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# Model-based prediction of potential distribution of the invasive insect pest, spotted lanternfly *Lycorma delicatula* (Hemiptera: Fulgoridae), by using CLIMEX

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ABSTRACT

*Lycorma delicatula* is one of the major invasive pests of Korea. Careful monitoring is required to protect domestic agriculture as this pest causes severe damage to agricultural crops, such as wilting and sooty mold. This study was designed to confirm the potential distribution of *L. delicatula* using the modeling software CLIMEX and to suggest fundamental data for preventing agricultural damage by *L. delicatula*. Our results show that Korean weather seems to be adequate for *L. delicatula* habitation, indicating that approximately 60% of areas examined have a very high possibility of potential distribution. Particularly, we showed that Gyeongsang-do and Jeonla-do, which have not yet been invaded by *L. delicatula*, were very suitable locations for its growth. Therefore, although it is necessary to set up feasible strategies for preventing further *L. delicatula* invasions, subsequent studies are needed for assessing other invasive species considering the impact of future climate change.



## Introduction

*Lycorma delicatula* is a plant hopper native to China, India, and Vietnam, countries with relatively hot climates. After the initial report of *L. delicatula* in 2006, its population has been increasing all over South Korea, including Seoul, Gyeonggi, Chungbuk, Chungnam, Jeonbuk, and Gyeongbuk (KFRI 2007; Han et al 2008; Choi et al 2012). *L. delicatula* uses its sucking mouthparts to feed on the sap of fruit trees, causing severe damage, such as wilting and sooty mold (Han et al 2008; Lee et al 2009; Park et al 2009; Shin et al 2010). Between 2008 and 2009, this pest was responsible for widespread agricultural-sector damage caused by its excreta leading to sooty mold. In particular, *L. delicatula* is expected to cause significant damage to the vineyards in Korea, as its eggs are able to survive the increasingly warm winters brought about by global warming.

Recently, numerous research studies have been performed in South Korea, demonstrating that *L. delicatula* causes harmful effects. One study, which conducted a morphometric analysis of *L. delicatula*, showed that it was found in 10 localities in Korea, China, and Japan; in addition, 14 morphometric characteristics of the forewing were analyzed (Kim et al 2013). This study showed that in Korea, *L. delicatula* morphology was similar within the northern area of the Yangtze River, but in Seoul and Buan, it was very similar to that of *L. delicatula* in Shanghai. In terms of its biological characteristics, *L. delicatula* has four instars (Park et al 2009). This study showed that the body color of the first to third instar nymphs was black, but the upper body became red. In addition, the adult forewings were brownish with black spots, whereas the hindwings were red. In addition to morphological studies of *L. delicatula*, its survival rate has also been investigated. The occurrence pattern of *L. delicatula* in the Gyeonggi area and the effect of winter temperature on the survival of *L. delicatula* eggs from 2010 to 2013 have been reported (Lee et al 2014). In Jeonnam Province, Choi et al (2012) predicted the hatching time of *L. delicatula* eggs by using an effective environmentally friendly agricultural material, suggesting that a low temperature threshold and thermal constant were required for eggs to mature to the larval stage. In addition, other studies have focused on the effect of specific types of insecticides for the control of *L. delicatula* (Lee et al 2011; Park et al 2009).

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Factors such as habitation, dispersion, and reduction of species according to global warming may result in the invasion of alien species. Advanced countries, including America, Australia, and Europe, have used predictive modeling to forecast the potential distribution of pests in order to prevent them from invading domestic ecology. CLIMEX (Hearne software, South Yarra, Victoria, Australia) is a software that has been used for model-based predictions of the distribution and dispersion of species by integrating information regarding the habitat of target species and climate of the target area (Sutherst et al 2000, 2007). In other words, CLIMEX emulates the mechanisms that limit geographical distribution of species, identifies their phenology, and predicts the potential geographical distribution and seasonal abundance in response to climate change (Sutherst et al 2007).

Although there are many studies of *L. delicatula* regarding its morphology, physiology, and population control, to our knowledge, a study for predicting its potential distribution has not yet been conducted. The objective of this study was to investigate the potential distribution of *L. delicatula* in South Korea by using CLIMEX, and to assess high-risk areas for the invasion of *L. delicatula* based on the simulation. Because *L. delicatula* has been considered a major invasive pest and has caused widespread damage in Korea, the results of this study are expected to provide a basic information for monitoring species distribution and preventing its dispersion in advance.

