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ORIGINAL ARTICLE

Impact of climate change on the potential distributions of two cicada species, *Platypleura octoguttata* and *Lemuriana apicalis* (Hemiptera: Cicadidae), in India and their conservation implications

Babu SADDAM and Cong WEI*

Key Laboratory of Plant Protection Resources and Pest Management of Ministry of Education, Key Laboratory of Integrated Pest Management on Crops in Northwest Loess Plateau of Ministry of Agriculture and Rural Affairs, College of Plant Protection, Northwest A&F University, Yangling 712100, Shaanxi, China; e-mails: bsmalik.malik@gmail.com, congwei@nwsuaf.edu.cn

Key words. Environmental variables, habitat change, distribution range, maximum entropy modelling

Abstract. The loss of habitat for numerous organisms due to climate change has significantly accelerated the rate of species extinction. Unfortunately, there have been no studies conducted on the impact of climate change and other factors on the distribution patterns of cicada species in India. In the present study, we investigated the current and potential future distribution of two cicada species, *Platypleura octoguttata* and *Lemuriana apicalis,* using environmental variables and occurrence data through maximum entropy modelling. The distribution ranges of both species show some similarities under the current climatic conditions. According to predictions based on future climate scenarios, the distribution areas for *P. octoguttata* and *L. apicalis* are predicted to decrease to varying extents. However, the anticipated reduction of distribution areas for these two cicada species is different, indicating that both species have distinct responses to climate change. The changes in the distributional centroids show a consistent trend of moving in a north-westward direction across all future periods under the four climate scenarios (SSP126, SSP264, SSP370, and SSP585), except for SSP370 in the case of *L. apicalis*, which shows the direction of overall migration north–eastwards over time. The creation of a new protected area at the border of Bijnor District in Uttar Pradesh Province and Haridwar District in Uttarakhand Province would be greatly helpful in future for the conservation of these two species. Our findings highlight the impact of climate change on the distribution range of these two cicada species, offering valuable insights for conservation efforts in India.

INTRODUCTION

The climate has a crucial role in determining the geographical distribution, spread and population fluctuations of insects worldwide. Among the most serious threats to biodiversity, climate change caused by humans is on par with, if not more so than, the loss of natural habitats (Hodkinson et al., 2011; Wagner et al., 2021; Bellard et al., 2012; Poloni et al., 2022; Raina et al., 2023). An estimated 1–2% annual decrease in insect abundance is attributable to a variety of factors, with climate change ranking high among them (Wagner et al., 2021; Poloni et al., 2022). However, the reproductive potential of some insect species may increase because of warmer temperatures, which might boost the number of generations produced each season and the overall pace of population expansion (Bajwa et al., 2020; Hamann et al., 2021; Aidoo et al., 2022) and changes in temperature might potentially trigger insect outbreaks (Raffa et al., 2015). As a broad concept, insects might adapt to a changing climate. Climate change's rate, species' life-history attributes, genetic architecture of important traits, and the rate at which an insect species may alter these traits in response to climate change are all factors that depend on how well they adapt to climate change (Kellermann & Van Heerwaarden, 2019; Poloni et al., 2022). However, it is uncertain whether most species will be able to adapt to the ongoing changes (Poloni et al., 2022). Insects evolved to high elevations and specialised habitats may suffer from this, and such kind of situation might harm them more due to their inability to respond to environmental changes (Dahlhoff et al., 2019; Yadav et al., 2021; Raina et al., 2021, 2023; Saddam et al., 2024).

Insects may be able to track climate change and prevent extinction by altering their distribution patterns (Liu et al., 2022). Undoubtedly, a previous study on the fossil record of quaternary insects revealed no significant extinction rates in response to climatic oscillations, which is likely due to their remarkable ability to adapt and migrate, along with the shifting geographic distribution of tolerable climates (Coope, 1994). However, it is worth noting that insect species may struggle to adapt their ranges quickly

* Corresponding author; e-mail: congwei@nwsuaf.edu.cn

enough to keep up with the rapid pace of climate change. This challenge is particularly pronounced at high altitude areas, where geographical limitations further restrict their ability to find a suitable climate.

