Variation in the potential distribution of *Agrotis ipsilon* (Hufnagel) globally and in Pakistan under current and future climatic conditions

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Abstract: *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae) is a polyphagous moth species that mainly damages various crops and ornamental plants. This widely distributed pest is particularly a nuisance in Pakistan where it damages many crops, e.g., wheat and vegetables. To assess the risk of damage by this moth, we used the CLIMEX model to predict the distribution of *A. ipsilon* under current and future climatic conditions. Using the literature data, we collected information on the biology and ecology of *A. ipsilon* relevant for modelling the distribution of this species in Pakistan and worldwide under current and future climatic conditions. Our results revealed that under future climatic scenarios, the highly favourable habitat area of *A. ipsilon* (ecoclimatic index EI > 30) would decrease globally from 19% at present to 14% in the future, and the moderately favourable habitat area (0 < EI ≤ 15) would increase from 21 to 29%. We found that the northern areas of Pakistan will become highly suitable for the establishment of *A. ipsilon*. Under the current climatic conditions, the optimal habitats of *A. ipsilon* (EI > 30) comprised 10% and moderately favourable habitats (EI < 17) accounted for 25% of the total land area in Pakistan. Under future climatic scenarios, the optimal habitat area of the moth in Pakistan could decrease to 5% and the moderately favourable habitat area could cover 63% of the entire land area. The results can be applied in the protection of various crops and ornamental plants against *A. ipsilon* in Pakistan as well as worldwide.

Keywords: black cutworm; CLIMEX model; climate change; current distribution; potential distribution; prediction

The black cutworm, *Agrotis ipsilon* (Hufnagel), is a globally distributed pest species belonging to the Noctuidae (Lepidoptera) family (Rings et al. 1975). It is a non-diapausing species (Clement et al. 1985; Beck 1986) with a life-cycle of 35–60 days (Capinera 2009). This polyphagous species (Shakur et al. 2007) feeds on most vegetable and grain crops (Capinera 2009). Bajwa and Gul (2000) identified *A. ipsilon* as an insect pest of *Paulownia* spp. *Agrotis ipsilon* is particularly widespread in Pakistan (CIE 1969) where it

damages many vegetable crops, including the ornamental tobacco, potatoes, tomatoes, bottle gourds, lady's fingers (okra), cabbages, sugar beets, turnips, and grams (chickpeas) (Shakur et al. 2007) as well as wheat (Hashmi et al. 1983). In the northern province of Pakistan, the larvae of the genus *Agrotis* (family Noctuidae) are very active insect pests of tobacco, okras, tomatoes, and other cultivated plants, including forest tree seedlings (Zethner et al. 1987), and they also damage potato crops (Shakur et al. 2007).

In the past, numerous studies have investigated attacks by *A. ipsilon* on wheat (Hashmi et al. 1983). Other studies have focused on the effectiveness of various insecticides (Shakur et al. 2007) as well as a solitary endoparasitoid *Microplitis mediator* (Haliday) (Hymenoptera) as a biological control agent of *A. ipsilon* (Khan 1999). Furthermore, the *Agrotis segetum* granulosis virus has been utilised as a biocontrol agent of *A. ipsilon* in various vegetable crops and tobacco seedlings (Zethner et al. 1987).

Insects are likely to adapt efficiently to climate change because they are ectotherms with limited life-cycles with a large variance in the size of the population over time and space (Bale et al. 2002). Extensively dispersing generalists like many pests will also be able to extend their range speedily relative to more sedentary or habitat-specific species (Pöyry et al. 2009). As most of the Lepidoptera species included in the Bern Convention have special habitat requirements and, thus, sparse habitat ranges, the rest will probably be able to traverse regions that become climate-friendly (Menéndez et al. 2006).

Many continents, including North and South America, Australia, and Europe (Senaratne et al. 2006; Yonow et al. 2013) have used predictive modelling to get acquainted with changes in the distribution of pest species to mitigate their negative effects on agricultural crops. For example, the CLIMEX software (version 3.0) has been used to predict the distribution and dispersion of various species by integrating information on the habitat of a target species as well as climatic factors such as the temperature, rainfall, and humidity in certain area (Sutherst et al. 2007). In general, the CLIMEX modelling system involves the accumulation of information which restricts to the geographical distribution of a target species and subsequently predicts its probable geographic dispersal and seasonal richness in response to the climate change (Sutherst et al. 2007).

Although there are many studies on the morphology, physiology and control of *A. ipsilon*, the potential distribution of this species under future climatic scenarios has yet to be investigated. Herein, we hypothesised that a future climate change would alter the distribution of *A. ipsilon* and the area that suits this pest on a global scale. We (*i*) investigated the potential distribution of *A. ipsilon* in Pakistan using the CLIMEX model and evaluated high-risk areas for *A. ipsilon* invasion; (*ii*) determined the susceptibility of various areas in Pakistan and worldwide to an attack by *A. ipsilon* and the establishment of the moth under current and future climates; and (*iii*) provided information on the future susceptibility of areas to the *A. ipsilon* establishment and attack worldwide.

MATERIAL AND METHODS

Experimental layout. Different parameters were taken into consideration such as information on the biology and ecology of *A. ipsilon* (lower and upper threshold temperature, optimum temperature, lower, upper and optimum moisture level), the meteorological data (minimum and maximum monthly temperature; monthly rainfall; relative humidity at 9 am and 3 pm) and a selection of representative sites to run the CLIMEX model and calculate the ecoclimatic index (EI) for the prediction of the climatic suitability of particular areas for *A. ipsilon*.

Climate data collection. Various meteorological data were collected and used for predicting the potential distribution of *A. ipsilon*, including the minimum monthly temperature, maximum temperature, precipitation, and relative humidity at 9 am and 3 pm. These data were obtained from various sources such as "CRU TS v. 4.03" (Harris et al. 2014), "Clim_cru_1987-2016" and "Clim_cmip5_rcp45_ensemble_2071-2100" (Kriticos et al. 2012, 2014) (https://www.climond.org), and used for the model predictions. Following the data collection, the values were adjusted and incorporated into the CLIMEX modelling software. Thereafter, we selected, in total, forty-four target locations in Pakistan representative of the following seven administrative areas: Gilgiit Baltistan (GB), Azad Jammu and Kashmir (AJK), Federal Administrative Tribal Areas (FATA), Khaber Pakthoonkhwa (KPK), Punjab (PJB), Sindh (SDH), Balochistan (BLCH) (Table S1 in Electronic Supplementary Material). The meteorological data from these areas were used in the CLIMEX model to predict the habitat suitability for *A. ipsilon*.

