



Predicting the Invasion Potential of Pink Muhly (*Muhlenbergia capillaris*) in South Korea

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ABSTRACT

Predictions of suitable habitat areas can provide important information pertaining to the risk assessment and management of alien plants at early stage of their establishment. Here, we predict the invasion potential of *Muhlenbergia capillaris* (pink muhly) in South Korea using five bioclimatic variables. We adopt four models (generalized linear model, generalized additive model, random forest (RF), and artificial neural network) for projection based on 630 presence and 600 pseudo-absence data points. The RF model yielded the highest performance. The presence probability of *M. capillaris* was highest within an annual temperature range of 12 to 24°C and with precipitation from 800 to 1,300 mm. The occurrence of *M. capillaris* was positively associated with the precipitation of the driest quarter. The projection map showed that suitable areas for *M. capillaris* are mainly concentrated in the southern coastal regions of South Korea, where temperatures and precipitation are higher than in other regions, especially in the winter season. We can conclude that *M. capillaris* is not considered to be invasive based on a habitat suitability map. However, there is a possibility that rising temperatures and increasing precipitation levels in winter can accelerate the expansion of this plant on the Korean Peninsula.

Keywords: Alien plant, *Muhlenbergia capillaris*, Random forest, Risk assessment, Suitable habitat

Introduction

The rise of global trade in living organisms has contributed to the spread of alien plants (Hulme, 2009; Myers *et al.*, 2003). Intentionally and unintentionally, countless plant species have long been transplanted to locations outside of their native ranges (Bradley *et al.*, 2010). Some of these alien plants have become invasive, having detrimental effects on biodiversity and ecosystem processes as well as harmful effects on the well-being of humans (Mack


et al., 2000; Richardson *et al.*, 2000). Previous studies indicate that global changes such as rising temperatures, altering precipitation patterns, increased carbon dioxide (CO₂) levels, and nitrogen (N) deposition will alter the effects of invasive plants on native species and ecosystems (Bellard *et al.*, 2013; Vilà *et al.*, 2007). It is well known that invasive alien species are more likely to be able to cope with environmental changes compared to native species due to their greater physiological and ecological plasticity (Pyšek & Richardson, 2008). More attention should be paid to the planting of alien plants when the risk to ecosystems by these species is not known. Furthermore, accurate risk assessments of alien species should be conducted before their introduction into the country or during the early stage of their establishment.

To improve the risk assessment and management of alien species, habitat model results can provide important

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information by, for instance, identifying key environmental variables that affect the expansion of alien species and predicting the distribution shifts of alien plants (Bradley *et al.*, 2010). Specifically, the habitat model (also known as the envelope model, niche-based model, and species distribution model) has become popular for the projection of alien plants under current conditions and in scenarios in which environmental variables change (Guisan & Zimmermann, 2000). We applied the habitat model to estimate the suitable habitat (potential distribution) of *Muhlenbergia capillaris*, which was introduced into South Korea as an ornamental plant prior to 2016. While this species has been planted in public parks and private gardens extensively due to its exotic colors and the shape of its inflorescence (Park *et al.*, 2019), invasive potential assessments for *M. capillaris* have not been conducted in South Korea.

In this study, using four habitat models, the distributions of *M. capillaris* in Central and North America were simulated under the current climate condition and suitable habitats in South Korea were projected. The primary objectives our study were 1) to characterize the relationship between environmental variables and the occurrence of *M. capillaris*, 2) to predict suitable habitats under climate condition in South Korea, 3) to evaluate the invasion potential of *M. capillaris* based on the projected map and on eco-physiological properties.

