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Predicting the potential distribution in South Korea of two mealybug species (Hemiptera: Pseudococcidae) intercepted on pineapples in quarantine

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Predicting the potential distribution in South Korea of two mealybug species (Hemiptera: Pseudococcidae) intercepted on pineapples in quarantine

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Abstract. *Dysmicoccus brevipes* (Cockerell) and *Dysmicoccus neobrevipes* Beardsley are major pests of pineapples, ornamentals, and vegetable crops in many countries around the world. The potential distribution of these mealybug pests into South Korea remains a prime concern because of their high incidence in interceptions screened during inspection. Hence, these species prompted a modelling effort to assess their potential risk of introduction. Potential risk maps were developed for these pests with the CLIMEX model based on occurrence records under environmental data. The potential distribution of these pests in South Korea in the 2020s, 2050s and 2090s is projected based on the RCP 8.5 climate change scenario. Results show that *D. brevipes* and *D. neobrevipes* have little potential for invasion in the exterior environment of South Korea due to high cold stress. However, for *D. brevipes*, three locations in Jejudo were predicted to be marginally suitable for this pest under future climate factors. In that respect, the results of these model predictions could be used to prepare a risk-based surveying program that improves the probability of detecting early *D. brevipes* and *D. neobrevipes* populations.

Key words. CLIMEX, *Dysmicoccus brevipes*, *Dysmicoccus neobrevipes*, invasive species, pests.

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Introduction

The introduction of an exotic species to new geographical areas without their natural enemies has often been followed by large outbreaks in their population and subsequent economic damage to plants (CABI 2023a). Mealybugs (Hemiptera: Pseudococcidae) are plant feeders that have a more-or-less cryptic way of life because of their small size and limited mobility (Kondo and Watson 2022a). They are almost always found associated with plants, and are commonly intercepted on imported plant material (PIS 2023). As a result, they can easily be transported to other areas on the plants on which they live. A total of 114 species have been considered as pests in the world (Kondo and Watson 2022b). As of 2005, some 255 exotic scale insect species had become established in the USA; of these, 53 species were mealybugs (Miller et al. 2005). In South Korea, 91 exotic species have been documented from 1910 to 2019; of these, three species are mealybugs (RDA 2019).

Numerous kinds of insect pests were intercepted during import inspections at South Korean ports of entry. Mealybugs comprised 16.3% of the 198,086 interceptions from 1996 to 2022 (PIS 2023), of which, *Dysmicoccus brevipes* (Cockerell) (22.9% of the mealybug interceptions) and *Dysmicoccus neobrevipes* Beardsley (54.3%) were intercepted most frequently (Table 1). The pink pineapple mealybug (PPM), *D. brevipes*, was described in 1893 from pineapples in Jamaica. Since then, it has become a major pest of pineapples, ornamental plants and vegetable crops in many other countries in the world where it has spread by the international trade of these goods (García Morales et al. 2016). The grey pineapple mealybug (GPM), *D. neobrevipes*, is probably native to the Australasian region and was first reported in 1959 from Hawaii. Over the last 60 years, this species has been found in 44 countries on a wide variety of host plants (García Morales et al. 2016).

Table 1. Collection details of *D. brevipes* and *D. neobrevipes* intercepted on imported plants. Total Int: number of intercepted records; Reg Orig: the region where the species was first described; In Kor: distributed in South Korea. Codes for the type of commodity are as follows: plants for planting (P), fruits (F), leaves and cut flowers (L).

