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Prediction of Spatiotemporal Invasive Risk by the Red Imported Fire Ant (Hymenoptera: Formicidae) in South Korea

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Abstract: In this study, we analyzed the potential distribution of red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae), in response to climate change in South Korea using CLIMEX, a species distribution model. We further attempted to evaluate the risk of the distribution/invasion and subsequent dispersion by considering climatic suitability, and functional characteristics of cities and covered cultivated areas. The climatic suitability has extended from the southern and coastal regions to inland regions due to climate change. The number of areas with EI (Ecoclimatic Index) values of more than 20 was 9 (12%) in the current climate; the value was assumed to increase to 23% (2040), 24% (2060), 42% (2080), and 62% (2100) from the South Korea coast to inland. We predicted that May to October would be the most active period in seven domestic high-habitation areas. We also analyzed the invasive risk of the red imported fire ant into covered domestic cultivation areas. Considering climatic suitability, we determined that Jeju, Pohang, Busan, Ulsan, Mokpo, and Gosan would be the most affected areas. This study can provide baseline data for the management of invasive species nationally and for regional control through predictions of the probability of settlement and direction of spread.

Keywords: climatic suitability; CLIMEX; digital mapping; potential distribution; invasive-risk analysis

1. Introduction

Although there are different factors affecting insect distribution [1], the climate is considered the most influential factor [2–5]. Therefore, many studies that examined the effects of climate change on pest distribution [6–8] or predicted invasion risk and potential pest distribution [9–11] use climate as the primary variable. CLIMEX is software that implements species distribution modeling [12]. It estimates bioclimatic parameters of target species by dominantly considering meteorological data to develop niche models; and it provides approximations for early monitoring reports and decision making in pest control [1,4]. Its application has been expanded to various pests in many countries [13]. South Korea is a recent region to use CLIMEX for predicting the potential distribution of invasive pests since climate change has increased the risk of invasion [14–20].

The Intergovernmental Panel on Climate Change (IPCC) proposed that global warming might shift species distribution [21]. Many reports have recently covered the introduction of alien species into

new areas. As a result of climate change, South Korea has also suffered nationwide damage caused by the introduction of invasive species [22]; the risk of new invasion is unfortunately increased by the accelerating climate change. Amongst new threats by invasive species, the red imported fire ant (*Solenopsis invicta*) is one of the biggest concerns in South Korea. This is because the red imported fire ant has caused severe damage to many aspects of human life and wildlife [23], various damages in agriculture [24–26], and even human health due to its aggressiveness and toxicity [27,28]. In addition, its rapid establishment and dispersion necessitate costly control measures that have not yet been completely effective, although various control treatments have been proposed [29,30]. Consequently, significant damage is expected once the ant becomes prominent in South Korea. Since the discovery of *Solenopsis invicta* in South Korea in 2017 and 2018, it has been recognized that developing an early monitoring system and management policy will be necessary.

Species distribution modeling is an effective method of providing fundamental background for developing such an early monitoring system and assessing the region of focus. The potential expansion range of the red imported fire ant was predicted by a dynamic model of colony growth based on climate data in the US [31] and the world [32]. In 2005, Sutherst and Maywald [33] used CLIMEX software to evaluate the potential distribution of red imported fire ant in the US and Oceania. Potential distribution of the red imported fire ant was predicted in South Korea by using a machine-learning-based statistical approach but this study used only distribution data [34]. There are other factors that induce invasion of red imported fire and determine their domestic establishment. Therefore, this study aims to analyze the invasive risk of the red imported fire ant based on climatic suitability, regional characteristics and the effect of agricultural facilities, which allow the red imported fire ant to endure unfavorable climate. To accomplish the study objectives, we first evaluated climatic suitability and predicted potential seasons for the red imported fire ant activity based on the characteristics of cities having high climatic suitability. Then, protected/covered cultivation areas were incorporated within the climatic suitability map to estimate the most vulnerable areas exposed to the red imported fire ant invasion and establishment.