Materials and Methods

Study species

M. capillaris is a perennial herb native to the United States, and other areas in North America, i.e., Florida, Georgia, and Mexico (GBIF). The most frequently used common name for *M. capillaris* is pink muhly or hair-grass. This gramineous plant forms a dense tuft with narrow leaves and flower stalks up to a meter tall (Engstrom, 2004). The spreading tufts have pinkish inflorescence, flowering in September and October. This species is reproduced by seeds and is mostly pollinated by wind. Each inflorescence produces approximately 900 seeds, with each tuft having more than 70,000 seeds (Park *et al.*, 2019). Germination rates are relatively low (maximum 20% under the best condition) compared to other species (Engstrom, 2004). This plant found in a wide variety of habitats ranging from open woods to savannah and can grow under diverse soil pH levels and textures (Barkworth *et al.*, 2003). *M. capillaris* is adapted to hotter, drier, and sunnier conditions than C3 species due to its C4 photosynthetic pathway (Gould & Shaw, 1983). *M. capillaris* was introduced into South Korea as an ornamental plant prior to 2016. Since then, this species has been planted in approximately 37 public parks and private gardens (as of 2018; Park *et al.*, 2019). This plant is popular in commer-

cial horticulture because the inflorescence presents the appearance of a pinkish mist at a distance.

Model variables

Distribution data for *M. capillaris* were obtained from the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/>) in 2019. We collected 630 presence data points in North America that extend from 15° and 43°N and from -118 to -73°E, representing areas where *M. capillaris* is native, whereas pseudo-absence locations (600) were randomly generated in the same area. We collected climate variables (bio1–bio19), topographic variables (elevation, aspect, slope), and solar radiation data as explanatory variables from WorldClim datasets (WorldClim, <https://www.worldclim.org/>) and from the Digital Elevation Model in QGIS. All raster explanatory variables used identical spatial extents, resolutions (1×1 km) and the same geographic coordinate system (WGS84, EPSG 4326), with a bilinear method in the raster package of R (version 3.6.3; <http://www.r-project.org>). To avoid collinearity, we removed variables highly correlated with each other based on the pairwise Pearson correlation coefficient (r pairwise ≥ 0.7) (Graham, 2003). Finally, we selected four climate variables considering the eco-physiological characteristics of *M. capillaris* (bio1: annual mean temperature, bio7: annual temperature range, bio12: annual precipitation, and bio17: precipitation of the driest quarter) and solar radiation.

Habitat suitability model

To predict the habitat suitability of *M. capillaris* in South Korea, we applied two statistical prediction models (generalized linear model [GLM], generalized additive model [GAM]) and machine learning models (random forest [RF], artificial neural network [ANN]). These modeling methods are commonly used and show high prediction performance when used in conjunction with habitat suitability modeling (Thuiller, 2003). Specifically, the RF method can estimate the importance of variables and can model complex interactions among many environmental variables. We used response curves and variable importance levels with the RF model to estimate the relationship between the occurrences of *M. capillaris* and environmental variables while running 30 evaluation trials. The sampled data points ($n=1,230$) were randomly divided into the model training dataset and the evaluation dataset at a ratio of 7:3.

The models accuracy levels were determined by the receiver operating characteristic (ROC), true skill statistic (TSS), Kappa statistics, sensitivity (omission error), and specificity level (commission error) (Allouche *et al.*, 2006). To convert continuous model predictions to a binary classification, in this case suitable habitats and unsuitable habitats, we used a threshold value that maximized the

sum of the sensitivity and specificity outcomes (Manel *et al.*, 2001). We considered ROC values below 0.7 as poor, those in the range of 0.7-0.9 as moderate, and those above 0.9 as good (Landis & Koch, 1977). Additionally, we used the following ranges to interpret the TSS and Kappa statistics: values of <0.4 were poor, 0.4-0.8 useful, and 0.8 >good (Zhang *et al.*, 2015). All of the evaluation values were calculated with the PresenceAbsence package in R version 3.6.3 (Freeman & Moisen, 2008).

Results

Two categories of environmental variables were considered for the prediction of the suitable habitats of *M. capillaris*. Four topographic variables and nineteen bioclimatic predictors derived from the WorldClim dataset were taken into account (Table 1). When we compared environmental variables between the presence and absence

areas of *M. capillaris*, seven environmental variables (srad, bio1, bio4, bio6, bio7, bio11, and bio18) showed more significantly differences compared to the other variables (F -value >100). *M. capillaris* was more frequently found in regions with higher annual mean temperatures and precipitation levels in North America. Temperature seasonality and the temperature annual range were lower in the presence areas than in the absence areas. Aspect, bio5, and bio19 were not different between the presence and absence areas. Solar radiation was positively correlated with temperature seasonality and the mean temperature of the warmest quarter. The annual temperature range was negatively correlated with the mean temperature of the coldest quarter (Fig. 1).

