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Predicting the potential distribution of *Pseudococcus longispinus* (Targioni-Tozzetti) (Hemiptera: Pseudococcidae) in South Korea using a CLIMEX model

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Predicting the potential distribution of *Pseudococcus longispinus* (Targioni-Tozzetti) (Hemiptera: Pseudococcidae) in South Korea using a CLIMEX model

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Abstract. *Pseudococcus longispinus* (Targioni-Tozzetti) (Hemiptera: Pseudococcidae) is a widely-distributed pest that feeds on many economically important hosts, particularly tropical fruits and ornamentals. The potential distribution of this mealybug pest in South Korea remains a primary concern because of its high incidence of interceptions screened during inspection. Hence, this species prompted a modelling effort to assess its potential risk of introduction. Potential risk maps were developed for this pest with a CLIMEX model based on occurrence records under environmental data. The potential distribution of these pests in South Korea in the 2020s, 2050s and 2090s was projected based on the RCP 8.5 climate change scenario. Results showed that *P. longispinus* has little potential for invasion in the outdoor environment of South Korea due to high cold stress in the 2020s. However, some locations in Jejudo were predicted to be marginally suitable under future climate factors. In that respect, the results of this model prediction could be used to prepare a risk-based surveying program that improves the probability of detecting early *P. longispinus* populations.

Key words. Climate change, interception, invasive species, long-tailed mealybug, risk prediction.

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Introduction

The ever-increasing worldwide trade of plant products has led progressively to a decreased impact of natural barriers on wild species movement (Liebhold and Tobin 2008). The accidental introduction of exotic pests may cause environmental alterations and the displacement of endemic species (Lee 2002). In the last 27 years, mealybugs (Hemiptera: Pseudococcidae) of 36 species have been intercepted on high-risk plants during import inspections at South Korean ports of entry (PIS 2023). Of them, the long-tailed mealybug, *Pseudococcus longispinus* (Targioni-Tozzetti) (1091 times, 56.4% of the mealybug interceptions) was the most frequently intercepted on imported ornamental plants such as *Dracaena* Vand. ex L. and *Polyscias* J.R. Forst. & G. Forst. plants from Indonesia (Table 1). This species is one of the most cosmopolitan mealybug species and has been recorded on many plant species belonging to 216 genera in 99 families (García Morales et al. 2023). Its area of origin is not known but this mealybug seems to have speciated in the Pacific region (Williams 2004). The species has been accidentally spread to most countries in the tropics and subtropics and now is a widely-distributed pest that feeds on many economically important hosts, particularly tropical fruits and ornamentals (Watson et al. 2022; García Morales et al. 2023). It is a common greenhouse pest around the world, but can also be found outdoors in warm climates (McKenzie 1967).

The long-tailed mealybug (LTM) is considered a potential invasive species to South Korea since it is usually found on imported plants of economic importance and may make its way into the South Korean environment,

Table 1. List of mealybugs intercepted on plants for planting between 1996 and 2022. Asterisks indicate South Korea Quarantine pests. Total int.: number of intercepted records of mealybugs.