2. Materials and Methods

2.1. Distribution Data of the Red Imported Fire Ant

The red imported fire ant is considered to have originated from Pantanau regions (Swampy areas) covering Brazil, Paraguay, and northern Argentina, and then migrated to Texas, Louisiana, Mississippi, Georgia, and Florida in the 1930s [35]. It is now known to be widely distributed from Oklahoma and Northern California to Virginia [30,33,36–38]. The red imported fire ant was also found in Australia, New Zealand, and Taiwan in 2003, and in Mainland China in 2004 [39–42]. In South Korea, its invasion was first reported in Busan, in 2017; it was subsequently found in Daegu in 2018 [43]. Distribution data were obtained from the CABI (Centre for Agriculture and Bioscience International; data by states) and GBIF (Global Biodiversity Information Facility; data by occurrence coordinates) public databases, defined in parameters of latitude and longitude [44,45]. The acquired data were projected onto a world map using ArcMap (version 10.4.1, ESRI, Redland, CA, USA). Data from the two databases had a similar global distribution and consistent with the distribution of red imported fire ant found in previous studies [32]. The developed distribution database and map were used to estimate optimal parameter values and validate the model in Section 2.3 so that the subsequent simulation would show the best fit to the current distribution [12,13].

2.2. Meteorological Data

Similar to previous laboratory studies [5,17–19], for climate data of South Korea, we used average daily maximum and minimum temperatures, precipitation and relative humidity at 9:00 a.m. and 3:00 p.m. for the past 30 years (1981–2010) measured at 74 observation stations under the Korea Meteorological Administration (KMA) because they are required to run the CLIMEX model [12].

The resulting data were converted into a climate-database format required by the CLIMEX software, with coordinates of 74 stations and averaged monthly values of the above meteorological data. For the climate change scenario, an RCP (Representative Concentration Pathway) of 8.5 was obtained from the KMA and converted into a suitable format in CLIMEX using MATLAB (version 2016a, The Mathworks, Inc., Natick, MA, USA). The constructed databases of an RCP 8.5 climate change scenario generated data estimates from 2040 to 2100, for every 20 years, with high resolution (1 km) suited for simulating South Korea [5,17–19]. The resulting climate-change-scenario database was composed of more than 97,000 coordinates and allowed high-density simulation for predicting the future distribution of red imported fire ant.

2.3. Parameter Estimation

Since CLIMEX connects climate in a specific region with biological characteristics of a target species, assessment of climatic suitability requires intensive estimation of parameters [12,13]. The initial values for model parameters were measured by three methods. The derived optimum parameters were combined to produce the best-fit simulation to the known distribution of red imported fire ant. The first method was to adopt CLIMEX parameter values from a previous study by Sutherst and Maywald [33]. The second used published observations from rearing experiments and seasonal variances such as temperature-dependent developmental rate [46], temperature-dependent survival rate [47], temperature-dependent metabolic activity [48], colony size at different temperatures [49], and survival rate related to soil moisture [50] that were subjected to statistical analysis. Based on these analyses, we determined the limiting low temperature (14.8 °C), lower and upper optimal temperatures (22 and 37 °C), limiting high temperature (40 °C), and degree-days (476). Low and high soil-moisture limits were set to 0.25 and 2, respectively, while upper and lower optimal-soil moistures were determined to be 1 and 1.5, respectively. The dry- and wet-stress rates were determined to be 0.026 and 0.0088, respectively, based on the survival rate and time exposure to specific soil moisture [50]. Cold- and heat-stress temperature thresholds were set at 10 °C and 40 °C, respectively, outside of which most previous studies could not observe red imported fire ant activity [47,49,51]. As the last method, we chose parameter values so that the simulation could produce the best fit for distribution in areas of origin, an approach that is commonly used in CLIMEX modeling [12]. None of the methods could exactly match the current distribution in the US where the distribution of red imported fire ant was the most detailed [52]. This suggested the need for further fine-tuning of parameter values. However, after repeated adjustment of parameter values incorporating the three methods, we finally determined optimal values of CLIMEX parameters with the least error in simulating the current distribution in the US at this time. The final parameter values used for predicting the potential distribution of red imported fire ant in South Korea are summarized in Table 1.

Table 1. Optimal values for CLIMEX parameters for red imported fire ant.

