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Article

Pest Risk Assessment of *Aeolesthes sarta* (Coleoptera: Cerambycidae) in Pakistan under Climate Change Scenario

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Abstract: *Aeolesthes sarta* (Solsky 1871) (Coleoptera: Cerambycidae) is a polyphagous longhorned beetle species that primarily damages broadleaved tree species. This pest is distributed in the western and northern regions of Pakistan, where it caused serious damage to *Populus* spp. plantations. However, the growth and dispersal patterns of insects and pests are changing due to climate change. Modeling the range expansion or contraction of *A. sarta* development regions in Pakistan was the goal of the current study, assuming climate change might influence the geographical distribution of *A. sarta* in Pakistan. Under historical and future climatic conditions, *A. sarta* distribution areas were estimated using the CLIMEX model. Three time periods, 2030 (early century), 2070 (late century), and 2100 (end century), were forecasted for habitat suitability using the two climate change scenarios (CCSs) A1B and A2. Under the historic climatic condition (HCC), *A. sarta* was distributed in most areas of Pakistan, and its optimum habitat accounted for 71.67% of its total potential distribution. In the early-century period, optimum habitat dropped to 50.60% and 52.22% under A1B and A2 scenarios in the suitable condition. In the late-century period, optimum habitat further reduced to 31.76% and 30.60% under A1B and A2 scenarios. Moreover, at the end-century period, severe range shrinkage was predicted in the optimum habitat (19.99% under both CSSs). The model predicted a shift in the suitable habitat areas for *A. sarta* to the west and north. Furthermore, most climatically suitable areas under historic conditions became unsuitable during the end-century period. These projected results will assist in identifying the impacts of global warming on the possible distribution of *A. sarta*, thereby offering vital information for developing early forecasting and pest-prevention techniques to prevent further loss of forest and woodland trees.

Keywords: *Aeolesthes sarta*; city longhorned beetle (CLB); Coleoptera; Cerambycidae; forest pest; climate change; A1B–A2 scenarios; ecological niche model; CLIMEX; invasive species

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1. Introduction

Approximately 30% of the Earth's land area is covered by forests [1]. Natural forests comprise about 5% of Pakistan's total land area, located mainly in the country's north and northwest mountainous regions [2]. Forests are essential to mitigate climate change as they serve as a carbon sink [2–4]. However, pathogens and pests each year kill millions of trees across commercial woodlands and natural forests [5]. The loss of trees resulting from major pest invasions can be catastrophic for total net productivity and carbon sequestration.

A hostile biotic potential threat to trees is pest infestations. The Coleoptera and Lepidoptera orders are home to the most frequently reported pest species [5]. In the Coleoptera order, Cerambycidae is one of the world's most prolific, diverse, ecologically and commercially significant families, which includes longhorn beetles [6]. *Aeolesthes sarta* (City Longhorned Beetle) is one of the dominant polyphagous pest species of the

Cerambycidae family, chiefly invading broadleaved tree species such as *Acer* spp., *Juglans* spp., *Malus* spp., *Platanus* spp., *Populus* spp., *Salix* spp., and *Ulmus* spp. [7]. Larvae of this family are internal feeders of living or dead tree tissues [8]. This behavior of internal feeding causes structural damage, which interjects the flow of water and nutrition, resulting in the loss of branches and, ultimately, whole tree death [9–12].

With a significant spread into Afghanistan, Iran, and other countries in central Asia, it is believed that *A. sarta* emerged in Pakistan and the western part of India [13,14]. Invasive pests thrive in areas with warm temperatures and their preferred host tree species [15]. This species may be highly hazardous in regions with hot and dry weather [16]. The longhorn beetle is a common pest in central Asia that attacks most broadleaved tree species. *A. sarta* can attack and proliferate on the main stem and major branches [17]. Infestations are particularly evident in highland forests, which may contribute to the decrease in poplar tree forests, which are a dynamic source of wood for the wood industry/market [18]. A severe infestation (high population) may cause the afflicted trees' canopy to decline and their leaves to dry off within two to three years [19].

Aeolesthes sarta has gained notoriety in Quetta and throughout Balochistan because it has harmed poplar, willow, and elm trees; for example, in the region (1900–1907), over 3000 trees were damaged by *A. sarta* [20]. *A. sarta* is one of the most destructive poplar borers [21] and has seriously harmed the number of *Populus* plantations across Pakistan [18,21,22].

The scientific foundation for assessing the hazards that plant pests cause to both cultivated and wild flora is supplied by pest risk assessments [23]. By calculating the potential for the introduction (entrance, transfer, and development) and spreading of plant pests and the ensuing effects on crops and plants in the larger environment, they include the rigorous synthesis of information and characterization of hazards [24].

Over the past century, global warming has been a major climate change concern [25]. The patterns of species dispersion have changed, affecting the areas where various species may survive and decreasing biodiversity [26]. Due to their ectothermic nature and wide variation in population size across time and geography, insects can acclimate to climate change well [27]. Many pests that widely disperse will also be able to expand their range more quickly than more stationary or habitat-specific species [28]. We can acquire vital information to control the spread of invasive pests by simulating how climate change impacts these pests [29].

Ecological niche models, including CLIMEX, CLIMATE, MaxEnt, DOMAIN, GARP, HABITAT, and ANUCLIM/BIOCLIM have all proven effective in evaluating the possible geographic dispersion of various invasive species [30]. Among these models, CLIMEX is a specialized toolset designed to investigate how climate affects invasive species and assess how such species might proliferate in the future [31]. Biological data can be frequently adjusted and simulated in CLIMEX, improving the findings. The key benefit of CLIMEX is that it can be theoretically tuned using knowledge of population demographics and phenological evidence [32].

Research on the precise potential distribution of *A. sarta* in Pakistan under projected climatic conditions is lacking. We modified parameter values following the literature published [7,18,21,22] to better match the known distribution in Pakistan. We hypothesized that a changing climate would affect the *A. sarta* range and the region in Pakistan where it thrives. Using the CLIMEX model, we looked into the potential distribution of *A. sarta* in Pakistan and assessed high-risk areas for its invasion. We assessed the vulnerability of different regions in Pakistan for *A. sarta* establishment under historical and future climates (A1B and A2 Climate Change Scenarios (CCSs)).

