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Article

Assessing the Global Pest Risk of *Aeolesthes sarta* with Regards to the Host Specie *Populus alba* under Climate Change Scenarios

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Abstract: *Aeolesthes sarta* or *Trirachys sarta* is a polyphagous long-horned beetle that has caused severe damage to the *Populus alba* forests/plantations in its regions of origin. Climate change could accelerate the introduction and spread of invasive pest species, potentially causing ecological damage and economic losses. Furthermore, globalization and increased trade can inadvertently transport pests across borders into regions where they do not already occur. Hence, it is crucial to identify areas where the climate is most suitable for the establishment of *A. sarta*'s and which areas of the world are suitable for the growth of *P. alba* under climate change scenarios. This study employed the CLIMEX model to estimate the potential global distribution of *A. sarta* and its correlation with its dominant host, *P. alba*, under current climatic conditions and potential future scenarios, namely the A1B and A2 climate change scenarios (CCSs). Under current climatic conditions, the model indicates that the establishment of a climatically suitable habitat for *A. sarta* extends beyond its current known range. The model estimated that, under the world's current climatic conditions, 41.06% of the world can provide suitable areas (EI > 0) for the survival of *A. sarta*. For *P. alba*, under the current climatic conditions, suitable regions for the growth of *P. alba* are present in all continents (excluding Antarctica); under the world's current climatic conditions, 53.52% of the world can provide suitable areas for the growth of *P. alba* (EI > 0). Climate change will significantly alter the number of suitable habitats for *A. sarta* development and *P. alba* growth globally. In future climatic conditions, the number areas capable of supplying suitable habitats (EI > 0) for *A. sarta* will slightly decrease to 40.14% (under A1B and A2 CCSs), while, for *P. alba*, the number areas capable of supplying suitable habitats will also marginally decrease to 50.39% (under A1B scenario), and this figure is estimated to drop to 48.41% (under A2 scenario) by the end century (2100). Asia, Europe, North America, South America, and Oceania have a high percentage of highly suitable areas for *A. sarta* development and *P. alba* growth under current climatic conditions; however, according to estimates of future climatic conditions, by the end century, only Asia, Europe, North America, and Oceania will have a high percentage of highly suitable areas for *A. sarta* development and *P. alba* growth. The range of highly suitable habitats is likely to increase in the northern hemisphere; however, this range is expected to shrink with regards to the southern hemisphere. The range contraction was higher under the A2 climate change scenario due to a higher warming trend than in the A1B scenario. Due to climate change, the range of *A. sarta* development shifted, as did the *P. alba* growth range, which, thanks to the suitable environmental conditions for the growth of *P. alba*, makes all those regions vulnerable to the introduction and development of *A. sarta*. Strict monitoring, prevention, and control measures at borders, airports, and seaports before the trade of *P. alba* and other suitable host species wood (logs/billets) are highly recommended to prevent the spread of *A. sarta* and ensure biodiversity security. It is expected that the *A. sarta* and *P. alba* climate models presented here will be useful for management purposes since both can be adapted to guide decisions about imparting resources to

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regions where the threat of pest invasion remains and away from regions where climate suitability is predicted to decrease in the future.

Keywords: *Aeolesthes sarta*; *Trirachys sarta*; *Populus alba*; CLIMEX; climate change; A1B–A2 scenarios; ecological niche model; invasive species; forest pest

1. Introduction

Over the past century, global warming has become a significant climate change challenge [1]. The dispersal patterns of species have been altered, changing the habitats that different species may thrive in and reducing biodiversity [2]. By modeling the effects of climate change on invasive pests and their predators, we can gain insight into the tools necessary to control their spread [3]. Climate change is an important topic because it can have direct and indirect effects on insect populations (by, for example, altering the frequency of species and hosts) [2].

Aeolesthes sarta or *Trirachys sarta*, commonly known as the City or Sarta Longhorned Beetle (belonging to the *Trirachys* genus), is one of the foremost species of the Cerambycidae family [4]. It is polyphagous, and mainly attacks broadleaved tree species, including *Populus* spp., *Juglans* spp., *Acer* spp., *Salix* spp., *Malus* spp., *Platanus* spp., and *Ulmus* spp. [4]. Larvae of this family primarily feed internally on live or dead plant tissues [5]. Boring by larvae can cause structural damage to host trees and block the movement of nutrients and water, resulting in the death of multiple branches and the tree as a whole [6–9].

A. sarta is thought to have originated in Pakistan and the western part of India, with significant distribution into Afghanistan, Iran, and other nations in Central Asia [10,11]. It may thrive in forests up to 2000 m above sea level [12]. The region's warm temperature and the fact that it hosts the pest's favored host tree species provides an ideal environment for it to thrive in [13]. The species is highly problematic in regions with hot, dry climates [14]. In central Asia, the longhorn beetle is a major pest affecting most broadleaved trees [4].

Poplar wood is broadly utilized to produce a wide range of goods, including pulp, paper, and other fiber-based products [15]. Poplars are also helpful for nontimber purposes, such as aesthetic planting, windbreaks, and soil binders [16]. Poplars are grown in over 70 countries worldwide, both in natural forest mixes and artificial forests [17]. However, the vast majority of poplars still thrive in natural forests [15]. *Populus alba* is among the dominant host species severely and repeatedly attacked and damaged by *A. sarta* in its countries of origin [4,18–21]. *A. sarta* can attack and reproduce on the main stem and large branches distinctively [18]. Infestations are especially visible in highland forests, where there may be declines in poplar tree forests. Despite being a key supplier of wood for the industry [20], *Populus* trees are entirely destroyed by the *A. sarta* borer, rendering it ill-suited for industrial use [19]. There were 200 trees of *P. alba* inspected for infestation in the Mustang, Balochistan area; 100% were found to be severely infested, and 34% were destroyed entirely [19]. *Populus alba* in the *Populus* genus has been reported to be among the dominant host species infested by *A. sarta* in the Mashhad and Zahedan regions of Iran, where the infestation rate was deemed to be 100% and the mortality rates was deemed to be 49 and 11%, respectively [18]. Because of climate change and changing ecological constraints, the breeding of drought-tolerant species such as *Populus alba* is becoming increasingly appealing [22].

The polyphagy is a major factor in the possibility of colonization. Compared to oligophagous and monophagous species, polyphagous species tend to have a larger potential for colonization [23]. Longhorn beetles, or Cerambycinae, appear more prone to introduction. Most species thrive on living plants, while numerous Cerambycinae complete their life cycle in live or dead wood, such as *A. sarta* [4]. Due to globalization, cerambycids have followed trade routes [23]. The documented established pathway includes importing timber for building homes or furniture, importing plants for planting in nurseries [24], and importing timber for pallets, pulp and wood packaging, and other wood-derived goods [23]. The danger of invasion is expected to rise due to escalating trade volumes, faster potential vector imports, and a wider variety of sources and introduction locations [24].

Regional changes in climate, most notably those associated with increases in temperature, impact several ecological systems [25]. Despite morphological and physiological alterations in one or both species, climate change may sabotage relationships between species [26]. Climate patterns, notably temperature, directly and significantly impact the phenology of poikilotherms, primarily invertebrates like insects [27].

Global warming alters pest distribution patterns and raises the possibility of invasive species causing ecological damage. The accelerated exchange of breeding and planting materials may introduce more insect pests and pathogens into new habitats as poplar cultivation develops more intensely and becomes ubiquitous. In order to track this species more effectively, it is crucial to investigate the shifting patterns of potentially favorable habitats for *A. sarta* under different climate change scenarios. However, in this study, we examine climate change's effect on *Populus alba,* one of the dominant host species of *A. sarta,* and correlate it with the distribution pattern of *A. sarta* globally. Until now, no detailed research studies have estimated the global distribution pattern of *A. sarta* and its preferred host, *P. alba,* for the future under different climate change scenarios. The present study is the first to investigate the pest's distribution pattern concerning its host species. Only a single study has been available till now, which mainly focused on the European continent and used very basic biological parameters to forecast the potential distribution of *A. sarta* [12]. Therefore, employing accurate and extensive information about the pest's known habitat, ecology, and biology, an attempt has been made to forecast the possible distribution of *A. sarta* globally under climate change scenarios using the CLIMEX model concerning its preferred host, *P. alba* (Figure 1). We assumed that climate change would alter the distribution pattern of insect pests and the host tree species globally. This study aimed to determine the possible global distribution of *A. sarta* and its preferred host, *P. alba,* under current climatic conditions and forecast the potential global distribution of *A. sarta* and its preferred host, *P. alba,* for the end of the century (2100) under different climate change scenarios (A1B and A2, respectively).