Species	Total int.	Reg. orig.	In Korea	Host genus	Consignment origin	Years intercepted
Dysmicoccus brevipes (Cockerell)	7412	Afrotropical	No	36 plant genera such as *Agave*(P), *Ananas*(F,P), *Citrus*(F,L), *Ficus*(P), *Musa*(F,L) and undermined plants	Australia, Bangladesh, Cambodia, China, Colombia, Costa Rica, Ecuador, Fiji, Honduras, India, Indonesia, Japan, Laos, Malaysia, Mexico, Myanmar, Netherlands, Panama, Peru, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, Togo, Tonga, US, Vietnam	1996–2022
Dysmicoccus neobrevipes Beardsley	17516	Australasian	No	22 plant genera such as *Agave*(P), *Ananas*(F), *Heptapleurum*(P), *Musa*(F), *Yucca*(P) and undermined plants	China, Colombia, Costa Rica, Ecuador, Guatemala, India, Indonesia, Malaysia, Mexico, Myanmar, Peru, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, Uganda, US, Vietnam	1996–2022

These two mealybug species are often found on imported pineapples and both are known to attack a wide variety of plant hosts throughout much of the world; they are considered as potential invasive species to South Korea. Although they are of potential economic importance, it is probable that they may not pose a threat to South Korean agriculture since they are native to subtropical and tropical habitats and the South Korean climate may not be appropriate for them. However, it is possible that they could pose a threat since they are usually found on imported plants of economic importance and may make their way into the South Korean environment, either in greenhouses or outdoor settings. Furthermore, the current South Korean weather conditions are changing towards becoming warmer and numerous imported subtropical and tropical crops are being grown in greenhouses in the southern area including Jejudo. In addition, invasive insect species may establish, survive and spread in cooler climates when the climatic conditions may be altered so as they can complete their development (Peacock et al. 2006).

In response to the growing risk of two quarantine pineapple mealybugs invading and establishing in South Korea, a modelling approach using the CLIMEX software may help assess the risk of them and determine the level of a surveillance program to detect the pest and provide an early warning of its presence in the country. The objectives of this study were to estimate the potential distribution in South Korea based on projections of climatic conditions in the remainder of the 2020s, the 2050s and the 2090s under representative concentration pathway (RCP) 8.5 climate change scenarios and to provide high-risk locations for monitoring these quarantine mealybugs efficiently. In addition, data on the interceptions of these two species on imported plants into South Korea during 1996–2022 based on records in the Pest Information System (PIS) database of South Korea were analyzed.

Materials and Methods

Interception data. Data on *D. brevipes* and *D. neobrevipes* intercepted at ports of entry to South Korea on imported plants between 1996 and 2022 were extracted from the Pest Information System (PIS), a database developed by the Animal Plant Quarantine Agency (APQA).

Occurrence data. The current global distribution data of *D. brevipes* and *D. neobrevipes* were obtained from the CABI database (CABI 2023a, b), ScaleNet (García Morales et al. 2016) and literature (Williams 2004; Wei et al. 2020; Sartiami and Kondo 2022; EPPO 2023a, b). Duplicate occurrences and potential errors in distribution data were cautiously checked and excluded. Data indicating country locations were removed, and the data referring to county, city and town of the specific location of the collections made within each country locations were usually used. Note that the species distribution model may not perform well if the climate in the target area is very different from that of the native and invaded areas such as the distribution of *D. neobrevipes* in Lithuania, which are an exotic species that is restricted to glasshouses and indoor plantings (Malumphy et al. 2008; Narouei Khandan et al. 2013).

Climate data. The CliMond CM30 World (1975H V1.1) climate dataset was used for global distribution of *D. brevipes* and *D. neobrevipes* (Kriticos et al. 2015). To predict climate suitability of two quarantine pests in South Korea, three meteorological datasets were used, comprised of data for 97,217 locations (2020s) and 97,379 locations (2050s and 2090s) in South Korea based on the RCP 8.5 climate change scenario of the Korea Meteorological Administration which was created for CLIMEX distribution modeling. Each location is represented as a unit of 1 km^2. CLIMEX requires data on the monthly long-term average maximum and minimum temperatures, rainfall and relative humidity at 09:00 and 15:00 h. All climatic data for South Korea were uploaded to the Met Manager program, which is directly accessible to the CLIMEX program. In addition, a top-up irrigation scenario of 2.5 mm day^{-1} throughout the year was applied to account for the potential effects of irrigation (Siebert et al. 2005).