The climatic characteristics used in the CLIMEX model, which govern the potential distributions of the species, are closely related to the altitude, as it is associated with the temperature and operative accumulated temperature. To reduce errors in projecting the distributions of *A. ipsilon*, we obtained climatic data (minimum and maximum temperature, precipitation, and relative humidity at 9 am and 3 pm) in Pakistan that were interpolated at 0.5 °C using the altitude of a region to obtain high-resolution climate data, thereby avoiding the influence of the altitude on the obtained ecoclimatic index (EI) values.

Determining the known distribution of *A. Ipsilon.* The current distribution of *A. ipsilon* in Pakistan was determined through the literature review using previously reported data on the damage and control measures for *A. ipsilon* (CIE 1969; Hashmi et al. 1983; Shakur et al. 2007). According to this review, *A. ipsilon* mostly occurs within the northern areas of Pakistan.

CLIMEX model. The CLIMEX software has two primary applications: "compare locations" and "compare years" (Sutherst et al. 2007). The "compare locations" application predicts the potential geographical dispersal of a species under climate change scenarios, whereas the "compare years" application shows the response of a species to successive years of monthly climate change within the same location (Sutherst & Maywald 2005; Sutherst et al. 2007). The CLIMEX model results are characterised by the EI which indicates the survival and growth of a species in many different sites. The EI value ranges from 0–100 and is calculated by multiplying the growth index (GI), stress index (SI), and interaction stress index (SX). The GI describes the potential population growth during a favourable season, whereas the SI represents the extent of the population reduction during an unfavourable season. The GI constitutes seven indices (temperature, moisture, radiation, substrate, diapause, light, and biotic index), whereas the SI is characterised according to four environmental stresses, namely: cold stress (CS), heat stress (HS), dry stress (DS), and wet stress (WS) (Sutherst et al. 2007). In the current study, we only evaluated one species (*A. ipsilon*) in response to the climate in Pakistan, and thus utilised the "compare location (1 species)" application of the CLIMEX software.

Temperature index. The temperature index (TI) is a parameterised form of temperature-related data. It includes four parameters, namely the lower temperature threshold (DV_0), lower optimum temperature (DV_1), upper optimum temperature (DV_2), and upper threshold temperature (DV_3) (Sutherst et al. 2007). The parameters DV_1 and DV_2 indicate the optimal temperature range for rapid insect growth and development, whereas the parameters DV_0 and DV_3 indicate the minimum and maximum temperature range below or above which the species survival is difficult. The population degree day (PDD) values indicate the daily degree requirements for an entire generation of a particular species to complete its life stages above DV_0.

Through the literature review, we gathered further parameters on *A. ipsilon* and used them in the CLIMEX model. The population degree days required for *A. ipsilon* generation were 575.3 (Dahi et al. 2009). We set DV_0 to 8 °C because this temperature appeared to be the lower threshold temperature for the pupal and larval developmental stages (Beck 1986). DV_3 was set to 34 °C as an upper threshold temperature because most females failed to lay eggs at this temperature (Archer et al. 1980). Finally, DV_1 and DV_2 were set to 17 °C and 27 °C, respectively. Regarding DV_2, the emperature 27 °C was selected as it was previously described as an optimal temperature for the larval development of *A. ipsilon* (Archer et al. 1980).

Moisture index. The soil moisture index (MI) is another parameter of the CLIMEX model, as it is indicative of the precipitation levels. The MI in the CLIMEX model is further categorised according to four parameters, namely: the lower soil moisture threshold (SM_0), lower optimum soil moisture (SM_1), upper optimum soil moisture (SM_2), and upper soil moisture threshold (SM_3) (Sutherst et al. 2007).

Regarding *A. ipsilon*, the soil moisture is critical because it significantly affects its growth and development. Thus, according to the literature review (Archer et al. 1980), we substituted the provided template parameters with the following values that were more relevant to the soil moisture requirements of *A. ipsilon*: SM_0 (0.1), SM_1 (0.5), SM_2 (0.9), and SM_3 (1.8). As *A. ipsilon* mainly attacks agricultural crops (Khan 1999; Maalik et al. 2013), we also included the irrigation pattern scenario in the CLIMEX model (Table 1).

Stress indices. In the CLIMEX modelling system, the SI consists of four environmental stresses (indices) representative of hostile conditions which limit the population development of a species, namely: CS, HS, DS and WS. Each index is represented by the stress threshold and stress rate of a species (Sutherst et al. 2007).

When the temperature drops below the cold stress threshold temperature (TTCS) of a species at a given rate (THCS), the stress begins to limit the growth of a species. In the current study, 0 °C was considered the TTCS for *A. ipsilon* because, below this temperature, its development is hindered (Beck 1988). The THCS was set to –0.0005 based on the TTCS value. Similarly, as the temperature rises above the heat stress temperature threshold (TTHS) of a species at a given rate (THHS), the heat stress begins to negatively impact the species. Bishara (1932)

Table 1. Monthly irrigation scenarios for *Agrotis ipsilon* used in the CLIMEX model

Month	Irrigation (mm/day)	Month	Irrigation (mm/day)
July	2.571	January	0
August	3.571	February	0
September	3.571	March	0
October	0	April	3.571
November	0	May	3.571
December	0	June	2.571

Top-up irrigation: acquired irrigation measurements represent the total water supply to crops, including rainfall; this irrigation pattern is based on the general semi-arid climatic conditions of the region

revealed that *A. ipsilon* did not survive at 36 °C and (Showers 1997) confirmed that 36 °C was the thermal limit for this species. In the current study, we set the TTHS to 36 °C and the THHS to 0.0005.

The dry and wet stresses occur at a given low or high soil moisture. As the soil moisture cascades below the dry stress threshold (SMDS) of a species at a given stress rate (HDS), or exceeds the wet stress threshold (SMWS) of a species at a given stress rate (HWS), the dry and wet stresses accumulate and begin to negatively impact the species. To obtain accurate ecoclimatic index (EI) values, we substituted the template values with those that more accurately reflect the dry and wet stress thresholds and rates of *A. ipsilon* as follows: SMDS (0.05 to 0.06) at HDS (−0.005) and SMWS (0.4 to 1.8) at HWS (0.002) (Table 2).