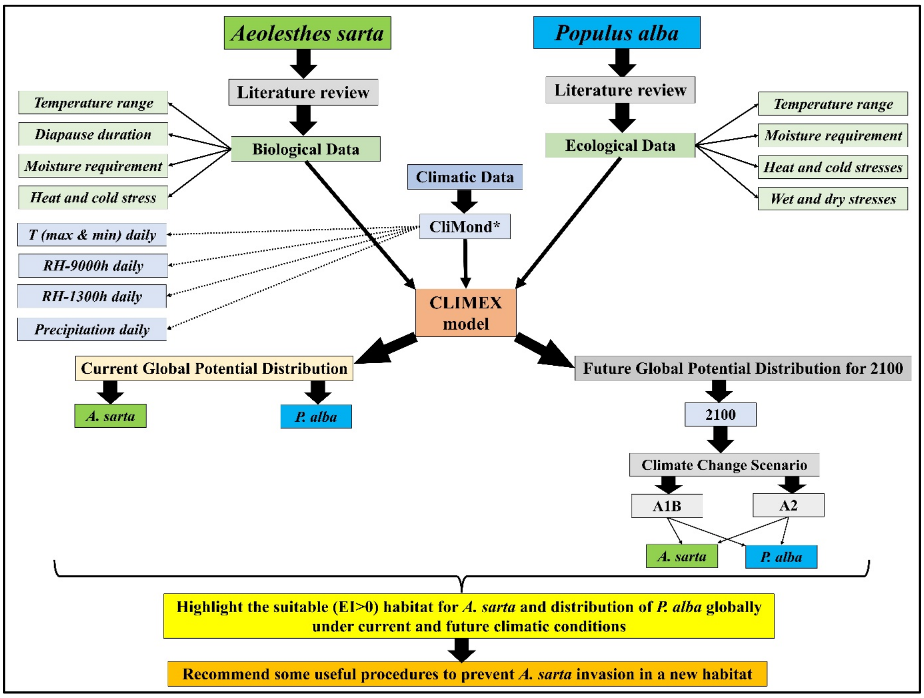

Figure 1. Experimental layout of the present study. T = Temperature; RH = Relative Humidity; * https://www.climond.org/CLIMEX.aspx (accessed on 2 March 2023).

2. Materials and Methods

2.1. CLIMEX Model

CLIMEX software version 4.0 (Hearne Scientific Software, Auckland, New Zealand) was used to model the potential distribution of *A. sarta* and *P. alba* under current and future climatic conditions using meteorological data and the physiological characteristics of the pest and host species. A "Compare Locations model" for a single species was utilized for this study. The annual growth index (GI) was determined as a function of soil moisture and temperature, and the possibility of the population sustaining unfavorable conditions was assessed using stress indices (cold, hot, dry, and wet) [28]. The "Ecoclimatic Index" (EI), an annual index of climatic readiness, was created by combining weekly calculations of growth indices and stress indices to provide an overall assessment of a location's favorability for the species to survive there permanently [29,30]. In this study, geographical areas with a $15 < EI \geq 30$ reflect climatic conditions ideal for the establishment, survival, and proliferation of *A. sarta* and *P. alba* (Table 1).

Table 1. Eco-Climatic index values used in the study and their representation.

Eco-Climatic Index	Representation
EI = 0	Unsuitable habitat—The climate and environment are not conducive to the growth and establishment of *A. sarta* and *P. alba*.
0 < EI = 15	Marginally suitable habitat—The climate and environment are marginally conducive to the growth and establishment of *A. sarta* and *P. alba*.
15 < EI = 30	Suitable habitat—The climate and environment are conducive to the growth and establishment of *A. sarta* and *P. alba*.
EI > 30	Highly suitable habitat—The climate and environment are highly conducive to the growth and establishment of *A. sarta* and *P. alba*.

Known species distribution data along with laboratory-derived ecological data were used to parameterize the model [6,7,10,19,31–36]. The parameters were iteratively adjusted according to the satisfactory agreement between the potential and known global distribution of *A. sarta* and *P. alba* [31,37]. The parameters were then verified by comparing the physiological and ecological data of *A. sarta* and *P. alba* to ensure they were biologically and ecologically reasonable.

2.2. Climatic Data

Climatic data were downloaded from CliMond [https://www.climond.org/CLIMEX.aspx (accessed on 20 February 2023)] and used to help model the potential distribution of *A. Sarta* and *P. alba* under current and future climatic conditions (Table 2). CliMond provides a fine-scale 10′ dataset with long-term monthly climate means for maximum temperature (T max), minimum temperature (T min), precipitation (P total), and relative humidity at 0900 (9 AM) and 1500 h (3 PM) [38]. For forecasting, we used A1B (2.8 °C rise in global temperature) and A2 (3.4 °C rise in global temperature) as per the Special Report on climate change scenarios (SRES) [39].

Table 2. Climatic data were used to run the CLIMEX model.

Climate Change Scenarios	Period	Data Set	Source
	Current	**CM10_1975H_CX_MM_V1.2**	**Climond**
A1B *	2100	CM10_2100_A1B_CS_Cx_MM_V1.2	Climond
A2 **	2100	CM10_2100_A2_CS_Cx_MM_V1.2	Climond

* 2.8 °C rise in global temperature at the end of the 21st century (a future characterized by very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technology). ** 3.4 °C rise in global temperature at the end of the 21st century (A future characterized by very high population growth, moderate economic growth, high demand for agricultural products, loss of grasslands to food crops, and reduced regulations).

2.3. *Aeolesthes sarta and Populus alba Global Distribution Data*

Known occurrence record data of *A. sarta* and *P. alba* were gathered from the Centre of Agriculture and Bioscience International [CABI → https://www.cabi.org/ (accessed on 8 February 2023)], Global Biodiversity Information Facility [GBIF → https://www.gbif.org/ (accessed on 8 February 2023)], European and Mediterranean Plant Protection Organization [EPPO → https://gd.eppo.int/ (accessed on 8 February 2023)], and from a literature review [4,6,7,10,19,31–36]. When published research papers did not provide precise geographic coordinates for positive sites, the coordinates for the site were pinpointed using Google Earth (https://www.google.com/earth/ accessed on 10 February 2023) and Google Maps (https://www.google.com/maps/preview accessed on 10 February 2023). All occurrences that were already recorded twice have been removed.

2.4. *Pest (Aelosthes sarta) Biological Data*

Due to its preference for dry, cold weather, *A. sarta* is most often found in temperate zones [4]; thus, the Temperate template included with CLIMEX software was used to create a "species parameter file." Physiological tolerance thresholds for *A. sarta* were used to calibrate the model. The existing occurrence data of *A. sarta* was used to determine the species climatic requirements. Parameter values for temperature, moisture, and diapause index (Table 3) were defined using inferred data from the published literature associated with developmental threshold temperatures, moisture, and diapause [4,6,15]. By repeatedly running the parameter file with different parameter values; the stress index values were fine-tuned until the predicted climate suitability patterns were consistent with *A. sarta's* observed distribution.

Table 3. Parameter values used in the CLIMEX model for *Aelosthes sarta* and *Populus alba*.

Parameters	Code	Values *Aelosthes sarta*	Values *Populus alba*
Temperature			
Limiting low temperature (°C)	DV0	10	−5
Lower optimal temperature (°C)	DV1	15	4
Upper optimal temperature (°C)	DV2	37	20
Limiting high temperature (°C)	DV3	40	35
Moisture Index			
Limiting low soil moisture	SM0	0	0.5
Lower optimal soil moisture	SM1	0.001	1
Upper optimal soil moisture	SM2	1.5	1.5
Limiting high soil moisture	SM3	2.5	2
Diapause Index			
Diapause induction day length	DPD0	12	-
Diapause induction temperature (°C)	DPT0	13	-
Diapause termination temperature (°C)	DPT1	10	-
Diapause development days	DPD	90	-
Summer or winter Diapause	DPSW	0	-
Cold Stress			
CS temperature threshold (°C)	TTCS	9	−15
CS temperature rate	THCS	−0.00001	−0.0001
Heat Stress			
HS temperature threshold (°C)	TTHS	41	35
HS temperature rate	THHS	0.005	0.005
Wet Stress			
Wet stress threshold	SMWS	-	2.5
Wet stress accumulation rate	HWS	-	0.002
Dry Stress			
Dry stress threshold	SMDS	-	0.2
Dry stress accumulation rate	HDS	-	−0.005
Population degree day	PDD	700	-

2.4.1. Temperature Index

In the beginning, the model was run using the following temperature values: DV0 = 11 °C, DV1 = 20 °C, DV1 = 35 °C, and DV4 = 40 °C [12,19]. However, these values did not predict *A. sarta's* occurrence in northern India, China, and Afghanistan. Hence, DV0, DV1, and DV2 were adjusted to 10 °C, 15 °C, and 37 °C [31] to include positive sites in Northern India, China, and Afghanistan and were finalized to forecast the potential distribution globally. The population day degree (PDD) value for *A. sarta* was set to be 700 [12,31], as it completes its lifecycle in almost two years [4,6,10,19].

2.4.2. Diapause Index

For *A. sarta*, Diapause Development Days (DPD) were set at 90 days [31] as, according to the literature, *A. sarta* diapause duration is approximately 90 days [4,6,10]. Other diapause parameters, such as Diapause induction day length (DPD0), Diapause induction temperature (DPT0), Diapause termination temperature (DPT1), and Summer or winter Diapause (DPSW) were set at 12 days, 13 °C, 10 °C, and 0 days, respectively [12,31].

2.4.3. Moisture Index

Another parameter the CLIMEX model uses is the soil moisture index (MI). SM0, SM1, SM2, and SM3 (for detail names, please see Table 3) are the four additional characteristics that the CLIMEX model uses to further categorize the MI [30]. For normal species development, SM0 was attuned to 0 [12,31]. SM1 and SM2 were set at 0.001 and 1.5, respectively [31]. Following a similar practice, the value for SM3 was set at 2.5 [12,31].