Species	Total int.	Host genus	Consignment origin	Years intercepted
**Pseudococcus longispinus* (Targioni-Tozzetti)	1091	23 plant genera such as *Dracaena*, *Ficus* and *Polyscias*; undetermined plants	Australia, China, Costa Rica, Germany, Indonesia, Japan, Malaysia, Netherlands, New Zealand, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, USA, Vietnam	1996–2022
**Planococcus minor* (Maskell)	209	13 plant genera such as *Codiaeum*, *Ixora* and *Philodendron*; undetermined plants	China, Indonesia, Malaysia, Philippines, Taiwan, Thailand, Vietnam	1999–2022
**Dysmicoccus brevipes* (Cockerell)	88	16 plant genera such as *Ficus* and *Rhapis*; undetermined plants	Australia, China, Colombia, Costa Rica, Indonesia, Malaysia, Netherlands, Philippines, Taiwan, Thailand, USA, Vietnam	1999, 2001–2003, 2005, 2007–2015, 2017, 2019–2021
**Dysmicoccus neobrevipes* Beardsley	76	*Agave, Aglaonema, Dracaena*, *Heliconia*, *Heptapleurum*, *Philodendron*, *Polyscias*, *Yucca*, undetermined plants	China, Costa Rica, Indonesia, Malaysia, Philippines, Taiwan, Thailand, Vietnam	1997, 1999, 2001–2002, 2008–2012, 2014–2021
**Vryburgia amaryllidis* (Bouché)	71	*Crassula*, *Echeveria*, undetermined succulents	Australia, Germany, Italy, Netherlands, South Africa, USA	2019–2021
**Phenacoccus solani* Ferris	61	*Aeonium*, *Crassula*, *Echeveria*, *Graptoveria*, *Pachyphytum*, undetermined succulents	Australia, Brazil, China, Indonesia, Italy, Japan, Netherlands, USA	2004, 2007–2010, 2012–2017, 2019, 2021–2022
Vryburgia trionymoides (De Lotto)	44	*Aeonium*, *Crassula*, *Echeveria*, *Sedum*, undetermined plants	Australia, Japan, Netherlands, New Zealand, USA	2011–2015
Planococcus citri (Risso)	43	15 plant genera such as *Ficus* and *Philodendron*; undetermined plants	China, Indonesia, Italy, Japan, Malaysia, Netherlands, Philippines, South Africa, Thailand, USA, Vietnam	1997, 2000-2004, 2007–2010, 2012, 2015, 2017–2022
**Pseudococcus jackbeardsleyi* Gimpel and Miller	35	10 plant genera such as *Cordyline* and *Polyscias*; undetermined plants	China, Costa Rica, Indonesia, Malaysia, Thailand, Vietnam	2008–2014, 2017, 2020
**Pseudococcus elisae* Borchsenius	33	*Codiaeum, Dracaena, Ficus, Nerium, Polyscias,* undetermined plants	Costa Rica, Indonesia, Malaysia, Thailand	1998, 2001–2005, 2007–2009, 2013, 2015
**Pseudococcus baliteus* Lit	31	*Ficus*, *Heteropanax*, *Polyscias*	China, Indonesia, Thailand	2008–2009, 2016–2021
Pseudococcus comstocki (Kuwana)	28	*Dracaena*, *Ficus*, *Heteropanax*, *Polyscias*	China, Indonesia, Philippines, Taiwan	1996, 1998–2003, 2008–2012, 2015–2016
**Ferrisia virgata* (Cockerell)	27	*Dracaena*, *Ficus*, undetermined plants	China, Costa Rica, Indonesia, Malaysia, Philippines, Taiwan	1997, 2000, 2002–2006, 2008, 2010–2012, 2015, 2017–2018, 2020, 2022
**Pseudococcus viburni* (Signoret)	27	*Echeveria*, *Punica*, *Vaccinium*, undetermined plants	Chile, China, Indonesia, Italy, Netherlands, USA	2002, 2010–2014, 2016–2017