2. Materials and Methods

2.1. Study Species

Pest species known as *Aeolesthes sarta* (City Longhorned Beetle) grow in temperate locations with warm, dry weather [7]. This pest species is considered harmful since it can harm and destroy healthy and weak trees [21]. On a regional level, climate change is anticipated to modify the region's ideal for growth and development. Numerous studies in Pakistan have described the damage [18,21,22] and mitigation measures [33]; however, ecological niche models have never been used to predict the state of *A. sarta* development areas in a semi-arid nation such as Pakistan under a future climate change scenario. Therefore, this species was chosen for the current modeling research. We divided Pakistan into six administrative parts (Punjab (PB), Khyber Pakhtunkhwa (KPK), Azad Jammu and Kashmir (AJK), Balochistan (BLC), Sindh (SD), and Gilgit Baltistan (GB)) so that we could illustrate the *A. sarta* distribution well (Figure 1).

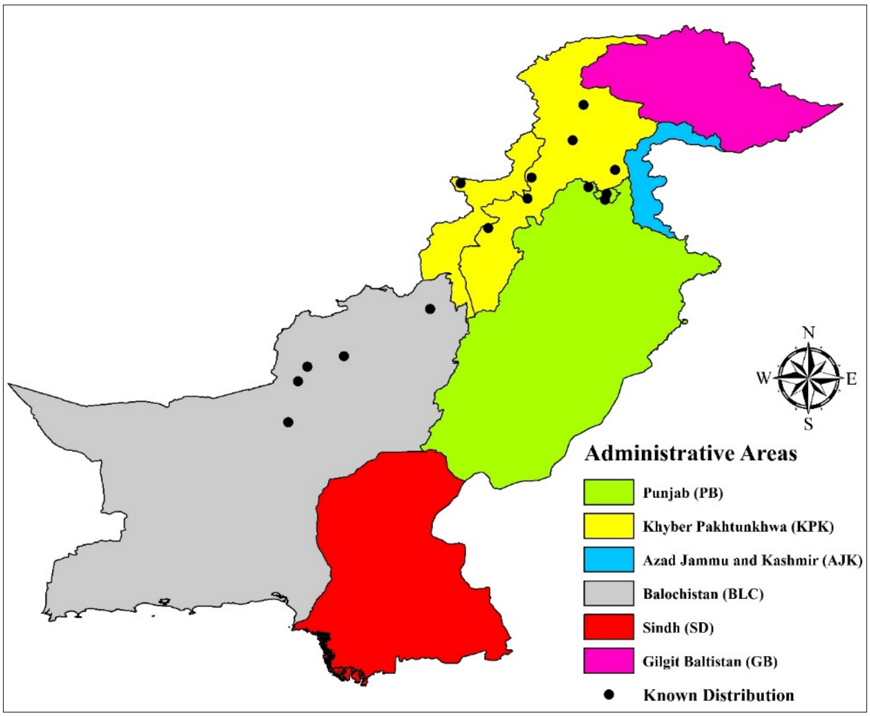

Figure 1. Map of Pakistan with six administrative areas (highlighted in six colors). Black dots represent the present known distribution of *Aeolesthes sarta* in Pakistan.

2.2. CLIMEX Model

In order to provide a set of yearly indices, the CLIMEX model incorporates generic morphological and physiological data and weekly interactions of the species to climate. The CLIMEX model takes on species distribution increases and decreases in response to suitable and unsuitable climatic conditions. The species' annual growth (GA) rate is used to compute the temperature index (TI) and moisture index (MI) and is further used to calculate the species' weekly growth [34]. Four different stresses (cold, dry, hot, and wet) impact the GA and add to stress indices (SI). Based on all these variables, CLIMEX generates an ecoclimatic index (EI) range of 0 to 100 [35]. EI = 0 represents that no growth is possible and EI = 100 indicates ideal growth. Geographical areas in this study that have an EI > 15, 0 < EI = 15, and EI = 0 indicate climatic conditions that are optimum, suitable, and unsuitable habitats for the establishment, survival, and proliferation of *A. sarta*. The CLIMEX uses a set of variables to determine the EI for a specific species [36]. The species' responsiveness determines these attributed to the environmental stresses stated above and its preferred temperature and moisture levels. These parameters' values might be inferred from the current distribution range or determined empirically. Therefore, the parameter fitting operation requires a thorough understanding of species biology and the current distribution spectrum [15]. The variables are modified until a good fit is attained. Following the fitting of a baseline model (under historical/current climatic conditions), predictions for future climatic conditions under various climate change scenarios could be established [37].

2.3. Climatic Data

Historical and future climatic data downloaded from CliMond (https://www.climond.org/ (accessed on 16 August 2022)). The 10′ gridded data had 26,323 location points for Pakistan and monthly averaged data on maximum and minimum temperature, rainfall, and daily relative humidity at 0900 h and 1500 h for each location. Historical climatic data averaged from 1961 to 1990 and finally averaged in 1975 [38].

Future climatic data are available based on two global circulation models (GCMs) and two separate climate change scenarios. These two GCMs were chosen for data generation because they performed better than the other available GCMs [38]. Data were acquired and utilized from the CliMond website for the 2030 (early-century), 2070 (late-century), and 2100 (end-century) time periods. Only data from the A1B and A2 SRES scenarios from CSIRO-Mk3.0 were employed to model the distribution of *A. sarta* in future climate change scenarios [39].

2.4. Collection of *A. sarta* Distribution Data in Pakistan

Aeolesthes sarta known distribution data in Pakistan collected from the Centre of Agriculture and Bioscience International (CABI →https://www.cabi.org/ (accessed on 15 November 2022)), Global Biodiversity Information Facility (GBIF →https://www.gbif.org/ (accessed on 15 November 2022)), European and Mediterranean Plant Protection Organization (EPPO →https://gd.eppo.int/ (accessed on 15 November 2022)), and from literature review [7,18,21,22,31] were used. Except in challenging environments, *A. sarta* has disseminated throughout Pakistan's western and northern mountainous regions.

2.5. Parameters Fitting

2.5.1. Temperature Index (TI) and Population Degree Days (PDD)

Aeolesthessarta is more common in temperate climates with dry and cold weather [7]; thus, while generating the "species parameter file," the Temperate template included with the CLIMEX software was used. Physiological tolerance criteria specific to each species were used to calibrate the model. According to Ahmad et al. [21], oviposition does not occur at <11 °C or >35 °C, whereas at 40 °C, species survive without laying viable eggs. However, Vanhanen et al. [40] used 20 °C and 37 °C as DV1 and DV2 values. Initially, we ran the model following Vanhanen et al. [40] and Ahmad et al. [21] using 11 °C, 20 °C, 35 °C, and 40 °C as DV0, DV1, DV2, and DV3 values, but we did not get all the known occurrence points covered, i.e., Kalam. Then, we adjusted the values to 10 °C (DV0), 15 °C (DV1), 37 °C (DV2), and 40 °C (DV3) and reran the model; it was able to predict the currently known occurrence. Therefore, we finalized these values as temperature indices to forecast the potential global distribution.