2.4.4. Stress Index

Dry stress (DS), wet stress (WS), cold stress (CS), and heat stress (HS) are four environmental stress indices in the CLIMEX that depict unfavorable conditions that limit a species' population development [30]. For *A. sarta,* only HS and CS were considered. The cold stress restricts species' development when the temperature falls below the cold stress threshold temperature (TTCS) of that species at a particular rate (THCS). In the present study, TTCS was set at 9 °C as, below this temperature, *A. sarta* development is impeded [19]. Following the TTCS value, the THCS value was set to −0.00001. This rate provided an appropriate fit to the observed occurrence of *A. sarta*. However, when temperatures rise above a species' heat stress temperature threshold (TTHS), the growth of that species is hindered. As *A. sarta* cannot survive above temperatures of 40 °C [19], the TTHS value was set at 41 °C. The weekly rate (THHS) was set at 0.005 [31]. The observed global distribution of *A. sarta* was seemingly in agreement with these values.

2.5. Host (Populus alba) Ecological Data

Populus alba is primarily found in temperate climates with moist and relatively cold weather [36]; thus, a Temperate template included with CLIMEX software was used to create a "species parameter file." Parameter values for temperature and moisture index (Table 3) were determined using data inferred from the literature [32–36,40,41]. By running the parameter file with varying parameter values, we were able to fine-tune the stress index values so that the predicted climate suitability patterns were consistent with *P. alba's* observed global distribution.

2.5.1. Temperature Index

Populus alba cannot tolerate frigid temperatures, and its growth is inhibited at low temperate (e.g., −5 °C) [36,40], whereas temperatures higher than 35 °C might be problematic for the growth of *P. alba* in temperate regions [41,42]. Therefore, lower (DV0) and upper (DV3) temperature thresholds for the temperature after which species stopped growing were set to −5 and 35 °C. The DV0, DV1, DV2, and DV3 values used to run the model were −5 °C, 4 °C, 20 °C, and 35 °C, respectively.

2.5.2. Moisture Index

Populus alba is a tree species that grows well in both moist and dry soils [43]. However, areas with moist soil conditions and moderate to heavy precipitation rates favor the growth rate of *P. alba* [36,40–42]. As a result, restricting low soil moisture (SM0) was set at 0.5 to enable normal species growth, and SM1 and SM2 soil moisture values were set up for optimal growth. In addition, the SM3 soil moisture upper limit was set at 2.5.

2.5.3. Stress Index

For *P. alba*, all four stress indices (CS, HS, WS, and DS) were considered. The cold stress restricts species' development when the temperature falls below the cold stress threshold temperature (TTCS) of that species at a particular rate (THCS). Three different cold temperature values (−5 °C, −15 °C, and −45 °C) were used to run the model. At −5 °C, many known distribution points were missing; at −15 °C and −45 °C, all known distributions were covered, and no notable difference was found. Therefore, in the current study, TTCS was set at −15 °C as *P. alba* growth is inhibited at extremely low temperatures [36,41]. A THCS value of −0.0001 was determined from the TTCS data. The same corresponds to heat stress; once temperatures rise above a species' heat stress threshold (TTHS) at a given rate (THHS), the growth and development of that species will be impeded. In the current study, TTHS was established at 35 °C because *P. alba* does not thrive above this temperature [41]. The weekly rate (THHS) was set at 0.005. Likewise, dry stress also affects a species' development. In the present research, SMDS was set at 0.2 as *P. alba* cannot grow well under low soil moisture conditions [42]. The dry stress accumulation rate (HDS) was set at −0.005. Through an algorithm of iteration, the wet stress value was mapped to the known distribution of *P. alba*. Therefore, the wet stress threshold (SMWS) was set at 2.5 with an accumulation rate (HWS) of 0.002, respectively.

2.6. Model Verification

The CLIMEX model was verified by assessing its ability to correctly predict the current known occurrence of *A. sarta* and *P. alba*. EI > 0 were viewed as correctly predicted occurrences. After verification, the parameter file was run with the "Compare Locations" function to look at the predicted global occurrence.

2.7. Map Generation

ArcMap version 10.7 was used to map CLIMEX output. To create a continuous surface, we processed the variance of the potential *A. sarta* and *P. alba* distributions using ArcMap's Spatial Analyst module. The data were then reclassified using the Kriging interpolation method, and the global potential *A. sarta* and *P. alba* distribution under current and future climatic conditions was visualized.

3. Results

3.1. Model Fitting/Verification and Current Global Distribution

Under current climate conditions, the predicted global distribution of *A. sarta* and *P. alba* is in very close agreement with the species' known geographic range. The current distribution of *A. sarta* and *P. alba* agrees well with the modeled climatic suitability for the location (Figure 2—yellow dots; Figure 3—red dots).

Under current climatic conditions, 41.06% of the world (excluding Antarctica) can provide habitats suitable for the survival of *A. sarta* (EI > 0), except for the Scandinavian and Nordic countries, Alaska, Canada, northern, eastern, and central Russia, and wet tropical countries (except the southern part of Brazil). Similarly, 80% of Southeast Asia is suitable for the survival of *A. sarta*. In total, 52 countries, including Ukraine, Moldova, Romania, Hungary, Croatia, Serbia, Bulgaria, Greece, Italy, France, Spain, Portugal, Cyprus, Morocco, Algeria, Tunisia, Libya, Egypt, Syria, Iraq, Lebanon, Israel, Jordan, Palestine, Saudi Arabia, Angola, Zambia, Zimbabwe, Namibia, Botswana, South Africa, Uruguay, Argentina, Brazil, Mexico, USA, Turkey, Azerbaijan, Iran, Kazakhstan, Uzbekistan, Turkmenistan, China, Pakistan, India, Afghanistan, Nepal, Myanmar, Japan, South Korea, Australia, and New Zealand can provide highly suitable habitats (EI > 30), accounting for 27.07% (36.41 million km^2) of the global area under the current climatic conditions (Figures 2 and 4). Whereas potentially suitable habitats (15 < EI = 30) and marginal habitats (0 < EI = 15) cover 9.15% (12.30 million km^2) and 4.84% (6.51 million km^2) of the globe, respectively.

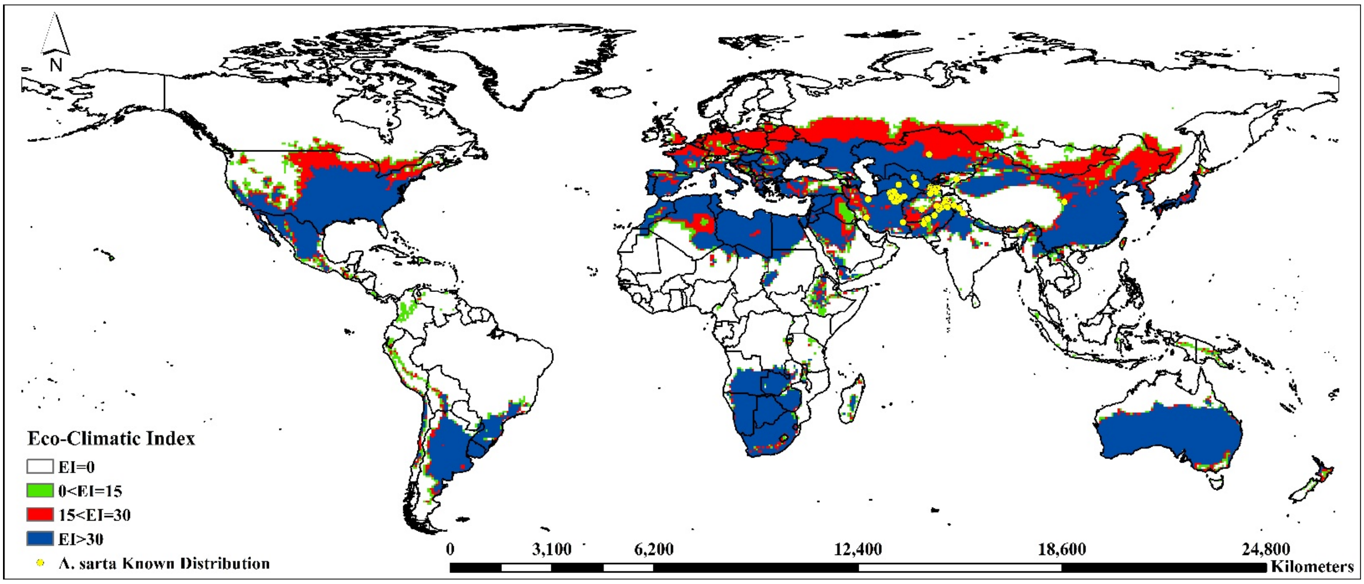

Figure 2. Predicted potential global distribution of *A. sarta* under current climatic conditions. The predicted global distributions (four colors) relate to the ecoclimatic index (EI) from the CLIMEX model: highly suitable (EI > 30), suitable (15 < EI = 30), marginally suitable (0 < EI = 15), unsuitable (EI = 0); yellow dots represent the known occurrence record of *A. sarta* (CABI, GBIF, EPPO, and Hayat 2022).