Species	Total int.	Host genus	Consignment origin	Years intercepted
**Phenacoccus solenopsis* Tinsley	16	*Dracaena*, *Euphorbia*, *Ficus*, *Polyscias*, undetermined plants	China, Indonesia, Philippines, Thailand, Vietnam	2007–2008, 2014, 2016, 2021
**Maconellicoccus hirsutus* (Green)	6	*Areca*, *Ficus*	China, Vietnam	2006, 2008–2009, 2018, 2020
**Planococcus lilacinus* (Cockerell)	6	*Dimocarpus*, *Ficus*, *Philodendron*, *Polyscias*, *Radermachera*	China, Indonesia, Thailand	2002, 2005, 2015–2016
**Pseudococcus calceolariae* (Maskell)	6	*Echeveria*, *Polyscias*, *Protea*	New Zealand, Indonesia, South Africa	2005, 2011, 2019–2020
Pseudococcus cryptus Hempel	6	*Ficus*, *Heliconia*, *Ixora*, *Polyscias*, undetermined plants	China, Indonesia, Sri Lanka, Thailand	2008–2009, 2012, 2016
Nipaecoccus nipae (Maskell)	3	*Philodendron*, *Portulacaria*	China, Indonesia	2020–2021
Planococcus kraunhiae (Kuwana)	3	*Dracaena*, *Polyscias*	Philippines	2009, 2021
**Pseudococcus maritimus* (Ehrhorn)	3	*Annona*, *Heptapleurum*	Taiwan, Thailand	2007, 2010, 2015
Exallomochlus hispidus (Morrison)	2	*Cocos*, undetermined plant	Indonesia	2012, 2017
**Hypogeococcus pungens* Granara de Willink	2	*Soehrensia*	Italy	2019, 2021
**Palmicultor palmarum* (Ehrhorn)	2	*Agave*, undetermined plant	Indonesia	2000, 2020
**Paracoccus marginatus* Williams and Granara de Willink	2	*Acacia*, *Ixora*	Indonesia, Thailand	2008–2009
**Paracoccus solani* Ezzat and McConnell	2	*Echeveria*	Brazil, Mexico	2009–2010, 2019
**Phenacoccus madeirensis* Green	2	*Ocimum*, undetermined plant	China, Ecuador	2008, 2013
**Spilococcus mamillariae* (Bouche)	2	*Graptopetalum*, undetermined cacti	Indonesia, Spain	2012
Vryburgia distincta (De Lotto)	2	*Crassula*, *Echeveria*	Netherlands	2006, 2008
Antonina crawi Cockerell	1	*Phyllostachys*	Japan	1999
Atrococcus paludinus (Green)	1	*Codonopsis*	China	2009
**Dysmicoccus nesophilus* Williams and Watson	1	*Ficus*	Indonesia	2002
**Neotrionymus monstatus* Borchsenius	1	*Arundo*	China	2007
**Pseudococcus landoi* (Balachowsky)	1	*Polyscias*	Costa Rica	2006
**Pseudococcus orchidicola* Takahashi	1	*Dendrobium*	Thailand	2003

either in greenhouses or outdoor settings. Furthermore, climate change is influencing pest species distribution and outbreaks (Hoffmann et al. 2008; Hill et al. 2012). In response to the growing risk of the quarantine LTM invading and establishing in South Korea, a modelling approach using the CLIMEX software may help assess the risk and inform 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 this quarantine mealybug efficiently.

Materials and Methods

Interception data. Data on mealybugs intercepted on plants for planting imported at ports of entry to South Korea from 1996 to 2022 was 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 *P. longispinus* was obtained from the CABI database (CABI 2023), ScaleNet (García Morales et al. 2023) and the literature (Balachowsky 1927; McKenzie 1967; Kawai 1980; Williams 1985, 2004; Watson et al. 2022; EPPO 2023). Duplicate occurrences and potential errors in distribution data were cautiously checked and excluded. Data indicating country locations were removed, and the location data referring to county, city and town of the specific location of the collections made within each country 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 *P. longispinus* in Central Europe, where it is restricted to glasshouses and indoor plantings (Kosztarab and Kozár 1998).

Climate data. The CliMond CM30 World (1975H V1.1) climate dataset was used for the global distribution of *P. longispinus* (Kriticos et al. 2015). To predict climate suitability of this quarantine pest in South Korea, three meteorological datasets corresponding to 97,379 locations (2020s, 2050s and 2090s) in South Korea based on the RCP 8.5 climate change scenario of the Korea Meteorological Administration were created for CLIMEX distribution modeling. A location represents the grid 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 2.5mm 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 *P. longispinus* 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 greater than or equal to 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 *P. longispinus* in South Korea was predicted by using the Compare Locations (one species) model of CLIMEX (version 4) (Kriticos et al. 2015). QGIS software (version 3.30) was used to generate an interpolated raster surface of EI values on the South Korean map.

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 method 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 *P. longispinus* obtained from published experimental studies (Santa-Cecilia et al. 2011; Jeong et al. 2018). The soil moisture parameters (SM0–SM3) were determined by calibrating parameters to match model output to the reported occurrence of this species (Finch et al. 2020). As there are no data available regarding the response of this species to stress conditions, these parameters were calibrated by comparing model results with the known distribution and other similar previous studies on mealybugs (Parsa et al. 2012; 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 this mealybug worldwide. CLIMEX was then run to project the meteorologically suitable distribution in South Korea.

