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Review Article

# Review of CLIMEX and MaxEnt for studying species distribution in South Korea

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ABSTRACT

The use of species distribution modeling to predict the possible extent of suitable habitat for significant pests has been accepted as an efficient method for determining effective management and countermeasures. CLIMEX and MaxEnt are widely used software for creating species distribution models. CLIMEX predicts climatic suitability of a specific region for target species, whereas MaxEnt uses various environmental variables with presence-only data to assess potential distribution. The software has so far mainly been used for assessing large countries and continents but scarcely used to assess relatively small areas such as South Korea. The objective of this study was to review previous CLIMEX- and MaxEnt-based studies in South Korea and their effectiveness in predicting the distribution of species that could cause nation-wide damage. We expect that, by reviewing recently used species distribution models and their results, this study will provide the basic information necessary to predict potential species distribution.



## Introduction

Climate change has caused extreme weather events such as droughts and floods and has had widespread impacts on the global ecosystem, including rising sea levels (Lee 2010), change of crop production areas, and distribution of species (Kwak et al 2008; Pearson and Dawson 2003). According to the Intergovernmental Panel on Climate Change (IPCC), the temperature of the earth is estimated to rise by about 1.4–5.8°C from 1990 to 2100, and precipitation is projected to increase by up to 1.0% for the mid- and high-latitude regions and 0.3% for the tropical zones (IPCC 2014). These climate changes have substantially altered species phenology, biodiversity, potential distribution range, and habitat and have induced invasion of alien species and extension of growing period, which are largely due to temperature rise (Lee 2010). Because climate is known to be the most important factor regulating growth and development (Rosenzweig et al 2001), pests are heavily influenced by climate change and can extend their range, thereby causing increased damage to human livelihoods. For example, major crops such as rice, wheat, corn, and potatoes have been globally damaged by pests, incurring losses of 70 billion dollars, of which the damage in Asia alone accounts for 63% (Rosenzweig et al 2001). In addition, it has been estimated that 13 billion dollars worth of agricultural production is annually damaged in the United States, and 12.5 to 20 billion euros per year is lost because of invasion by alien insect pests in Europe (Kettunen et al 2009; US Fish and Wildlife Service 2012).

South Korea is no exception when it comes to the suffering from climate change. In South Korea, the influx of foreign pests and the damage they cause are increasing due to recent climate change combined with the expansion of international trade. Since the 1900s, 85 species have been introduced, and 26% of them have become invasive since 2009, indicating that the rate of inflow is growing rapidly. For example, 6.7 hundred million dollars was used to control *Bursaphelenchus xylophilus* in 1988, but it continues to occur. Also, it has been reported that the area where *Pochazia shantungensis* (Hemiptera: Ricaniidae) is found has doubled in 2 years.

Assessment of pest populations has been reported to have a direct impact on successful pest management (Kim and Jeong

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2010). There are ways to use long-term field data, species rearing data, and a model to predict the effect of climate change on the response of living organisms. In the case of insects, modeling has been a recent approach used in empirical studies and in predicting of lifestyle changes in response to environmental conditions (Jung et al 2014). Population dynamics models and species distribution models are famous examples of model-based studies (Buse et al 2007; Estay et al 2009). Among the various modeling approaches used for predicting pest response, species distribution models (SDMs), which combine numerical tools with observations of species occurrence and environmental factors (Elith and Leathwick 2009), are typical methods for predicting the potential distribution of pests. CLIMEX and MaxEnt (Maximum Entropy models) are software embedding SDMs that are frequently used by researchers at present. CLIMEX is a climate-specific tool that can assess the suitability of specific regions for target species with respect to climate change and predict potential distribution, climate similarity, and seasonal phenology (Jung et al 2016; Kriticos et al 2015). Meanwhile, MaxEnt predicts the distribution of a target species by using information about its presence, based on the maximum entropy distribution. Unlike CLIMEX, MaxEnt makes it possible to apply environmental variables such as land cover, distance, and geographical factors and to assess the contribution of each variable (Phillips et al 2006).

In advanced countries, there has been increased use of SDMs, including CLIMEX and MaxEnt, for predicting pest distribution liable to cause environmental damage (Kumar et al 2015), evaluating the possibilities of importing biological control agents or natural enemies of pests (Poutsma et al 2008) and assessing interactions of alien and endemic species (Sutherst et al 2007).

However, the use of SDMs has been limited to assessing only a few species in South Korea and has involved only simulations for potential distribution without further application of the modeling results. Hence, this study aims to review the basic functions, capabilities, and applications of CLIMEX and MaxEnt, which are two typical SDM tools. The review comprises three parts. First, we provide basic explanations and describe the method of application of CLIMEX and MaxEnt. Second, we review some notable studies using CLIMEX and MaxEnt in South Korea. Finally, we make conclusions on the benefits of applying modeling tools such as CLIMEX and MaxEnt to agriculture. We expect that this review will provide basic information on the use of SDMs and encourage their application in South Korea and elsewhere.