## Materials and methods

### *CLIMEX software*

The CLIMEX Model (version 3.0) has mainly two applications: "Compare Locations" and "Compare Years" (Sutherst et al 2007). The "Compare Locations" application can predict the potential geographical distribution of a species according to climate preference, whereas the "Compare Years" application is used to show the response of a species to consecutive years of monthly climate in the same location (Hughes and Maywald 1990; Worner 1988; McKenney et al 2003; Sutherst and Maywald 2005; Sutherst et al 2007). The results of CLIMEX Model are represented by the ecoclimatic index (EI), which indicates the survival and growth of a species in many different locations. The EI is a number between 0 and 100, calculated by multiplying the growth index (GI), stress index (SI), and interaction stress index (SX). The GI describes the potential population growth during a favorable season, whereas the SI addresses the extent in population reduction during an unfavorable season. The GI contains seven indices (temperature, moisture, radiation, substrate, diapause, light, and biotic index). The SI is defined by four stresses: cold stress (CS), heat stress (HS), dry stress (DS), and wet stress (WS) (Sutherst et al 2007). In the present study, "Compare Location (1 species)" was applied among eight different applications as we are only evaluating one species (*L. delicatula*) in response to climate in South Korea.

### *Known distribution of L. delicatula*

The distribution of *L. delicatula* was determined by data on the occurrence of *L. delicatula* eggs reported by the Korea Forest Service in 2013 (KFS 2016) and by Han et al (2008) (Figure 1). The report showed that *L. delicatula* had spread throughout the country with particularly high concentrations in Gyeonggi-do ("do" is the equivalent of province, the largest administrative district in Korea), whereas it had not been reported in Geongsangnam-do. Specifically, from 2006 when *L. delicatula* was first introduced to Korea, its population had increased in various parts of the country (KFRI 2007; Han et al 2008; Choi et al 2012). This information was used to calibrate parameters of CLIMEX so that it could correctly simulate the current distribution of *L. delicatula* in Korea, as well as in China.

### *Climate data*

Meteorological data for predicting the potential distribution of *L. delicatula* consisted of five factors: minimum temperature, maximum temperature, precipitation, and relative humidity at 9 A.M. and 3 P.M. Meteorological data were modified based on the monthly data of the Climatological Standard Normal (1981–2010) provided by the Korea Meteorological Administration (KMA) and entered into CLIMEX software. Then, we selected 74 representative locations where CLIMEX applied meteorological datasets and predicted the suitability of habitation by *L. delicatula* (KMA 2016) (Table 1 and Figure 2).

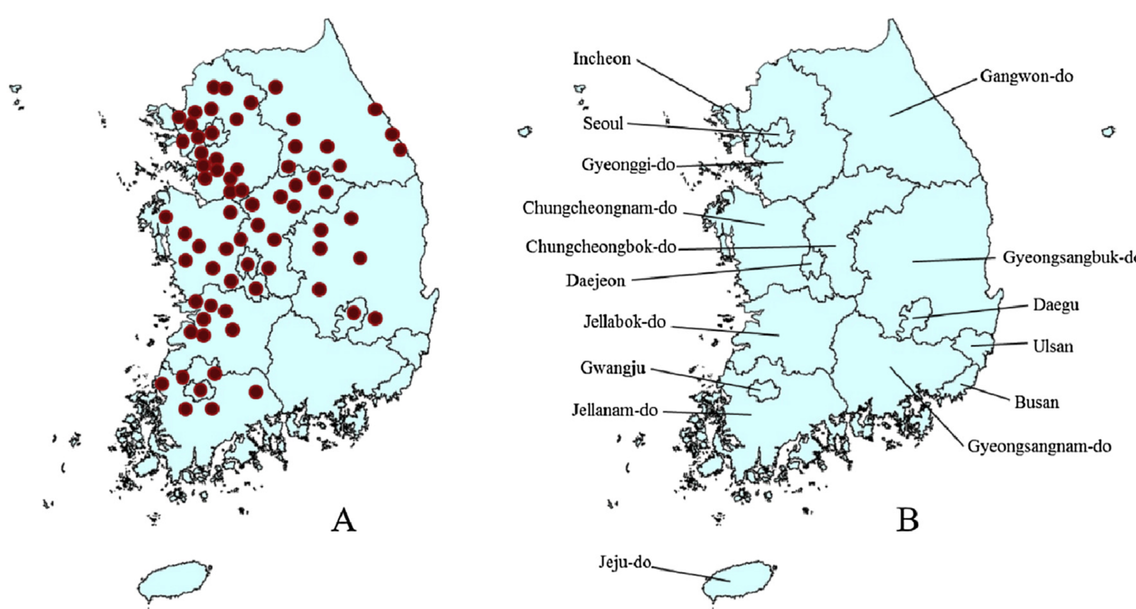


**Figure 1.** A, Distribution map of *Lycorma delicatula* consulted to KFS 2013; B, administrative districts in Korea including eight provinces and seven major cities. KFS = Korea Forest Service.

### Template in CLIMEX

CLIMEX provides templates that contain default parameter values for five climatic zones: wet tropical, Mediterranean, temperate, semiarid, and desert region. The template helps to set parameter values, and therefore, the appropriate utilization of a template is a very effective and important first step in setting up parameter values. For example, the desert template sets a soil moisture index (MI) of 0, 0.001, 0.2, and 0.3, but the wet tropical template has default MI values of 0.35, 0.7, 1.5, and 2.5. Understandably, templates differ from one another in terms of their parameter settings (Sutherst et al 2007).

