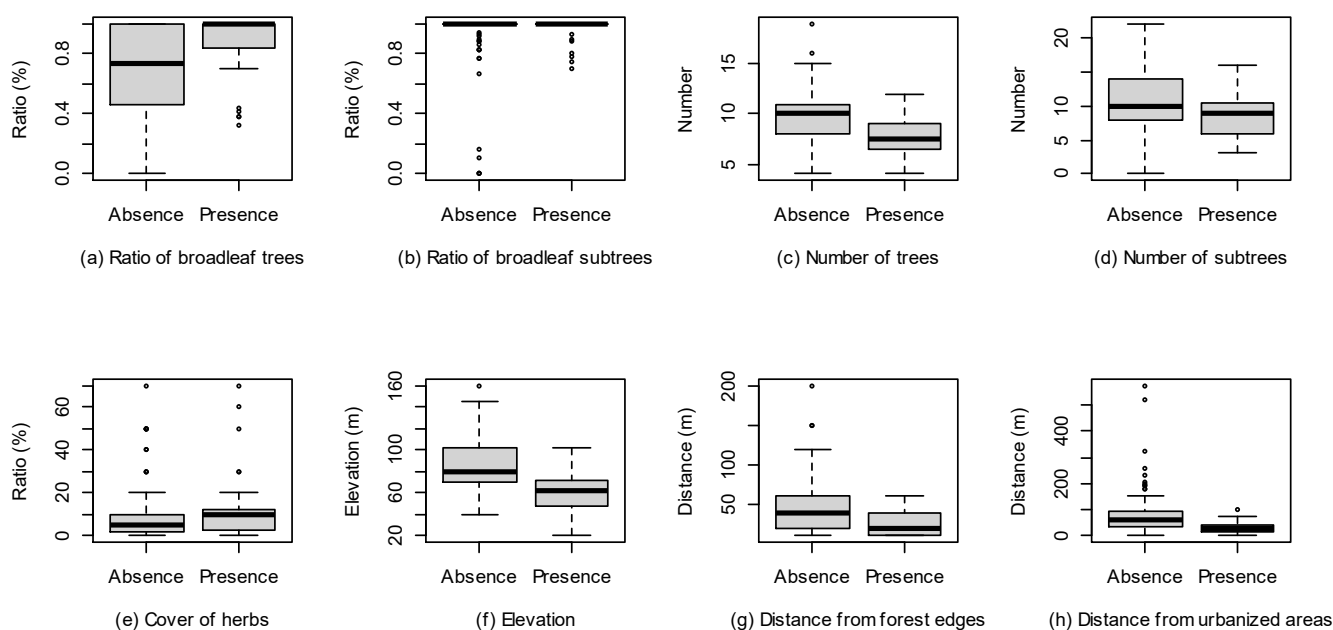


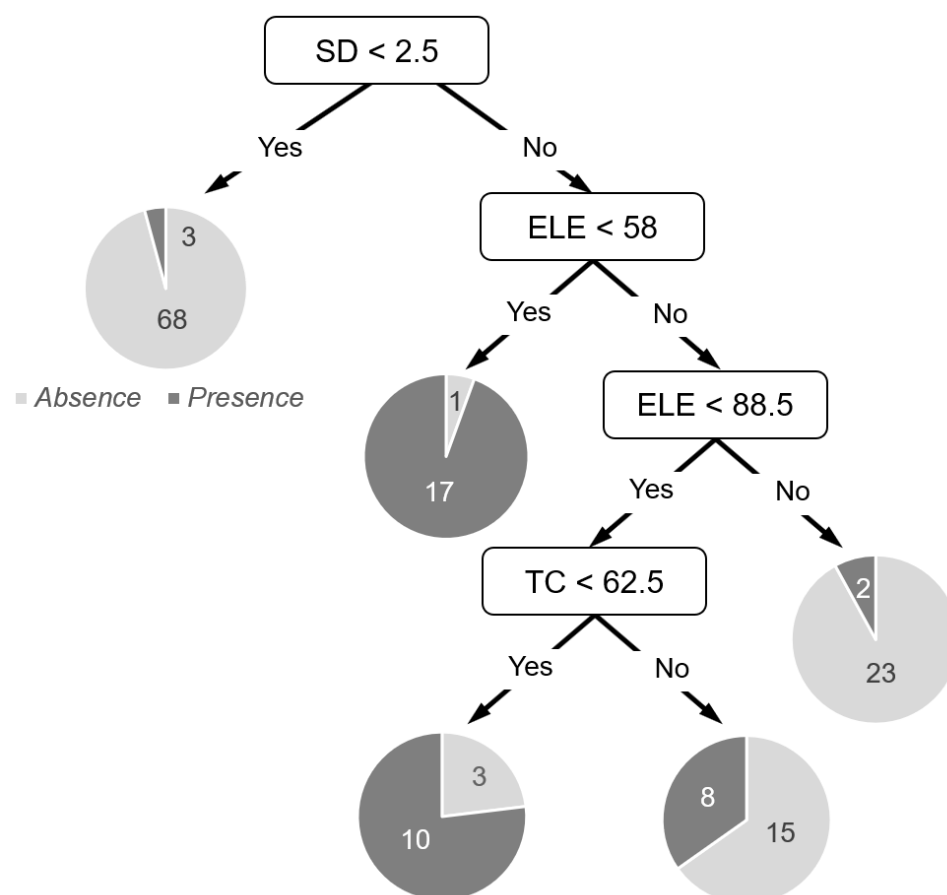
Figure 5. Environmental variables that were significantly related to the establishment of *Ageratina altissima* in the forest interior. “Presence” and “Absence” refer to the presence or absence of the target species in the study site. These eight variables were significantly different in the regions with and without *Ageratina altissima* (p -value < 0.05).

Table 3. *Ageratina altissima* distribution model using the logistic regression results in the forest interior (see Table 1 for the definitions of environmental variables RBT, TC, STC, ELE, SD, SR, SI, and ED).

	Estimate	Std. Error	t Value	Pr (> t)
(Intercept)	47.370	14.110	3.356	0.001 **
RBT	4.612	1.939	2.379	0.017 *
TC	−0.154	0.059	−2.608	0.009 **
STC	−0.080	0.035	−2.293	0.022 *
ELE	−0.170	0.040	−4.214	0.000 **
SD	1.483	0.371	4.002	0.000 **
SR	−0.000	−0.000	−2.475	0.013 *
SI	−0.623	−0.181	−3.438	0.001 **
ED	−462.300	−167.500	−2.759	0.006 **

Significance codes: ‘***’ 0.01, ‘**’ 0.05.

Through the DT model, it was possible to understand the process by which *Ageratina altissima* spreads into the forest (Figure 6). This species did not occur in 68 of the 71 sites with poor soil drainage ($SD < 2.5$). When the soil drainage was good and the altitude was below 58 m, the target species was found in 17 out of 18 areas. Even if the soil drainage was good, the target species did not inhabit 23 out of 25 areas when the altitude was 88.5 m or more. When the soil drainage was good and the altitude was less than 88.5 m, *Ageratina altissima* was identified in 10 out of 13 areas when the tree canopy coverage was less than 62.5%.