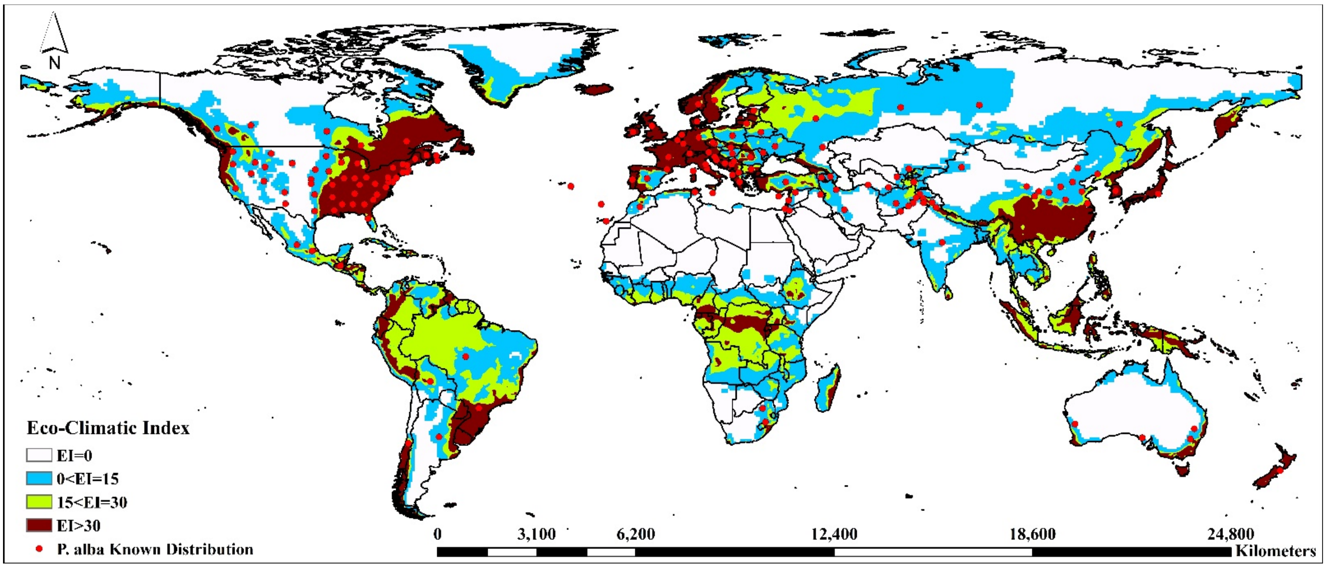

Figure 3. Predicted potential climatic favorability of *P. alba* under current climatic conditions. The predicted global climatic favorability (four colors) relate to the ecoclimatic index (EI) from the CLIMEX model: highly suitable (EI > 30), suitable (15 < EI = 30), marginally suitable (0 < EI = 15), unsuitable (EI = 0); red dots represent the known occurrence record of *P. alba* (CABI, GBIF, EPPO).

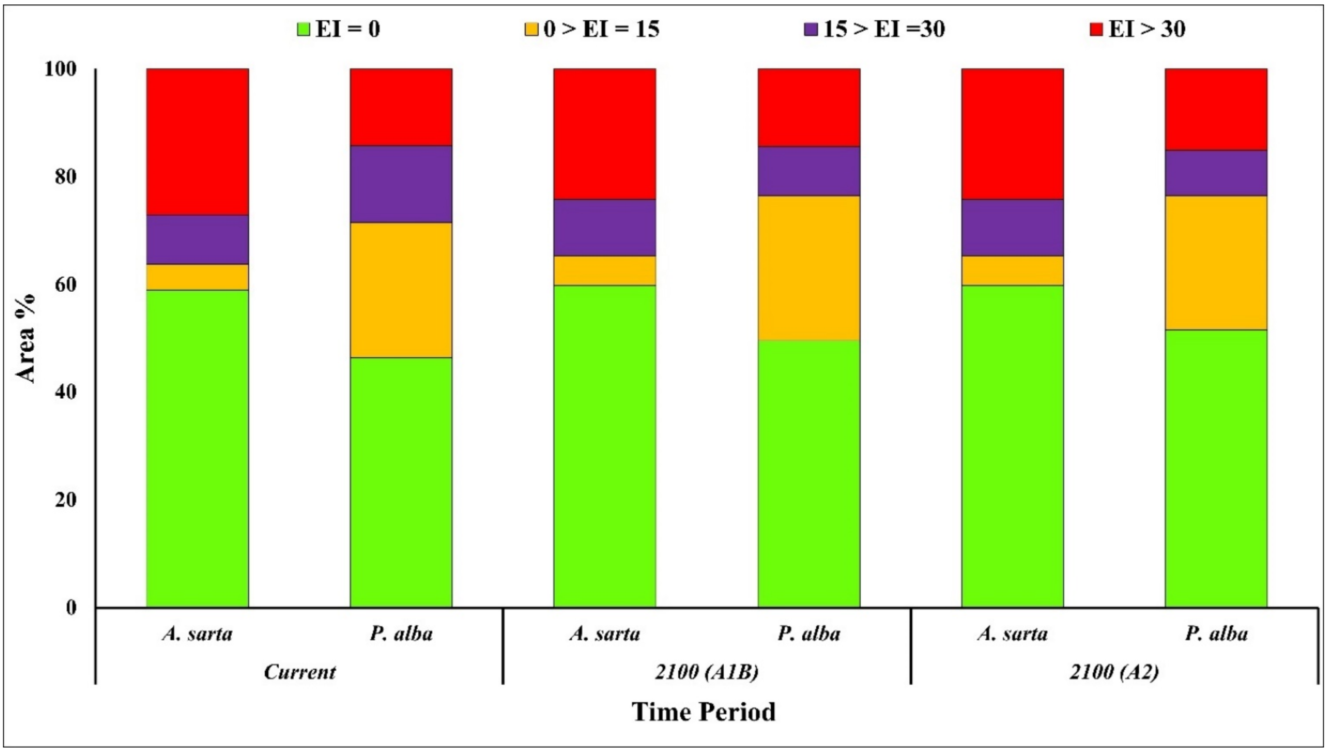

Figure 4. Percentage of the land area distribution of *Aelosthes sarta* and *Populus alba* within the four ranges of the ecoclimatic index under current and future climatic conditions on a global scale under A1B and A2 climate change scenarios. Highly suitable (EI > 30); suitable (15 < EI = 30); marginally suitable (0 < EI = 15); unsuitable (EI = 0).

However, around 85 countries under the current climatic conditions have suitable environmental conditions (EI > 0) for the growth of *P. alba*, which covers 53.52% of the globe's land area (excluding Antarctica), except for northern Canada, northern African states, and central Australia. Similarly, almost the entirety of Europe, South America, and the southern and eastern North American regions are suitable for *P. alba* growth. Regions that have highly suitable environmental conditions (EI > 30) cover 14.24% (20.16 million km^2) of the globe's land area (Figures 3 and 4). Whereas regions with suitable environmental conditions (15 < EI = 30) and marginal environmental conditions (0 < EI = 15) account for 14.31% (20.26 million km^2) and 24.97% (35.35 million km^2) of the globe's land area, respectively.

3.2. Potential Global Distribution under Future Climate Conditions

The model forecasted a decreasing trend in the number of areas capable of providing highly suitable habitats for *A. sarta* at the end of century 2100 under A1B and A2 CCSs (Figures 4 and 5). No noticeable differences were observed for both scenarios. This decrease was mainly observed in the southern hemisphere and central part of the world. Overall, the highly suitable area (EI > 30) decreased to 24.20% (32.55 million km^2) from 27.07% (36.41 million km^2) compared to the current climatic condition. However, a shift in number of areas capable of providing highly suitable habitats in the northern hemisphere was observed. Furthermore, the model forecasted an increase in total countries with highly suitable habitats (EI > 30), with up to 68 countries being capable of providing highly suitable habitats by the end century under both CSSs, compared to 52 countries under current climatic conditions. The countries that are most likely going to be capable of providing highly suitable habitats (EI > 30) at the end of the century (2100) are Australia, New Zealand, Afghanistan, Pakistan, India, China, Kazakhstan, Iran, Azerbaijan, Turkey, Kyrgyzstan, Russia, Mongolia, Tajikistan, Bhutan, Democratic People's Republic of Korea, Republic of Korea, Japan, Nepal, Canada, USA, Mexico, Argentina, Uruguay, South Africa, Namibia, Jordan, Lebanon, Tunisia, Algeria, Morocco, Germany, UK, Spain, Portugal, France, Italy, Greece, Bulgaria, Serbia, Croatia, Hungary, Romania, Moldova, Ukraine, Cyprus, Belgium, Poland, Bosnia and Herzegovina, Albania, Macedonia, Estonia, Lithuania, Belarus, Slovenia, Slovakia, Czech Republic, Luxembourg, Latvia, Montenegro, Armenia, Georgia, The Netherlands, Sweden, Finland, Switzerland, Austria, Denmark. Compared to current climatic conditions, suitable and marginally suitable habitat areas will likely increase to 10.46% and 5.74% by 2100 under both CCSs.