CLIMEX model. CLIMEX was used to predict the potential geographic distribution of *D. brevipes* and *D. neobrevipes* in South Korea (Kriticos et al. 2015). CLIMEX models a species distribution by selecting values for a set of parameters that describe its response to temperature and moisture. Four stress indices (corresponding to cold, hot, wet and dry), and in some cases their interactions, describe the extent to which the population is reduced during the unfavourable season. The growth and stress indices are combined into an Ecoclimatic Index (EI), to give an overall measure of favourableness of the location or year for permanent occupation by the target species. The EI is scaled to an integer between 0 and 100, with an EI close to 0 indicating that the location is not favourable for the long-term survival of the species. An EI value of 0 is considered unfavourable, 1–10 is marginal, 11–25 is favourable and 26+ is considered very favourable for establishment of that species (Sutherst et al. 2000; Vera et al. 2002; Kriticos et al. 2015). The potential geographic distribution of *D. brevipes* and *D. neobrevipes* in South Korea was predicted by using the Compare Locations (one species) model of CLIMEX (version 4) (Kriticos et al. 2015).

Parameter fitting. The values of the CLIMEX parameters, which reflect a species' climatic requirements, are inferred from information on the species' known geographic distribution. Then CLIMEX model parameters should be acquired not only from previous published data analyses, but manually adjusted until the modeled geographic distribution matches the observed distribution as closely as possible (Vera et al. 2002; Kriticos et al. 2012; Kriticos et al. 2015). The methodology described in Kriticos et al. (2015) was used to fit the growth and stress parameters. The initial temperature index parameters (DV0–DV3) were set based on minimum, optimum and maximum temperature requirements of *D. brevipes* and *D. neobrevipes* obtained from published experimental studies (Colen et al. 2000; Qin et al. 2013; Hu et al. 2017; Bertin et al. 2018; He et al. 2018; Finch et al. 2020). The soil moisture parameters (SM0–SM3) were determined by calibrating parameters to match model output to the reported occurrence of these species (Finch et al. 2020). As there are no data available regarding the response of these species to stress conditions, these parameters were calibrated by comparing model results with the known distribution and previous study on other similar studies on mealybugs (Parsa et al. 2012; García Morales et al. 2016; Finch et al. 2020). The final parameter values are shown in Table 2. Model fit was visually assessed and the criteria were to observe the closest match of suitable habitats projected by CLIMEX and the reported distribution patterns of these mealybugs in area of the world. CLIMEX was then run to project the meteorologically suitable distribution in South Korea.