*L. delicatula* was reported to have been brought from China (e.g. Shanxi, Shandong, Hebei, and Beijing), and settled in Korea. Because both reported regions of China and Korea have a temperate climate, we chose the temperate template in CLIMEX (Kim et al 2013). To reproduce the current reported distribution of *L. delicatula*, we additionally modified the default parameter values in the temperate template based on the actual current distribution data.

### Temperature index

The temperature index (TI) is a parameterized version of temperate-related data. The TI is defined by four parameters: the lower temperature threshold (DV0), the lower optimum temperature (DV1), the upper optimum temperature (DV2), and the upper temperature threshold (DV3) (Sutherst et al 2007). When the temperature is between DV1 and DV2, it is very favorable for a species. Conversely, a species may not survive at temperatures that are either lower than DV0 or higher than DV3. Population degree day (PDD) represents the total number of the degree-days above DV0 required for completing an entire generation.

For *L. delicatula*, the DV0 and PDD were 8.14°C and 355.4, respectively, whereas the DV3 of *L. delicatula* was 30°C, at which point the eggs of *L. delicatula* did not hatch (Choi et al 2012). Hence, we decided that the favorable temperature range was between 15°C and 25°C. DV0 and DV3 were set to 8°C and 33°C, respectively. This latter value was determined by the fact that adult *L. delicatula* can survive up to 33°C. DV1 and DV2 were estimated to be16°C and 30°C, respectively. DV2 was set higher than the favorable temperature range because the number of *L. delicatula* has been reported to increase in August in Korea. Finally, PDD for one generation was set to 355.4, as reported in the study by Choi et al 2012.

### Moisture index

Soil moisture is another crucial factor in CLIMEX because it indicates precipitation. MI, the soil moisture index in CLIMEX, is composed of four parameters: the lower soil moisture threshold (SM0), the lower optimum soil moisture (SM1), the upper optimum soil moisture (SM2), and the upper soil moisture threshold (SM3) (Sutherst et al 2007). Population growth peaks at the optimal soil moisture, represented by the range between SM1 and SM2.