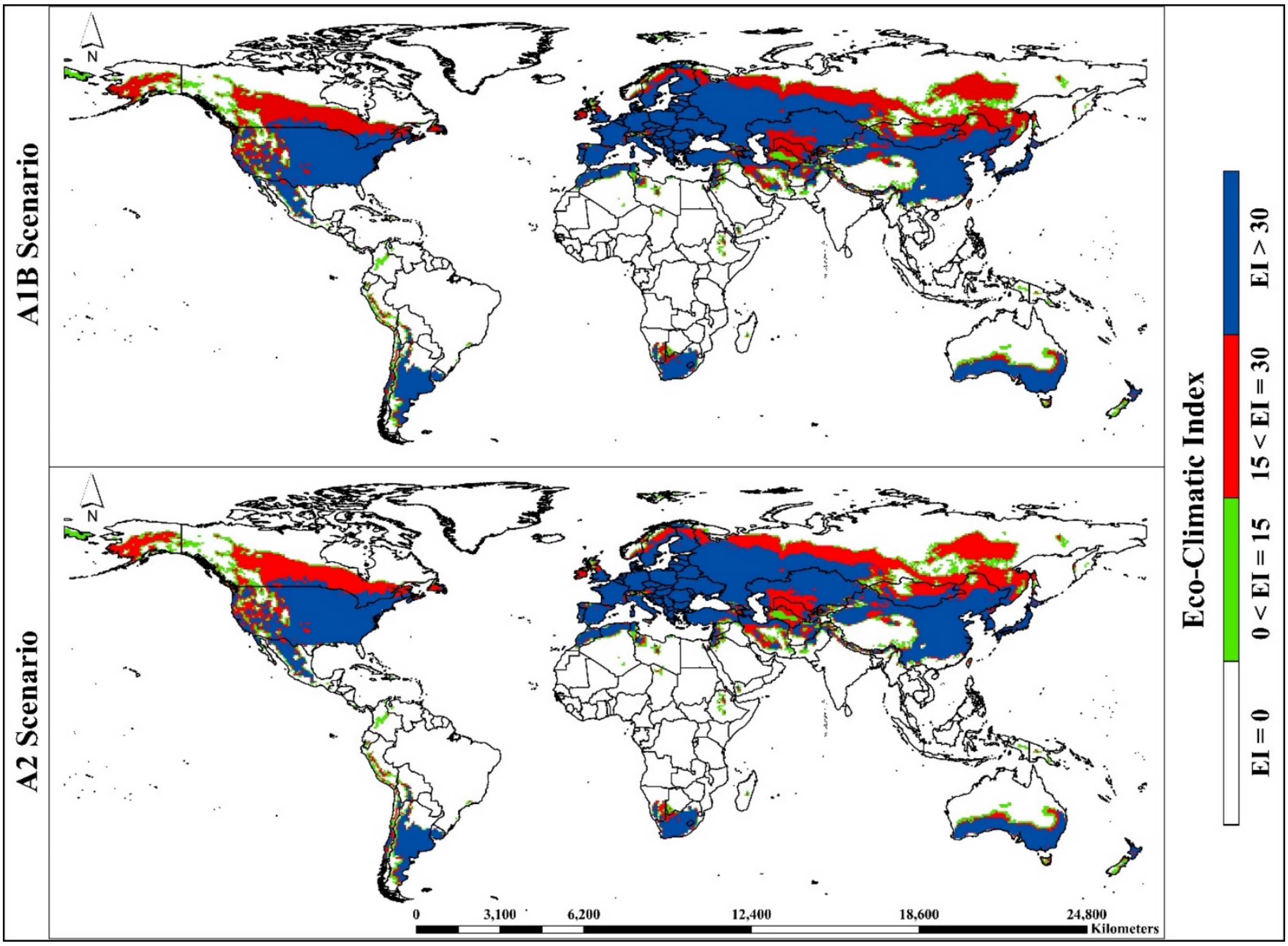

Figure 5. Predicted potential global distribution of *A. sarta* under future climatic conditions (2100) under A1B and A2 climate change scenarios (CCSs). The predicted global distributions (four colors) relate to the ecoclimatic index (EI) from the CLIMEX model: highly suitable (EI > 30), suitable (15 < EI = 30), marginally suitable (0 < EI = 15), unsuitable (EI = 0).

On a global level, the model forecasted a gradual increase in the number of highly suitable habitat (EI > 30) areas for the growth of *P. alba* till the end century under both CCSs (Figures 4 and 6). Under A1B CCS, highly suitable habitat areas increased to 14.41% (20.40 million km^2), and under A2 CCS, this increase is forecasted to be 15.10% (21.38 million km^2). Under current climatic conditions, this figure is estimated to be 14.24% (20.16 million km^2). This increase was mainly observed in the northern hemisphere and central part of the world. The countries that are likely to be capable of providing highly suitable habitat areas under future climatic conditions (EI > 30) (at the end of the century; 2100) are the USA, Canada, New Zealand, Afghanistan, Pakistan, India, China, Azerbaijan, Turkey, Russia, Bhutan, North Korea, South Korea, Japan, Nepal, Malaysia, Indonesia, Papua New Guinea, Fiji, Canada, Argentina, Uruguay, Germany, UK, Ireland, Spain, Portugal, France, Italy, Greece, Bulgaria, Serbia, Croatia, Hungary, Romania, Moldova, Cyprus, Belgium, Poland, Estonia, Lithuania, Belarus, Slovenia, Slovakia, Luxembourg, Latvia, Armenia, Georgia, The Netherlands, Sweden, Finland, Switzerland, Austria, Denmark, Australia.

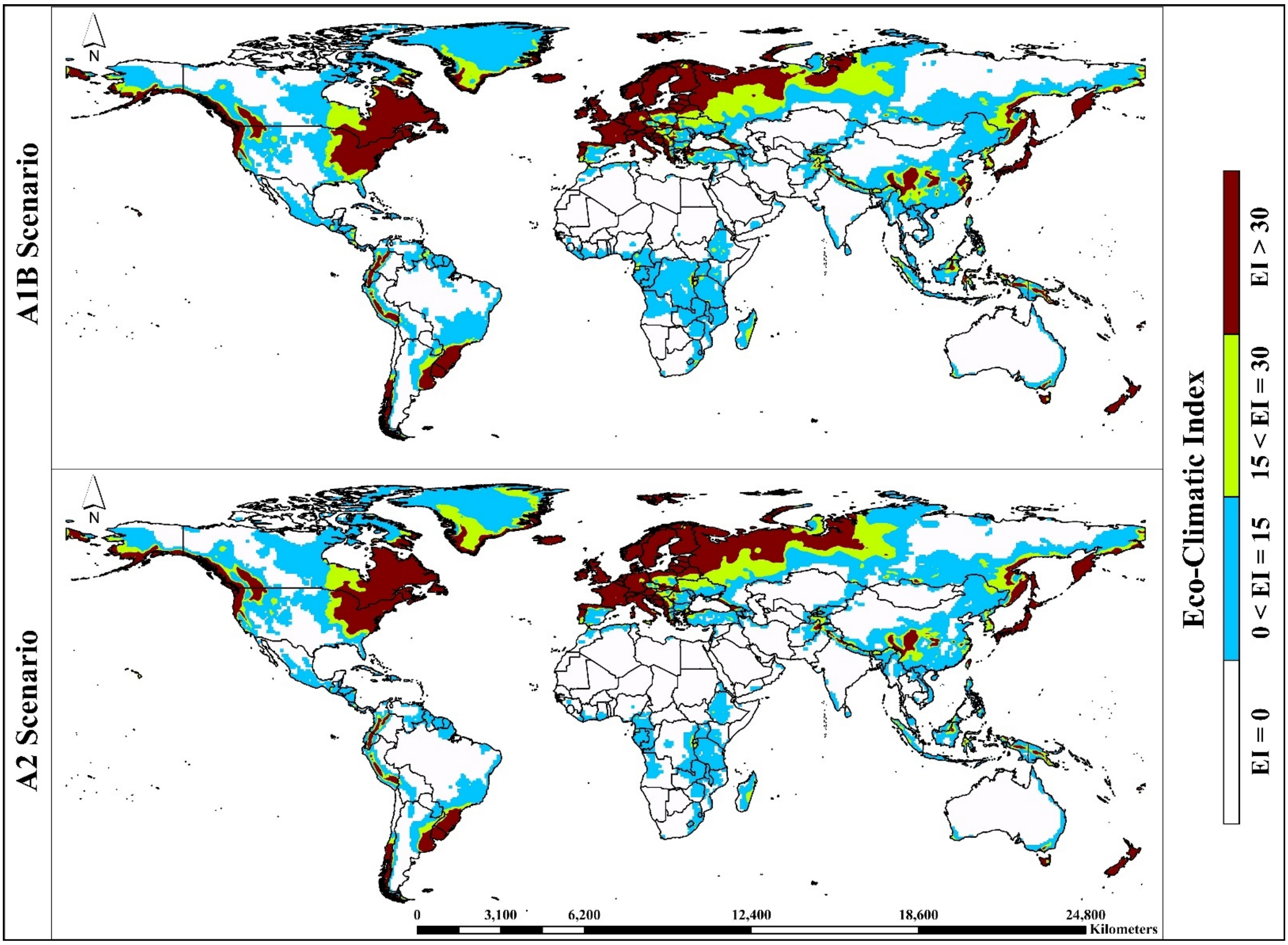

Figure 6. Predicted potential climatic favorability of *P. alba* under future climatic conditions 2100 under A1B and A2 climate change scenarios (CCSs). The predicted global climatic favorability (four colors) relates to the ecoclimatic index (EI) from the CLIMEX model: highly suitable (EI > 30), suitable (15 < EI = 30), marginally suitable (0 < EI = 15), unsuitable (EI = 0).