**Figure 6.** DT model for the forest interior. *Ageratina altissima* was identified in several regions with good soil drainage ($SD < 2.5$), low elevation ($ELE < 58$ m), and less than 62.5% of tree canopy coverage among the regions with an elevation of less than 88.5 m (see Table 1 for definitions of the environmental variables SD, ELE, and TC).

4. Discussion

Our analyses suggest that *Ageratina altissima* tends to be easily introduced to forest edges with low density [9]. Lower elevation and gentler slope were also associated with a higher probability of this plant's occurrence [23]. Moreover, its introduction was associated with disturbance, ease of invasion, and propagule pressure, in addition to the ecological characteristics of the IAS. We also found that soft soils with low levels of hardness favored the introduction of *Ageratina altissima*. Vegetation variables also played a very important role in the invasion. When the number of shrubs was low, the *Ageratina altissima* occurrence was also low. *Ageratina altissima* also settled down easily in a tree layer with a high rate of deciduous trees. In contrast, the probability of *Ageratina altissima* occurrence diminished in a subtree layer with a higher rate of deciduous trees. The subtree layer forms the middle layer of forests, and a high deciduous tree rate indicates that the forest is undergoing vegetation succession. As the tree layer on the top and the following sub-tree layer are replaced, the forest stability is weakened during vegetation succession. Therefore, these transitional characteristics presumably facilitate the invasion of alien species. Previous studies have also found that the distribution of invasive alien species correlates with the habitat types [22].