A. sarta completes its life cycle in almost two years [9,13,21]; therefore, we set the population day degree (PDD) value as 700, according to Vanhanen et al. [40].

2.5.2. Moisture Index (MI)

Another variable of the CLIMEX model is the soil moisture index (MI), which provides information about the amount of precipitation. The lower soil moisture threshold (SM0), lower optimal soil moisture (SM1), upper optimum soil moisture (SM2), and upper soil moisture threshold (SM3) are the four additional characteristics that the CLIMEX model uses to classify the MI [34]. SM0 was adjusted to 0 to allow for normal species development [40]. Soil moisture values for optimal growth (SM1 and SM2) were established at 0.001 and 1.5 to suit the observed occurrence of species in known distribution. Following a similar procedure, an upper soil moisture level (SM3) of 2.5 was adjusted [40].

2.5.3. Diapause Index

Diapause duration was reported to be around 90 days [9,13], so we set the DPD (diapause development days) as 90 days. DPD0 (diapause induction day length), DPT0 (diapause induction temperature), DPT1 (diapause termination temperature), and DPSW (summer or winter diapause) were set to be 12 days, 13 °C, 10 °C, and 0 days, respectively, according to [40].

2.5.4. Stress Index (SI)

Cold stress (CS), heat stress (HS), dry stress (DS), and wet stress (WS) are the four environmental stress indices in the CLIMEX modeling system that are reflective of hostile circumstances that restrict the population development of a species [34]. We only took CS and HS into consideration for this research study. Stress starts to restrict a species' development when the temperature falls below that species' cold stress threshold temperature (TTCS) at a particular rate (THCS). In the current study, 9 °C was considered the TTCS for *A. sarta* since *A. sarta* development is inhibited below this temperature [21].

Based on the TTCS result, the THCS was set to −0.00001. Similarly, heat stress affects a species as soon as the temperature surpasses its heat stress temperature threshold (TTHS) at a specific rate (THHS). In the present research, we set the TTHS to 41 °C and the THHS to 0.005 since *A. sarta* did not survive over 40 °C [21]. The parametric values used to run the CLIMEX model are shown in Table 1.

Table 1. *Aeolesthes sarta* parameter values used in the CLIMEX model.

Parameters	Code	Settled Values
Temperature		
Limiting low temperature (°C)	DV0	10
Lower optimal temperature (°C)	DV1	15
Upper optimal temperature (°C)	DV2	37
Limiting high temperature (°C)	DV3	40
Population degree day	PDD	700
Moisture Index		
Limiting low soil moisture	SM0	0
Lower optimal soil moisture	SM1	0.001
Upper optimal soil moisture	SM2	1.5
Limiting high soil moisture	SM3	2.5
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
CS temperature rate	THCS	−0.00001
Heat Stress		
HS temperature threshold (°C)	TTHS	41
HS temperature rate	THHS	0.005

3. Results

3.1. Potential Distribution of A. sarta in Pakistan under Historic Climatic Conditions (HCC)

The model calculation results illustrate that the known distributions gathered from CABI, EPPO, GBIF, and the literature review were within the potential distribution area projected by CLIMEX under historic climate conditions (HCC) (Figure 2). This demonstrates that the finalized parameters can accurately predict Pakistan's *A. sarta* distribution pattern. Using the map developed by ArcMap, we estimated the potential area of *A. sarta* distribution in Pakistan to be 7.32 HT-Km^2 (100,000 square kilometers), or 83.43% of Pakistan's total area (Figure 3).

The area covering optimum habitat (EI > 15) was 6.26 HT-Km^2, which is 71.67% of the total area of Pakistan, accounting for 85.91% of the total potential distribution area. This potential distribution comprises 100% of the area of Punjab (PB), 78.23% of Khyber Pakhtunkhwa (KPK), 67.48% of Azad Jammu and Kashmir (AJK), 80.58% of Balochistan (BLC), 37.45% of Sindh (SD), and 3.53% of Gilgit Baltistan (GB).

The area covering suitable habitat (0 < EI = 15) was 1.03HT-Km^2, 11.76% of the total area of Pakistan, accounting for 14.09% of the total potential distribution area. This covers 15.60% of KPK, 13.35% of AJK, 12.45% of BLC, 19.47% of SD, and 22.48% of GB. However, only 1.45 HT-Km^2, which is 16.57% of the total area of Pakistan, covers unsuitable habitats (EI = 0).