**Table 1.** Geographical information of 74 locations in South Korea for CLIMEX simulation.

| No. | Location | Latitude (N) | Longitude (E) | Elevation (m) | No. | Location | Latitude (N) | Longitude (E) | Elevation (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Sokcho | 38°15′ | 128°33′ | 18.1 | 38 | Seogwipo | 33°14′ | 126°33′ | 49.0 |
| 2 | Cheolwon | 38°08′ | 127°18′ | 153.7 | 39 | Jinju | 35°09′ | 128°02′ | 30.2 |
| 3 | Dongducheon | 37°54′ | 127°03′ | 109.1 | 40 | Ganghwa | 37°42′ | 126°26′ | 47.0 |
| 4 | Daegwallyeong | 37°40′ | 128°43′ | 772.6 | 41 | Yangpyeong | 37°29′ | 127°29′ | 48.0 |
| 5 | Chuncheon | 37°54′ | 127°44′ | 77.7 | 42 | Ichon | 37°15′ | 127°29′ | 78.0 |
| 6 | Baengnyeongdo | 37°57′ | 124°37′ | 144.9 | 43 | Inje | 38°03′ | 128°10′ | 200.2 |
| 7 | Gangneung | 37°45′ | 124°53′ | 26.0 | 44 | Hongcheon | 37°41′ | 127°52′ | 140.9 |
| 8 | Donghae | 37°30′ | 129°07′ | 39.9 | 45 | Taebaek | 37°10′ | 128°59′ | 712.8 |
| 9 | Seoul | 37°34′ | 126°57′ | 85.8 | 46 | Jecheon | 37°09′ | 128°11′ | 263.6 |
| 10 | Incheon | 37°28′ | 126°37′ | 68.2 | 47 | Boeun | 36°29′ | 127°44′ | 175.0 |
| 11 | Wonju | 37°20′ | 127°56′ | 148.6 | 48 | Cheonan | 36°46′ | 127°07′ | 21.3 |
| 12 | Ulleungdo | 37°28′ | 130°53′ | 222.8 | 49 | Boryeong | 36°19′ | 126°33′ | 15.5 |
| 13 | Suwon | 37°16′ | 126°59′ | 34.1 | 50 | Buyeo | 36°16′ | 126°55′ | 11.3 |
| 14 | Yeongwol | 37°10′ | 128°27′ | 240.6 | 51 | Geumsan | 36°06′ | 127°28′ | 170.4 |
| 15 | Chungju | 36°58′ | 127°57′ | 115.1 | 52 | Buan | 35°43′ | 126°42′ | 12.0 |
| 16 | Seosan | 36°46′ | 126°29′ | 28.9 | 53 | Imsil | 35°36′ | 127°17′ | 247.9 |
| 17 | Uljin | 36°59′ | 129°24′ | 50.0 | 54 | Jeongeup | 35°33′ | 126°51′ | 44.6 |
| 18 | Cheongju | 36°38′ | 127°26′ | 57.2 | 55 | Namwon | 35°24′ | 127°19′ | 90.3 |
| 19 | Daejeon | 36°22′ | 127°22′ | 68.9 | 56 | Jangsu | 35°39′ | 127°31′ | 406.5 |
| 20 | Chupungnyeong | 36°13′ | 127°59′ | 244.7 | 57 | Suncheon | 35°04′ | 127°14′ | 74.4 |
| 21 | Andong | 36°34′ | 128°42′ | 140.1 | 58 | Jangheung | 34°41′ | 126°55′ | 45.0 |
| 22 | Pohang | 36°01′ | 129°22′ | 2.3 | 59 | Haenam | 34°33′ | 126°34′ | 13.0 |
| 23 | Gunsan | 36°00′ | 126°45′ | 23.2 | 60 | Goheung | 34°37′ | 127°16′ | 53.1 |
| 24 | Daegu | 35°53′ | 128°37′ | 64.1 | 61 | Bongwhoa | 36°56′ | 128°54′ | 319.8 |
| 25 | Jeonju | 35°49′ | 127°09′ | 53.4 | 62 | Yeongju | 35°62′ | 128°31′ | 210.8 |
| 26 | Ulsan | 35°33′ | 129°19′ | 34.6 | 63 | Mungyeong | 36°37′ | 128°08′ | 170.6 |
| 27 | Changwon | 35°10′ | 128°34′ | 37.2 | 64 | Yeongdeok | 36°31′ | 129°24′ | 42.1 |
| 28 | Gwangju | 35°10′ | 126°53′ | 72.4 | 65 | Uiseong | 36°21′ | 128°41′ | 81.8 |
| 29 | Busan | 35°06′ | 129°01′ | 69.6 | 66 | Gumi | 36°07′ | 128°19′ | 48.9 |
| 30 | Tongyeong | 34°50′ | 128°26′ | 32.7 | 67 | Yeongcheon | 35°58′ | 128°57′ | 93.6 |
| 31 | Mokpo | 34°49′ | 126°22′ | 38.0 | 68 | Geochang | 35°40′ | 127°54′ | 221.4 |
| 32 | Yoesu | 34°44′ | 127°44′ | 64.6 | 69 | Hapcheon | 35°33′ | 128°10′ | 33.1 |
| 33 | Heuksando | 34°41′ | 125°27′ | 76.5 | 70 | Miryang | 35°29′ | 128°44′ | 11.2 |
| 34 | Wando | 34°23′ | 126°42′ | 35.2 | 71 | Sancheong | 35°24′ | 127°52′ | 138.1 |
| 35 | Jeju | 33°30′ | 126°31′ | 20.4 | 72 | Geoje | 34°53′ | 128°36′ | 46.3 |
| 36 | Gosan | 33°17′ | 126°09′ | 74.3 | 73 | Namhae | 34°48′ | 127°55′ | 45.0 |
| 37 | Seongsan | 33°23′ | 126°52′ | 17.8 | 74 | Paju | 37°52′ | 126°45′ | 29.4 |

The geographical locations with corresponding numbers are represented in Figure 2.