## Overview of CLIMEX and MaxEnt

### *Overview of CLIMEX*

CLIMEX (version 4.0, Hearne software, Australia) is a computational tool for studying the effects of climatic conditions on species distribution and relative abundance. CLIMEX has two main functions, and each function includes a total of 10 applications. The first function is called “CLIMEX Model,” and its main applications are Compare Locations, Compare Years, and Compare Locations/Years, whereas the second function is “Climate Matching” and includes applications of Match Climates and Match Climates (Regional). The CLIMEX Model is based on the assumption that we can infer the suitable climatic conditions for a target species when information about its habitat is known. The main application used in the CLIMEX Model for species distribution modeling is “Compare Locations,” and this is what we focus on in this review.

By using “Compare Locations,” researchers can predict the potential geographical distribution of target species with regard to climatic conditions (Jung et al 2016; Kriticos and Leriche 2010; Kriticos et al 2015; Stephens et al 2007). The result of a CLIMEX test is expressed as the ecoclimatic index (EI), which quantifies habitat suitability for a target species in a specific location based on the climate. The EI, expressed as numbers between 0 and 100, is calculated by multiplying growth index, stress index, and stress interaction index. While an EI close to 0 means that the target species cannot live in the location, an EI larger than 30 means the species can thrive in the given area. An EI between 0 and 10 means that the location has marginal suitability, whereas $10 < EI < 30$ indicates that the target species can survive in the location. Growth index, the collective indicator of facilitating species growth, is based on temperature, soil moisture, radiation, substrate, amount of light exposed, and diapause ability, whereas stress index is calculated from four stress indices, i.e., cold stress (CS), heat stress, wet stress, and dry stress, all of which are factors that limit the species population (Byeon et al 2017; Hill et al 2014; Kriticos et al 2015).

The CLIMEX software is used globally for analyzing potential distributions of species. For example, distributions of *Rhagoletis pomonella* (Diptera: Tephritidae) and *Spodoptera exigua* were predicted in China (Zheng et al 2012), whereas studies about the future risks posed by *Liriomyza huidobrensis* (Mika and Newman 2010) and *Metcalfa pruinosa* (Strauss 2010) were conducted in North America and Austria, respectively. Australia is a country that has actively used CLIMEX to predict the potential distribution of plants and diseases, as well as of insects. For example, Lanoiselet et al (2002) simulated the potential occurrence of rice blast disease in southeastern Australia, and Kriticos et al (2003) predicted the distribution of an invasive alien plant, *Acacia nilotica* ssp. *indica*, in accordance with climate change. Also, CLIMEX has been used to analyze the possibility of the import of natural enemies. For instance, the suitability of a biocontrol agent of *Chromolaena odorata* was analyzed in South America (Kriticos et al 2005), and the occurrence of *Binodoxys communis*, a natural enemy of *Aphis glycines*, was predicted in North America (Wyckhuys et al 2009). As shown in the aforementioned examples, predicting and analyzing potential distribution of species using CLIMEX is actively performed in various parts of the world; however, the use of CLIMEX to study pest distribution is just beginning in South Korea (Byeon et al 2017; Jung et al 2017a, 2017b, 2017c), and there is scope for intensive application of CLIMEX.

### *Overview of MaxEnt*

The MaxEnt software is used to find the maximum entropy distribution probability and can be used to predict potential distribution of a target species when it satisfies the maximum entropy under various conditions (Phillips et al 2006). In addition, MaxEnt, which adopts machine learning model using appearance information, can be used when distribution data are limited; this software requires only information about the occurrence of a species to predict the most suitable habitat. Consequently, this model has an advantage because it can achieve highly accurate classifications with available appearance information only. Specifically, MaxEnt predicts the potential distribution by analyzing the location data of the target species, a dependent variable, as a function of environmental variables. Location data are generally obtained as occurrence data from distribution data, through the field survey, while preexisting information—including land cover, forest type, ecological zone, distance, and geographical feature as well as climatic data—can be used to provide the environmental variables. The prediction ability of the model is evaluated by the area under cover (AUC) value (Phillips and Dudík, 2008). In MaxEnt, the receiver operating characteristic (ROC) curve is a plot showing the performance of a binary classifier, and AUC is the area under the ROC curve. In general, the minimum value of the AUC is 0.5, and predictive ability is considered to be convincing, with the AUC value larger than 0.8 (Franklin 2010; Lee and Kim 2010).

Globally, a few notable studies have been performed to predict potential distributions of pests using MaxEnt. For example, it has been used to predict the potential distribution of *Phenacoccus solenopsis* (Fand et al 2014; Kumar et al 2014) and *Justicia adhatoda* L. (Yang et al 2013) in India. Also, in Europe, distributions of large pine weevil and horse-chestnut leaf miner were predicted (Barredo et al 2015). In China, distributions of *Dacus bivittatus*, *D. ciliatus, D. vertebratus* (Li et al 2009), and *Lobesia botrana* (Lv et al., 2011) were simulated to predict the potential habitats of these pests. However, in South Korea, apart from one study that predicted the potential distribution of the *Pochazia shantungensis*, a planthopper (Kim et al 2015), most of the MaxEnt-based studies have targeted plants such as *Juglans sinensis* (Lee et al 2015), *Abeliophyllum distichum* (Lee et al 2011), and *Pinus koraiensis* (Choi et al 2015) and large animals such as *Ursus thibetanus* (Kim et al 2016b) and *Hydropotes inermis argyropus* (Song and Kim 2012).