When we estimated the habitat suitability in native areas of North America, suitable habitats were mainly concentrated in the southeast US (i.e., Florida, Georgia, Texas) and on the west coast of Mexico. These areas had

Table 1. Comparison of mean and ranges values of environmental variables between the presence and absence spots of *Muhlenbergia capillaris* in North America

ID	Description	Presence (n=630)			Absence (n=600)			F-value
		Mean	Min.	Max.	Mean	Min.	Max.	
elev (m)	Elevation	920	3	3,737	875.2	-2	3713	0.65
aspect (degree)	Aspect	168.9	0	359.9	169.2	0	359.8	<0.01
slope (degree)	slope	32.7	0.2	87	38.2	0.5	85.4	10.1
srad (kJ m ⁻² day ⁻¹)	Solar radiation	21,320	17,504	27,656	23,317	17,690	28,240	219.1
bio_1 (°C)	Annual mean temp.	17.4	7.7	26.4	13.6	-1.4	28	146.9
bio_2 (°C)	Mean diurnal range	13.6	8.3	19.8	14.1	7.8	20.2	10.1
bio_3	Isothermality	50.4	28.9	75.4	43.5	24.8	78.6	72.4
bio_4 (°C)	Temp. seasonality	514.4	106.6	1,016	738	73	1,328	164
bio_5 (°C)	Max. temp. of warmest month	31	15.4	40.6	31.2	16.4	42.8	0.47
bio_6 (°C)	Min. temp. of coldest month	2.9	-11.6	17.4	-3.1	-22.1	19.7	157.7
bio_7 (°C)	Temp. annual range	28.1	14.6	42.3	34.2	11.4	48.9	185.6
bio_8 (°C)	Mean temp. of wettest quarter	20.3	4.5	28.7	17.4	-8.2	32.9	45.6
bio_9 (°C)	Mean temp. of driest quarter	14.2	-3.1	28.5	10.4	-13.5	28.9	44.7
bio_10 (°C)	Mean temp. of warmest quarter	23.5	8.8	31.2	22.6	7.7	33.1	11.7
bio_11 (°C)	Mean temp. of coldest quarter	10.8	-4.1	23.3	4.4	-13.5	26.3	188.8
bio_12 (mm)	Annual precipitation	1,037	130	1,907	807	59	3,607	65.0
bio_13 (mm)	Precip. of wettest month	161.4	17	439.4	123.9	10	632.6	61.7
bio_14 (mm)	Precip. of driest month	38.6	0.9	113	26.7	0	99.9	45.7
bio_15	Precip. seasonality	57.1	6.8	132.7	51.5	8.7	119.7	7.8
bio_16 (mm)	Precip. of wettest quarter	429	44	1,172	331	24	1,777	58.3
bio_17 (mm)	Precip. of driest quarter	134.7	5.9	370.3	95.4	1	336.9	45.4
bio_18 (mm)	Precip. of warmest quarter	324	12.1	967.2	227.9	2	870.5	128.6
bio_19 (mm)	Precip. of coldest quarter	161.4	16.6	453.4	151.5	12.5	1,118.2	1.2

Min., minimum; Max., maximum; Temp., temperature; Precip., precipitation.