Parameters	Code	Optimal Value
Temperature		
Limiting low temperature (°C)	DV0	15
Lower optimal temperature (°C)	DV1	22
Upper optimal temperature (°C)	DV2	37
Limiting high temperature (°C)	DV3	40
PDD		476
Moisture		
Limiting low soil moisture	SM0	0.05
Lower optimal soil moisture	SM1	0.3
Upper optimal soil moisture	SM2	0.9
Limiting high soil moisture	SM3	1.3

Table 1. Cont.

Parameters	Code	Optimal Value
Cold stress		
CS temperature threshold (°C)	TTCS	0
CS temperature rate	THCS	−0.00447
CS degree-day threshold	DTCS	0
CS degree-day rate	DHCS	0
Heat stress		
HS temperature threshold (°C)	TTHS	40
HS temperature rate	THHS	0.0018
Dry stress		
DS threshold	SMDS	0.05
DS rate	HDS	−0.0025
Wet stress		
WS threshold	SMWS	1.3
WS threshold	HWS	0.01

2.4. CLIMEX Operation for Assessing Climatic Suitability and Seasonal Occurrence

The Compare Location function in the CLIMEX model was used quantitatively to evaluate the potential distribution of the red imported fire ant in South Korea as a function of climatic suitability. By connecting a regional climate with the biological characteristics of a target species, the CLIMEX model produces the Ecoclimatic Index (EI) that provides a representative assessment of climatic suitability. The EI ranges from 0 to 100, with a value greater than 20 indicating that the area is highly suitable for species establishment. In this study, we specifically categorized regions by applying the following EI ranges: impossible ($EI \leq 2$), unsuitable ($2 < EI \leq 10$), moderately suitable ($10 < EI \leq 20$), and ideal climates ($EI > 20$) for red imported fire ant survival. In addition, the occurrence time and duration were predicted by the Growth Index (GI), which evaluates the potential population growth under favorable climate conditions [33]. Since GI addresses how the potential growth of a species changes over 365 days, the occurrence time of the red imported fire ant was evaluated from changes in GI values and predicted to occur during the time with GI over zero [53]. Therefore, we analyzed changes in GI to predict the time of occurrence for 74 cities in South Korea and combined the results with climatic suitability to identify areas at risk for red imported fire ant invasion.

2.5. Constructing the Map for Covered Cultivation Areas

It is reported that the red imported fire ant invades artificial structures used for cultivating and storing food and horticultural crops to overcome unfavorable conditions [25]. To consider the effect of agricultural structures, we constructed a map recording the number of covered cultivation areas (e.g., greenhouse). For this purpose, we obtained the land-cover map provided by the National Environment Information Network System (NEINS) of the Korea Environment Institute [54]. The land-cover map is composed of complex images acquired by satellites and classified into physical conditions of the earth's surface such as agricultural areas, forests, grassland, and concrete pavement. From the land-cover map, covered cultivation areas, being a subclass of agricultural areas, was extracted by using ArcMap. We then converted extracted data from the polygon to raster format and classified the data according to the number of covered cultivation areas in each administrative district. The final map recorded areas by categories of 50, 100, 200, 400, and 800.

3. Results and Discussion

3.1. Prediction of Climatic Suitability and Seasonal Occurrence under the Current Climate

Quantitative evaluation of the climatic suitability of the red imported fire ant in South Korea was performed and recorded on the map shown in Figure 1A. The overall results indicate that 54 of the 74 cities (73%) are inhospitable to the red imported fire ant, while five cities (7%) have little climatic suitability. The red imported fire ant is known to be suited for tropical climates with an extreme low-temperature isotherm of -17.8°C [23]; thus, relatively low climatic suitability was expected. Eleven cities (15%) have EI values between 10 and 20, including Pusan, Changwon, Daegu, Gangneung, Gwangju, and Yeosu, suggesting that a relatively higher potential for accommodating red imported fire ant in those locations. Only 7% of cities (5 out of 74) have EI values larger than 20, suggesting a high possibility of ants' settlement after introduction. Two of them are located on Jeju Island, while Pohang, Ulsan, and Mokpo are large cities including a trading port. Cities showing high climatic suitability are located close to the sea and have ports and airports; such situation demands intensive monitoring due to a high risk of invasion [17,32]. Overall, high EI values were generally observed in cities adjacent to the sea, suggesting that introduction of red imported fire ant by ship could result in their distribution into the corresponding areas because of favorable climate [55]. This is confirmed by the way red imported fire ant was introduced to the Southern US from South America; they incidentally infiltrated the cargo carried by ships and then rapidly spread throughout the US [30]. Red imported fire ant in Taiwan, China, and Australia was also thought to have been introduced from the US by infested cargo, suggesting that trade to a specific area with favorable climate is a major route of red imported fire ant invasion [30]. The first reported introduction of red imported fire ant in South Korea was from a harbor in Busan where the EI value is larger than 10, with an ant of the same species as those found in the US [56]. This case serves as a reminder that trade cities with similar climate and population movement by tourism and business trip are at a high risk of new species introduction [57–59]. Considering these criteria, Mokpo, Pohang, Ulsan, and Jeju are areas with the highest probability of invasion of red imported fire ant.