## Review of studies using CLIMEX in South Korea

As mentioned previously, CLIMEX is software specialized in predicting the potential distribution of species based on climate data (Sutherst et al 2007). In South Korea, it is mainly used to predict the distribution of pests to obtain data for risk assessment. Most studies using CLIMEX have concentrated on monitoring invasive alien pests that have already been introduced or are likely to invade (Jung et al 2017b, 2017c). As climate change increases the risk of pest invasion, the use of CLIMEX is gaining importance in South Korea. For this reason, this section will review domestic CLIMEX-based studies aimed at predicting insect distribution in South Korea. All the studies to be reviewed are listed in Table 1, and the parameters used in operating CLIMEX for each study are summarized in Table 2. According to the parameter values published for eight species in Table 2 and historical climate data of 30 years (1981–2010) in South Korea, we simulated and reconstructed figures by CLIMEX and ArcMap (version 10.4.1, ESRI Inc., Redlands, CA, US). Because the parameters were already determined to minimize errors in prediction compared to actual distribution by each study (Kriticos et al 2015), we only use them for reconstructing the potential distribution map. The result showed that *Lycorma delicatula*, *Metcalfa pruinosa*, *Monochamus alternatus*, *Vespa velutina,* and *Aedes albopictus* could be found on a national scale, whereas *Thrips palmi*, *Aedes aegypti,* and *Anoplolepis gracilipes* could be found only in Jeju Island or in the northern parts of the inland regions of South Korea (Figure 1). Detailed analyses can be found in the articles referred to in Tables 1 and 2.

**Table 1.** Summary of previous studies using CLIMEX in South Korea.

| Authors (Year) | Species | Objective |
|---|---|---|
| Jung et al (2017a) | *Lycorma delicatula* | CLIMEX was used to predict potential distribution of *L. delicatula* and provide basic information for prevention of agricultural damage |
| Park et al (2014) | *Thrips palmi* | The habitat changes of *T. palmi* were estimated at 70 locations in South Korea by using CLIMEX |
| Byeon et al (2017) | *Metcalfa pruinosa* | The geographical distribution of *M. pruinosa* was predicted in South Korea from 2020 to 2100 with 20-year intervals |
| Kim et al (2016a) | *Monochamus alternatus* | Potentially vulnerable areas of *M. alternatus* were predicted under RCP (Representative Concentration Pathway) 8.5 climate change scenario in 2050 and 2090 |
| Park and Jung (2016) | *Vespa velutina* | CLIMEX model was used to evaluate critical regions of *V. velutina* in South Korea from 2000 to 2080 |
| Jung et al (2017b) | *Aedes albopictus* and *Aedes aegypti* | CLIMEX predicted future distribution of *Aedes albopictus* and *Aedes aegypti* and assessed risk of areal overlapping for disease transfer |
| Jung et al (2017c) | *Anoplolepis gracilipes* | Risk assessment of *A. gracilipes* invasion was performed by administrative district based on climatic suitability estimated by CLIMEX |

### *Lycorma delicatula (Spotted lanternfly)*

*Lycorma delicatula* mainly lives in parts of Southeast Asia and China, where the climate is relatively hot, and was first reported in South Korea in 2006. This species is known to cause significant damage by sucking the sap of trees, causing wilting, and covering with soot. (Jung et al 2017a) assessed climate adaptability of *L. delicatula* in Korea using the "Compare Location" function of the CLIMEX model. Seventy-four cities in South Korea were evaluated for their suitability as habitat for *L. delicatula,* using averaged climatic data (maximum temperature, minimum temperature, precipitation, and relative humidity at 9 a.m. and 3 p.m.) from 1981 to 2010. The data were provided by the Korea Meteorological Administration at 74 representative regions in South Korea. Based on the temperate template provided by CLIMEX and breeding data (Choi et al 2012), the parameters were initially determined and then optimized to be consistent with actual distribution. Because of low CS in CLIMEX results, high EI values (larger than 50) were shown in the southern parts of the country such as Busan, Changwon, Yeosu, and Wando County, whereas the lowest EI values were observed in inlands Gangwon-do and northern Gyeonggi-do. Of the 74 areas in South Korea, 71 areas were assessed to be suitable for the survival of *L. delicatula*, whereas three cities, including Daegwallyeong, were unsuitable because of high CS. The results suggested that South Korea has a highly suitable climate for *L. delicatula* inhabitation, and this is consistent with the nationwide problem caused by spotted lanternfly breakout.