Even in the forest interior, the distance from urbanized areas is a notable factor affecting invasiveness and thus serves as an important environmental variable. Given that forests in urban areas are constantly visited by urban residents, forests close to cities are more easily invaded by *Ageratina altissima*. Additionally, our results demonstrate that *Ageratina altissima* easily invaded the forest interior regions in the forests with fewer tree species. Moreover, the spread and permeability of the seeds were facilitated by low elevations, gentle terrains, and soft soil. Lower solar radiation, lower elevation, and better soil drainage also promoted *Ageratina altissima* occurrence [20]. Vegetation is an important factor for IAS infiltration from the forest border to the interior. Moreover, the rate of broadleaf trees is a factor that influences the open-leaf forest canopy and determines whether the target species can settle within [33].

Ageratina altissima is an invasive species classified as a level two dangerous species in South Korea. Although no cases of direct damage have been reported in South Korea, this plant has been classified as a hazardous species due to the adverse effects of its toxins on livestock and human health in other parts of the world [34]. In South Korea, the adverse effects of this species have been largely limited to native species' habitat invasion or ecosystem disturbances [35].

Managing the indigenous vegetation of forest ecosystems is critical to prevent fragmentation due to ecological disturbances such as those observed in South Korea. An invasive plant management strategy is a collection of activities or projects aimed at preventing, eradicating, containing, and/or suppressing targeted invasive plant species [32]. South Korea is striving to develop a national strategy to manage its ecosystems by establishing a "Foreign Organism Management Plan (2019–2023)". Importantly, policies to prevent the spread of alien organisms are being addressed within this framework. However, there are important challenges associated with the preparation of specific management strategies due to the lack of research on the propagation of specific IAS. Therefore, the results of this study are of great significance, as they quantitatively characterize the forest settlement process of *Ageratina altissima*. Based on these results, it is possible to propose a management strategy that can minimize the spread of this species (Figure 7). Additionally, we need to strengthen monitoring efforts in forests near urbanized areas, and shrub species diversity should be maintained to prevent the introduction of invasive species. Moreover, to minimize the spread of target species in the forest, forest transition should also be considered when managing invasive species. Monitoring and vegetation management should also be strengthened in low altitude forests, whereas these measures can be minimized in high-altitude forests. Similarly, monitoring and vegetation management should also be strengthened in areas with high soil drainage levels and low tree canopy coverage.