Table 2. *Agrotis ipsilon* parameter values used in the CLIMEX model

Parameters	Code	Template values	Settled values
Temperature			
Limiting low temperature (°C)	DV_0	10	8
Lower optimal temperature (°C)	DV_1	20	17
Upper optimal temperature (°C)	DV_2	32	27
Limiting high temperature (°C)	DV_3	38	34
Population degree day	PDD	1 100	575.3
Moisture			
Limiting low soil moisture	SM_0	0.1	0.1
Lower optimal soil moisture	SM_1	0.2	0.5
Upper optimal soil moisture	SM_2	0.25	0.9
Limiting high soil moisture	SM_3	0.3	1.8
Cold stress (CS)			
CS temperature threshold	TTCS	0	0
CS temperature rate	THCS	0	−0.0005
CS degree-day threshold	DTCS	15	0
CS degree-day rate	DHCS	−0.002	0
Heat stress (HS)			
HS temperature threshold (°C)	TTHS	39	36
HS temperature rate	THHS	0.002	0.0005
Dry stress (DS)			
DS threshold	SMDS	0.05	0.06
DS rate	HDS	−0.005	−0.005
Wet stress (WS)			
WS threshold	SMWS	0.4	1.8
WS rate	HWS	0.01	0.002

The values were adjusted according to the semi-arid climatic conditions of the study region

Parameter mapping. Our corrected results regarding the parameter values used for the CLIMEX modelling were transferred into GIS software (version 10.7) to visualise several potential distributions of *A. ipsilon* under current and future climatic conditions in Pakistan and worldwide. By using the Spatial Analyst module of ArcMap, we performed variance processing on the potential *A. ipsilon* distributions to produce a continuous surface. Subsequently, the Kriging interpolation method was used to reclassify the data and visualise the potential *A. ipsilon* distributions in Pakistan and globally under the current and future climatic conditions. The same approach was adopted to present the distribution of the eucalyptus gall wasp *Leptocybe invasa* Fisher & LaSalle (Hymenoptera, Chalcidoidea) in China (Huang et al. 2019).

RESULTS

Potential global distribution of *A. ipsilon* under current and future climatic conditions. Figure 1 depicts the predicted potential global distribution of *A. ipsilon* under the current climatic conditions (1987–2016). All the recorded occurrences (Figure 1; blue dots) of *A. ipsilon* were located within the moderately to highly favourable habitats, except one occurrence in Iceland, indicating that the selected parameters in the model were highly suitable with more than 99.5% accuracy. Based on the ecoclimatic index (EI) values, the following four habitat categories were recognised: unfavourable habitat (EI = 0), moderately favourable habitat (0 < EI ≤ 15), favourable habitat (15 < EI ≤ 30), and highly favourable habitat (EI > 30). Under the current climatic conditions, most of the world is suitable for *A. ipsilon* survival, except the poles and other frigid areas, such as northern, eastern, and central Russia, Antarctica, Iceland, Norway, Alaska, most of Canada, and Uzbekistan. Under the current conditions, countries containing highly favourable habitats (EI > 30) include south-eastern USA, Mexico, Chile, Argentina, Uruguay, Paraguay, south-eastern Brazil, Peru, Lesotho, South Africa, Zimbabwe, Madagascar, Tanzania, the Republic of Congo, Zambia, Ethiopia, Yemen, Oman, Israel, southern Saudi Arabia, Egypt, Libya, Morocco, Western Sahara, Portugal, Italy, France, Germany, United Kingdom, south-eastern Iran, north-eastern and southwestern Pakistan, north-eastern India, Myanmar, China, Taiwan, eastern Indonesia, Australia, and New Zealand, comprising
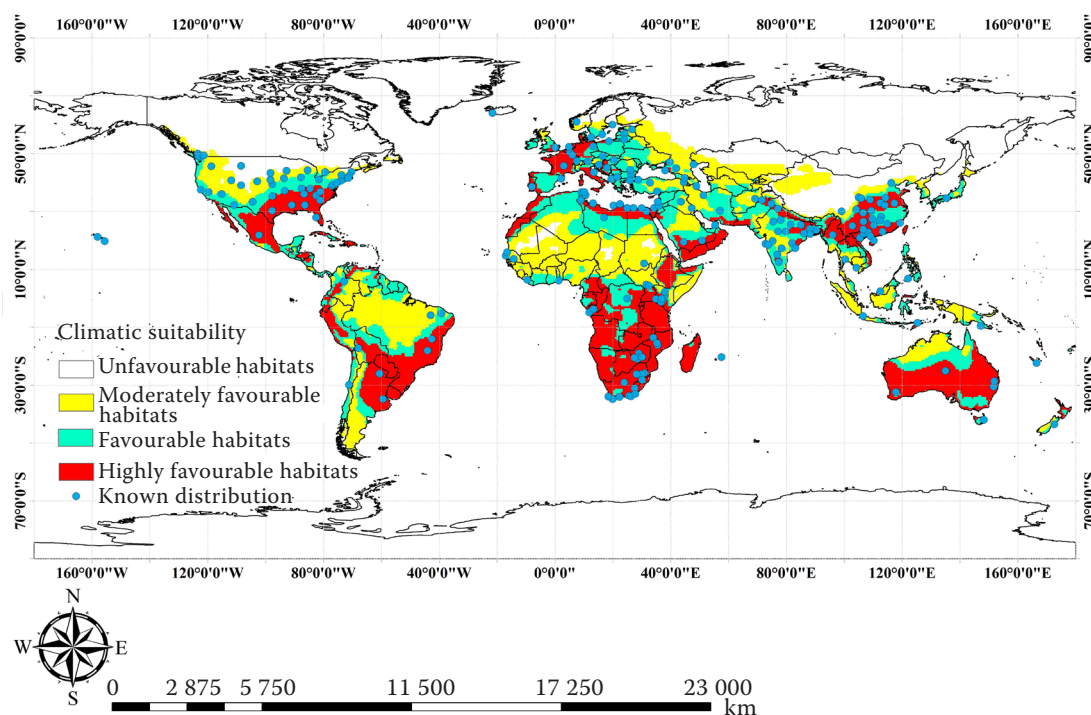

Figure 1. Predicted potential global distribution of *Agrotis ipsilon* under the current climatic conditions (1987–2016)

The predicted global distributions (four colours) relate to the ecoclimatic index (EI) from the CLIMEX model: highly favourable habitats (EI > 30); favourable habitats (15 < EI ≤ 30), moderately favourable habitats (0 < EI ≤ 15), unfavourable habitats (EI = 0); blue dots represent the records of *A. ipsilon* from the Centre for Agriculture and Bioscience International (CABI)

19% of the world. Of this 19%, the highly favourable *A. ipsilon* habitats comprise only 0.7% in Pakistan.