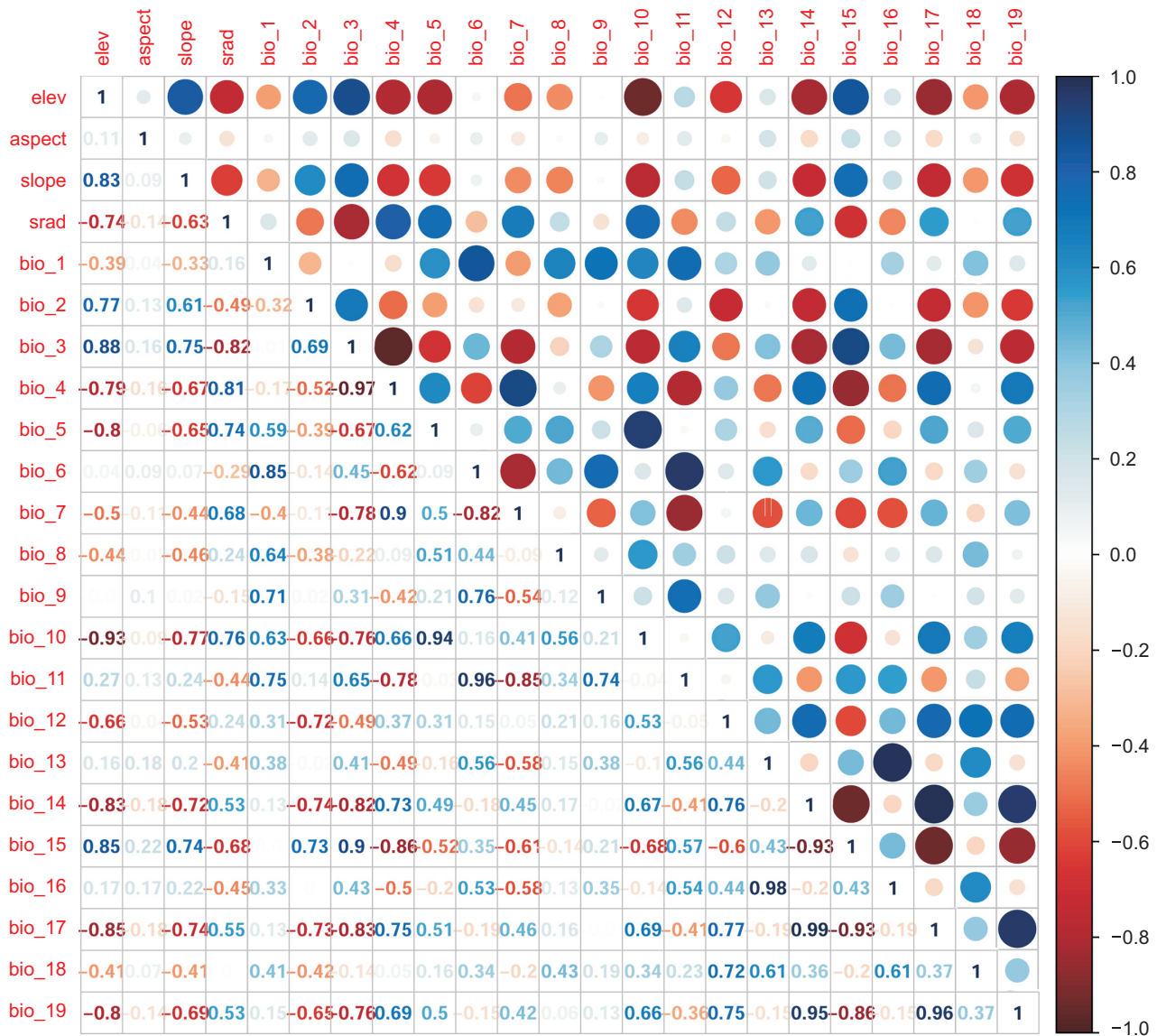


Fig. 1. Pearson correlation coefficient matrix comparing paired environmental variables. Positive correlations are shown in blue, and negative correlations are in red. The upper diagonal shows the strength of the correlation according to the dot size and the degree of red or blue color saturation. The lower diagonal presents the actual correlation coefficient values.

higher minimum temperatures in the coldest month and lower temperature seasonality compared to unsuitable areas (habitat suitability <20). However, highly suitable habitats (habitat suitability >80) differed depending on the model (Fig. 2).

All model showed good performance based on the ROC values (>0.7) and TSS and Kappa (>0.4) outcomes. The RF method yielded the highest performance, while GLM had the lowest predictive power among the four models (Table 2).

Variable importance

When we calculated the importance levels of the vari-

ables as assigned by the four models (Table 3), the annual mean temperature was the decisive factor determining the distribution of *M. capillaris* according to the RF model. In contrast, the precipitation of the driest quarter and the amount of solar radiation had stronger effects compared to the other variables in GLM.