3.3. Continent-Wise Distribution under Future Climate Conditions

Under current climate conditions, out of the 48 countries in Asia, 20 are capable of providing highly suitable habitats (EI > 30) for the development of *A. sarta*, accounting 26.79% (11.68 million km^2) of the globe's land area. According to our predictions, this will reduce to 14 countries by the end of the century (2100) under A1B and A2 CCSs. Under future climatic conditions, highly suitable, suitable, and marginally suitable habitat areas will increase up to global area figures of 27.11% (11.82 million km^2), 16.45% (7.17 million km^2), and 7.35% (3.20 million km^2) in 2100 under both CSSs (Table 4). While, under current climatic conditions, areas with highly suitable habitats for the growth of *P. alba* account for 10.16% (5.04 million km^2) of the globe's land area, and this is predicted to increase to 10.53% (5.23 million km^2) under A1B CCS and decrease to 7.64% (3.79 million km^2) under A2 CCS at the end century.

Table 4. Continent-wise percentage of the land area distribution of *Aelosthes sarta* and *Populus alba* within the four ranges of the ecoclimatic index under current and future climatic conditions on a global scale under A1B and A2 climate change scenarios.

	Eco-Climatic Index		Asia		Europe		Africa		North America		South America		Oceania	
			%	Mi. km^2	%	Mi. km^2	%	Mi. km^2	%	Mi. km^2	%	Mi. km^2	%	Mi. km^2
Current	EI = 0	*A. sarta*	53.81	23.46	37.59	3.60	63.70	18.84	65.06	15.30	77.62	13.53	29.60	2.32
		P. alba	53.21	26.41	5.44	0.72	56.58	13.32	53.10	18.17	15.19	2.15	74.10	5.04
	0 < EI = 15	*A. sarta*	5.96	2.60	5.61	0.54	3.74	1.11	4.36	1.03	5.05	0.88	3.53	0.28
		P. alba	27.39	13.59	39.70	5.25	20.12	4.74	20.21	6.91	28.21	3.99	12.66	0.86
	15 < EI = 30	*A. sarta*	13.44	5.86	28.35	2.72	3.28	0.97	8.27	1.94	2.78	0.48	2.92	0.23
		P. alba	9.25	4.59	24.26	3.21	17.73	4.17	7.85	2.69	38.53	5.45	2.23	0.15
	EI > 30	*A. sarta*	26.79	11.68	28.44	2.73	29.28	8.66	22.31	5.25	14.55	2.54	63.95	5.01
		P. alba	10.16	5.04	30.60	4.05	5.57	1.31	18.84	6.44	18.07	2.56	11.00	0.75
2100 (A1B)	EI = 0	*A. sarta*	49.09	21.40	7.29	0.70	91.06	26.93	43.38	10.20	82.99	14.46	60.34	4.73
		P. alba	52.60	26.11	3.48	0.46	72.90	17.16	36.04	12.33	59.43	8.41	84.93	5.78
	0 < EI = 15	*A. sarta*	7.35	3.20	3.38	0.32	2.18	0.65	7.07	1.66	4.96	0.87	7.21	0.56
		P. alba	29.68	14.73	13.84	1.83	25.23	5.94	34.18	11.69	24.24	3.43	7.03	0.48
	15 < EI = 30	*A. sarta*	16.45	7.17	10.39	1.00	1.64	0.48	18.22	4.28	2.52	0.44	6.03	0.47
		P. alba	7.19	3.57	23.23	3.07	1.63	0.38	9.68	3.31	4.92	0.70	2.01	0.14
	EI > 30	*A. sarta*	27.11	11.82	78.94	7.57	5.12	1.51	31.34	7.37	9.52	1.66	26.41	2.07
		P. alba	10.53	5.23	59.45	7.87	0.24	0.06	20.10	6.88	11.41	1.61	6.03	0.41
2100 (A2)	EI = 0	*A. sarta*	49.09	21.40	7.29	0.70	91.06	26.93	43.38	10.20	82.99	14.46	60.34	4.73
		P. alba	53.23	26.42	3.77	0.50	82.61	19.44	33.48	11.45	66.34	9.39	85.85	5.84
	0 < EI = 15	*A. sarta*	7.35	3.20	3.38	0.32	2.18	0.65	7.07	1.66	4.96	0.87	7.21	0.56
		P. alba	29.52	14.65	12.40	1.64	16.42	3.86	34.72	11.88	19.03	2.69	7.34	0.50
	15 < EI = 30	*A. sarta*	16.45	7.17	10.39	1.00	1.64	0.48	18.22	4.28	2.52	0.44	6.03	0.47
		P. alba	9.61	4.77	19.30	2.55	0.90	0.21	10.85	3.71	4.16	0.59	1.44	0.10
	EI > 30	*A. sarta*	27.11	11.82	78.94	7.57	5.12	1.51	31.34	7.37	9.52	1.66	26.41	2.07
		P. alba	7.64	3.79	64.52	8.54	0.08	0.02	20.96	7.17	10.46	1.48	5.37	0.37

Note: Highly suitable (EI > 30); suitable (15 < EI = 30); marginally suitable (0 < EI = 15); unsuitable (EI = 0).

Under current climatic conditions, out of the 44 countries in Europe, 15 provide highly suitable habitats for *A. sarta* development, accounting for 28.44% (2.73 million km^2) of the globe's total land area. Under future climatic conditions and A1B and A2 CCSs, 32 countries are likely to have highly suitable habitat areas (EI > 30), accounting for 78.94% (7.57 million km^2) of the globe's total land area. Comparatively, under current climatic conditions, regions offering highly suitable habitat areas for *P. alba* growth account for 30.60% (4.05 million km^2) of the globe's total land area, and by the end of the century, this figure is forecasted to gradually increase to 59.54% (7.87 million km^2) and 64.52% (8.54 million km^2) under A1B and A2 CCSs, respectively. In our predictions, unsuitable habitat (EI = 0) areas for *P. alba* growth reduced compared to current climatic conditions under future climatic conditions under both CCSs at the end century.

In Africa, only 11 countries out of 54 offer highly suitable habitats (EI > 30) for *A. sarta* development, accounting for 29.29% (8.66 million km^2) of the globe's total land area under current climate conditions, and this will supposedly reduce to only four countries covering 5.12% (1.51 million km^2) of the globe's total land area by the end of the century (2100) under A1B and A2 CCSs. However, highly suitable habitat areas for the growth of *P. alba* under future climatic conditions are predicted to reduce to 0.24% (0.06 million km^2) and 0.08% (0.02 million km^2) under A1B and A2 CCSs at the end of century compared to current climatic conditions, for which the same value is estimated to be 5.57% (1.31 million km^2).

In the North American continent, only two countries, Mexico and America, offer highly suitable habitat areas for the development of *A. sarta*, accounting for 22.31% (5.25 million km^2) of the globe's total land area under current climatic conditions; however, this figure is estimated to increase to three countries, including South Canada, covering 31.34% (7.37 million km^2) at the end of the century under both CCSs. At the same time, the unsuitable habitat (EI = 0) areas will reduce to 43.38% (10.20 million km^2) of the globe's total land area in 2100 compared to current climatic conditions, the corresponding value of which is 65.06% (15.30 million km^2). Highly suitable habitats for the growth of *P. alba* under current climatic conditions account for 18.84% (6.44 million km^2) of the globe's total land area, which is predicted to increase to 20.10% (6.88 million km^2) and 20.96% (7.17 million km^2) under A1B and A2 CCSs at the end century. Unsuitable habitat areas also experienced respective decreases to 36.04 (12.33 million km^2) and 33.48% (11.45 million km^2) under A1B and A2 CCSs in our predictions for 2100. Under current climatic conditions, this figure is estimated to be 53.10% (18.17 million km^2).

Out of the 12 countries in South America, under current climatic conditions, 5 offer highly suitable habitats (EI > 30) for *A. sarta* development, accounting for 14.55% (2.54 million km^2) of the globe's total land area; whereas, at the end of the century (2100), this will reduce to 4 countries, accounting for 9.52% (1.66 million km^2) of the globe's total land area under A1B and A2 CCSs. However, under future climatic conditions, the land area comprising unsuitable habitats increases up to 82.99% (14.66 million km^2). For current climatic conditions, this figure was estimated to be 77.62% (13.43 million km^2). Highly suitable habitat areas for *P. alba* growth account for 18.07% (2.56 million km^2) of the globe's total land area under current climatic conditions, and this is predicted to gradually decrease to 11.41% (1.61 million km^2) and 10.46% (1.48 million km^2) under A1B and A2 CCSs, respectively, by the end century.

In Oceania, under current climatic conditions, the global land area comprising highly suitable habitats for *A. sarta* development is 63.95% (5.01 million km^2), while this area continues to reduce up to 26.41% (2.07 million km^2) at the end of the century under A1B and A2 CCSs. Under future climatic conditions, unsuitable areas decreased by up to 60.34%. (4.73 million km^2). For the current climatic conditions, this figure was estimated to be 29.60% (2.32 million km^2). However, highly suitable habitat areas for the growth of *P. alba* under future climatic conditions are predicted to reduce to 6.03% (0.41 million km^2) and 5.37% (0.37 million km^2) under A1B and A2 CCSs at the end century. For the current climatic conditions, this figure was estimated to be 11% (0.75 million km^2).