### *Thrips palmi (Melon thrips)*

*Thrips palmi* is a pest that damages flowers and leaves of young crops such as cucumbers, peppers, and tomatoes. In South Korea, it was first found in a pepper greenhouse in 1993 and is now distributed along the southern coastal areas. Park et al (2014) used CLIMEX for predicting potential distributions of the species in South Korea based on past climate data and Representative Concentration Pathway (RCP) 8.5 climate change scenarios. In this study, climate data were obtained from 70 selected regions. Data from 2000, 2005, and 2010 were used as past climate data, and the RCP 8.5 scenario from 2015 to 2100 at intervals of 5 years was used for the prediction of future *T. palmi* distribution. Parameters were initially estimated based on the study by Dentener et al (2002) and finally determined by iterative tuning to fit the simulation to distribution data obtained from McDonald et al (2000), Cannon et al (2007), Sutherst et al (2007), Park et al (2010), and EPPO (2013). Model validation was conducted by comparing EI distribution of *T. palmi* with actual observations. The results showed that most of the southern regions in South Korea were suitable for *T. palmi* inhabitation from 2000 to 2010. As to the future, CLIMEX based on an RCP 8.5 climate change scenario predicts that *T. palmi* will be limited to the southern region until 2020 but will spread throughout South Korea over time.

**Table 2.** CLIMEX parameter values used in previous CLIMEX studies.

| Parameters | Code | *L. delicatula*[*] | *T. palmi*[†] | *M. pruinosa*[‡] | *M. alternatus*[§] | *V. velutina*[‖] | *A. albopictus*[¶] | *A. aegypti*[#] | *A. gracilipes*[**] |
|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | | | | | | | | | |
| Lower temperature threshold | DV0 | 8 | 10.6 | 13 | 10.8 | 10 | 5 | 18 | 15 |
| Lower optimum temperature | DV1 | 16 | 25 | 22 | 15 | 18 | 12 | 25 | 25 |
| Upper optimum temperature | DV2 | 30 | 30 | 28 | 30 | 26 | 30 | 32 | 35 |
| Upper temperature threshold | DV3 | 33 | 39 | 31 | 33 | 31 | 37 | 38 | 38 |
| Soil moisture | | | | | | | | | |
| Lower soil moisture threshold | SM0 | 0.3 | 0.25 | 0.25 | 0.1 | 0.2 | 0.2 | 0 | 0.01 |
| Lower optimum soil moisture | SM1 | 0.5 | 0.8 | 0.5 | 0.55 | 0.6 | 0.7 | 0.2 | 0.2 |
| Upper optimum soil moisture | SM2 | 1.5 | 1.5 | 1.0 | 1.35 | 1.5 | 2 | 0.5 | 1.5 |
| Upper soil moisture threshold | SM3 | 2.5 | 2.5 | 1.5 | 4 | 2.5 | 3 | 4 | 2.5 |
| Cold stress (CS) | | | | | | | | | |
| CS temperature threshold | TTCS | 0 | 4.4. | −1 | 8 | 0 | – | 4 | 5 |
| CS temperature rate | THCS | −0.0005 | −0.002 | −0.0001 | −0.00013 | 0 | – | −0.02 | −0.003 |
| CS degree-day threshold | DTCS | – | – | – | 0 | 10 | 10 | – | 0 |
| CS degree-day rate | DHCS | – | – | – | 0 | −0.00014 | −0.00015 | – | 0 |
| Heat stress (HS) | | | | | | | | | |
| HS temperature threshold (°C) | TTHS | 35 | 40 | 31 | 33 | 32 | – | 42 | 40 |
| HS temperature rate | THHS | 0.0005 | 0.0005 | 0.002 | 0.0001 | 0.0035 | – | 0.9 | 0.0002 |
| HS degree-day threshold | DTHS | – | – | – | 0 | 0 | 200 | – | – |
| HS degree-day rate | DHHS | – | – | – | 0 | 0 | 0.001 | – | – |
| Dry stress (DS) | | | | | | | | | |
| DS threshold | SMDS | 0.1 | 0.2 | 0.25 | 0.25 | 0.15 | 0.2 | 0.001 | – |
| DS rate | HDS | −0.005 | −0.005 | −0.005 | −0.001 | −0.008 | 3 | −0.001 | – |
| Wet stress (WS) | | | | | | | | | |
| WS threshold | SMWS | 2.5 | 2.5. | 1.5 | 4 | 2.5 | 3 | 4 | 2.5 |
| WS rate | HWS | 0.002 | 0.002 | 0.002 | 0.001 | 0.002 | 0 | 0.001 | 0.002 |
| PDD[††] | | 355.4 | 183.3 | 500 | 1690 | 462 | 100 | 126 | – |

[*] Jung et al (2017a).
[†] Park et al (2014).
[‡] Byeon et al (2017).
[§] Kim et al (2016a).
[‖] Park and Jung (2016).
[¶] Jung et al (2017b).
[#] Jung et al (2017b).
[**] Jung et al (2017c).
[††] PDD is a minimum amount of required thermal accumulation to complete a cycle during the growing season (Kriticos et al, 2015).