Our results revealed that under future climatic conditions (2070–2100), compared with the current climatic conditions (1987–2016), the highly favourable habitat area of *A. ipsilon* (EI > 30) will be reduced from 19 to 14%, whereas the moderately favourable habitat area (0 < EI ≤ 15) will increase from 21 to 29% globally (Figures 2 and 3). Countries containing highly favourable habitats (EI > 30) under future climatic conditions include south-eastern USA, Mexico, Peru, Bolivia, Argentina, Chile, Uruguay, Paraguay, Brazil, South Africa, Lesotho, Namibia, Angola, Zimbabwe, Mozambique, Tanzania, Zambia, Kenya, Uganda, Madagascar, Yemen, Oman, Ethiopia, Morocco, Western Sahara, Algeria, Libya, Egypt, Israel, Tunisia, Portugal, Spain, Ireland, the United Kingdom, France, Germany, Greece, India, China, Myanmar, Australia, and New Zealand, comprising 14% of the entire world area. Of this 14%, the highly favourable *A. ipsilon* habitats comprise only 0.2% in Pakistan.

Potential distribution of *A. ipsilon* in Pakistan under current and future climatic conditions. Figure 4 illustrates the predicted potential
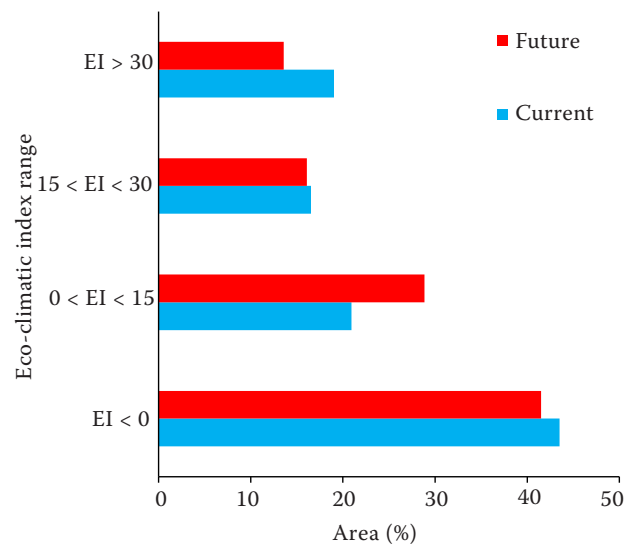

Figure 3. Percent of land area (different habitats of *Agrotis ipsilon*) within the four ranges of the ecoclimatic index under the current and future climatic conditions on a global scale

Highly favourable habitats (EI > 30); favourable habitats (15 < EI ≤ 30); moderately favourable habitats (0 < EI ≤ 15); unfavourable habitats (EI = 0); EI – ecoclimatic index

distribution and known distribution of *A. ipsilon* under the current climatic conditions (1987–2016)
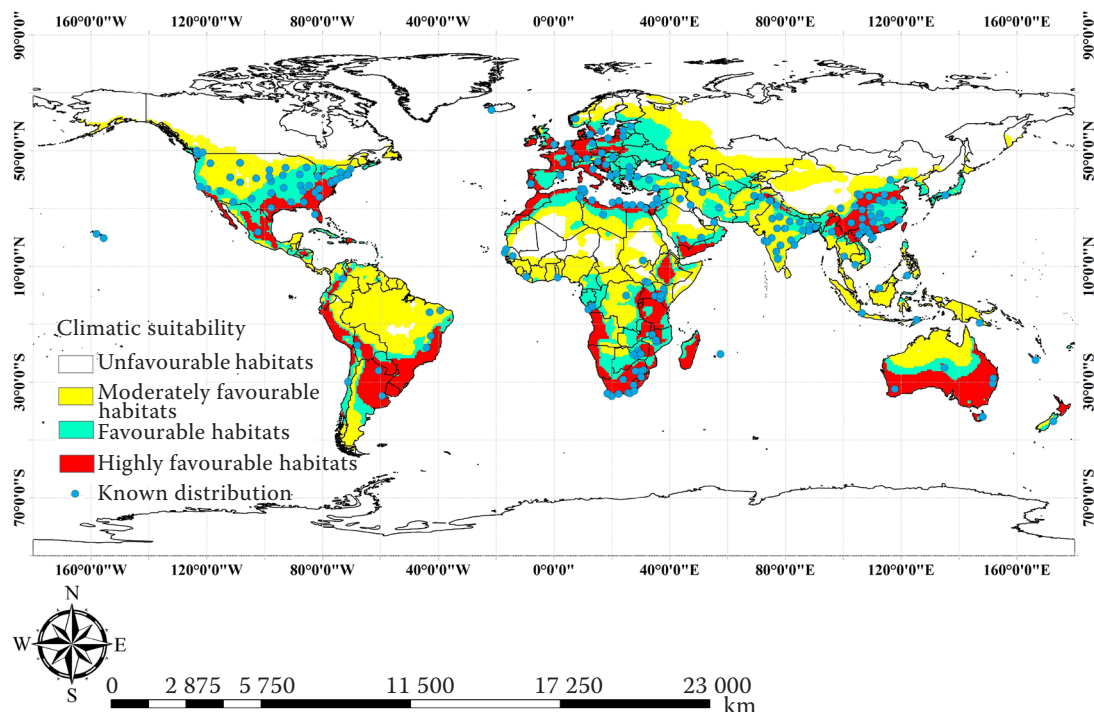

Figure 2. Predicted potential global distribution of *Agrotis ipsilon* under future climatic conditions (2070–2100)