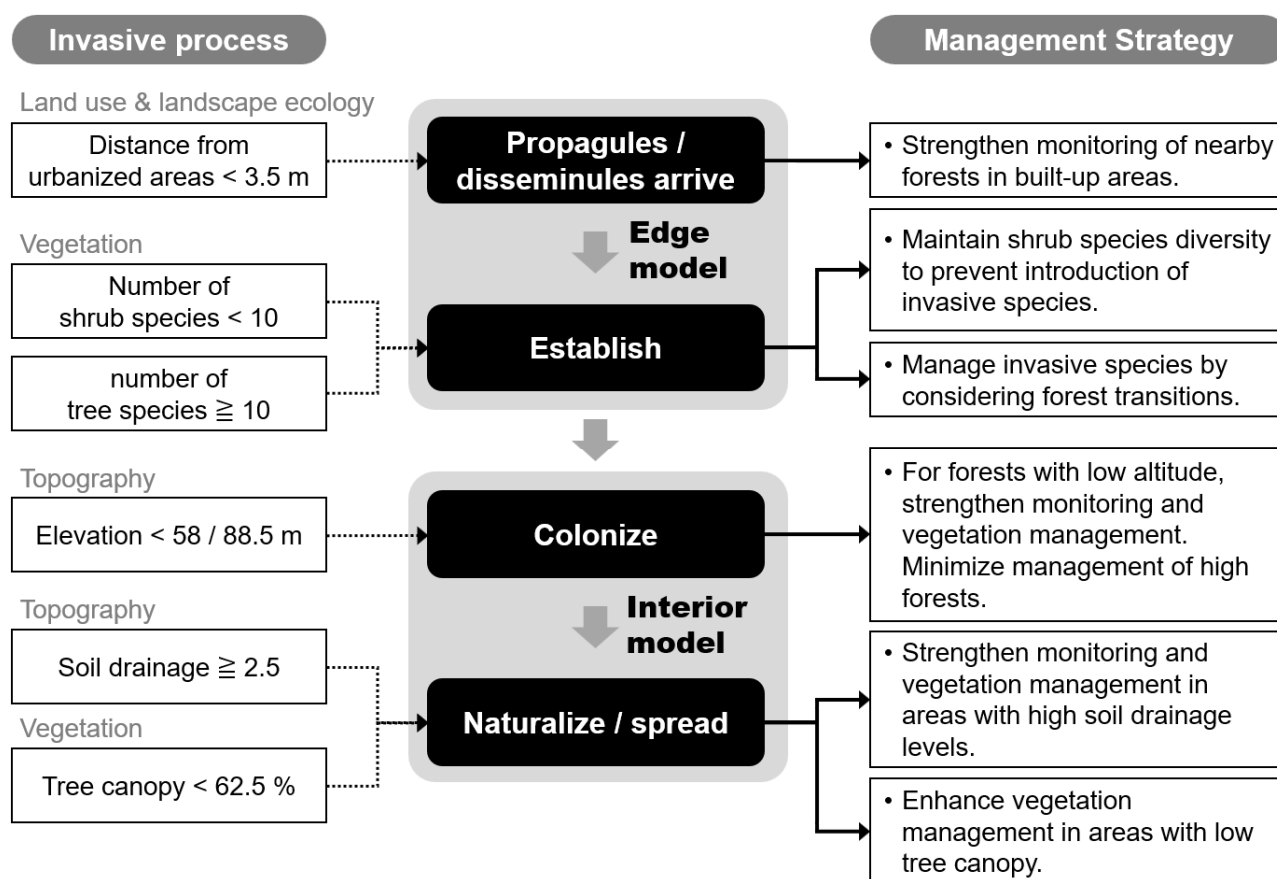


Figure 7. A management strategy that could minimize the spread of *Ageratina altissima*. Step-by-step management strategies are important, as invasive plants spread into forests through the forest edges. As a preventive measure, areas with a high likelihood of alien species invasion should be aggressively monitored. After introduction, management priority should shift to areas with a higher risk of spreading.

Both the analysis of *Ageratina altissima* occurrence in the forest edges and the DT model rendered very interesting results. The analysis of herbaceous species provided a very good explanation for the occurrence of *Ageratina altissima*. This species was identified in 40 out of 42 sites where naturalized species accounted for $\geq 6.5\%$ of the total herbaceous species. In contrast, no *Ageratina altissima* was found in the forest interior where naturalized species accounted for less than 6.5% of the total herbaceous species. These results suggest that *Ageratina altissima* has established itself in South Korea as a naturalized species, despite being currently classified as an invasive alien species. Generally, the forest interior has more unfavorable conditions for the penetration of invasive alien species than the forest edges. However, it appears that *Ageratina altissima* has established itself in South Korean forests in much the same way as naturalized species have (Figure 8). Invasive plant species possess efficient reproductive strategies that enable them to sustain self-replacing populations and produce capable offspring, even in remote areas [36,37].

As such, the characteristics of the species, the environmental conditions, and human-related factors affect the path of invasion, thereby affecting propagule pressure and invasion success/failure rates. The invasion dynamics occurring after the settlement of invasive species are also affected by propagule pressure. Among other factors, propagule pressure was found to be a key contributor to invasiveness and invasibility [2]. In the same vein, studies on invasive alien species should consider propagule pressure to allow for the development of more effective invasive species management strategies [38].