Global predictive maps based on the model's results demonstrate that cold stress and heat stress limit the potential climatic zone for *A. sarta* to specific regions (Figure 7). Cold stress limits the potential climatic zone boundaries in the northern hemisphere, but heat stress limits those in the southern hemisphere and the central region of the world. However, the intensity of cold and heat stress increased with time under A1B and A2 CCSs.

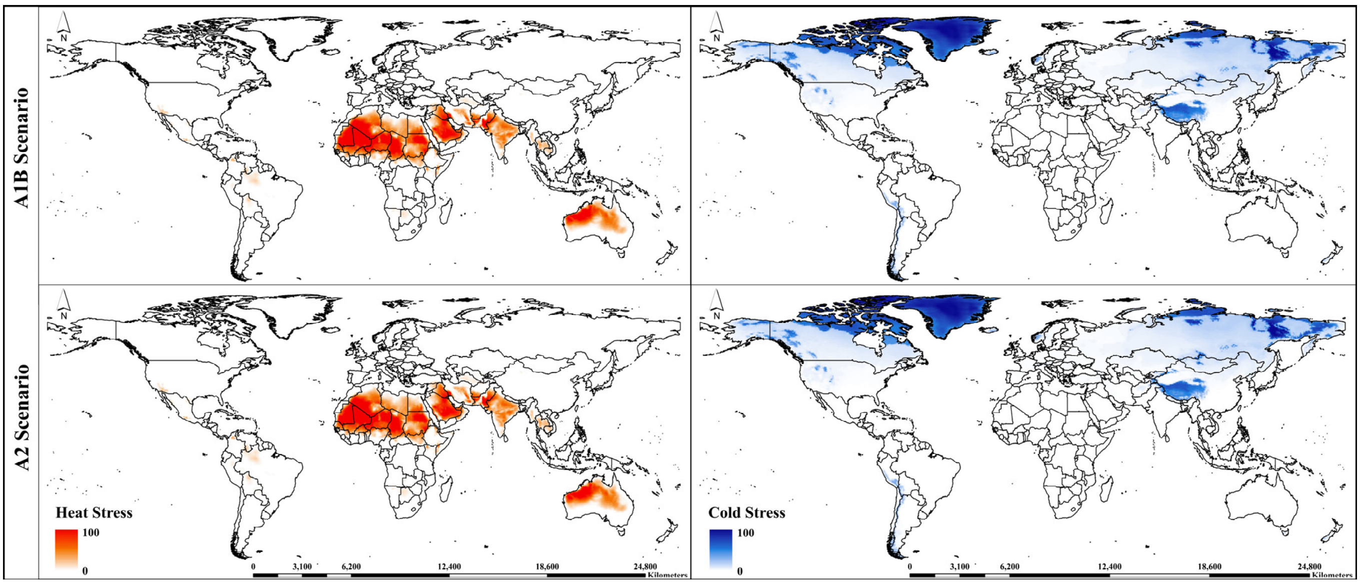

Figure 7. The predicted region where *A. sarta* survival is affected globally by cold stress and heat stress under A1B and A2 climate change scenarios at the end of this century (2100).

Globally, cold, heat, and dry stress tend to limit the potential climatic zone for *P. alba* on predicted maps (Figure 8), but in the northern hemisphere, only cold stress limits the potential climatic zone. However, heat stress and dry stress limit the potential climate zone range in the southern hemisphere and the central region of the earth. In contrast, heat stress and dry stress intensified over time under A1B and A2 CCSs, but the intensity of cold stress decreased.

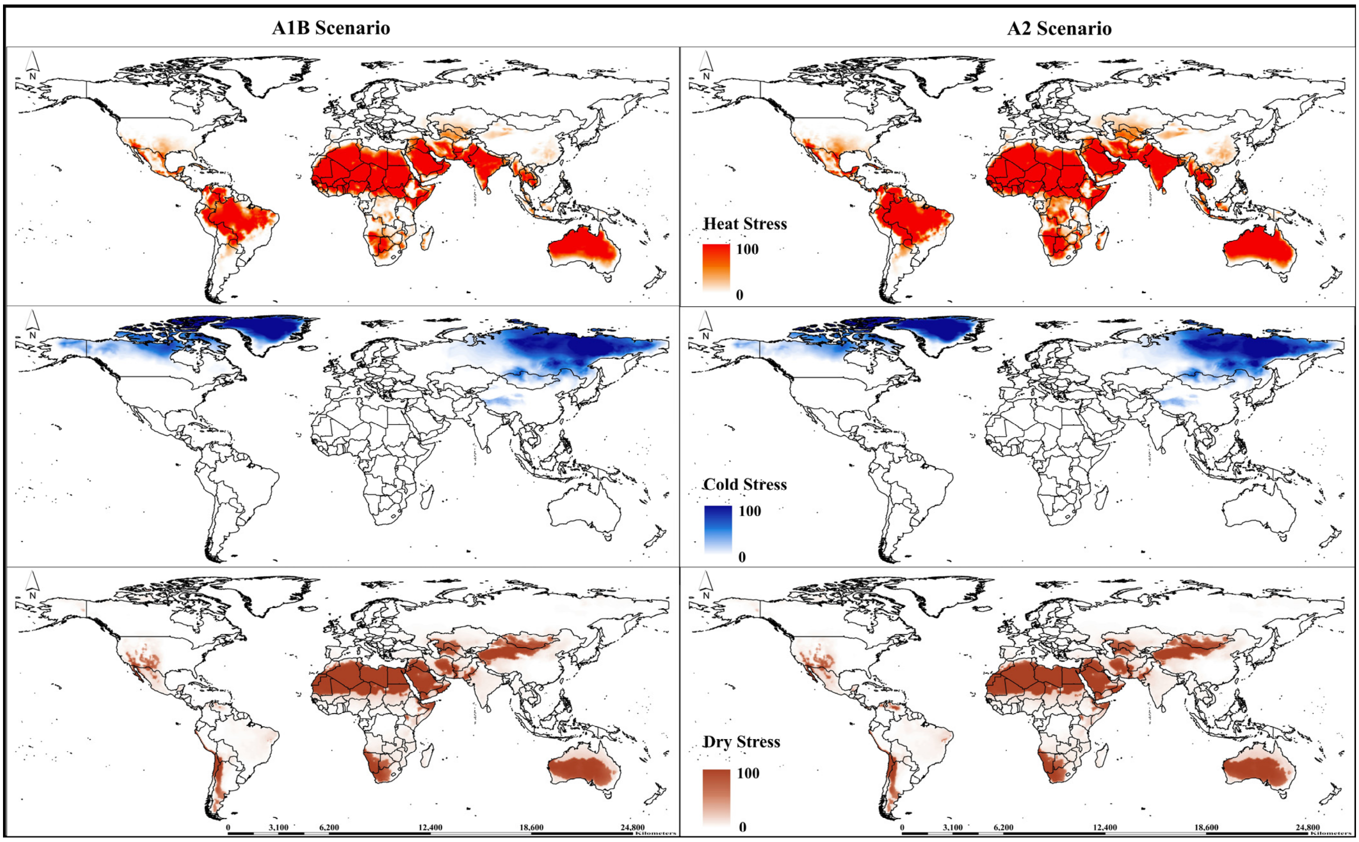

Figure 8. The predicted region where *P. alba* survival is affected globally by cold, heat, and dry stresses under A1B and A2 climate change scenarios at the end of this century.

4. Discussion

Our goal was to use a modeling technique (CLIMEX) to demonstrate a comprehensive approach to analyzing the distribution pattern of *A. sarta* and its dominant host, *P. alba*, under current and future climatic conditions. The modeled climate suitability for *A. sarta* and *P. alba* under current climatic conditions extends well beyond the existing recorded occurrences and provides considerable insight into the likelihood of the pest outbreaks in the region having host distribution. The findings of this study confirmed that, in comparison to the current climate, the distribution of *A. sarta* and growth pattern of *P. alba* are significantly altered by future climatic conditions under A1B and A2 CCSs.

The climate is among the most crucial factors that significantly impact species' dispersion globally [37]. The habitat range of many species, especially cold-blooded species like insects, is significantly impacted by climate change [44] (not only insects but also the forest species growth/distribution pattern) [45]. Estimating the geographic ranges of a targeted pest species under future climatic scenarios has been made simpler due to advancements in climate modeling methodologies and technology, which has further improved the monitoring of pests and pest management strategies [46]. An earlier attempt to characterize climatic influences on *A. sarta* distributions using CLIMEX was explored in a study by Vanhanen et al., wherein they explored its distribution in Europe only [12].