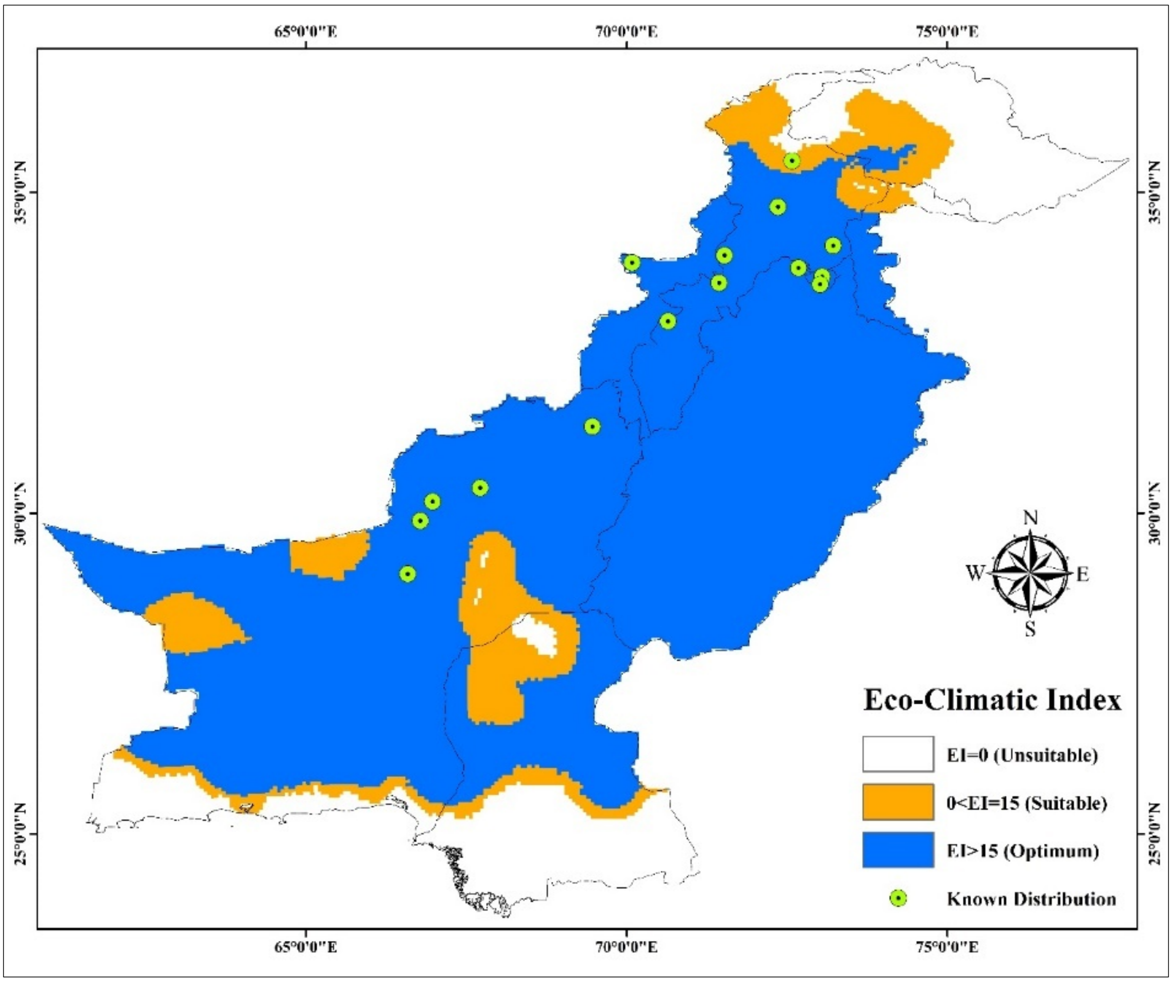

Figure 2. Potential distribution of *Aeolesthes sarta* in Pakistan under historic climatic conditions. Blue color indicates optimum habitat (EI > 15), orange color indicates suitable habitat (0 < EI = 15), white color indicates unsuitable habitat (EI = 0), and green circles indicate the current known distribution of *A. sarta* in Pakistan.

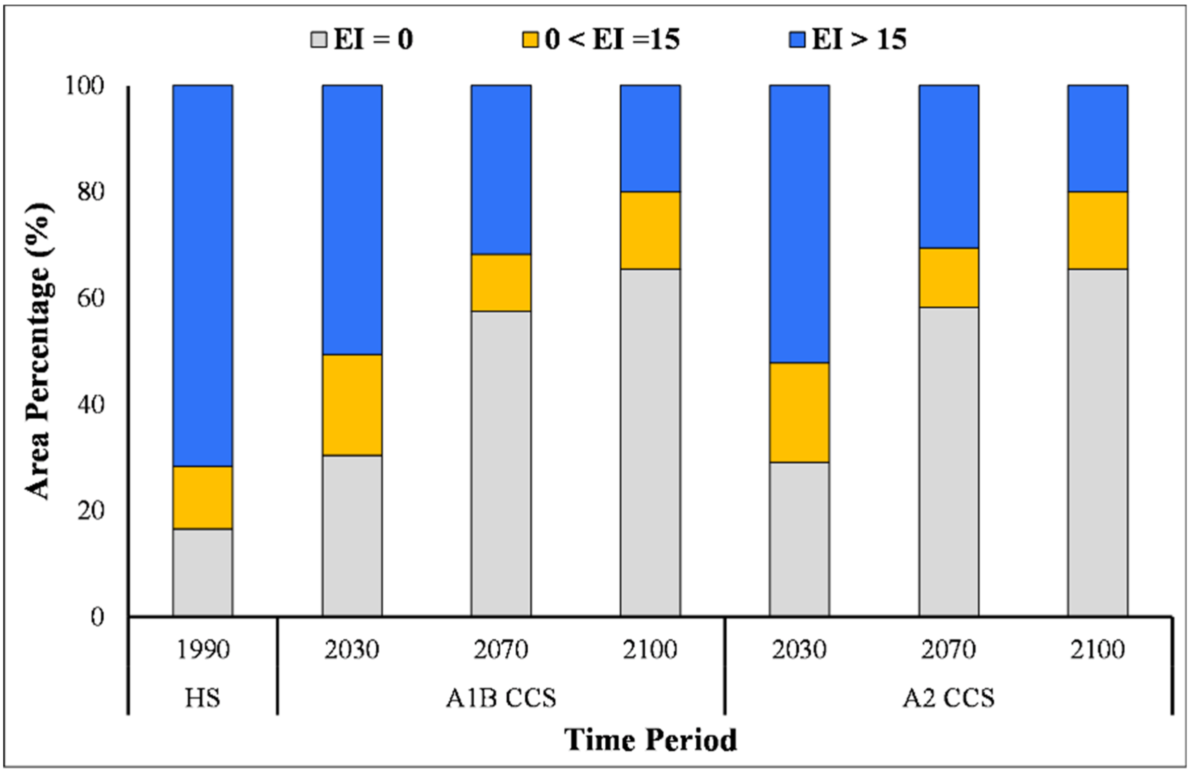

Figure 3. The global land area percentage of *Aelosthes sarta* within the three ecoclimatic index ranges under the historic and future climatic conditions under A1B and A2 climate change scenarios. Optimum habitat (EI > 15); suitable habitat (0 < EI = 15); and unsuitable habitat (EI = 0). HS = historic; CSS = climate change scenario.

3.2. Potential Distribution of A. sarta in Pakistan under Future Climatic Condition (FCC)

Under the future climatic condition (FCC), the model projected a gradual upsurge in the suitable habitat for *A. sarta* development areas for the early-century period (Figures 3 and 4). The unsuitable areas' percentage increased compared with HCC. Under A1B and A2 CCSs for the early-century period, the optimum habitat area for *A. sarta* development decreased to 50.60% (4.44 HT Km^2) and 52.22% (4.58 HT Km^2) compared with HCC 71.67% (6.28 HT Km^2), while the suitable habitat area increased to 19.02% (1.67 HT Km^2) and 18.71% (1.64 HT Km^2) compared with HCC 11.76% (1.03 HT Km^2). The unsuitable habitat area increased to 30.38% (2.66 HT Km^2) and 29.08% (2.55 HT Km^2) compared with historic climatic conditions and 16.57% (1.45 HT Km^2), respectively.