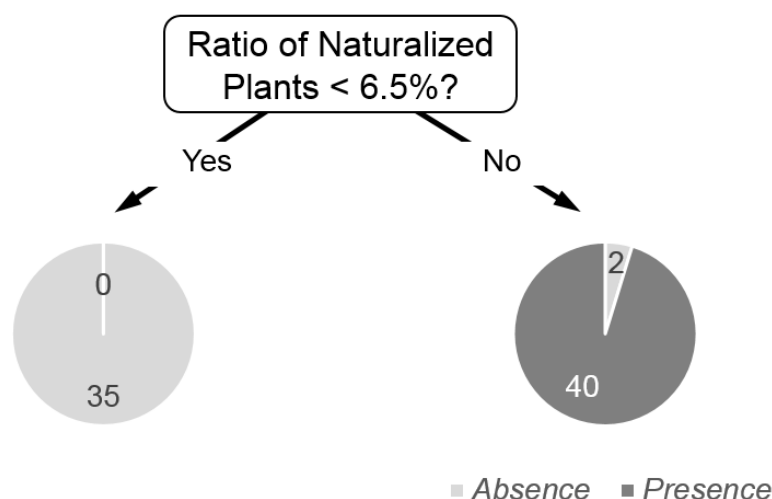


Figure 8. DT model for the forest interior. In forests, the occurrence of *Ageratina altissima* can be clearly explained by the ratio of naturalized plants. *Ageratina altissima* was found in 40 of the 42 sites in which the ratio of naturalized plants exceeded 6.5%.

5. Conclusions

The spread of *Ageratina altissima* across South Korean forests can be explained by dividing the processes into the following two categories: settlement in forest edges and invasion in the forest interior. *Ageratina altissima* shows a low level of occurrence in forest edges with low density and complex shapes, as well as areas with high elevations, pronounced slopes, and hard soils. Additionally, the settlement processes of *Ageratina altissima* are also affected by vegetation. The distance from urbanized areas, the elevation, and the number of tree species were important environmental variables that affected the penetration of *Ageratina altissima* into the forest interior. Moreover, these factors are thought to also be closely related to persisting invasion intensity, permeability, and vegetation stability. Our analyses of the settlement process of *Ageratina altissima* in forest edges coupled with our decision model suggested that *Ageratina altissima* is more likely to occur in forests adjacent to urban areas or in forests that have approximately 30% of their surrounding area within a 500-m radius of an urbanized area. The surrounding land use also has a great impact on the settlement and invasiveness of invasive species such as *Ageratina altissima*. It was also found that *Ageratina altissima* spreads into the forest interior in much the same way as naturalized herbaceous plants. Therefore, an effective management strategy for invasive plant species such as *Ageratina altissima* should consider the characteristics of naturalized species and land use management policy on forest edges.

Author Contributions: Conceptualization, E.K. and W.S.; methodology, E.K. and W.S.; investigation, E.K. and W.S.; writing—original draft preparation, E.K.; writing—review and editing, W.S. and J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was conducted with the support of the Korea Environment Industry & Technology Institute (KEITI) through its “Development of ecological restoration management technology and demonstration (test-bed) of technology” Project and funded by the Korea Ministry of Environment (MOE) (2018000210008).

Institutional Review Board Statement: Not applicable for studies not involving humans or animals.

Informed Consent Statement: Not applicable for studies not involving humans.

Data Availability Statement: The data presented in this study are available in article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Environmental variables and analysis methods.