We evaluated the probability of the occurrence of *M. capillaris* while increasing each variable in the response curve of the RF model (Fig. 3). The response curves for bio1 revealed a sharp increase in the predicted presence of the species above an annual temperature 12°C and below 24°C. The probability of occurrence steadily decreased as

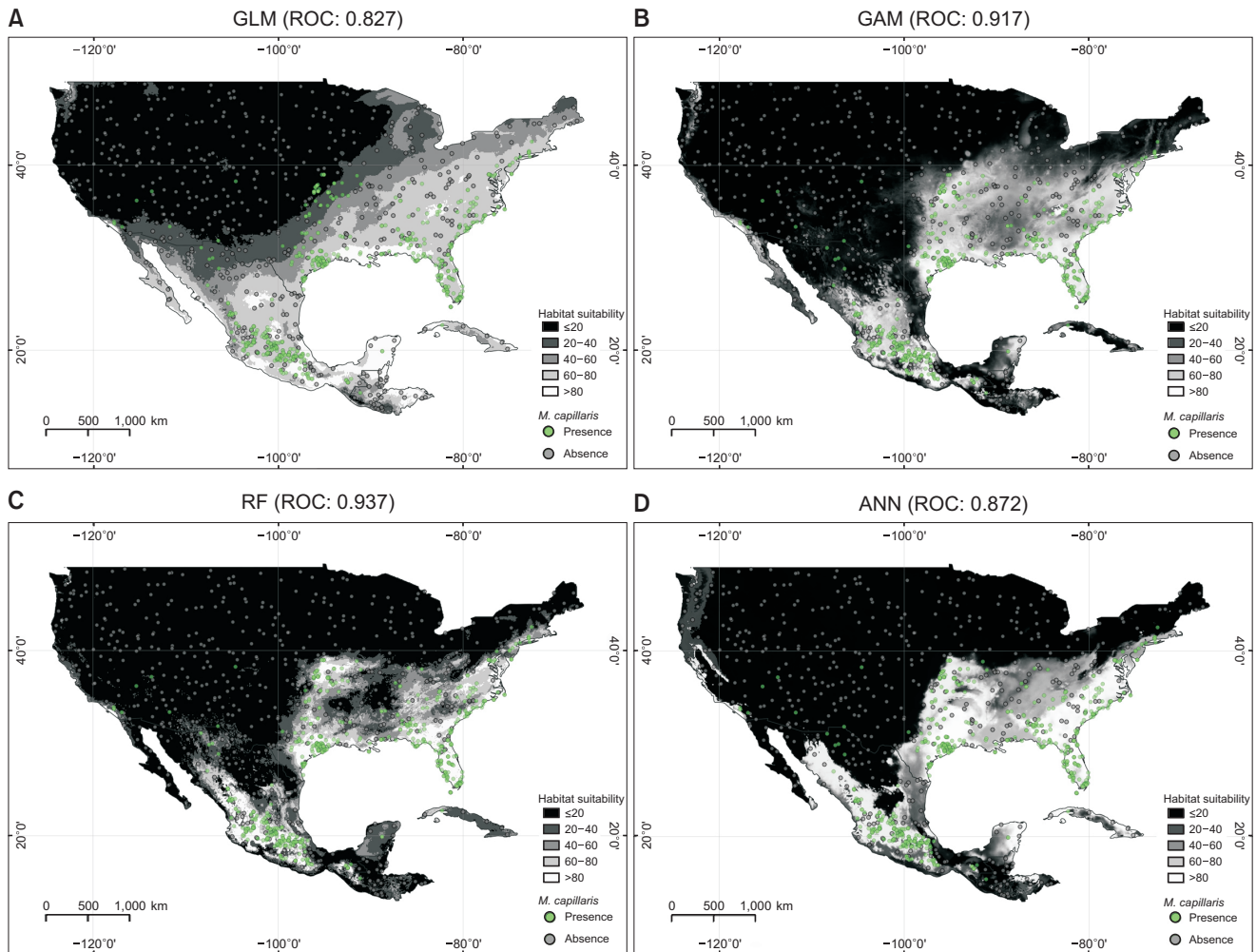


Fig. 2. Maps of the suitable habitats (white zone) for *Muhlenbergia capillaris* in North America. (A) GLM, (B) GAM, (C) RF, (D) ANN. Green dots show the presence of *M. capillaris* (n=630), Grey dots show the absence of *M. capillaris* sampled with pseudo-absence selection (random sampling strategy) (n=600). GLM, generalized linear model; ROC, receiver operating characteristic; GAM, generalized additive model; RF, random forest; ANN, artificial neural network.