### *Metcalfa pruinosa (Citrus flatid planthopper)*

In South Korea, *Metcalfa pruinosa* is an alien pest native to the United States. This species attacks a wide variety of host plants, including fruit trees and forest trees, as well as causes sanitary problems in urban areas. Byeon et al (2017) predicted the potential distribution of *M. pruinosa* in South Korea from 2020 to 2100 at 20-year intervals with application of the RCP 8.5 climate change scenario. In this study, parameter values were set in a similar way as that in a study by Strauss (2010), and suitability was classified into four types; unsuitable for EI = 0, marginal for 0 < EI < 10, suitable for 10 < EI <30, and optimal for EI > 30. One of the notable features of this study was to construct an RCP 8.5 scenario database with 1-km high resolution, which would be specialized for South Korea. As a result of the simulations, EI values appeared in the whole country in 2020, with the lowest value in the mountainous area where Baekdudaegan is located and a tendency to increase in Gangwon-do. From 2080 to 2100, *M. pruinosa* began to be found where they were unable to survive, and the highest EI was formed in mountainous areas. This pattern occurred because of an increase in average temperatures, causing high heat stress everywhere except mountainous regions. This study also evaluated the colonization risk according to provinces. The risk assessment showed that Jeolla-do and Chungcheong-do, which have an EI higher than 20 under the present climate, would have a low risk under an average EI value of 1 in 2100, but the risk for Gangwon-do was expected to increase, with 14.6 of average EI. This finding suggests that areas exposed to the risk of *M. pruinosa* invasion will change as a result of global warming and that areas with high altitude in Gangwon-do will be at the greatest risk.

### *Monochamus alternatus (Japanese pine sawyer)*

*Monochamus alternatus* is an insect vector that, along with *Monochamus saltuarius*, transmits pine wilt disease. Its presence has been confirmed in South Korea, and it is mainly distributed in the southern part of Gyeongsangnam-do, where there has been a drastic increase in damage to Pinaceae timber, despite various control measures. To provide information for future control and assess potential damage, Kim et al (2016a) predicted the potential distribution of *M. alternatus* under current and future climates. Their study obtained 10-year average climatic data from 68 domestic weather stations, from 2006 to 2015, and data for the 2050s and 2090s were used as future distribution data. The default parameter values were adopted from the study by Song and Xu (2006), and their sensitivity was evaluated by setting eight parameter groups based on developmental and distribution data. In this study, the final result was simulated by comprehensively considering different developmental data and by determining the final parameter values that had the most similar distribution to the actual observations. The area of *M. alternatus* distribution under the current climate was larger than the actual outbreak area, and simulations of 2050 and 2090 showed increased EI in most areas of South Korea compared with the current distribution. In particular, the EI values for 2050 and 2090 drastically increased in Incheon, Chungcheong-do, and Gangwon-do, showing an EI that was double the current distribution.

### *Vespa velutina nigrothorax (Asian Hornet)*

*Vespa velutina nigrothorax*, an alien pest causing fatal damage to honey bees in apiaries, began to expand in a domestic apiary in