The ecological niche of *A. sarta* concerning its dominant host species, *P. alba*, was modeled globally for the first time in the present study, which also evaluates the significance of environmental factors in relation to modeling ranges and spatial patterns. Additionally, the present study is the very first to forecast the global distribution of *A. sarta* and its dominant host species, *P. alba*, under A1B and A2 climate change scenarios. The only prior use of this method, regarding *A. sarta* generally, was outlined in a study by Vanhanen et al. [12]. Notably, we observe that the maps produced by this approach vary markedly from those seen in the study of Vanhanen et al. (*A. sarta* distribution only restricted to southern Europe) [12] (Figures 2 and 5). In particular, we noted that, under both CCSs, by 2100, highly suitable habitat areas (EI > 30) are estimated to stretch from south to north, covering entire central regions in Europe, North America, and NE and NW Asia. Likewise, by 2100, habitat areas highly suitable for *P. alba* are estimated to expand towards the northern hemisphere, covering almost the entirety of Europe, Eastern USA, SE Canada, and the entirety of New Zealand.

According to an ecological niche model for *A. sarta* and *P. alba*, under current climatic conditions, the range for the distribution of suitable habitats for *A. sarta* is primarily restricted to the southern and central regions of the world due to cold stress, while *P. alba*'s distribution range stretches from the southern to the northern hemisphere, excluding central African regions, where heat and dry stresses restrict the distribution as warming induces the dry stress by raising the demand for atmospheric water [47,48]. Moreover, in northern regions where cold stress restricted the distribution under cold climatic conditions, *P. alba* finds less suitable conditions under cold climatic conditions, suffering from high moisture, frigid temperature, and frost [36]. However, it is predicted that under future climatic conditions (A1B and A2 scenarios), the distribution of suitable habitats for *A. sarta* will expand to the Northern Hemisphere but shrink in the Southern Hemisphere, while warm temperate and tropical coastlines remain beyond the *A. sarta* suitable habitat areas (EI = 0).

Furthermore, *P. alba's* suitable growth range under future climatic conditions will expand to the northern hemisphere, covering Europe and Eastern and Southern North America, but shrink in the southern hemisphere. As heat and dry stresses are predicted to increase at the end century, the central part of the world becomes unsuitable for the growth of *P. alba*. Climate change will cause species' distribution range to shift or expand or decrease, significantly impacting species occurrence [3,46].

No extensive datasets or maps have been developed for the global distribution and growth pattern of *A. sarta* and *P. alba*, respectively. The present study implies that *A. sarta* can establish itself in areas broader than initially expected, and *P. alba* forests in these areas are at high risk. Understanding the scope of this species' distribution can help us take the necessary measures to limit the spread of this pest. The global distribution of *A. sarta* throughout the warm and dry temperate zones demonstrated its vast climate niche and extensive climatic adaptability. The projection of *P. alba's* suitable growth regions also exhibits the availability of the favorable host species of *A. sarta*. In this climate zone lies a variety of phenotypic traits that *A. sarta* exhibits and the availability of preferred host species [4].

The climates of Asia, Europe, North America, and Oceania are the most suitable for introducing and growing *P. alba*. These continents support the growth of *P. alba* under current and future climatic conditions. However, the likelihood of *A. sarta* occurring in any of these continents is mainly unknown (except in some Asian countries). The same may be stated about New Zealand, a nation in Oceania projected to be capable of providing moderate to highly suitable habitats for *A. sarta*, though this has not been thoroughly investigated. If *A. sarta* were introduced in any of these areas, *P. alba* plantations would be highly affected, as has already been the case in Asian countries Pakistan, Iran, India, Turkmenistan, and Tajikistan [4], where infested trees become unsuitable for pulp and wood exploitation.

Several studies have reported both latitudinal and altitudinal temperature-related range alterations in various insects [49–51]. These demonstrate how strongly climate influences species distribution and offer a solid framework for climatic modeling. Distribution models are an initial step in assessing the danger of a pest, together with the distributions of its possible hosts. However, it has been demonstrated that the absence of congeneric or native host plants hinders the establishment of alien phytophagy insects [52,53]. However, our results revealed that, in many Asian, European, North American, and Oceania forests, the growth of *P. alba*, commercial stands, and urban areas facilitates the establishment of the *A. sarta*.

Over the past 50 years, a continuous increase in the trade of wood-based products has been observed globally [54]. Around thirty items are made from poplar wood, making it substantial for trade [55]. As commerce in commodities with related wood packaging, such as forest products, expands globally, there is an ongoing issue with the movement of wood and tree pests [54]. *A. sarta* invades trees inside a domain of 500 m from its nursery tree [12,56]. Although capable of long-distance dispersion, human-aided dispersal through *P. alba* wood shipment would still be the major route for long-distance dispersion if a species wished to establish itself in a new continent. In the USA, through human-aided dispersal, spongy moth (*Lymantria dispar*) has been observed to populate new remote areas outside of its continuous dispersion span; however, its constant dispersion span in the Eastern USA only expands westward by natural dispersal at a rate of 2 km per year [57], primarily due to strong flight [58]. Similar to the Spongy moth in North America, *A. sarta* has had an invasion sequence in Asia comparable to its original distribution zone [4,56]. The proliferation of invasive species, i.e., the global distribution of *A. sarta*, poses profound economic implications [59,60].

Generally, models are calibrated using data onto the native range or a composite of the native and invaded area [31,37]. We analyzed worldwide occurrence data To configure the model used in the present study and capture the range of suitable environmental conditions for the development of *A. sarta* and the growth of *P. alba*. As a result, the model is more responsive [61]. The model would understate the target species' potential distribution if the parameters were fitted within a narrow range. The rationality of the model relies on how precisely the predictions match reality [31,37]. Map comparisons reveal good agreement regarding simulated and actual *A. sarta* and *P. alba* distributions, demonstrating that climate-based models may produce helpful forecasts with little input data [13,31,37]. The geographical distribution of *A. sarta* is influenced by various biotic and abiotic variables, such as the availability of the host tree species [4]. Our *P. alba* distribution model demonstrated that, out of many preferred host species, *P. alba* is mainly available in the regions highly suitable for developing *A. sarta* under current and future climate conditions.

Since the egg, larva, and pupal life stages of *A. sarta* are within the host tree, it is simple for it to disperse with the host for a very long time [4]. *A. sarta* will continue to spread extensively over the world if robust control measures are not implemented. Therefore, intelligent detection systems should be installed in airports and seaports to precisely detect and intercept *A. sarta* eggs, larvae, or pupa. Additionally, before trading *P. alba* wood/logs/billets, phytosanitary measures, such as stem debarking and kiln drying, are recommended. In the case of invasion, the use of Click beetle Alaus larvae, which feed on *A. sarta* larvae; *Proctolaelaps* spp, which feeds on *A. sarta* grubs [20]; *Sclerodermus turkmenicus*, which are parasites of *A. sarta* larvae [14]; and *Beauveria bassiana*, which infects the *A. sarta* adults [62], are recommended as biological control agents. We recommend avoiding the use of pesticides as they are not environmentally friendly [63].

In this work, the aforementioned modeling software was used for the first time on a global scale to simulate the ecological niche of *A. sarta* insight with its dominant host, *P. alba*, using precision parametric variables. The habitat suitability forecasts may pinpoint areas where the species may establish itself as a potential invasive pest because the distribution is projected at the species level. The CLIMEX forecasting of known distribution and the impact of environmental conditions on *A. sarta* development have a high degree of accuracy, which suggests that this modeling strategy has great potential for assisting in the creation of pest control plans.

5. Conclusions

Globally, invasive insect species like *A. sarta* seriously threaten native biodiversity and ecological processes. Economic globalization and climate change have exacerbated their invasion. This paper is the first study of its kind to use the CLIMEX model to predict the global habitat distribution of *A. sarta* regarding its dominant host species, *P. alba,* under current and future climatic conditions (using A1B and A2 climate change scenarios). This study demonstrated a practical method for creating a global habitat suitability map for *A. sarta* development and *P. alba* growth. Overall, under future climatic conditions, the global land area comprising highly suitable habitats for the development of *A. sarta* is estimated to decrease globally, and the same can be said for global land area comprising highly suitable habitats for *P. alba* growth range areas; however, regions like North America, Europe, Oceania, and most parts of Asia will remain highly suitable for the growth of *P. alba* and the development of *A. sarta*. Under climate change scenarios (A1B and A2), due to changes in temperature intensity, areas of cold stress decreasing, and areas of heat stress increasing, a shift will occur toward the northern hemisphere regarding the global land area of suitable habitats for *A. sarta*, while the global land area of suitable habitats will shrink at the southern hemisphere; whereas, under climate change scenarios, *P. alba* growth regions are estimated to shrink with the same pattern as that of *A. sarta* due to the heat stress, cold stress, and dry stress. For *A. sarta*, the expanding areas are mainly located in Asia, Europe, and North America, while for *P. alba,* the continents where the suitability of climatic conditions will increase are Europe, North America, Oceania, and Asia. Regions where the eco-climatic suitability index decreases for *A. sarta* development and *P. alba* growth under future climatic conditions are Africa (central states of Africa), South America (states with hot and dry stresses), Oceania (excluding New Zealand), some parts of Australia (where hot and dry stresses predicted to be minimum), and some regions in Asia. Strict monitoring, prevention, and control measures at borders, airports, and seaports before the trade of *P. alba* and other suitable host species wood (logs/billets) are highly recommended to prevent the spread of *A. sarta* and ensure biodiversity security. The *A. sarta* and *P. alba* climate models presented here should be useful for quarantine pest management purposes because they can be used to direct resources toward locations where the threat of pest invasion is high and away from places where climate suitability is expected to decline in the future.

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Abbreviations

CCS	Climate Change Scenario
EI	Ecoclimatic index

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