The predicted global distributions (four colours) relate to the ecoclimatic index (EI) from the CLIMEX model: highly favourable habitats (EI > 30); favourable habitats (15 < EI ≤ 30); moderately favourable habitats (0 < EI ≤ 15); unfavourable habitats (EI = 0); the blue dots represent the records of *A. ipsilon* from the Centre for Agriculture and Bioscience International (CABI)
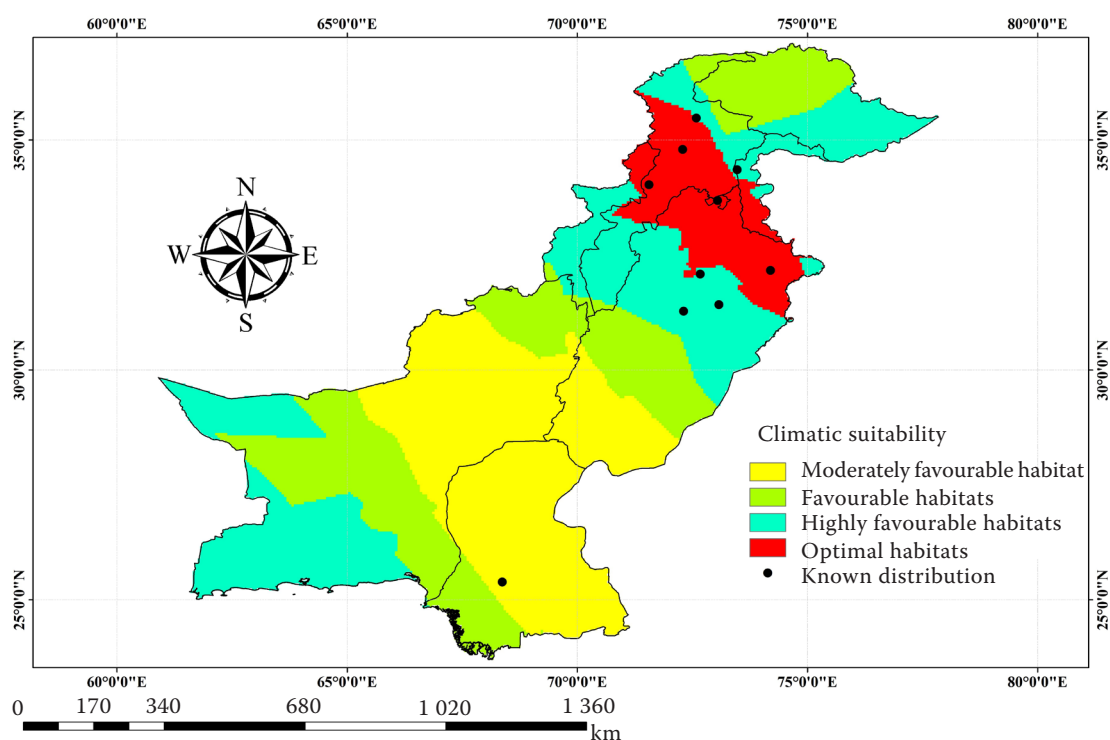
Figure 4. Predicted potential distribution (distinguished by the four colours) and known distribution (black dots) of *Agrotis ipsilon* under the current climatic conditions (1987–2016) in Pakistan

The potential distributions comprise four habitat types further represented by the associated ecoclimatic index (EI) values: optimal habitats (EI >30); highly favourable habitats (25 <EI ≤ 30); favourable habitats (17 < EI ≤ 25); moderately favourable habitats (EI < 17)

in Pakistan. The known distributions of *A. ipsilon* occurred within the optimal (EI > 30) to favourable habitats (17 <EI ≤ 25) (Figure 4). Under future climatic conditions (Figure 6), the percentage area of land with EI values < 17 increased from 25 to 63%, and the percentage area of land with EI > 30, 25 < EI ≤ 30, and 17 <EI ≤ 25 decreased from 10 to 5%, 28 to 9%, and 36 to 23%, respectively, compared with the current climatic conditions (Figure 5).

Under the current climatic conditions, high EI values (> 30), which indicate the optimal habitats for *A. ipsilon*, were recorded in 14 of the 44 analysed target locations in Pakistan, comprising four of the seven administrative areas (KPK, AJK, PJB, FATA). Specifically, in KPK, the EI values > 30 were recorded in Bhatagram, Shangla, Balakot and Tangi, accounting for four of the eight target locations in this administrative area. In AJK, we selected only one target location (Muzafarabad) which had an EI value > 30. In FATA, EI values > 30 were recorded in both target locations, Mohammad Agency and Bara. Lastly, in PJB, we found that five of the twelve
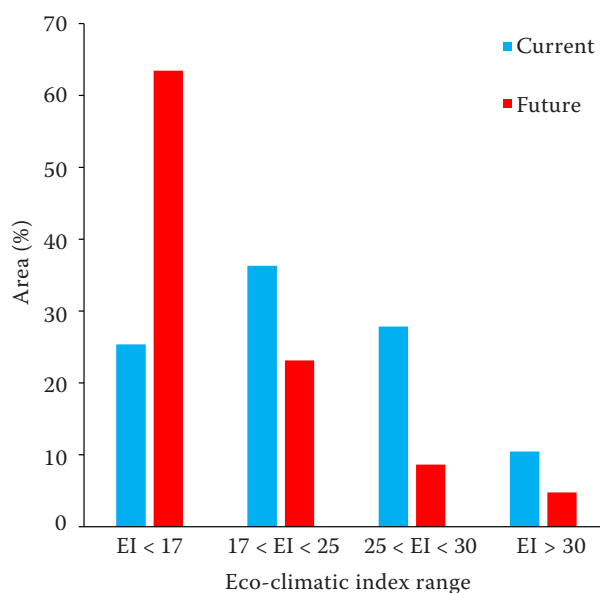

Figure 5. Percent of land area (different habitats of *Agrotis ipsilon*) within the four ranges of ecoclimatic index (EI) under current and future climatic conditions in Pakistan