For the late-century period under A1B and A2 CCSs, the optimum habitat area for *A. sarta* development further decreased to 31.76% (2.78 HT Km^2) and 30.60% (2.68 HT Km^2) compared with historic climatic conditions, 71.67% (6.28 HT Km^2). In comparison, the suitable habitat area also decreased to 10.73% (0.94 HT Km^2) and 11.13% (0.98 HT Km^2) compared with HCC 11.76% (1.03 HT Km^2), and the unsuitable habitat area further increased to 57.51% (5.04 HT Km^2) and 58.26% (5.11 HT Km^2) compared with the historic climatic conditions of 16.57% (1.45 HT Km^2), respectively.

However, during the end-century period, the optimum habitat area for *A. sarta* development further decreased to 19.99% (1.75 HT Km^2) under A1B and A2 CCSs compared with HCC 71.67% (6.28 HT Km^2); the suitable habitat area increased to 14.60% (1.28 HT Km^2) under A1B and A2 CCSs compared with the late-century period but decreased compared with HCC 11.76% (1.03 HT Km^2); and the unsuitable habitat area further increased to 65.41% (5.74 HT Km^2) under A1B and A2 CCSs compared with HCC 16.57% (1.45 HT Km^2), respectively.

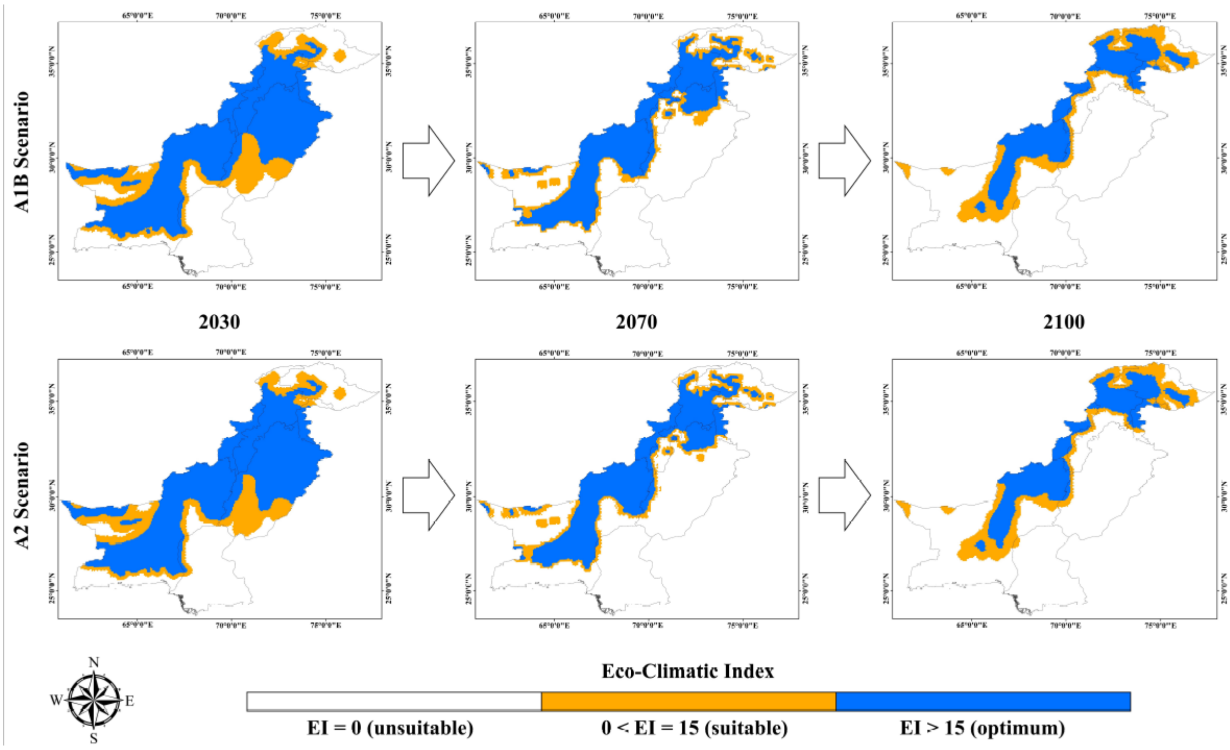

Figure 4. Forecast potential distribution of *Aelosthes sarta* in Pakistan under future climatic conditions for time periods of 2030, 2070, and 2100 under A1B and A2 climate change scenarios. The projected global distributions (three colors) narrate the ecoclimatic index (EI) from the CLIMEX model: blue →optimum (EI > 15); orange →suitable (0 < EI = 15), and white →unsuitable (EI = 0).

3.3. Administrative Area-Wise Distribution under Historic and Future Climatic Conditions

The optimum habitat area distribution was forecasted to decrease in five administrative areas except for GB (Table 2; Figure 5).

In Punjab (PB), 100% (20.63 TT Km^2) of the area under HCC was optimum for *A. sarta* development, but this trend decreased under FCC. In the early-century period, optimum habitat area decreased to 64.69% (13.34 TT Km^2) and 68.78% (14.18 TT Km^2) under A1B and A2 CCSs. In the late-century period, optimum habitat area decreased to 14.71% (3.03 TT Km^2) and 13.07% (2.69 TT Km^2) under both CCSs, and in the end-century period, the optimum habitat area further decreased to 1.29% (0.27 TT Km^2), whereas the unsuitable habitat area increased to 95.88% (19.77 TT Km^2) under both CCSs.

In Khyber Pakhtunkhwa (KPK) under HCC, 78.23% (7.85 TT Km^2) of the area comprised optimum habitat, and suitable habitat area accounted for 15.60% (1.57 TT Km^2). In the early-century period, the optimum habitat area shrunk to 78.79% (8.01 TT Km^2) and 79.99% (8.03 TT Km^2); in the late-century period, the optimum habitat area further reduced to 67.57% (6.78 TT Km^2) and 66.18% (6.64 TT Km^2) and in the end-century period, the optimum habitat area further reduced to 51.18% (5.14 TT Km^2) under both CCSs. However, suitable habitats decreased in the early and late centuries but increased in the end-century period to 27.73% (2.28 TT Km^2) under both CSSs.

In Azad Jammu and Kashmir (AJK), under HCC, optimum and suitable habitat areas comprise 67.48% (0.93 TT Km^2) and 13.35% (0.18 TT Km^2). In the early-century period, the optimum habitat area increased to 68.93% (0.95 TT Km^2) and 68.45% (0.94 TT Km^2), and suitable habitat decreased to 12.62% (0.17 TT Km^2) and 12.38% (0.17 TT Km^2) under both CCSs. However, in the late- and end-century periods, the optimum habitat decreased, and suitable habitat increased under both CCSs.