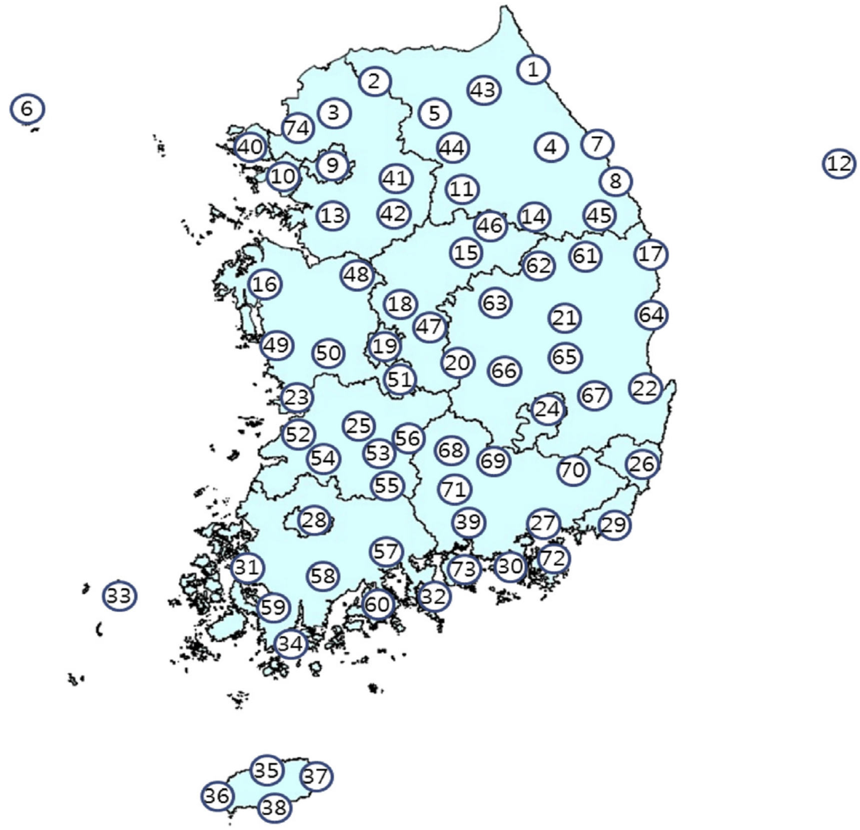


**Figure 2.** Target locations (74 cities) in Korea for CLIMEX. Detailed geographical information including city name, geographic coordinates, and altitude is listed in Table 1 with the corresponding numbers.

It is known that *L. delicatula* does not live on the ground at any life stage. However, evidence about the relationship between moisture and development of the *L. delicatula* is rare. For this reason, we adopted the parametric values provided by the temperate template in CLIMEX. We modified SM1 to 0.5, which is less than the default value from the temperate template because Beijing showed a very low EI because of low precipitation (Choi et al 2012). By the same rationale, SM0 was modified to 0.3 from 0.25. In summary, the final values for SM0, SM1, SM2, and SM3, were 0.3, 0.5, 1.5, and 2.5, respectively.

*Stress indices*

In CLIMEX, environmental stresses are parameterized by the SI index. It is defined by four types of stress parameters: CS, HS, DS, and WS. Indices of these four environmental stresses represent unfavorable conditions that limit the population growth of a species. Each index is specified by the stress threshold and the calculated stress rate (Sutherst et al 2007). All stress parameters cumulatively affect the population growth of a species when it is exposed to a range outside of its developmental limits.

Cold stress begins to accumulate when temperatures drop below a cold stress temperature threshold (TTCS, °C) at a given rate (THCS). The hatching of *L. delicatula* eggs is significantly limited at −11°C, and this temperature was initially used for defining TTCS (Choi et al 2012; Lee et al 2014). However, even though *L. delicatula* had not been reported in Russia, CLIMEX predicted that *L. delicatula* would survive there when TTCS was set to −11°C. Thus, we slightly modified TTCS to 0°C, and THCS was set to −0.0005 to be consistent with the current distribution.

When temperature is higher than the heat stress temperature threshold (TTHS; °C) at a given rate (THHS), heat stress begins to accumulate. As the temperature increases, the hatching rate of *L. delicatula* increased whereas the time required for hatching decreased. *L. delicatula* eggs did not hatch at 30°C, and the hatching rate became zero (Choi et al 2012). However, adult *L. delicatula* can survive at more than 30°C, suggesting that heat stress is insignificant under the current climate of South Korea. Based on this, TTCS and THCS were determined to be 35°C and 0.0005, respectively.

Dry and wet stresses occur when soil moisture is too low or too high. Dry and wet stresses start to accumulate when soil moisture falls below the dry stress threshold (SMDS) at a dry stress rate (HDS) or exceeds the wet stress threshold (SMWS) at a wet stress rate (HWS). Dry stress was calibrated by considering the precipitation of Beijing and the reported distribution of *L. delicatula* in China (Kim et al 2013). In order to achieve an EI value greater than 10 for Beijing, dry stress needed to be modified from 0.2 (a value provided by the template) to 0.1, setting SMDS and HDS to 0.1 and −0.005, respectively. Unfortunately, we could not find any report regarding wet stress on *L. delicatula*; therefore, the default values of the template were used: 2.5 for the SMWS and an HWS of 0.002.

*Potential geographical distribution of L. delicatula*

All the calibrated parameters used to run CLIMEX for the potential distribution of *L. delicatula* are listed in Table 2. In the simulation, an EI greater than 25 (EI > 25) generally means that the area is suitable for the distribution and habitation of the target species. In contrast, an EI less than 10 (EI < 10) indicates that the