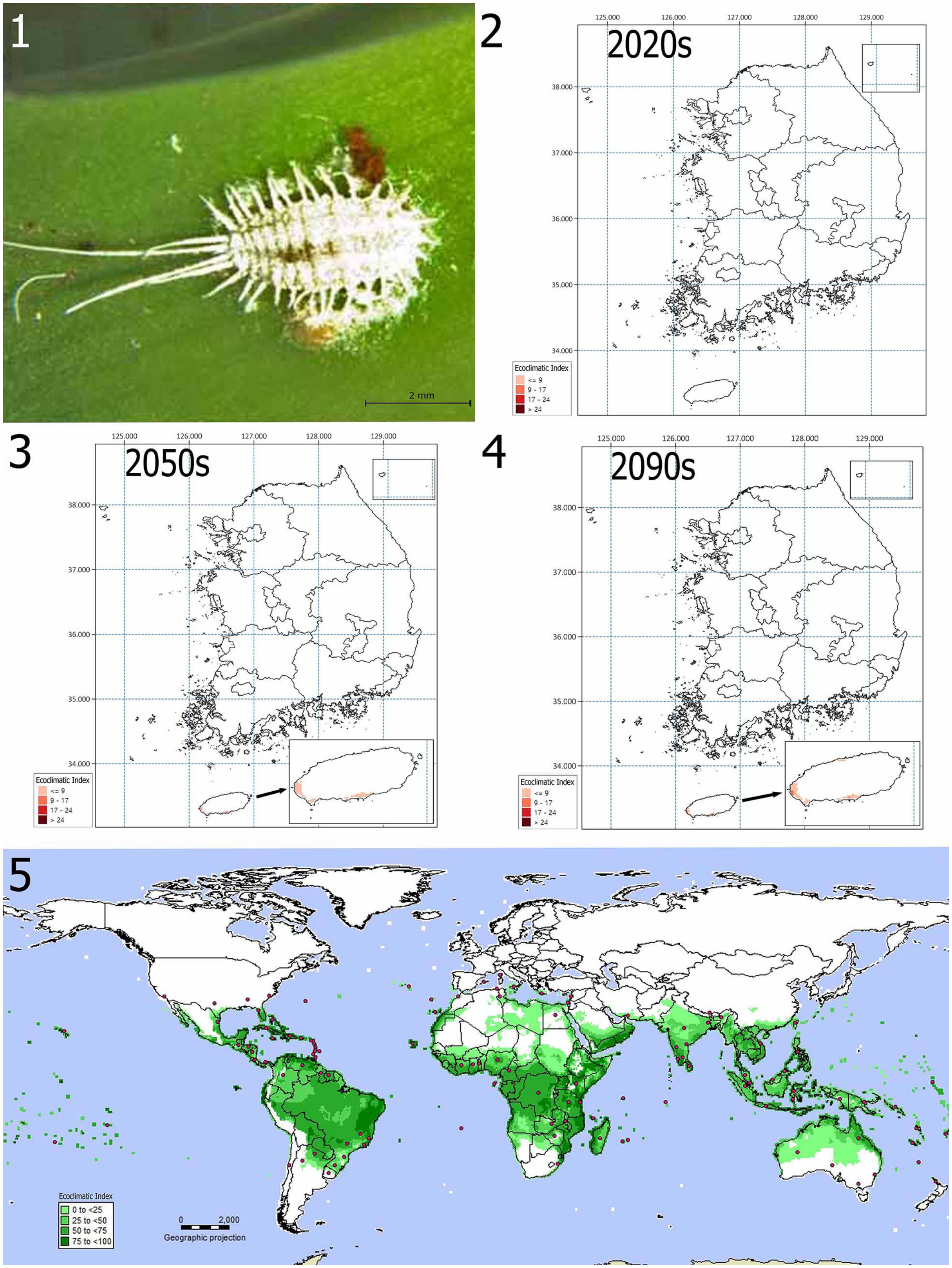
Results

Pseudococcus longispinus is a South Korean quarantine pest and apart from direct damage caused by feeding, it can also transmit Grapevine leafroll-associated virus and Cacao swollen shoot virus (Golino et al. 2002; Tsai et al. 2008; Gyamera et al. 2023). The LTM has been the most frequently intercepted mealybug on plants for planting during phytosanitary inspections at South Korean ports and were mainly found on *Dracaena* plants (36.1% of LTM interceptions) and *Polyscias* plants (27.6%) from countries such as China, Indonesia, Malaysia, the Philippines, Thailand, Vietnam and Costa Rica (Fig. 1).