In Balochistan (BLC), for the early-century period, optimum habitat area reduced to 60.94% (20.91 TT Km^2) and 62.58% (21.47 TT Km^2), while the suitable habitat area increased to 21.07% (7.23 TT Km^2) and 20.99% (7.20 TT Km^2) under both CCSs compared with HCC 80.58% (27.65 TT Km^2) and 12.45% (4.27 TT Km^2). However, in the late- and end-century periods, optimum and suitable habitats decreased under both CCSs. In the end-century period, optimum habitat covers 25.55% (8.77 TT Km^2) while suitable habitat covers 18.65% (6.4 TT Km^2) tunder both CCSs.

In Sindh (SD), under HCC, the optimum and suitable habitat areas covered 37.35% (5.21 TT Km^2) and 19.47% (2.71 TT Km^2). In the early, late, and end centuries, optimum and suitable habitat areas were reduced to the minimum, while unsuitable habitat areas increased to the maximum under both CCSs.

In Gilgit Baltistan (GB) under HCC, optimum and suitable habitat areas covered 3.53% (0.24 TT Km^2) and 22.48% (1.53 TT Km^2). In the early-century period, optimum habitat area increased to 7.95% (0.54 TT Km^2) and 7.51% (0.51 TT Km^2), while suitable habitat also increased to 23.47% (1.59 TT Km^2) and 23.66% (1.61 TT Km^2) under both CCSs. However, in the late and end centuries, optimum and suitable habitat areas gradually increased with a decrease in unsuitable areas. At the end of the century, the optimum habitat area increased to 36.03% (2.45 TT Km^2) under both CCSs.

Based on the assessment of the model's findings, predictive maps on a regional basis of Pakistan show that the potential climate zone for *A. sarta* is confined in different areas by cold and heat stress (Figure 6). The northern region, such as the GB potential climatic zone boundaries, is restricted by cold stress under historic and early-century climatic conditions, which reduce under FCC at the end of the century. In contrast, the potential climatic zone limits of the southern, central, and eastern regions such as SD, PB, and south BLC are constrained by heat stress. However, the cold stress severity decreased under A1B and A2 CCSs, whereas heat stress increased over time.

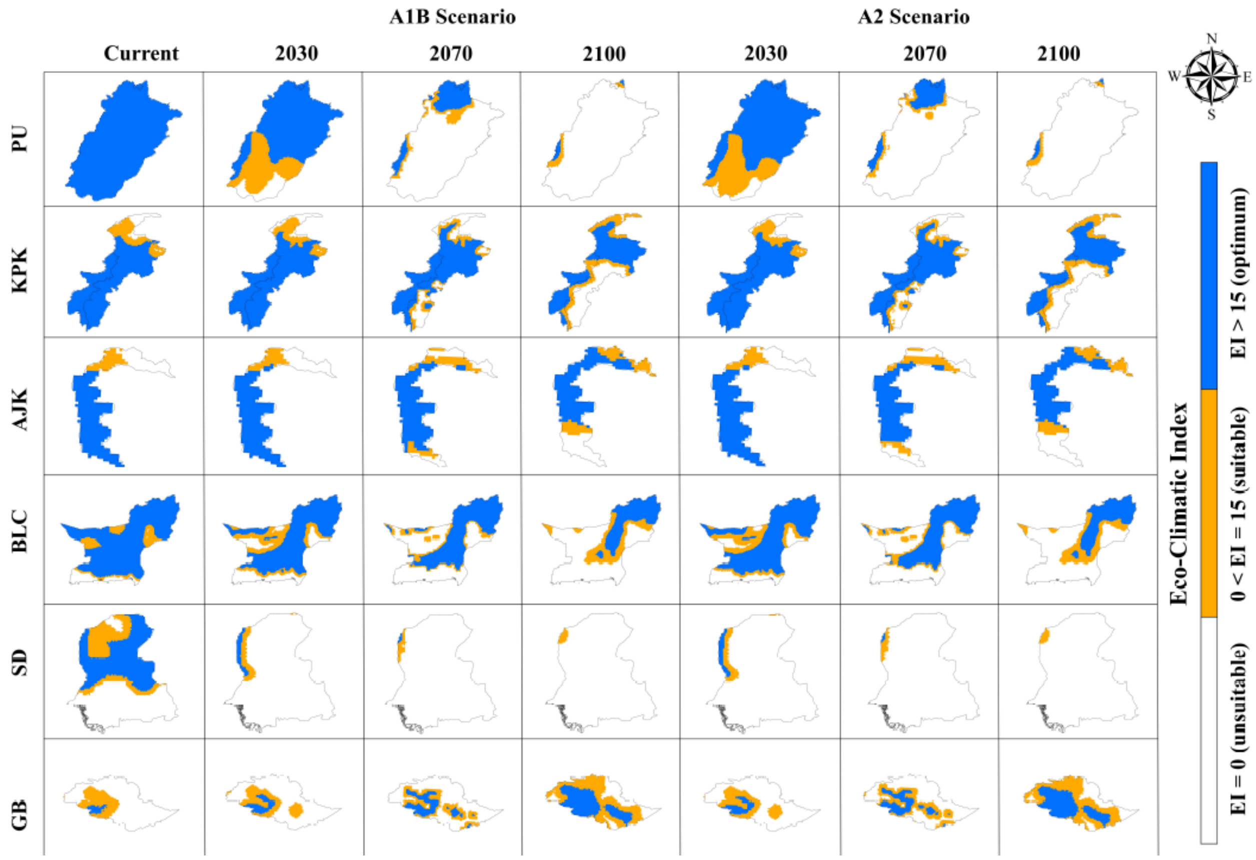

Figure 5. Predicted administrative area-wise potential distribution of *Aelosthes sarta* in Pakistan under historic and future climatic conditions in the time periods of 2030, 2070, and 2100 under A1B and A2 scenarios. Predicted regional distributions (three colors) narrate the ecoclimatic index (EI) from the CLIMEX model: blue = optimum habitat (EI > 15); orange = suitable habitat (0 < EI = 15); white = unsuitable habitat (EI = 0). PB = Punjab; KPK = Khyber Pakhtunkhwa; AJK = Azad Jammu and Kashmir; BLC = Balochistan; SD = Sindh; GB = Gilgit Baltistan.

Table 2. Administrative area-wise land area percentage of *Aelosthes sarta* within the three ecoclimatic index ranges under the historic and future climatic conditions under A1B and A2 scenarios.