Table 2. Model validation statistics and cut-off (threshold) values for suitable habitats

Model	Sensitivity	Specificity	TSS	ROC	Kappa	Cut-off
GLM	86.6	74.3	0.609	0.827	0.614	59
GAM	89.7	84.7	0.737	0.917	0.739	64
RF	92.9	85.7	0.786	0.937	0.790	55
ANN	96.1	78.1	0.742	0.872	0.753	44

TSS, true skill statistic; ROC, receiver operating characteristic; GLM, generalized linear model; GAM, generalized additive model; RF, random forest; ANN, artificial neural network.

bio7 increased above an annual temperature of 20°C. The presence probability of *M. capillaris* was highest when the annual precipitation was 1,200 mm. The occurrence of *M. capillaris* was positively associated with the precipitation of the driest quarter. When we compared each environ-

mental variable in native habitats with those in South Korea, the annual mean temperature in South Korea was much lower than the optimal temperature in the native habitats. The annual temperature range was higher in South Korea than in the native habitats in North America.

Table 3. Mean variable importance values (\pm standard deviation, $n=30$) for each selected variable and four habitat models

Variable	GLM	GAM	RF	ANN
bio1	0.19 \pm 0.05	0.35 \pm 0.04	0.31 \pm 0.03	0.36 \pm 0.09
bio7	0.17 \pm 0.07	0.29 \pm 0.07	0.18 \pm 0.02	0.17 \pm 0.06
bio12	0.17 \pm 0.02	0.13 \pm 0.02	0.17 \pm 0.02	0.76 \pm 0.02
bio17	0.51 \pm 0.04	0.43 \pm 0.06	0.09 \pm 0.01	0.28 \pm 0.04
srad	0.34 \pm 0.05	0.11 \pm 0.03	0.10 \pm 0.02	0.11 \pm 0.02

Variable descriptions are given in Table 1.

GLM, generalized linear model; GAM, generalized additive model; RF, random forest; ANN, artificial neural network.