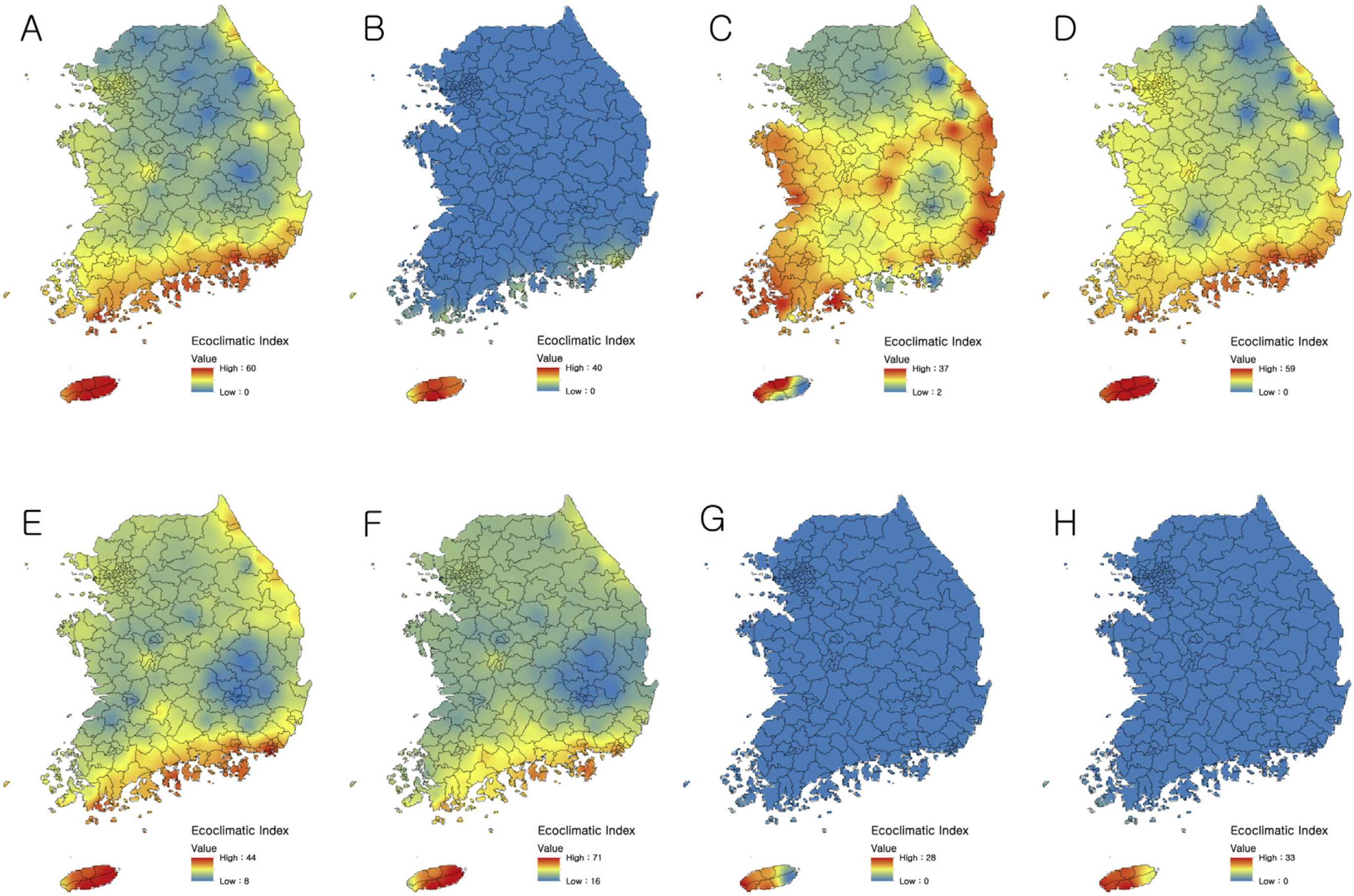


**Figure 1.** Reconstructed distribution maps of previous studies using CLIMEX in South Korea: A, *Lycorma delicatula* (Jung et al 2017a); B, *Thrips palmi* (Park et al 2014); C, *Metcalfa pruinosa* (Byeon et al 2017); D, *Monochamus alternatus* (Kim et al 2016a); E, *Vespa velutina* (Park and Jung 2016); F, *Aedes albopictus* (Jung et al 2017b); G, *Aedes aegypti* (Jung et al 2017b); H, *Anoplolepis gracilipes* (Jung et al 2017c).

Gyeongsangnam-do near Busan in 2007. Park and Jung (2016) used CLIMEX to predict the potential distribution of *V. velutina* in 70 major regions in South Korea with application of past (2000 and 2012) and future (2050 and 2080) climatic data sets. Also, this study investigated the relationship between EI values and years by assigning simple weights to the years using regression analysis. Because the biological information available for the target species was very limited, calibration of parameters was based on bumblebees, which have similar basic ecological characteristics to *V. velutina* (Sutherst et al, 2007). In other words, parameters of *Vespula germanica* provided by the CLIMEX software were readjusted for hot–wet stress parameters and used for domestic simulation As a result of CLIMEX, only 8.5% of the total area in 2000 was estimated to be suitable for *V. velutina* inhabitation, but it was expected to be 74% in 2012. Moreover, it was predicted that the species would inhabit the whole country by the 2080s. Additional regression analysis showed that there was no significant correlation between EI and year, but this study proposes a methodology to use CLIMEX results for further statistical analysis that has rarely been tried in domestic studies.

### *Aedes albopictus and Aedes aegypti*

*Aedes albopictus* and *Aedes aegypti* are notorious pests that transfer dengue virus, yellow fever virus, chikungunya virus, and Zika virus. In particular, the Korea Centers for Disease Control and Prevention reported in 2017 that *A. albopictus* could increase transmission of disease spreading from *A. aegypti* and suggested that *A. aegypti* introduction would pose a threat. To analyze the risk associated with an overlapping distribution of these two species in South Korea, Jung et al (2017b) simulated current and future potential distributions of *A. albopictus* and *A. aegypti* in South Korea using CLIMEX. Because the environments inhabited by the two species are different, parameters for each species have been estimated separately. Based on the information reported by Khormi and Kumar (2014) and Hill et al (2014), parameter values were estimated by iterative adjustment to derive the simulation result most similar with the currently recorded global distribution. For climate data in CLIMEX, average data from 74 domestic regions from 1981 to 2010 and RCP 8.5 climate change scenarios were used for the current and future predictions, respectively. In the simulation, *A. albopictus* was widely distributed all over the country, showing 73 of 74 areas in South Korea as suitable habitats, but the climate in South Korea was not appropriate for *A. aegypti* survival as only three cities showed EI larger than 0. In the future prediction performed from 2020 to 2100 with a 20 year-interval, *A. albopictus* was still expected to occur across the country, except for a few cities such as Gangwon-do, in 2020, and Daegu, after 2040. In the case of *A. aegypti*, EI values appeared only in coastal areas of Jeju Island in 2020 and 2040. However, it is expected that this species will have invaded the mainland of South Korea by 2060 and that it will spread out along the coastal regions by 2100. Concerning overlapping of the species distributions, which may increase the possibility of interspecies disease transfer, Jeju Island is exposed to this risk, and the overlap will gradually increase until 2100 along the coastal areas. In addition, as *A. albopictus* lives all over the country, disease transmitted from *A. aegypti* will spread rapidly, causing significant problems.