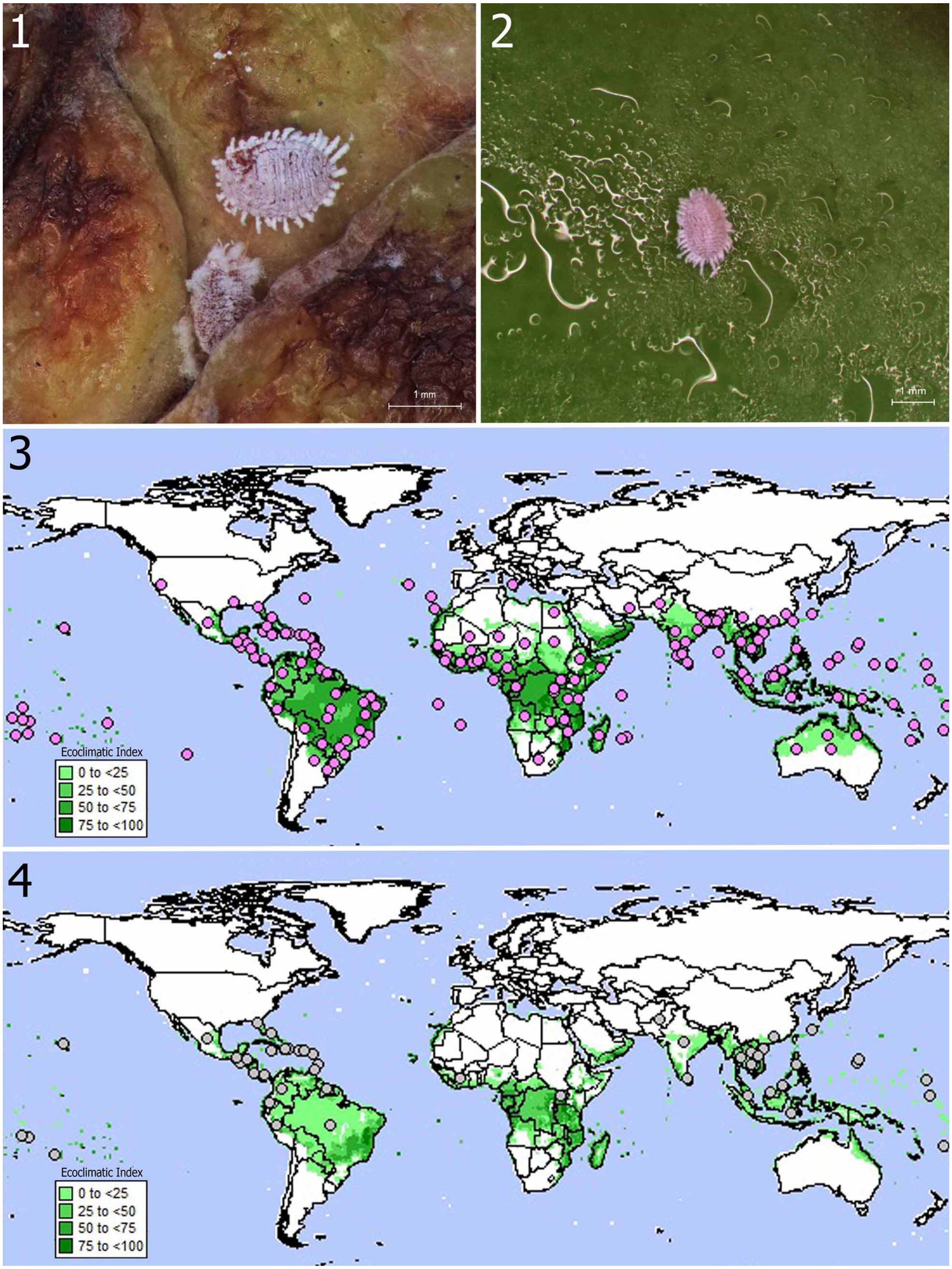
Results and Discussion

Dysmicoccus brevipes and *D. neobrevipes* are quarantine pests and apart from direct damage caused by feeding, they are responsible for transmission of a virus which causes mealybugs wilt disease that devastates pineapples (Kabi et al. 2016; Moreno et al. 2023). These mealybug species have been most frequently intercepted during phytosanitary inspections at South Korean ports and were mainly found on pineapples (28% of PPM and GPM interceptions) and banana fruits (70%) from countries such as the Philippines, Thailand, Ecuador and Costa Rica (Fig. 1–2). It has been also intercepted approximately 1% (164 times) from plants for planting such as *Agave* L., *Heptapleurum* Gaertn. and *Yucca* L. plants. The remaining 1% was found on undetermined plants (Table 1).