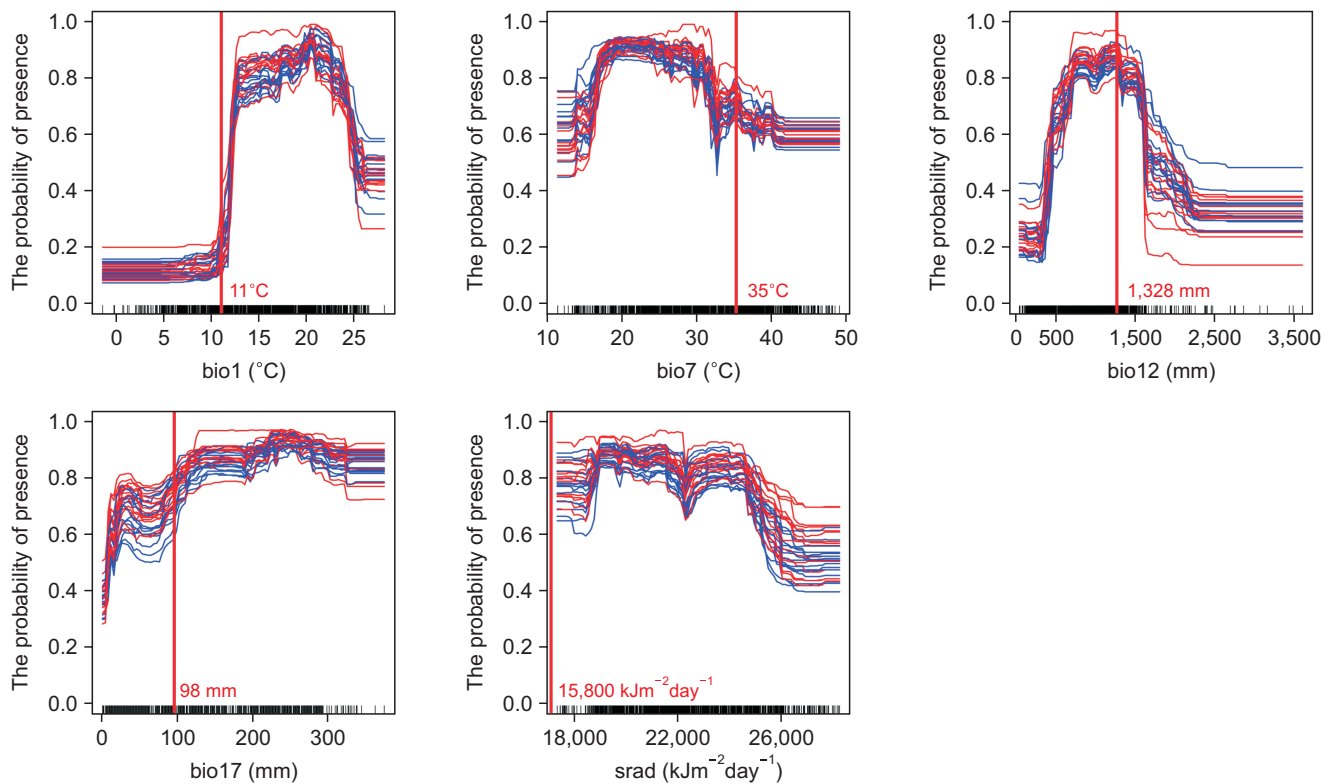


Fig. 3. Response curves of the random forest model with 30 evaluation runs. The Y-axis represents the probability of the presence of this plant, and the black marks along the x-axis represent empirical observations of each variable. The red line and letters indicate the mean values of the environmental variables in South Korea. bio1, annual mean temperature; bio7, Annual temperature range; bio12, annual precipitation; bio17, precipitation of the driest quarter; srad, solar radiation.

Furthermore, solar radiation was lower in South Korea compared to that in North America.

We predicted the suitable habitats for *M. capillaris* in South Korea based on the cut-off values (>55 , the maximum sensitivity plus the specificity), and the potential distribution area was found to account for 20.5% of the surface area of South Korea according to the RF model. The map showed that the suitable areas were mainly concentrated in southern coastal areas. These areas were characterized by higher annual temperatures and a lower

temperature annual range compared to other regions in South Korea.

Discussion

M. capillaris has been planted in approximately 37 public parks and private gardens over a short period of time due to its beautiful pinkish inflorescences (Park et al., 2019). It was reported that this species can produce numerous seeds and that it has a wide habitat range (Pfaff

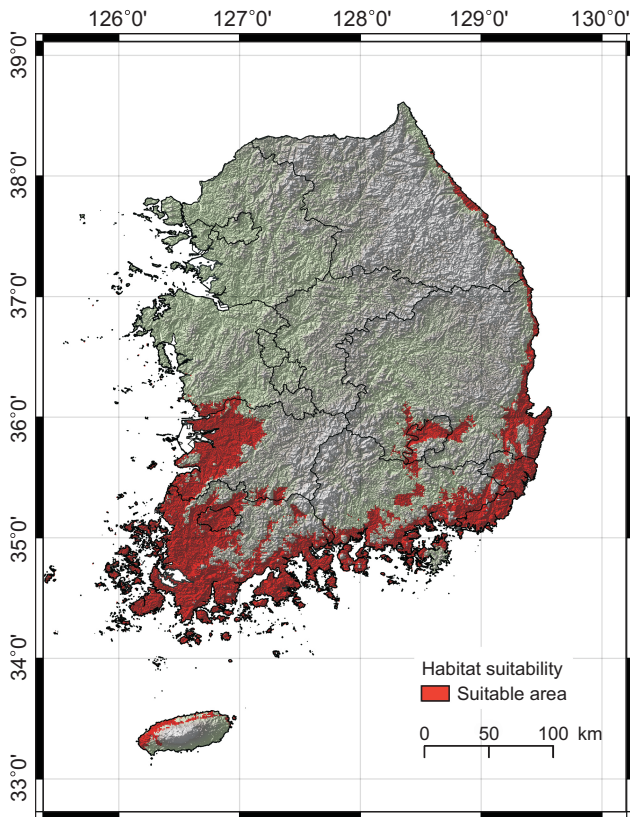


Fig. 4. Map of the suitable habitat (red zones) for *Muhlenbergia capillaris* in South Korea.

et Maura, 2000). The present study estimated the habitat suitability of *M. capillaris* in certain areas of North America (native habitat) and in South Korea using bioclimatic variables and predicted the invasion potential of *M. capillaris* under the climate conditions of South Korea.