**Table 2.** Parameter values used for *Lycorma delicatula* in CLIMEX.

| Parameters | Code | Value in template | Calibrated value |
|---|---|---|---|
| Temperature | | | |
| Limiting low temperature (°C) | DV0 | 8 | 8 |
| Lower optimal temperature (°C) | DV1 | 18 | 16 |
| Upper optimal temperature (°C) | DV2 | 24 | 30 |
| Limiting high temperature (°C) | DV3 | 28 | 33 |
| PDD | | 600 | 355.4 |
| Moisture | | | |
| Limiting low soil moisture | SM0 | 0.25 | 0.3 |
| Lower optimal soil moisture | SM1 | 0.5 | 0.5 |
| Upper optimal soil moisture | SM2 | 1.5 | 1.5 |
| Limiting high soil moisture | SM3 | 2.5 | 2.5 |
| Cold stress (CS) | | | |
| CS temperature threshold | TTCS | 0 | 0 |
| CS temperature rate | THCS | 0 | −0.0005 |
| CS degree-day threshold | DTCS | 15 | – |
| CS degree-day rate | DHCS | −0.0001 | – |
| Heat stress (HS) | | | |
| HS temperature threshold (°C) | TTHS | 30 | 35 |
| HS temperature rate | THHS | 0.005 | 0.0005 |
| Dry stress (DS) | | | |
| DS threshold | SMDS | 0.2 | 0.1 |
| DS rate | HDS | −0.005 | −0.005 |
| Wet stress (WS) | | | |
| WS threshold | SMWS | 2.5 | 2.5 |
| WS rate | HWS | 0.002 | 0.002 |

PDD = population degree day.

species barely survives in the area (Sutherst and Maywald 1985; Sutherst et al 1995, 1999, 2000, 2007; Vera et al 2002; Park et al 2014).

EI values were converted to a rater surface using Arcmap 10.5 (ESRI, Redland, CA, USA) to map the potential geographical distribution in the world (Figure 3). In addition, EI values for 74 representative locations in South Korea were marked with blue circles (Figure 4A), and we perform inverse distance weighting, which is an interpolation method in Arcmap 10.5 (Figure 4B). Based on the EI values, we finally assessed the potential risk of *L. delicatula* occurrence in specific areas under the current climate in South Korea.

## Results

The global distribution of *L. delicatula* predicted by CLIMEX is shown in Figure 3. In the simulation, *L. delicatula* had a high potential for distribution in the United States, Brazil, Mexico, Congo, China, Japan, and the southern part of Korea. In lower densities, *L. delicatula* may also survive in Europe, including the United Kingdom, France, Belgium, Switzerland, Spain, and Italy.

Southern areas of the Korean peninsula showed a high EI value, suggesting that those regions are very suitable for *L. delicatula* (Figure 4). Throughout South Korea, 97% of selected areas (71 of 74 total areas) were predicted to be favorable for *L. delicatula* habitation, whereas 3% would limit its survival. Seoul and Gyeonggi-do were suitable for the growth and survival of *L. delicatula*. The EI values for Seoul and Suwon were higher than 25, whereas Dongducheon, Ichon, Yangpyeong, and Paju in Gyeonggi-do showed EI values between 16 and 20. In addition, cold stress for Seoul and Gyeonggi-do was higher than 40, except in Suwon, which had a cold stress value of 28 and the lowest EI value. The EI values for Daejeon and Chungcheong-do were similar to those of Seoul and Gyeonggi-do. The EI value for Daejeon was the highest (EI = 35) because of the low cold stress and higher GI value compared to that of other locations near the Chungcheong Province. In addition, Cheonan was predicted to be suitable for the survival of *L. delicatula*, consistent with reports that the city was the initial area invaded by *L. delicatula* in 2008. In addition to the cities mentioned above, Chungcheong-do, including Seosan, Boryeong, and Buyeo, was found to be adequate for the survival and spread of *L. delicatula*. Areas inland from Gangwon-do, such as Cheorwon, Chuncheon, Wonju, Yeongwol, Hongcheon, and Taebaek, turned out to be favorable for *L. delicatula* habitation as the EI values were more than 10. However, Daegwanryeong has an EI value of zero,