Estimation of a likely occurrence time was performed based on GI in the cities with the EI larger than 20 (Sutherst and Maywald) [33] (Figure 1B). As previously mentioned, Jeju (two cities), Ulsan, Mokpo, and Pohang are densely populated cities with active human migration and international trade, and consequently are at a high risk for red imported fire ant invasion. Once red imported fire ant is introduced and settled in these areas, they are expected to be active from early May to late October but can be present from the end of March to mid-November in some areas, including Ulsan. Specifically, Jeju was predicted to have high red imported fire ant activity between June and September, a high-tourism period, suggesting a large potential for invasion [60,61]. For metropolitan Ulsan, the third-largest logistics hub in South Korea (accounting for 15.1% of total trade volume), active trade may result in the artificial introduction of the red imported fire ant and its rapid dispersion. In addition, analysis of activity periods through GI predicted that Ulsan would show the longest period of ant activity. The volume of trade in the port of Ulsan does not change significantly from month to month, but the volume of trade through the port was steadily increasing and reached its all-time high in 2017 [62]. Therefore, the possibility of introducing red imported fire ant into the location would be expected to show a corresponding increase, since the spread by imports is considered to be most active during the longest period of activity of the analyzed time.

The effect of host plants has been considered to be negligible on the distribution of the red imported fire ant because it is known to be an omnivorous organism, feeding on various resources [33]. These ants are known to have damaged not only crops, animals, and humans but also agricultural and electrical equipment [63]. Since ants are ectotherms and temperature regulates metabolic functions including growth and reproduction, climate is a driving factor in determining the settlement outcome once the species is introduced into a new area; hence, simulation based on meteorological data is likely reliable. Therefore, it is worthwhile to identify high-risk areas for distribution of red imported fire ant

based on climatic suitability and seasonal occurrence. Further, because of the high possibility of human introduction of red imported fire ant into new countries [23], cities having either ports or airports with significant tourism population and trade have an increased invasion risk when combined with high climatic suitability. For example, stings from red imported fire ant are most common in summer [64], greatly affecting areas with high tourism. Consequently, cities with a high risk of ant's introduction should require intensive quarantine.

3.2. Prediction of Future Distribution Using an RCP 8.5 Climate Change Scenario

Changes in the potential distribution in response to climate change allow us to predict dispersion patterns after settlement. Thus, climatic suitability is quantitatively evaluated by applying an RCP 8.5 climate change scenario in South Korea. Future potential distributions were estimated by deriving EI values for the years 2040 to 2100 with a 20-year interval and projecting them onto a map of administrative districts in South Korea (Figure 2A–D). After categorizing areas into four types of suitability based on EI value, we counted the number of regions by the EI value and its change (Figure 2E). According to the projected map, the area that fire ant could inhabit was predicted to increase through climate change, and the number of areas with EI values greater than 10 tended to rapidly increase to 25 (34%), 32 (43%), and 47 (63%) in 2040, 2060, and 2080, respectively. In 2100, 64 areas are predicted to have EI values greater than 10, and many of them are located inland. Among 64 suitable areas in 2100, forty-six had EI greater than 20, suggesting ideal climate for supporting red imported fire ant. Overall, high climatic suitability was observed in coastal areas first, but the suitability of inland areas increased with time. This suggests that once the red imported fire ant is introduced via port facilities in coastal areas and settles in climatically suitable areas, it can widely disperse inland with climate change. In the US, red imported fire ant spreads to the west at a rate of about 120 miles per year after their first introduction; they steadily dispersed even in Texas where the climate is less suitable than in other regions [23,64]. Current distribution reaches north to regions recording a minimum temperature of -17.8°C and west to California, all occurring much faster than expected [64,65]. In China, Hong Kong was considered to be the initial point of invasion, with the distribution expected to reach the mainland within 10 years [66]. The red imported fire ant has also distributed through direct movement but often with human assistance [23,40]. It has distributed varying distances by vehicles loading timber, sod, livestock feed, and construction equipment [66,67]. Therefore, with favorable climatic conditions, the red imported fire ant is likely to invade inland regions more rapidly than expected, reaching even unexpected regions. This suggests that species distribution modeling is necessary to predict the direction of dispersion with climate and thus provide fundamental data to be used for putting in place quarantine systems and control points.