Classification	Variables	Analysis Method (Unit)	Reference
Vegetation	Rate of broadleaf trees (RBT)	Percentage of broad-leaved trees among trees exceeding 6 m (%)	Field survey
	Rate of broadleaf subtrees (RBST)	Percentage of broad-leaved trees among trees of 2–6 m in height (%)	Field survey
	Rate of broadleaf shrubs (RBS)	Percentage of broad-leaved trees among trees with a height of 2 m or less (%)	Field survey
	Tree canopy (TC)	Percentage of canopy cover of trees exceeding 6 m in height (%)	Field survey
	Subtree canopy (STC)	Percentage of canopy cover for trees 2–6 m in height (%)	Field survey
	Shrub canopy (SC)	Percentage of canopy cover for trees under 2 m in height (%)	Field survey
	Number of tree species (NTS)	Number of tree species exceeding 6 m in height (N)	Field survey
	Number of subtree species (NSTS)	Number of species of trees 2–6 m in height (N)	Field survey
	Number of shrub species (NSS)	Number of tree species up to 2 m in height (N)	Field survey
	Herbaceous ground cover (HGC)	Percentage of herbaceous covering the ground (%)	Field survey
Topography	Distance from forest edges (DFE)	Calculate Euclidean distance from forest boundary (m)	Land cover map
	Elevation (ELE)	Elevation extracted from a Digital Elevation Model at 30 m spatial resolution (m)	DEM (Digital Elevation Map)
	Slope (SLO)	Degree inclination analyzed by spatial analysis using Arcmap 10.5 (degree)	DEM (Digital Elevation Map)
	Soil drainage (SD)	Extraction of soil drainage divided into five grades included as attributes in the soil map (grade)	Soil map
	Soil hardness (SH)	Field measurement using a soil hardness tester SHM-1 (mm)	Field survey
	Solar radiation (SR)	Analysis incoming solar radiation from a raster surface using Arcmap 10.5 (WH/m ²)	DEM (Digital Elevation Map)
Land use and landscape ecology	Size of forested areas (SFA)	Calculation of forest area extracted from land cover map (m ²)	Land cover map
	Shape index (SI)	Calculation of area-weighted mean shape index of forest extracted from land cover map using landscape ecology index (m/m ²)	Land cover map
	Edge density (ED)	Edge ratio per forest area (m/km ²)	Land cover map
	Distance from urbanized areas (DUA)	Distance from urbanized area extracted from land cover map (m)	Land cover map
	Distance from roads (DR)	Distance from roads extracted from land cover map (m)	Land cover map
	Rate of urbanized areas (RU500)	Proportion of urbanized areas within a 500-m radius of the survey sites (%)	Land cover map
	Rate of agricultural areas (RA500)	Proportion of agricultural areas within a 500-m radius of the survey sites (%)	Land cover map

References

- McGeoch, M.A.; Butchart, S.H.M.; Spear, D.; Marais, E.; Kleynhans, E.J.; Symes, A.; Chanson, J.; Hoffmann, M. Global indicators of biological invasion: Species numbers, biodiversity impact and policy responses. *Divers. Distrib.* **2010**, *16*, 95–108. [\[CrossRef\]](#)
- Roiloa, S.R.; Yu, F.H.; Barreiro, R. Plant invasions: Mechanisms, impacts and management. *Flora Morphol. Distrib. Funct. Ecol. Plants* **2020**, *267*, 151603. [\[CrossRef\]](#)
- Lososová, Z.; Chytrý, M.; Tichý, L.; Danihelka, J.; Fajmon, K.; Hájek, O.; Kintrová, K.; Láníková, D.; Otýpková, Z.; Řehořek, V. Biotic homogenization of Central European urban floras depends on residence time of alien species and habitat types. *Biol. Conserv.* **2012**, *145*, 179–184. [\[CrossRef\]](#)
- Kim, E.; Song, W.; Yoon, E.; Jung, H. Definition of invasive disturbance species and its influence factor. *J. Korea Soc. Environ. Restor. Technol.* **2016**, *19*, 155–170. [\[CrossRef\]](#)
- Choi, B.S.; Song, D.Y.; Kim, C.G.; Song, B.H.; Woo, S.H.; Lee, C.W. Allelopathic effects of common ragweed (*Ambrosia artemisiifolia* var. *elatior*) on the germination and seedling growth of crops and weeds. *Weed Turfgrass Sci.* **2010**, *30*, 34–42.