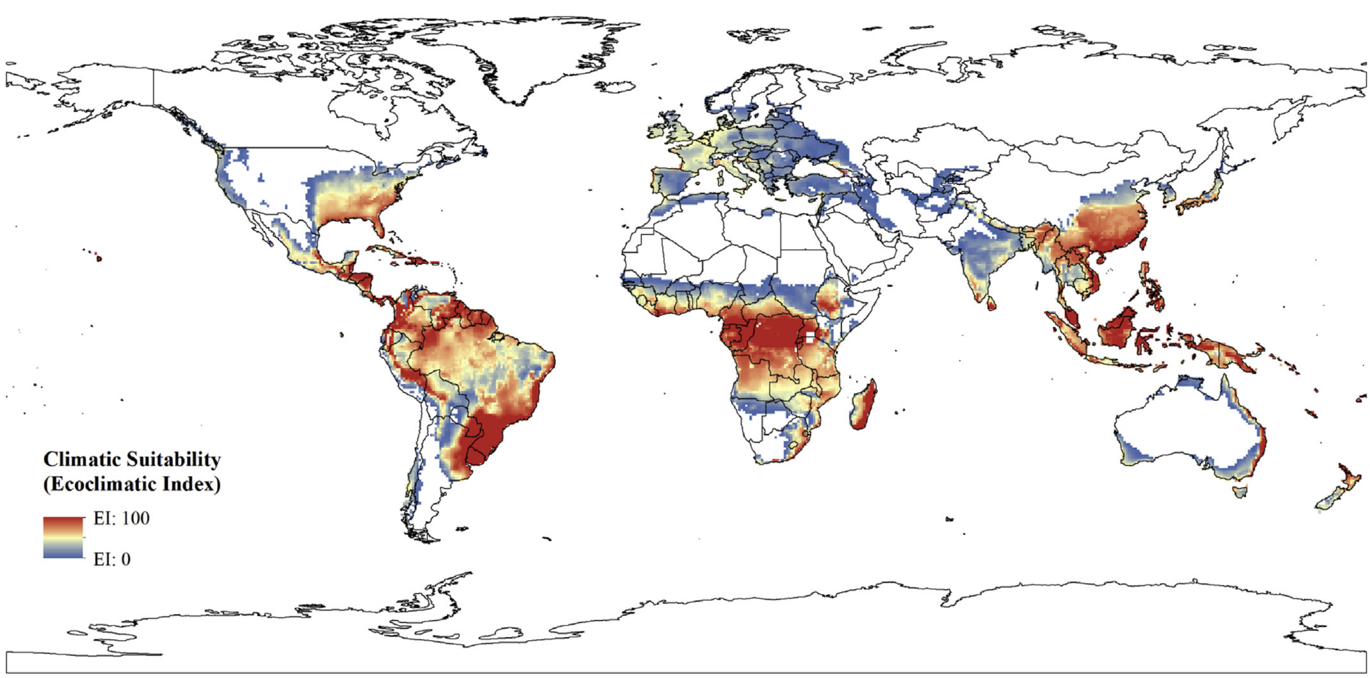


**Figure 3.** Predicted potential global distribution of *Lycorma delicatula* by CLIMEX. Ecoclimatic index (EI) values from 0 to 100 are represented by color ramp. The deeper red color represents the more favorable location for *L. delicatula* establishment, whereas deeper blue color represents the unfavorable region.