Optimal habitats (EI > 30); highly favourable habitats (25 < EI ≤ 30); favourable habitats (17 < EI ≤ 25); moderately favourable habitats (EI < 17)
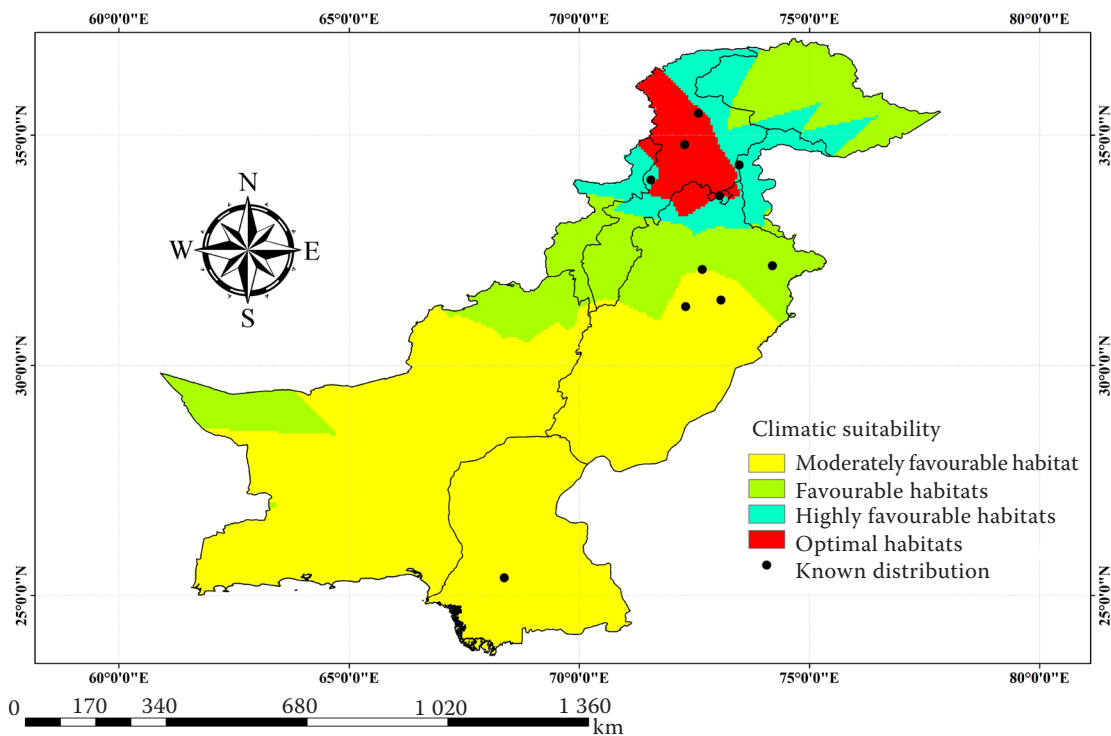
Figure 6. Predicted potential distribution (distinguished by the four colours) and known distribution (black dots) of *Agrotis ipsilon* under future climatic conditions (2070–2100)

The potential distributions comprise four habitat types further represented by the associated ecoclimatic index (EI) values: optimal habitats (EI > 30); highly favourable habitats (25 < EI ≤ 30); favourable habitats (17 < EI ≤ 25); moderately favourable habitats (EI < 17)

target locations had EI values > 30, including Murree, Attock, Daska, Rawalpindi and Lahore. Overall, within the seven administrative areas of Pakistan (GB, AJK, KPK, FATA, PJB, SDH, BLCH), the percentage of land area containing EI values > 30 was 0, 41, 20, 45, 22, 0, and 0%, respectively (Figure 7).

Under future climatic conditions, optimal *A. ipsilon* habitats (EI > 30) occurred in KPK, FATA, and a small portion of PJB, comprising 43, 6, and 3% of total land area, respectively. In KPK, five of the eight target locations had optimal habitats (EI > 30; Balakot, Bhatgram, Shangla, Tangi, and Upper Dir).
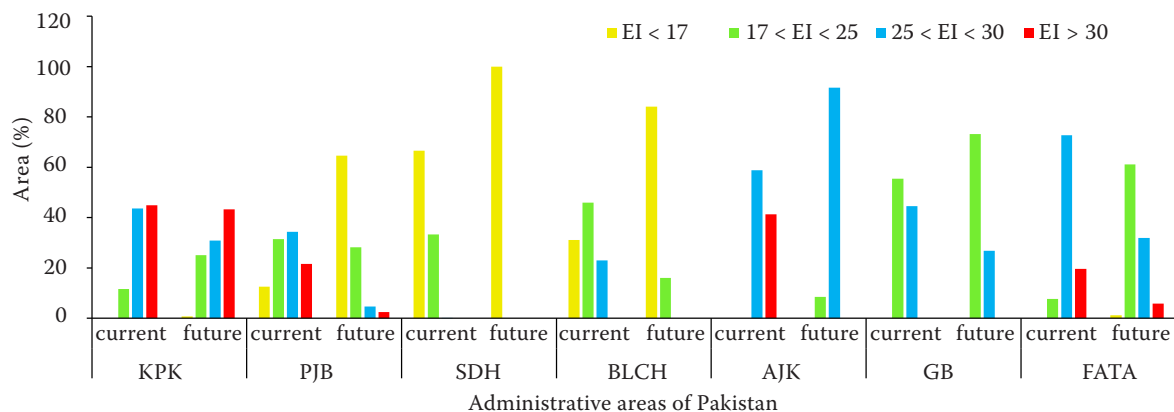

Figure 7. Percent of land area (different habitats of *Agrotis ipsilon*) represented by the ecoclimatic index (EI) ranges under the current and future climatic conditions in the seven administrative areas of Pakistan

Optimal habitats (EI > 30); highly favourable habitats (25 < EI ≤ 30); favourable habitats (17 < EI ≤ 25); moderately favourable habitats (EI < 17); GB – Gilgiit Baltistan; AJK – Azad Jammu and Kashmir; FATA – Federal Administrative Tribal Areas; KPK – Khaber Pakthoonkhwa; PJB – Punjab; SDH – Sindh; BLCH – Balochistan

In PJB, only two of the twelve target locations exhibited ecoclimatic index (EI) values > 30 (Murree and Attock). Furthermore, in FATA one of the two target locations contained optimal habitats (EI > 30; the Mohammad Agency). Overall, under future climatic conditions, the percentage of land area containing optimal *A. ipsilon* habitats (EI > 30) within the seven administrative areas of Pakistan (GB, AJK, FATA, KPK, PJB, SDH, BLCH) was 0, 41, 6, 43, 3, 0, and 0%, respectively (Figure 7).