Figure 1. Map for climatic suitability represented by the Ecoclimatic Index (EI) under current climate with the main cities showing a high risk of the red imported fire ant invasion (A). Potential active seasons represented by the Growth Index in the 5 main risky cities (B). Brown circles and pink triangles mean cities with a EI value more than 10 and 20, respectively.

Figure 2. Predicted distribution of red imported fire ant ((A): 2040, (B): 2060, (C): 2800, (D): 2100), and changes in EI values by the number of areas and times in response to climate change (E).

3.3. Risk Analysis of the Red Imported Fire Ant Invasion and Dispersion by Considering Covered Cultivation Areas

Red imported fire ant is distributed in agricultural fields and croplands in the United States and Puerto Rico, suggesting the possibilities of invasion into agricultural facilities and construction of microclimates due to dense crop canopy with water supplementation [32]. Even when overall climatic suitability was predicted to be low under the current climate, it might be possible that unfavorable conditions are altered through the introduction of covered agricultural structures where the environment is independent of the external climate. To evaluate the risk of introduction into highly concentrated covered cultivation areas, a map of covered domestic cultivation areas was constructed. Most domestic covered cultivation areas are located in the southern end of Jeju Island (Figure 3A). Areas with less than 50 of covered cultivation areas in the administrative district were excluded because the distance between covered cultivation areas was too long for the red imported fire ant to migrate under unfavorable climatic condition. Administrative areas having more than 50 such structures were marked with a red hatch and overlaid with the map of climatic suitability (Figure 3B–F). Regions with high climatic suitability but with few covered cultivation areas may cause local damage in the east coast due to increasing climate suitability along the coast. In contrast, areas with low climate suitability but with large covered cultivation areas might generate some risk due to migration from adjacent areas with high climatic suitability and entry into facilities to overcome unfavorable climate. The most dangerous areas were thought to be areas with a large number of cultivation structures and with high climatic suitability. Thus, a high possibility of establishment was expected in Jeju Island and areas near Pohang under the current climate. In 2040, climate change would expand the risk to south coast areas adjacent to a large number of covered cultivation areas. In 2060, as the potential habitat of red imported fire ant expanded inland, the risks would be highest in southern inland areas where covered cultivation areas are concentrated, while the risk of invasion into Jeju Island would be lowered due to reduced climatic suitability. In 2080, the likelihood of invasion becomes high in all covered cultivation areas except in the northern regions, but most of the covered cultivation areas are predicted to become vulnerable to red imported fire ant invasion in 2100. In summary, five areas among 34 major covered cultivation areas of the administrative district (14%) showed high climatic suitability. The number is expected to increase up to 11 areas (32%) in 2040. The number of cultivation areas with high climatic suitability is to increase steadily up to 25 (74%), 31 (89%), and 34 (97%) areas in 2060, 2080, and 2100, respectively.