6. Alston, K.P.; Richardson, D.M. The roles of habitat features, disturbance, and distance from putative source populations in structuring alien plant invasions at the urban/wildland interface on the Cape Peninsula, South Africa. *Biol. Conserv.* **2006**, *132*, 183–198. [\[CrossRef\]](#)
7. Lockwood, J.L.; Cassey, P.; Blackburn, T. The role of propagule pressure in explaining species invasions. *Trends Ecol. Evol.* **2005**, *20*, 223–228. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Memmott, J.; Fowler, S.V.; Paynter, Q.; Sheppard, A.W.; Syrett, P. The invertebrate fauna on broom, *Cytisus scoparius*, in two native and two exotic habitats. *Acta Oenol.* **2000**, *21*, 213–222. [\[CrossRef\]](#)
9. Pauchard, A.; Alaback, P.B. Edge type defines alien plant species invasions along *Pinus contorta* burned, highway and clearcut forest edges. *For. Ecol. Manag.* **2006**, *223*, 327–335. [\[CrossRef\]](#)
10. Lozano, V.; Marzalletti, F.; Carranza, M.L.; Chapman, D.; Branquart, E.; Dološ, K.; Große-Stoltenberg, A.; Fiori, M.; Capece, P.; Brundu, G. Modelling *Acacia saligna* invasion in a large Mediterranean island using PAB factors: A tool for implementing the European legislation on invasive species. *Ecol. Indic.* **2020**, *116*, 106–116. [\[CrossRef\]](#)
11. Mack, R.N.; Simberloff, D.; Lonsdale, W.M.; Evans, H.; Clout, M.; Bazzaz, F.A. Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecol. Appl.* **2000**, *10*, 689. [\[CrossRef\]](#)
12. Deng, X.; Ye, W.H.; Feng, H.L.; Yang, Q.H.; Cao, H.L.; Xu, K.Y.; Zhang, Y. Gas exchange characteristics of the invasive species *Mikania micrantha* and its indigenous congener *M. cordata* (Asteraceae) in South China. *Bot. Bull. Acad. Sin.* **2004**, *45*, 213–220. [\[CrossRef\]](#)
13. McKinney, M.L. Effects of human population, area, and time on non-native plant and fish diversity in the United States. *Biol. Conserv.* **2001**, *100*, 243–252. [\[CrossRef\]](#)
14. Richard, T.; Forman, T.; Deblinger, R.D. The ecological road-effect zone of a Massachusetts (U.S.A.) suburban highway. *Conserv. Biol.* **2000**, *14*, 36–46. [\[CrossRef\]](#)
15. Jeong, S.Y.; Lee, J.W.; Kwon, Y.H.; Shin, H.T.; Kim, S.J.; Ahn, J.B.; Huh, T.I. *Invasive Alien Plants in South Korea*; Korea National Arboretum: Pocheon, Korea, 2016; ISBN 979-11-87031-52-9 93480.
16. Kim, D.E. Management system of invasive alien species threatening biodiversity in Korea and suggestions for the improvement. *J. Environ. Impact Assess.* **2018**, *27*, 33–55.
17. Kim, E.; Song, W.; Lee, D. A multi-scale metrics approach to forest fragmentation for strategic environmental impact assessment. *Environ. Impact Assess. Rev.* **2013**, *42*, 31–38. [\[CrossRef\]](#)
18. Davis, T.Z.; Lee, S.T.; Collett, M.G.; Stegelmeier, B.L.; Green, B.T.; Buck, S.R.; Pfister, J.A. Toxicity of white snakeroot (*Ageratina altissima*) and chemical extracts of white snakeroot in goats. *J. Agric. Food Chem.* **2015**, *63*, 2092–2097. [\[CrossRef\]](#)
19. Kim, H.; Jang, Y.L.; Park, P.S. Distribution pattern of *Ageratina altissima* along trails at Mt. Umyeon in Seoul, Korea. *Korean J. Agric. For. Meteorol.* **2014**, *16*, 227–232. [\[CrossRef\]](#)
20. Kil, J.H.; Shim, K.C.; Jeon, Y.M.; Lee, H.J. Distribution pattern of *Eupatorium rugosum* in various forest types and soils in Mt. Namsan. *Korean J. Environ. Ecol.* **2004**, *27*, 291–300. [\[CrossRef\]](#)
21. Kim, E.; Kim, J.; Song, W. Current status of invasive disturbance species and its habitat characteristics in Urban Forest. *J. Korea Soc. Environ. Restor. Technol.* **2016**, *19*, 93–102. [\[CrossRef\]](#)
22. Höfle, R.; Dullinger, S.; Essl, F. Different factors affect the local distribution, persistence and spread of alien tree species in floodplain forests. *Basic Appl. Ecol.* **2014**, *15*, 426–434. [\[CrossRef\]](#)
23. Lemke, D.; Hulme, P.E.; Brown, J.A.; Tadesse, W. Distribution modelling of Japanese honeysuckle (*Lonicera japonica*) invasion in the Cumberland Plateau and Mountain Region, USA. *For. Ecol. Manag.* **2011**, *262*, 139–149. [\[CrossRef\]](#)
24. Spear, D.; Foxcroft, L.C.; Bezuidenhout, H.; McGeoch, M.A. Human population density explains alien species richness in protected areas. *Biol. Conserv.* **2013**, *159*, 137–147. [\[CrossRef\]](#)
25. Hortal, J.; Borges, P.A.V.; Jiménez-Valverde, A.; de Azevedo, E.B.; Silva, L. Assessing the areas under risk of invasion within islands through potential distribution modelling: The case of *Pittosporum undulatum* in São Miguel, Azores. *J. Nat. Conserv.* **2010**, *18*, 247–257. [\[CrossRef\]](#)
26. Badalamenti, E.; Gristina, L.; La Mantia, T.; Novara, A.; Pasta, S.; Lauteri, M.; Fernandes, P.; Correia, O.; Máguas, C. Relationship between recruitment and mother plant vitality in the alien species *Acacia cyclops* A. Cunn. ex G. Don. *For. Ecol. Manag.* **2014**, *331*, 237–244. [\[CrossRef\]](#)
27. Taylor, S.; Kumar, L. Potential distribution of an invasive species under climate change scenarios using CLIMEX and soil drainage: A case study of *Lantana camara* L. in Queensland, Australia. *J. Environ. Manag.* **2013**, *114*, 414–422. [\[CrossRef\]](#)
28. Bigirimana, J.; Bogaert, J.; De Canniere Charles, C.; Lejoly, J.; Parmentier, I. Alien plant species dominate the vegetation in a city of Sub-Saharan Africa. *Landsc. Urban. Plan.* **2011**, *100*, 251–267. [\[CrossRef\]](#)
29. Shanubhogue, A.; Gore, A.P. Using logistic regression in ecology. *Curr. Sci.* **1987**, *56*, 933–935.
30. Song, Y.; Ying, L.U. Decision tree methods: Applications for classification and prediction. *Shanghai Arch. Psychiatry* **2015**, *27*, 130–135. [\[PubMed\]](#)
31. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
32. U.S. Fish and Wildlife Service and California Invasive Plant Council. *Land Manager's Guide to Developing an Invasive Plant Management Plan*; Cal-IPC Publication, 2018-01; National Wildlife Refuge System, Pacific Southwest Region, Inventory and Monitoring Initiative: Sacramento, CA, USA; California Invasive Plant Council: Berkeley, CA, USA, 2018.