DISCUSSION

Climate change has a considerable influence on the habitat range of various species, especially cold-blooded species such as insects (Wilson & Maclean 2011; Aljaryian et al. 2016). Through the advancement of climate modelling techniques and technologies, it has become easier to predict the geographical distributions of a targeted pest species under future climatic scenarios, which has further facilitated the employment of timely monitoring and control tactics (Wei et al. 2018). Considering the accuracy of the CLIMEX model used, out of the 225 known distribution points for *A. ipsilon* globally (the global EI value ranges from 0–90, while the EI value ranges from 9–60 for Pakistan), only a single point fell outside the ecoclimatic index (EI) range > 0 − > 30. For Pakistan, out of ten known distribution points, not one was outside the given range which indicates that the accuracy of the CLIMEX model was 100% for the current study.

Our CLIMEX models predicted that *A. ipsilon* could be established in most parts of Pakistan under both the current and future climatic conditions. Specifically, they revealed that KPK, FATA, and north-eastern PJB are highly susceptible to an *A. ipsilon* establishment. In reality, previous reports suggested that the distribution of *A. ipsilon* in Pakistan included KPK and PJB, in accordance with our model predictions.

A. ipsilon is a pest species which mainly attacks and damages agricultural crops. The temperature can affect the development of this species and hinder its distribution and/or migration. We observed that the EI values shifted from southern to northern Pakistan. Southern Pakistan mainly consists of plain areas and agricultural land 5 m up to 150 m above sea level, while the mountain range above reaches elevations up to approximately 6 600 m. Because of the diverse elevation, temperature changes are frequent in this area. Furthermore, the surface temperatures of the southern plain areas in Pakistan are relatively higher than those in the northern mountainous areas. According to the Government of Pakistan (Ministry of Climate Change 2006), Pakistan is one of the countries more vulnerable to climate change (Chaudhry et al. 2015). The most suitable temperature range for *A. ipsilon* survival is 0–36 °C (Showers 1997). Thus, the temperature shifts and overall higher temperature in southern Pakistan would not be suitable for the *A. ipsilon* habitation, likely resulting in the shift in its distribution under future climatic conditions. The impact of temperature indetermining the development of insect populations is well understood (Ives 1973), and temperature data can, therefore, be used in forecasting insect movement and spread, and the appearance of signs of insect development during the growing season (Wagner et al. 1984).

Low ecoclimatic index (EI) values (< 17) under the current conditions accounted for 25% of the total land area in Pakistan, comprising PJB, SDH, and BLCH. However, under future climatic scenarios, low ecoclimatic index (EI) values comprised 63% of the total land area in Pakistan, specifically within SDH, BLCH, and PJB. These areas occupy more than 60% of the plain areas, deserts, and basin lands (land along the Indus river, one of the largest rivers in Pakistan). Furthermore, the climatic conditions of these areas are semi-arid to arid; thus, they are more vulnerable to climate change than the northern area of Pakistan given that even small temperature fluctuations can cause extreme heat under these climatic conditions. Through historical climatic data analysis, we found that the semi-arid area of Pakistan (PJB) experienced warming (Abbas 2013). Globally, over the last 50 years, the regularity of massive precipitation events has increased, steadily with warming, and wide fluctuations in extreme temperatures have been detected (IPCC 2007). Furthermore, due to changes in the climatic pattern, the frequencies of cold days, cold nights, and frost events have been reduced, whereas the frequencies of hot days, hot nights, and heat waves have increased (Caesar et al. 2006; Tebaldi et al. 2006).

It is likely that the suitable *A. ipsilon* habitat area will shift northward in Pakistan under future climatic scenarios as a result of the heat stress. According to the CLIMEX model, heat stress under future climatic conditions was maximal in the PJB and SDH regions and was gradually reduced northwards, resulting in marginal changes in the ecoclimatic index

(EI) values compared to those under the current climatic scenario. The ecoclimatic index (EI) values did not fall within the low ranges (0 < EI < 5 or EI = 0) under future climatic conditions in Pakistan. However, compared with the current conditions, suitable *A. ipsilon* habitats significantly changed with an increase in the moderately favourable habitats than the favourable, highly favourable, and optimal habitats under future climatic scenarios.

CONCLUSION

We conclude that Pakistan is one of the countries which is favourable to both the survival and breeding of *A. ipsilon* under both current and future climatic scenarios. We revealed that the entire region is suitable for the establishment of *A. ipsilon*, especially the northern areas of Pakistan (e.g., KPK, AJK, FATA and GB). As Pakistan is an agricultural country and a significant portion of the economy, thus, depends upon agriculture, the implementation of more effective control measures is critical to prevent the further spread of this pest species. Using the CLIMEX modelling, we determined the potential future distribution of *A. ipsilon* in Pakistan and also worldwide. These data will prove useful for the creation of improved monitoring systems and pest control programmes for *A. ipsilon*.

REFERENCES

Abbas F. (2013): Analysis of a historical (1981–2010) temperature record of the Punjab province of Pakistan. Earth Interactions, 17: 1–23.

Aljaryian R., Kumar L., Taylor S. (2016): Modelling the current and potential future distributions of the sunn pest *Eurygaster integriceps* (Hemiptera: Scutelleridae) using CLIMEX. Pest Management Science, 72: 1989–2000.

Archer T., Musick G., Murray R. (1980): Influence of temperature and moisture on black cutworm (Lepidoptera: Noctuidae) development and reproduction. The Canadian Entomologist, 112: 665–673.

Bajwa G., Gul H. (2000): Some observations on insect species of Paulownia species at Pakistan Forest Institute Campus, Peshawar. Pakistan Journal of Forestry, 50: 71–80.

Bale J.S., Masters G.J., Hodkinson I.D., Awmack C., Bezemer T.M., Brown V.K., Butterfield J., Buse A., Coulson

J.C., Farrar J., Good J.E. (2002): Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. Global Change Biology, 8: 1–16.

Beck S.D. (1986): Effects of photoperiod and thermoperiod on growth of *Agrotis ipsilon* (Lepidoptera: Noctuidae). Annals of the Entomological Society of America, 79: 821–828.

Beck S.D. (1988): Cold acclimation of *Agrotis ipsilon* (Lepidoptera: Noctuidae). Annals of the Entomological Society of America, 81: 964–968.

Bishara I. (1932): The Greasy Cutworm (*Agrotis ipsilon*, Rott.). Cairo, Ministry of Agriculture, Egypt.