*Anoplolepis gracilipes (Yellow crazy ant)*

Yellow crazy ant is one of the world's 100 most dangerous pest species and is generally found in the tropical regions, although it has never been reported in South Korea. However, because of the extreme damage it causes to the local ecology (Feare 1999; Hill et al 2003; McKenney et al 2003) and the possibility of its introduction due to global warming and trade, early prediction of possibility of yellow crazy ant invasion is a worthwhile exercise. For this reason, Jung et al (2017c) applied CLIMEX to predict potential distribution of *Anoplolepis gracilipes* in South Korea for every 20 year period from 2020 to 2100 by using RCP 8.5 climate change scenario and assess invasion risk for each administrative unit, taking into consideration geographic characteristics such as trade ports, islands, and wetlands. *In silico* analysis by CLIMEX indicated that yellow crazy ant could survive on the southern coast, including Jeju Island, in 2020, and climatic suitability would increase until 2060 (33 areas showed EI in 2040, but 76 areas showed E1 in 2060). Moreover, it was predicted that *A. gracilipes* would be able to invade South Korea after 2100 because 210 areas showed suitable EI value, suggesting that the invasion threat would increase due to rapid climate change in South Korea. In detail, the highest EI values were found in Jeollanam-do and Gyeongsangnam-do, while the west coast and Gyeonggi-do coastal areas also showed high EI values.

## Review of studies using MaxEnt in South Korea

MaxEnt, a species distribution modeling tool, predicts potential distribution by analyzing the relationship between species and environment using appearance data and environmental variables such as climate information, ecological zone, and distance (Phillips et al 2006). It has predominantly been used to predict distribution of plants in South Korea (Jones 2012; Kleinbauer et al 2010; Lee et al 2016a; Taylor and Kumar 2013), whereas CLIMEX is generally used for insects in limited applications as previously described. Because there is a possibility of alien plants occurring in places other than those where they have been observed, non-emergence information is hard to obtain for plants (Lee et al 2016a; Philips et al 2006). For this reason, MaxEnt, which requires only appearance information, is suitable for predicting plant distribution. Also, one of the features distinguishing MaxEnt from CLIMEX is the function showing which climate variable affects potential distribution of target species the most. There have been some studies that have applied MaxEnt for South Korea (Table 3), but in this study, we focus only on those concerned with invasive alien species. Therefore, in this section, we review three studies using MaxEnt for predicting potential distribution of invasive alien species in South Korea; one invasive insect pest, *Pochazia shantungensis*, and two invasive plants, *Amaranthus viridis* and *Paspalum distichum* var. *indutum*.

*Pochazia shantungensis*

*Pochazia shantungensis* is an invasive pest, which may come from an area in eastern China adjacent to the West Sea. It is known to cause significant economic damage to fruit trees. Its first discovery in South Korea was in 2010, and it spread to the east from the West Sea region, presumably moving along the valleys between mountains. Kim et al (2014) used MaxEnt to compare actual distribution of *P. shantungensis* with potential distribution generated by MaxEnt under the current climate. The occurrence data of *P. shantungensis* were obtained from field survey in 2014, and the environmental variables were classified into climate, land cover, forest type, ecological zoning, and distance type. Climate data ranged from 2010 to 2013, whereas other variables were taken from geographical maps from the Ministry of Environment Environmental Space Information Service (http://egis.me.go.kr) and the Korea Forest Service spatial information (http://www.forest.go.kr). As a result of simulation, the suitability of the model was convincing, having an AUC value of 0.884, and it predicted that *P. shantungensis* might be able to live in Seoul, Gyeonggi-do, Chungcheong-do, and Jeolla-do. This result was consistent with actual distribution data. Also, this study predicted that it was possible for *P. shantungensis* to survive in Gangwon-do and Gimhae in Gyeongsangnam-do, where actual occurrence had not been reported. Among environmental factors, summer precipitation and summer mean temperature were the variables that most affected potential distribution as previously notified (Andrewartha and Birch 1954; Krebs 1978; Woodward 1987).

*Amaranthus viridis*

Lee et al (2016a) analyzed the potential distribution of *Amaranthus viridis*, a foreign plant that disturbs domestic biodiversity, in relation to climate change. The MaxEnt model was first used to predict the potential habitat, and then the difference between distributions predicted by RCP 4.5 and 8.5 scenarios was compared. Coordinate records were obtained from field surveys between 2014 and 2015 to be used as distribution data for *A. viridis*, and 19 variables of Bioclim provided by the WorldClim website as biological climate and altitude were used as the geographical factors. The AUC