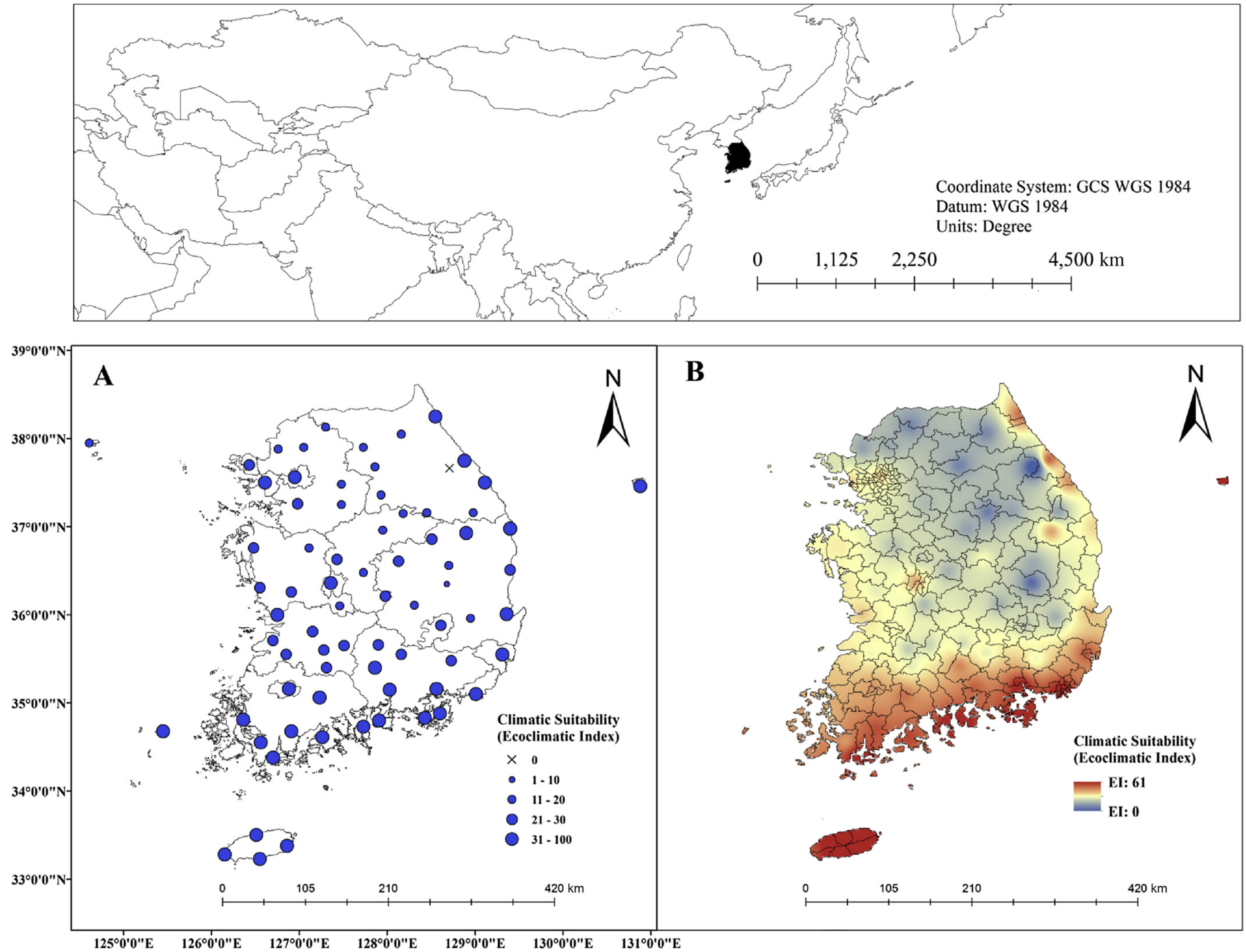


**Figure 4.** Predicted potential distribution of *Lycorma delicatula* by CLIMEX in South Korea. A, Larger circle and B, high intensity of red color indicates the more favorable for *L. delicatula* survival.

extremely limiting the survival of *L. delicatula*. The coastal areas in Gangwon-do, which normally exhibit a moderate climate compared with inland areas, were simulated to have favorable conditions for *L. delicatula*. Interestingly, the EI values for Gangneung and Sokcho were more than 40. The southern part of Korea—the Jeonla and Gyeongsang Provinces—had the highest potential for the distribution of *L. delicatula*. Gwangju and Jeonla-do were deemed as suitable locations for *L. delicatula*, with the exception of the cities of Geochang, Imsil, Inje, and Jangsu. The lowest EI value in Jeonla-do was 13; it occurred in the city of Inje, which had a cold stress value of 61. In contrast, Wando and Yoesu showed EI values of more than 50 because of zero cold stress. CLIMEX predicted that 17 locations in Gyeongsang-do, such as Busan, Ulsan, and Daegu, had a very favorable climate for the habitation and distribution of *L. delicatula*. In particular, Busan and Changwon showed EI values higher than 50. Meanwhile, Ulseong was the only city inhospitable to *L. delicatula*. As expected, all locations on Jeju Island were very favorable for *L. delicatula* survival and distribution. Jeju, Seongwipo, and Seongsan in Jeju-do have the highest EI values in South Korea. However, the geographical barriers to Jeju Island (i.e. sea) may prevent *L. delicatula* from invading this location.

## Discussion

The distribution of species will vary based on many variables, and experimental approaches cannot account for all of them. Therefore, a modeling approach has been emphasized as an effective tool for analyzing the suitability of specific areas for a target species. CLIMEX is a unique software program that can determine the distribution of insects, animals, and even plants, based on climatic information and the physiological features of a species.

In this study, CLIMEX predicted that *L. delicatula* could occur in most parts of South Korea. In particular, the potential distribution of *L. delicatula* was strongly predicted along the coast. In reality, *L. delicatula* was reported in coastal regions including Incheon, Donghae, and Gangneung (KFS 2016), which is consistent with the CLIMEX prediction. In addition, there was a very low distribution potential for *L. delicatula* in the Taebaek Mountains, which is consistent with the regional characteristics of that area, specifically low temperature (high cold stress) and high elevation limiting the travel of *L. delicatula*. However, the KFS reported that *L. delicatula* did not occur in Gyeongsangnam-do, Jeju-do, and southern coastal regions, which was not consistent with the prediction by CLIMEX. This inconsistency may be attributable to the characteristics of the regional topography such that the Sobaek Mountains and the South Sea block migration routes of *L. delicatula* to Gyeongsangnam-do and Jeju-do, respectively. As another possible explanation, we suggest that the pest control policies of Gyeongsangnam-do are rigorously established and adhered to, which could help mitigate the potential for *L. delicatula* invasion. Nevertheless, it is necessary to note that *L. delicatula* will rapidly spread throughout Gyeongsangnam-do and Jeju-do once introduced to any areas in those provinces because of the suitable climate represented by a high EI in CLIMEX. For this reason, we still need to monitor the distribution routes of *L. delicatula*.

In conclusion, this study has demonstrated that CLIMEX predicted similar patterns in potential geographical distribution of *L. delicatula* to those actually reported, suggesting possible usage of CLIMEX in predicting the expansion and distribution of species into new environments. Because the future projection of pest distribution can be fundamental for the creation of an early monitoring system and pest control program, it is expected that the use of CLIMEX will increase in the fields of ecology and agriculture in order to minimize agricultural damages by pests in advance. However, it should be noted that the simulation is significantly affected by parameter values. Therefore, fine-tuned parameterization is crucial for improving the predictive accuracy, and this requires collecting as much information as possible about the target areas and the pest species' developmental requirements.

## Conflicts of interest

The authors declare that there is no conflict of interest.

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