Caesar J., Alexander L., Vose R. (2006): Large-scale changes in observed daily maximum and minimum temperatures: Creation and analysis of a new gridded data set. Journal of Geophysical Research: Atmospheres, 111: D05101. doi: org/10.1029/2005JD006280

Capinera J.L. (2009): Black Cutworm, *Agrotis ipsilon* (Hufnagel) (Insecta: Lepidoptera: Noctuidae). Gainesville, University of Florida.

Chaudhry Q., Rasul G., Kamal A., Ahmad M., Mahmood S. (2015): Technical Report on Karachi Heat wave June 2015. Government of Pakistan Ministry of Climate Change. Available at http://www.ndma.gov.pk/files/heatwave.pdf (accesed Mar 23, 2016).

CIE (1969): Distribution Maps of Plant Pests, No. 261. Wallingford, CAB International.

Clement S.L., Kaster L.V., Showers W.B., Schmidt R.S. (1985): Seasonal changes in the reproductive condition of female black cutworm moths (Lepidoptera: Noctuidae). Journal of the Kansas Entomological Society, 58: 62–68.

Dahi H.F., Ibrahem W.G., Ali M.M. (2009): Heat requirements for the development of the black cutworm, *Agrotis ipsilon* (Hüfnagel) (Noctuidae: Lepidoptera). Egyptian Academic Journal of Biological Sciences, 2: 117–124.

Harris I., Jones P.D., Osborn T.J., Lister D.H. (2014): Updated high-resolution grids of monthly climatic observations – the CRU TS3. 10 Dataset. International Journal of Climatology, 34: 623–642.

Hashmi A., Hussain M., Ulfat M. (1983): Insects pest complex of wheat crop. Pakistan Journal of Zoology, 15: 169–176.

Huang M., Ge X., Shi H., Tong Y., Shi J. (2019): Prediction of current and future potential distributions of the eucalyptus pest *Leptocybe invasa* (Hymenoptera: Eulophidae) in China using the CLIMEX model. Pest management Science, 75: 2958–2968.

IPCC (2007): Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

Ives W. (1973): Heat units and outbreaks of the forest tent caterpillar, *Malacosoma disstria* (Lepidoptera: Lasiocampidae). The Canadian Entomologist, 105: 529–543.

Khan S.M. (1999): Effectiveness of *Microplitis mediator* (Hym.: Braconidae) against its hosts *Agrotis segetum* and *A. ipsilon* (Lepidoptera: Noctuidae). Pakistan Journal of Biological Sciences, 2: 344–346.

Kriticos D.J., Jarošik V., Ota N. (2014): Extending the suite of bioclim variables: A proposed registry system and case study using principal components analysis. Methods in Ecology and Evolution, 5: 956–960.

Kriticos D.J., Webber B.L., Leriche A., Ota N., Macadam I., Bathols J., Scott J.K. (2012): CliMond: Global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. Methods in Ecology and Evolution, 3: 53–64.

Maalik S., Rana S.A., Khan H.A., Ashfaq M. (2013): Diversity and abundance of lepidopteran populations from selected crops of district Faisalabad, Pakistan. Pakistan Journal of Agricultural Sciences, 50: 95–101.

Menéndez R., Megías A.G., Hill J.K., Braschler B., Willis S.G., Collingham Y., Fox R., Roy D.B., Thomas C.D. (2006): Species richness changes lag behind climate change. Proceedings of the Royal Society B: Biological Sciences, 273: 1465–1470.

Pöyry J., Luoto M., Heikkinen R.K., Kuussaari M., Saarinen K. (2009): Species traits explain recent range shifts of Finnish butterflies. Global Change Biology, 15: 732–743.

Rings R.W., Arnold F.J., Johnson B.A. (1975): Host range of the black cutworm on vegetables: A bibliography. Bulletin of the ESA, 21: 229–234.

Senaratne K.W., Palmer W.A., Sutherst R.W. (2006): Use of CLIMEX modelling to identify prospective areas for exploration to find new biological control agents for prickly acacia. Australian Journal of Entomology, 45: 298–302.

Shakur M., Ullah F., Naem M., Amin M., Saljoqi A., Zamin M. (2007): Effect of various insecticides for the control of potato cutworm (*Agrotis ipsilon* Huf., Noctuidae: Lepidoptera) at Kalam Swat. Sarhad Journal of Agriculture, 23: 423–426.

Showers W.B. (1997): Migratory ecology of the black cutworm. Annual Review of Entomology, 42: 393–425.

Sutherst R., Maywald G., Kriticos D. (2007): CLIMEX version 3 user's guide. South Yarra: Hearne Scientific Software; CSIRO.

Sutherst R.W., Maywald G. (2005): A climate model of the red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae): Implications for invasion of new regions, particularly Oceania. Environmental Entomology, 34: 317–335.

Tebaldi C., Hayhoe K., Arblaster J.M., Meehl G.A. (2006): Going to the extremes. Climatic change, 79: 185–211.

Wagner T.L., Wu H.I., Sharpe P.J., Schoolfield R.M., Coulson R.N. (1984): Modelling insect development rates: A literature review and application of a biophysical model. Annals of the Entomological Society of America, 77: 208–220.

Wei J., Zhao Q., Zhao W., Zhang H. (2018): Predicting the potential distributions of the invasive cycad scale *Aulacaspis yasumatsui* (Hemiptera: Diaspididae) under different climate change scenarios and the implications for management. PeerJ, 6:e4832. doi: 10.7717/peerj.4832

Wilson R.J., Maclean I.M. (2011): Recent evidence for the climate change threat to Lepidoptera and other insects. Journal of Insect Conservation, 15: 259–268.

Yonow T., Hattingh V., de Villiers M. (2013): CLIMEX modelling of the potential global distribution of the citrus black spot disease caused by *Guignardia citricarpa* and the risk posed to Europe. Crop Protection, 44: 18–28.

Zethner O., Khan B.M., Chaudhry M.I., Bolet B., Khan S., Khan H., Nawaz G. (1987): *Agrotis segetum* granulosis virus as a control agent against field populations of *Agrotis ipsilon* and *A. Segetum* [Lep.: Noctuidae] on tobacco, okra, potato and sugar beet in northern Pakistan. Entomophaga, 32: 449–455.