To guide management decisions for high-risk areas where *P. longispinus* is absent, but where they are frequently found on imported host plants such as South Korea and could establish, we used the CLIMEX model to estimate the 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 LTM (Fig. 5). South Korea was evaluated for its suitability as habitat for *P. longispinus*, using climatic data from the 2020s. It was predicted that the EI of all locations was not suitable for the long-term survival of LTM in open fields (Fig. 2). Based on future climates projected for the 2050s and the 2090s, most locations for *P. longispinus* were unsuitable (EI=0). However, EI values of *P. longispinus* indicated that 67 locations in the southern coastal area of Jejudo, South Korea were marginal ($1 \leq EI \leq 8$) in the 2050s (Fig. 3). In the 2090s, this expanded to an additional 19 suitable locations in the eastern and northern coastal areas of Jejudo ($1 \leq EI \leq 10$) (Fig. 4).

Discussion

Climate is the most influential factor in the ecology of species, and climate change is now causing shifts in the geographical distribution and phenology of species (Rosenzweig et al. 2001). This change can be used as data for early detection and rapid response for invasive species. Some locations along the coastal lines of Jejudo were predicted to have a marginal possibility of distribution of *P. longispinus* under future climates. This species may be able to establish successfully in the southwestern of Jejudo if the pest is inadvertently transported to these habitats outside the distribution of its natural enemies. In that respect, these model results could help design a risk-based surveying program, specific in space and in time, that improves the probability of detecting early *P. longispinus* populations. Nonclimatic factors, which are not included in CLIMEX, also affect this pest's distribution in South Korea. Most exotic mealybugs known to occur only in greenhouses were usually found on imported plants brought into South Korea, these failing to establish in open fields (Ji and Suh 2012; Suh et al. 2013). Thereby imported plant cultivation sites should be considered in the additional surveillance for this quarantine mealybug.



Figures 1–5. *Pseudococcus longispinus* habitus and distribution. **1)** *Pseudococcus longispinus* on *Dracaena* plant from the Philippines. **2–4)** Simulated geographic distribution of *P. longispinus* in South Korea using CLIMEX model with meteorological data. **2)** The 2020s. **3)** The 2050s. **4)** The 2090s. **5)** Present global distribution of *P. longispinus* used in CLIMEX model.

Table 2. CLIMEX parameter values for *Pseudococcus longispinus*.

Parameters	Description	Value	Unit
Moisture			
SM0	Lower soil moisture threshold	0.1	*
SM1	Lower optimum soil moisture	0.2	*
SM2	Upper optimum soil moisture	0.9	*
SM3	Upper soil moisture threshold	2	*
Temperature			
DV0	Lower temperature threshold	12	°C
DV1	Lower optimum temperature	24	°C
DV2	Upper optimum temperature	32	°C
DV3	Upper temperature threshold	35	°C
Cold stress			
TTCS	Cold stress temperature threshold	12	°C
THCS	Temperature threshold stress accumulation rate	–0.001	Week-1
Heat Stress			
TTHS	Heat stress temperature threshold	35	°C
THHS	Temperature threshold stress accumulation rate	0.001	Week-1
Dry stress			
SMDS	Soil moisture dry stress threshold	0.1	*
HDS	Stress accumulation rate	–0.001	Week-1
Wet stress			
SMWS	Soil moisture wet stress threshold	2	*
HWS	Stress accumulation rate	0.01	Week-1
Threshold heat sum			
PDD	Number of degree-days above DV0 needed to complete one generation	770	°C days

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