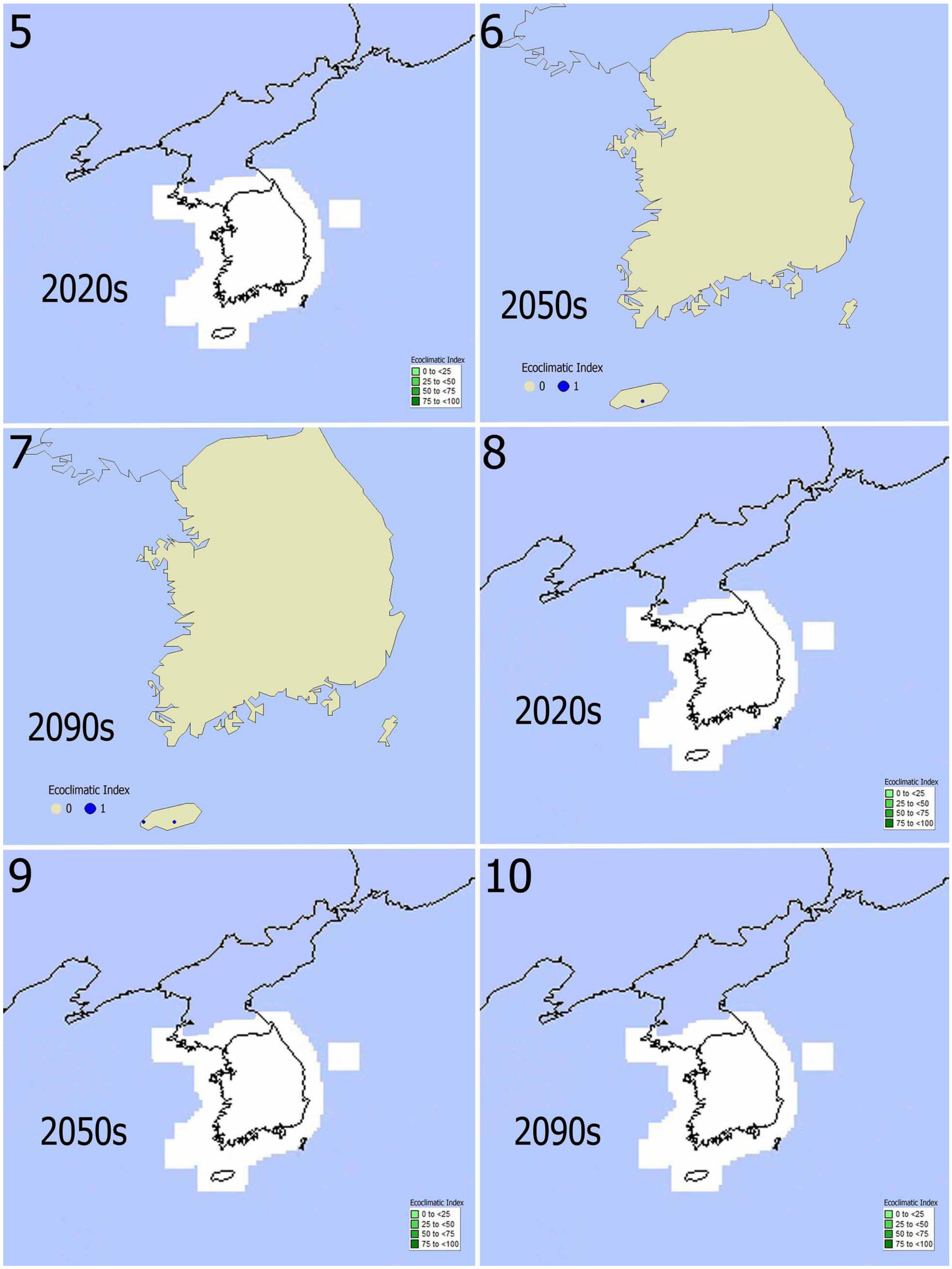
Table 2. CLIMEX parameter values for *D. brevipes* and *D. neobrevipes*.

Parameters	Description	Value		Unit
		D. brevipes	*D. neobrevipes*	
Moisture				
SM0	Lower soil moisture threshold	0.1	0.1	*
SM1	Lower optimum soil moisture	0.2	0.2	*
SM2	Upper optimum soil moisture	0.9	0.9	*
SM3	Upper soil moisture threshold	2	2	*
Temperature				
DV0	Lower temperature threshold	13	14	°C
DV1	Lower optimum temperature	24	23	°C
DV2	Upper optimum temperature	32	29	°C
DV3	Upper temperature threshold	35	32	°C
Cold stress				
TTCS	Cold stress temperature threshold	13	14	°C
THCS	Temperature threshold stress accumulation rate	−0.001	−0.001	$Week^{-1}$
Heat Stress				
TTHS	Heat stress temperature threshold	35	32	°C
THHS	Temperature threshold stress accumulation rate	0.001	0.001	$Week^{-1}$
Dry stress				
SMDS	Soil moisture dry stress threshold	0.1	0.1	*
HDS	Stress accumulation rate	−0.001	−0.001	$Week^{-1}$
Wet stress				
SMWS	Soil moisture wet stress threshold	2	2	*
HWS	Stress accumulation rate	0.01	0.01	$Week^{-1}$
Threshold heat sum				
PDD	Number of degree-days above DV0 needed to complete one generation	606	491	°C days