-
33. Landenberger, R.E.; Ostergren, D.A. *Eupatorium rugosum* (Asteraceae) flowering as an indicator of edge effect from clearcutting in mixed-mesophytic forest. *For. Ecol. Manag.* **2002**, *155*, 55–68. [[CrossRef](#)]
 34. Sharma, O.P.; Dawra, R.K.; Kurade, N.P.; Sharma, P.D. A review of the toxicosis and biological properties of the genus *Eupatorium*. *Nat. Toxins* **1998**, *6*, 1–14. [[CrossRef](#)]
 35. Kil, J.H.; Shim, K.C.; Lee, H.J. Allelopathic effect of volatile extracts from *Eupatorium rugosum*. *Korean J. Ecol.* **2005**, *28*, 135–139. [[CrossRef](#)]
 36. Kumar Rai, P.; Singh, J.S. Invasive alien plant species: Their impact on environment, ecosystem services and human health. *Ecol. Indic.* **2020**, *111*, 106020. [[CrossRef](#)] [[PubMed](#)]
 37. Guo, W.; Liu, Y.; Ng, W.L.; Liao, P.C.; Huang, B.H.; Li, W.; Li, C.; Shi, X.; Huang, Y. Comparative transcriptome analysis of the invasive weed *Mikania micrantha* with its native congeners provides insights into genetic basis underlying successful invasion. *BMC Genom.* **2018**, *19*, 1–17. [[CrossRef](#)] [[PubMed](#)]
 38. Colautti, R.I.; Macisaac, H.J. A neutral terminology to define ‘invasive’ species. *Divers. Distrib.* **2004**, *10*, 135–141. [[CrossRef](#)]