Location	Area (10,000 Km^2)														
	EI = 0					0 < EI = 15					EI > 15				
	1990		2030	2070	2100	1990		2030	2070	2100	1990		2030	2070	2100
PB	0	A1B scenario	1.70	15.98	19.77	0	A1B scenario	5.59	1.61	0.58	20.62	A1B scenario	13.34	3.03	0.27
KPK	0.62		0.58	1.76	2.61	1.57		1.45	1.50	2.28	7.85		8.01	6.78	5.14
AJK	0.26		0.25	0.25	0.28	0.18		0.17	0.28	0.30	0.93		0.95	0.85	0.78
BLC	2.39		6.18	14.41	19.15	4.27		7.23	4.07	6.39	27.65		20.91	15.83	8.77
SD	5.99		12.95	13.63	13.74	2.71		0.61	0.24	0.17	5.21		0.35	0.04	0
GB	5.02		4.65	3.96	1.37	1.53		1.59	1.69	2.97	0.24		0.54	1.14	2.45
PB	0	A2 scenario	0.98	16.56	19.77	0	A2 scenario	5.46	1.37	0.58	20.62	A2 scenario	14.18	2.69	0.27
KPK	0.62		0.69	1.78	2.62	1.57		1.32	1.62	2.28	7.85		8.03	6.64	5.14
AJK	0.26		0.26	0.30	0.28	0.18		0.17	0.28	0.31	0.93		0.94	0.80	0.78
BLC	2.39		5.64	14.64	19.15	4.27		7.20	4.36	6.40	27.65		21.47	15.32	8.77
SD	5.99		12.94	13.61	13.74	2.71		0.60	0.27	0.17	5.21		0.37	0.04	0
GB	5.02		4.67	3.77	1.37	1.53		1.61	1.84	2.97	0.24		0.51	1.18	2.45

EI = ecoclimatic index; PB = Punjab; KPK = Khyber Pakhtunkhwa; AJK = Azad Jammu and Kashmir; BLC = Balochistan; SD = Sindh; GB = Gilgit Baltistan.

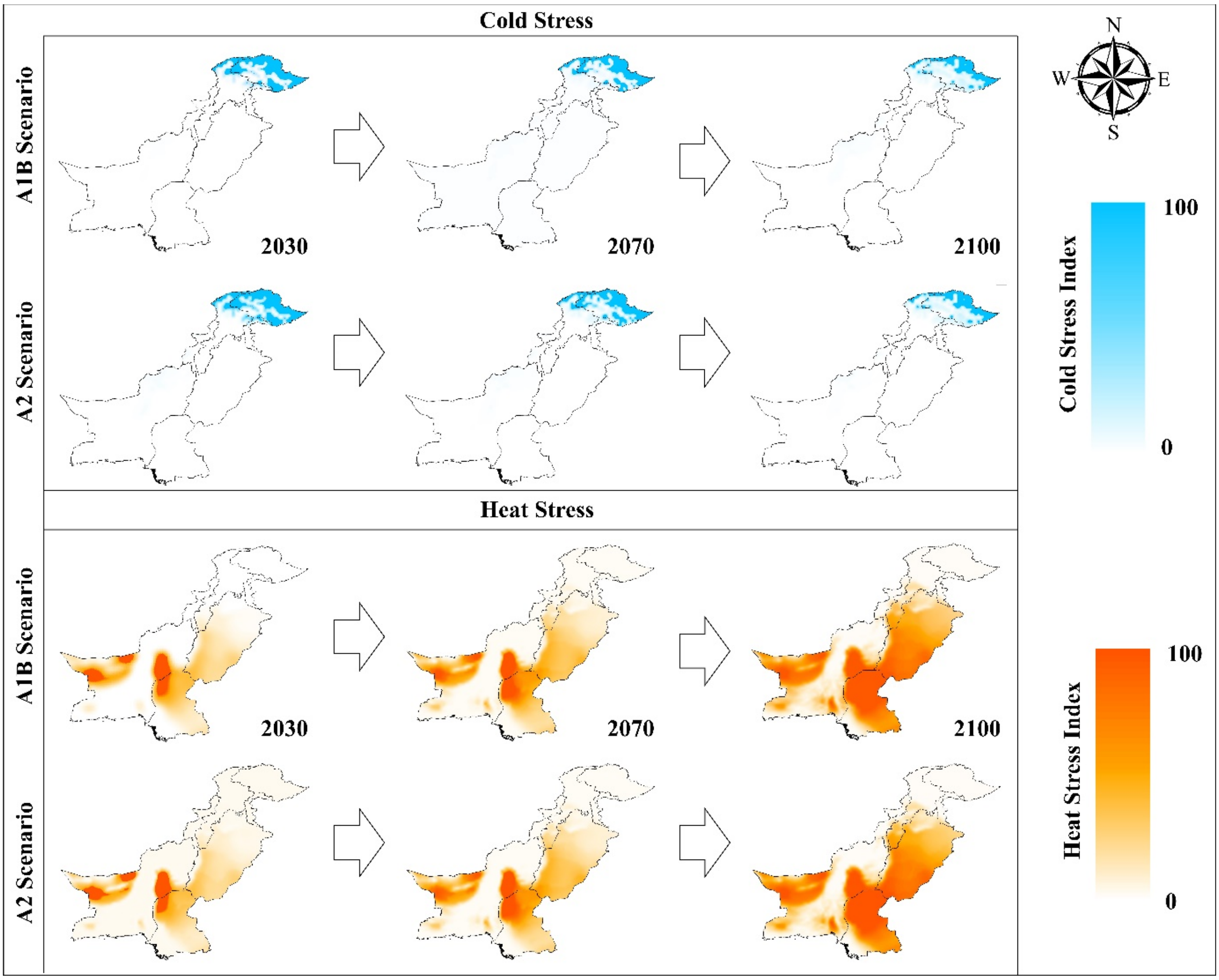

Figure 6. The predicted region in Pakistan where *Aelosthes sarta* survival is affected by cold and heat stress for different periods under the scenarios of A1B and A2 climate change.

4. Discussion

We aimed to provide a robust method for investigating the geographical distribution of *A. sarta* in Pakistan under the historic and future climates using CLIMEX. The results of this study demonstrated that, compared with the historic climate, future climatic conditions under A1B and A2 CCSs strongly influence the distribution pattern of *A. sarta* in Pakistan.

The habitat range of many species is significantly impacted by climate change, particularly cold-blooded species such as insects [41]. With the improvement of tools and techniques for climate modeling, it is now convenient to forecast the geographical range of a specified pest species under projected climate conditions, making timely monitoring and management strategies even more feasible [32,42]. CLIMEX can simulate a species' seasonal environmental adaptability [43] and numerous insect species' habitats have been predicted using it [15,43,44]. The notion that *A. sarta* exhibits polyphagous traits and has wreaked havoc on the plantations and forests in its native environment [7] suggests that it has the potential to damage trees seriously. As a result, we forecasted its possible distribution in Pakistan under the historic and future A1B and A2 climatic scenarios. All the cities in Pakistan where the distribution of *A. sarta* is documented fall within our projected range, demonstrating our model's accuracy.