To guide management decisions for high-risk areas where *D. brevipes* and *D. neobrevipes* are absent such as South Korea but they frequently found on their import host plants, the CLIMEX model has been used for estimating potential distribution in South Korea. The results of parameter fitting of the CLIMEX model are presented in Table 2, indicating soil moisture, temperature and stress parameters achieved by calibration or iterative adjustments. Results were checked to see if they were biologically reasonable. Based on the currently available presence data, the CLIMEX results were a good fit to the current global distribution of PPM and GPM (Fig. 3–4). South Korea (97,217 locations) was evaluated for its suitability as habitat for *D. brevipes* and *D. neobrevipes*, using climatic data from 2020 to 2029. It was predicted that the EI of all locations was not suitable for the long-term survival of them in open fields as zero (Fig. 5, 8). Based on future climates projected for the 2050s and the 2090s, the potential distribution areas (97,379 locations) estimated to be climatically suitable for *D. neobrevipes* turned out to be unsuitable due to high cold stress (Fig. 9–10). Based on the projections of future climatic conditions, the distribution in most of locations for *D. brevipes* was unsuitable (EI=0). However, EI values of *D. brevipes* indicated that two locations in the southern area of Jejudo, South Korea (33°15′18.0″N 126°33′54.0″E, 33°15′18.0″N 126°34′30.0″E) were marginal (EI=1) in the 2050s (Fig. 6). In the 2090s, one location with an EI value of 1 was further expanded in the southwestern area of Jejudo (33°17′42.0″N 126°11′06.0″E) (Fig. 7).



Figures 1–4. Habitus and distribution of *Dysmicoccus* spp. **1)** *Dysmicoccus brevipes* on fruit of pineapple from the Philippines. **2)** *Dysmicoccus neobrevipes* on fruit of banana from the Philippines. **3–4)** Global distribution of *D. brevipes* (top) and *D. neobrevipes* (bottom) used in CLIMEX model.



Figures 5–10. Simulated geographic distribution of *Dysmicoccus* spp. in South Korea using CLIMEX model with meteorological data (2020s, 2050s and 2090s). **5–7)** *Dysmicoccus brevipes*. **8–10)** *Dysmicoccus neobrevipes*.

Discussion

The potential distribution of *D. brevipes* and *D. neobrevipes* in South Korea remains a prime concern because of the high interceptions of these species found during inspection. To support decisions to manage these quarantine pests, the potential distribution of these pests in South Korea was projected for the 2020s, the 2050s and the 2090s. Results from the model areas that are climatically suitable for these mealybugs have little potential for invasion in the exterior environment of South Korea due to cold barriers. However, for *D. brevipes*, three locations in the southwestern area of Jejudo were predicted to have a marginal possibility of establishment under future climates. This species may be able to establish successfully in the southern area of Jejudo if the pest is inadvertently transported to these newly climatically habitats outside the distribution of its natural enemies. In that respect, this model's results could help design a risk-based surveying program, specific in space and in time, that improves the probability of detecting early *D. brevipes* and *D. neobrevipes* populations. Nonclimatic factors, which are not included in CLIMEX, also affect these pests' distribution in South Korea. Some scale insect species (Hemiptera: Coccomorpha) known to occur only in greenhouses were usually found on import plants brought into South Korea, being considered to have failed to establish in open fields (Suh et al. 2009; Ji and Suh 2012). Therefore, imported plant cultivation sites should be considered in the constant surveillance for these quarantine mealybugs. In addition, intensifying phytosanitary efforts in these areas, in particular regarding trade in live plants and plant parts imported from a country with the presence of these quarantine mealybugs, is required to overcome this challenge.

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