Plant seeds are one of the main food sources for red imported fire ant [68], suggesting that the insect could spread into agricultural facilities including greenhouses and storage areas. In addition, the introduction of red imported fire ants through the transport of manure has been recognized [67]; thus, insects could migrate into facilities with the manure used as a fertilizer. Cities along the west coast are actively involved in international trade with China where the distribution of red imported fire ant has already been confirmed [40]. Thus, even though these regions currently show low climatic suitability, the red imported fire ant could possibly disperse throughout covered cultivation areas after being introduced via the above man-assisted artificial route. Moreover, Korea-China FTA (Free Trade Agreement) [69] and the rapid spread of red imported fire ant reported in China [67] increase the risk of invasion. In fact, in 2018, the red fire ant was brought from China in containers delivered to Incheon Port. Since red imported fire ant was discovered at Busan port in 2017, the possibility of the species introduction through shipment is likely the highest [43]. The risk of damage to people working in agricultural facilities needs to be considered since red imported fire ant stings. It was reported that 30% of residents in an area inhabited by the red imported fire ant was affected. Another study found that 89% of residents living in the red imported fire ant habitat were stung each year [23,70]. Even though the toxicity of the red imported fire ant is relatively low, allergic reactions can cause serious symptoms, such as difficulty breathing, confusion and even death if adequate treatment is delayed [23].

Figure 3. Map recording the number of cultivation areas under structure (A), and maps overlaid climatic suitability of the red imported fire ant and the number of cultivation areas ((B): current; (C); 2040, (D): 2060, (E): 2080, and (F): 2100).

Overall, the areas with the highest risk were evaluated in consideration of climatic suitability, the number of covered cultivation areas, and the location of possible artificial ingress (e.g., ports and airports). As a result, Jeju and Pohang were expected to have the highest risk under the current climate, while Busan and Mokpo would be the most at risk in 2040. However, as previously mentioned, most areas in South Korea will be exposed to the threat of red imported fire ant invasion due to climate change. Finally, we summarized a list of cities exposed to a high potential for red imported fire ant invasion by comprehensively considering factors affecting its introduction (Table 2). The major areas at risk of red imported fire ant invasion in South Korea are six cities (except for Gosan) that have harbors involved in regular international trade. In the case of Busan where the climatic suitability is relatively low, sufficient risk may still exist because of the largest volume of international trade that operates in that port.

Table 2. List of most dangerous cities exposed to red imported fire ant invasion.

	Jeju	Pohang	Busan	Ulsan	Mokpo	Gosan
EI (current)	40	34	16	29	34	38
Areas cultivation under structures	241	56	99	56	172	717
Port	○	○	○	○	○	○
Airport	○	○	○	○	X	X
International trades	○	○	○	○	○	X

All the cities are marked in Figure 1A.

We finally would like to indicate the modeling itself. The developed model was used to evaluate the climatic suitability of the red imported fire ant in South Korea. For the reliable prediction, we estimated parameter values based on a previous study [34] and refined them to generate the best fit with the actual distribution obtained from a public database. The current model could produce distributions in Arizona and New Mexico in the United States where the distribution was confirmed. Since there is a time difference between previous and current predictions this suggests that the red imported fire ant have continuously expanded its habitat. Even though the current model updated the parameter values to represent the actual distribution, it should be noted that the model depends on the distribution database that we used in estimating parameter values; thus, uncertainty in the distribution data could result in uncertainty in the model prediction. The actual field survey may help reduce uncertainty caused by distribution data. However, it is only applicable to a limited area and requires significant time, cost, and labor. As an alternative to overcome the weakness caused by the distribution uncertainty, an ensemble modeling, which integrate more than two different modeling techniques can be used [71,72].

4. Conclusions

This study developed a CLIMEX-based species-distribution model for predicting the current potential risk of invasion by the red imported fire ant and evaluated dispersion possibility with consideration of cultivating areas under cover. Current climatic suitability was relatively high in Jeju Island and some port cities along the southern coast where seasonal occurrence would be high in summer. Climate change is expected to make inland areas a more suitable habitat for the ant, indicating the likely direction of dispersion in South Korea. In addition, there will be a high probability of spread when the red imported fire ant penetrates into agricultural facilities after being introduced through ports into areas of high climate suitability. The red imported fire ant is notorious for causing widespread damage to local agriculture and ecosystem, its ability to adapt to poor circumstances, and its rapid rate of dispersion to new areas via various routes. Thus, the importance of early control and prevention of ant's invasion should be noted.

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