Our CLIMEX models predicted that most of the regions in Pakistan, such as PB (EI > 15 = 100%), KPK (EI > 15 = 78.23), AJK (EI > 15 = 67.48%), BLC (EI > 15 = 80.58%), and SD (EI > 15 = 37.58%) under HCC were optimum for *A. sarta* development; the models also forecasted reduced development of the species at the end-century period under A1B and A2 CCSs. With some variations in climate change scenarios, the suitable regions predicted to be suitable under HCC would become unsuitable by the end of the century. The variations in the expected regions are caused by their various GHG emission scenarios [45]. Numerous researchers have stated that global warming will affect the possible insect/pest dispersion pattern [15,42–44].

Model predictions revealed that at the end-century period, the optimum habitat area reduced to northwest BLC, northwest KPK, central AJK, and eastern GB areas. Areas within the current known distribution of *A. sarta* are likely to remain in optimum habitat range for its development under FCC.

CLB is a diapause species [7]; adults undergo a suspended development phase during cold winter and require optimum temperatures such as 20 °C [46] to break dormancy and come out from the pupal chamber in spring [9,21]; therefore, its growth and mobility, as well as its dispersal, can be impacted by temperature.

We observed the shift of EI values from eastern to western regions and southern to northern regions of Pakistan. Central, eastern, and southern regions of Pakistan mainly comprise plain areas with dominancy of agricultural lands, while western and northern regions comprise hills and mountain ranges reaching up to 6600 m msl [15]. Moreover, due to the diversity of elevation, the surface temperatures of the central, eastern, and southern regions are higher than the western and northern mountain ranges. Almost 86% of natural forests in Pakistan are present in the country's northern regions (AJK, GB, and KPK) [47], with a diverse distribution of *A. sarta* preferred host tree species such as *Juglans* spp., *Malus* spp., *Platanus* spp., *Populus* spp., *Prunus* spp., *Pyrus* spp., *Salix* spp., *Ulmus* spp. [7,18,21,22,31], and *Quercus* spp. [7,48]. Therefore, the availability of preferred host species and suitable environmental conditions (temperature and elevation) makes these regions optimum for *A. sarta* development.

Pakistan is a region that is highly susceptible to climate change [49]. The optimum temperature range for *A. sarta* survival is between 10 and 40 °C. As a result, the temperature changes and generally higher temperatures in central and southern Pakistan would not be conducive to *A. sarta* habitation, which would probably cause a shift in the *A. sarta* distribution under FCC. Furthermore, the development of *A. sarta* in the PB, SD, and south BLC was observed to be constrained by increasing heat stress at the end of the 21st century period, but the GB region became more suitable due to a potential decline in cold stress (Figure 6). In addition, these regions have semi-arid to dry climates, making them more sensitive to climate change than Pakistan's northern region because even slight temperature changes can result in high heat in such climates. Over the past 50 years, extreme temperature variations and increased frequency of heavy rainstorms have been seen globally [39]. The frequency of cold days, cold nights, and frost occurrences has also decreased owing to changes in the climate, while the frequency of hot days/nights and heat waves has climbed [50,51].

The CLIMEX model predictions are mainly based on climatic variables, although non-climatic variables such as biological linkages, genetic evolution, visual barriers, and human activities might impact studies of species dispersion [52]. Recent research suggests invasive pest range changes under future climates may be predicted using genetic variation and climatic models [53]. The impact of non-climatic variables on the potential spread of *A. sarta* will be further investigated with the conception and advancement of species distribution models. In the following research, we will continue investigating *A. sarta* distribution in Pakistan, analyze the precise impacts of changes in the *A. sarta* external environment on its biological characteristics, and set up a method for evaluating model performance.

According to the study's model, in the next 78 years, most of Pakistan's western and northern regions will be a potentially suitable distribution area for *A. sarta*. Since the commencement of the 21st century, cultivation of trees on farmland and woodland in northern Pakistan has amplified considerably and has been utilized in furniture, wood, and sawmill industries and shipped to other parts of the country to fulfil the demand for timber and fuelwood. Additionally, *A. sarta* spends its egg, larvae, pupae, and young adult stages inside a tree trunk [7], so it easily spreads in the host for a long time. If efficient control measures are not implemented, *A. sarta* will continue to expand in Pakistan. *A. sarta* advanced surveillance and early warning technology can precisely predict its temporal dynamics and provide a firm assurance for halting it from spreading and causing more damage.

Once a tree is detected to be infected by *A. sarta,* it is recommended to fall and burn the contaminated tree [18,54]. Furthermore, it is recommended to follow sanitary/phytosanitary procedures before using the wood for trading, such as stem debarking and kiln drying [48]. Biological control techniques can be more economical, practical, ecologically safe, and long lasting [55]; therefore, we highly recommend the use of biological control agents such as the use of click beetle *Alaus* larvae (a predator of *A. sarta* grubs) [22], *Proctolaelaps* spp. (Acarina) (a predator of *A. sarta* grubs) [22], parasitoid *Sclerodermus turkmenicus* (a parasite of *A. sarta* larvae) [56], and *Beauveria bassiana* white muscardine fungus (a parasite of *A. sarta* adults) [18,56,57]. All these are very effective biological agents in stem borer control. We highly advise avoiding excessive chemical use for *A. sarta* control as these are not environmentally friendly and costly [5,58].

5. Conclusions

In this model-based research study, the CLIMEX model was used, which is the first study of its kind, leveraging accurate parametric variables to forecast the probable distribution of *A. sarta* in Pakistan under historic and future climatic conditions (A1B and A2 climate change scenarios). This work illustrated a helpful technique for mapping *A. sarta* habitat adaptability. The results show that in the next 78 years, most of Pakistan's western and northern regions will be potential distribution areas for *A. sarta*. With the warming of the climate, the optimum habitats are mainly located in the western and northern parts of Pakistan, while the central, eastern, and southern parts of Pakistan appear likely to become unsuitable areas. Four of the six administrative areas will remain the optimum habitat under FCC, such as BLC, KPK, AJK, and GB. To avoid the further spread of *A. sarta* in Pakistan and to guarantee the forest's security and the forest industry, Pakistan should continue to undertake stringent monitoring, preventive, and control measures.

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Abbreviations

CCS	Climate change scenario
HCC	Historic climatic condition
FCC	Future climatic condition

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