Our results showed that the regional distribution of *M. capillaris* was influenced greatly by three climate conditions in South Korea. First, the annual mean temperature was lower in South Korea compared to the optimal annual mean temperature (approximate from 13 to 24°C) in the native habitats of this plant. This finding suggested that the establishment of *M. capillaris* can be inhibited by the low temperatures of South Korea based on temperature seasonality and the minimum temperatures in the coldest months. *M. capillaris* has a relatively low germination rate compared to those of other plants; the maximum germination rate was 20% under the optimal temperature and in humid conditions (Engstrom, 2004). We can speculate that the germination rate may drop dramatically in low-temperature field conditions. Furthermore, this plant may not easily survive the winter in the central parts of the Korean Peninsula, where the minimum temperature can drop below zero Celsius. In our projection map, suitable habitats are mainly concentrated in the southern coastal

areas and in regions of low elevation, where winter temperatures are relatively high compared to those in other areas (Fig. 4).

Secondly, the low precipitation in the driest quarter can be another stress factor preventing the establishment of *M. capillaris* in South Korea. The Korean Peninsula has low levels of winter and early spring precipitation, and much of the annual precipitation mainly occurs in the summer season. Although this C₄ plant can grow under drier conditions when formed into a bunch of tufts, this species is vulnerable to dry conditions at the seedling stage, like other gramineous plants (Kirk & Belt, 2010). *M. capillaris* is neither rhizomatous nor stoloniferous, reproducing through seeds (Engstrom, 2004). Northern inland areas of the Korean Peninsula have lower winter and spring precipitation rates than those of the southern coastal areas. These results suggest that the vulnerability to dry conditions as a seedling will present another obstacle preventing the establishment of this species in the central parts of South Korea.

Lastly, the lower solar radiation level in South Korea compared to those in the native habitats can inhibit the growth of *M. capillaris*. This plant is a C₄ grass adapted to hotter and sunnier conditions than C₃ plants. C₄ plants can utilize carbon dioxide efficiently with a specialized cell anatomy and chemical pathways under high solar radiation (Barbour et al., 1980). The biomass of *M. capillaris* mainly increases in the summer, from June to August. The Korean Peninsula has significantly less solar radiation than the native habitats in summer due to the effect of a rainy monsoon season (KMA, www.weather.go.kr). In addition, shading by woods can be another potential obstacle preventing this sun-loving plant from expanding into other habitats.

We speculated that the population of *M. capillaris* can be established in southern coastal areas, and this plant will not easily invade northern inland areas due to the unfavorable climate conditions in these areas. Additionally, the invasion potential of this plant may be lower than expected due to the competition with native plants and habitat disturbances by human activities. Although our modeling results showed good performance and provide a broad basis by which to estimate the invasion potential, there are several limitations that must be carefully considered. First, different resolutions can influence the performance of the model and can change the importance of the selected variables. A fine-scale approach is needed to design a management plan in South Korea (Suárez-Seoane et al., 2014). Second, eco-physiological properties such as the germination rate, dispersal ability, and competition with native plants should be incorporated into future studies for more accurate predictions. Third, further research must explore human-induced factors such as land use and disturbances.

In summary, we estimated the invasion potential of *M. capillaris* in South Korea with the RF model, which had highest performance among the four modeling methods tested here. Suitable habitats of *M. capillaris* were concentrated in southern coastal areas, where the temperature and precipitation levels are higher than those in other area in winter. We can conclude that *M. capillaris* is not considered to be invasive based on a habitat suitability. However, there is the possibility that rising temperatures and increasing precipitation in winter can accelerate the expansion of this plant on the Korean Peninsula. To prevent seed dispersal, the part of *M. capillaris* above ground which is planted in suitable habitat areas should be thoroughly removed in November.

Author Contributions

JSP analyzed the data and wrote the paper. DHC and YHK. provided technical assistance to JSP and helped with field data collection. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

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