**Table 3.** List of previous studies using MaxEnt in South Korea.

| Authors (Year) | Species | Objective |
|---|---|---|
| Kim et al (2015) | *Pochazia shantungensis* | MaxEnt was used to predict potential distribution of *P. shantungensis* under current climate and investigate range of host plants |
| Lee et al (2016a) | *Amaranthus viridis* | MaxEnt was used to predict potential distribution of *A. viridis* under RCP 4.5 and 8.5 from 2030 to 2100 |
| Kwon and Kim (2015) | *Scopura laminate* | Distribution changes of *S. laminate* in Odaesan National Park were estimated by using MaxEnt |
| Cho and Lee (2015) | *Paspalum distichum* var. *indutum* | MaxEnt predicted geographical distribution of *Paspalum distichum var. indutum* under RCP 2.6 and 8.5 scenario |
| Lee et al (2016b) | *Paspalum distichum and Ambrosia artemisiifolia* | MaxEnt was used to predict distribution of *P. distichum and A. artemisiifolia* and analyze main variables |
| Kim et al (2016b) | *Ursus thibetanus* | Distribution of *U. thibetanus* was evaluated to draw appropriate regions for effective preservation |
| Lee et al (2011) | *Abeliophyllum distichum* | This study estimated suitable habitat of *A. distichum* in the future and provided basic information for conservation |
| Cho et al (2015) | *Accipiter gentilis* | MaxEnt was used to predict potential distribution of *A. gentilis* and select alternative habitat |
| Song and Kim (2012) | *Hydropotes inermis argyropus* | MaxEnt and GARP were used to predict geographical distribution and to confirm applicability of species distribution modeling in South Korea |

value was 0.95 for training, whereas the test value of AUC was 0.86, suggesting that the model was reliable. The environmental variables contributing to the distribution of *A. viridis* were, in order, average annual temperature (63%), altitude (12%), and the coldest month of cumulative precipitation (11%). For the simulation based on RCP 4.5, the distribution of *A. viridis* was limited to the inland region of Jeollanam-do from 2030 to 2100. In contrast, in the analysis of RCP 8.5, distribution decreased in 2030, but dispersal would be possible in most areas, except Gangwon-do and the Baekdudaegan Mountains, in 2100. Scenario-specific differences by applying two different climate change scenarios suggested that future distribution of *A. viridis* may vary depending on climate change patterns.

*Paspalum distichum var. indutum*

Cho and Lee (2015) predicted the potential distribution of *Paspalum distichum* var. *indutum* according to current and climate changes using MaxEnt model. In addition, they evaluated the application of a species distribution model to assist with the development of management measures because *P. distichum* var. *indutum* is an invasive alien plant that negatively affects the watersides of freshwater ecosystems in terms of environmental and economic impacts. The location data of *P. distichum* var. *indutum* were collected from NIER (2012), NIE (2014), KNA (2015), and NIBR (2015) as well as from field investigation. Climate factors that have a substantial impact on plant distribution were used as environmental variables, and the potential distribution was predicted for 2050 by applying RCP 2.6 and 8.5 scenarios. The model was judged to be very suitable, as AUC value was 0.987. The climatic factors governing the distribution of *P. distichum* var. *indutum* were as follows: precipitation of the warmest quarter was 31.4%, average annual temperature was 23.1%, and average temperature of the coldest quarter was 14.6%. By using the RCP 2.6 scenario to assess the potential distribution of *P. distichum* var. *indutum* in 2050, it was predicted that its occurrence would be significantly reduced on the west coast and in Jeollanam-do and Gyeongsangnam-do, whereas distribution along the east coast could be increased, with the main occurrence in Chungcheong-do and Gyeongsangbuk-do inland. With the RCP 8.5 scenario, MaxEnt showed a similar pattern to the RCP 2.6 scenario on the east coast, but a higher rate of distribution was predicted in the inland region.

## Conclusion

Climate is the most influential factor in the ecology of species, and climate change is now causing shifts in geographical distribution and phenology of species (Rosenzweig et al 2001). As these changes can be used as data to predict the impact of climate change on species and to prevent damage from introduction of invasive species (Jung et al 2017a), it is, therefore, desirable to develop and use a species distribution model for systemic monitoring of harmful species. CLIMEX and MaxEnt software are widely used in many parts of the world to implement species distribution modeling effectively. However, in South Korea, they have not been extensively used because of differences in topographic characteristics and research focus. All the CLIMEX-based studies introduced in this review are recent studies predicting potential distribution of invasive pests in South Korea after 2014, whereas the MaxEnt studies have focused on invasive plants. CLIMEX is climate-specific software that analyzes the factors affecting the distribution of species; it has been suggested that combined use of CLIMEX with other software, for example, ArcGIS (Wong and Lee 2005), would overcome the limitations of CLIMEX through consideration of additional variables (Kriticos et al 2003; Sutherst et al 2007). On the contrary, MaxEnt includes factors besides climate and can estimate the contribution of each variable based on species emergence information. However, MaxEnt has a disadvantage in that it is impossible to refine the details of climate data using this software, which are the most important factors governing species distribution (Yang et al 2013), and this may drastically decrease the model's prediction ability. For this reason, a very novel approach has been emerged in the field of species distribution modeling which takes advantage of both these software using dual modeling (or ensemble modeling) (Kumar 2015). In conclusion, the use of species distribution modeling in South Korea is limited in comparison with that in advanced countries, but its importance is growing because of its ability to provide and accumulate important data on which measures for precontrol and management of alien species are based (Taylor and Kumar 2012). In addition, species distribution modeling has been used to evaluate whether a species imported to act as a biological control agent will become successfully established (Poutsma et al 2008). Therefore, we expect that the demand on species distribution modeling and its software will be continuously increased in South Korea, and sustained research on species distribution modeling is necessary to meet the current demand.

## Conflicts of interest

The authors declare that there is no conflicts of interest.

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