The activity period of cicadas is specific to each species. Annual cicadas emerge at a specific time of the year, while periodical cicadas emerge at intervals of time (Yoshimura et al., 2009; Koenig & Liebhold, 2013). There is currently only one study available that provides information on the activity period of a cicada population, specifically the study on *Chremistica ribhoi* from India (Hajong & Yaakop, 2013). Understanding emergence is essential when studying population dynamics and the ecology of cicadas. Recent studies have revealed that most cicadas are specific to certain habitats (Karban, 1983; Williams & Simon, 1995; Giri et al., 2019; Sarkar, 2019), and/or prefer certain host plants (Williams & Simon, 1995). These findings indicate that the characteristics of hostplants have a significant influence on the choice of habitat. A study on the natural history and geographic distribution of *Lahugada doherti* between 2014 and 2016 showed that cicadas are also responsive to changes in their environment (Sarkar, 2019).

All the recorded species of cicadas in India are known either from a big region or from a point locality. For example, the type locality of *Macrosemia saturata* was stated as Himalaya, which expands in five nations and 2400 km long; and type locality was stated as even enormous areas such as 'N. India' in case of *Haphsa nicomache* and 'Hindostan' in case of *Khimbya evanescens* (Price et al., 2016). These mentioned type localities of the existing Indian cicadas based on the collection records are not sufficient representations of species-specific geographical distribution of cicadas resulting into a significant gap in our understanding of Indian cicadas.

Here, we investigate the impact of climate change on the potential distribution of two Indian cicadas: one large, *Platypleura octoguttata* (Fabricius, 1798), and one small, *Lemuriana apicalis* (Germar, 1830) (Hemiptera: Cicadidae). We selected these two species for the study because of their sympatric distribution patterns (distributed in almost all zoogeographic regions in India except Trans-Himalayas and Upper Himalayan Region including highly populated cities to natural dense forest) and their population are under pressure because of urbanization, deforestation, and high uses of chemical pesticides. *P. octoguttata* and *L. apicalis* are found in North, Central and South India, but their geographical distribution in the whole of India is still unknown. *P. octoguttata* is a common cicada species in some provinces of India, such as Uttar Pradesh, Haryana, Punjab, Rajasthan, Maharashtra, Tamil Nadu, Karnataka, Bihar, West Bengal, and the planned region of Uttarakhand (Price et al., 2016). However, *L. apicalis* is small when compared to *P. octoguttata* and was recorded from Uttar Pradesh, Maharashtra, Tamil Nadu, West Bengal, and Karnataka (Price et al., 2016*)*. The general distribution of these two cicadas is given in the checklist published by Price et al. (2016). Recently, no specific study has been conducted that provides the detailed geographical distribution and impact of climate change on the potential distribution of *P. octoguttata* and *L. apicalis* from India.

MATERIAL AND METHODS

Occurrence records

The data on the open field distribution of *P. octoguttata* and *L. apicalis* in India excluding some part of Northeast India were acquired from four different sources. First, between the years 2019 and 2023, field studies of these two species were carried out in open areas at various locations throughout India. Second, the data on occurrences from the Cicadas of India (https://www.indiancicadas.org/, accessed on 15 December 2023). Third, the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/species/7544182, accessed on 20 December 2023), and fourth, scientific literature (Distant, 1906; Sanborn, 2014; Price et al., 2016) corresponding to the same period. The occurrences data was carefully checked before used to make sure that it was correct and reliable. To minimise sampling deviation, a single occurrence record was kept in each grid cell to align with the spatial resolution of the environmental variables. For modelling purposes, a total of 111 occurrence records for *P. octoguttata* and 89 occurrence records for *L. apicalis* were used after filtering (Fig. 1).

Environmental variables and future model selection

To standardise the model for current climatic conditions, the bioclimatic variables used in this study have a resolution of 2.5 arc-minutes, making them suitable for use as environmental layers for insects (Liu et al., 2023). The Worldclim Global Climate Database (version 2.1, http://www.worldclim.org., accessed on December 25, 2023) was used for obtaining the 19 bioclimate variables for the current environmental layers (1970–2000) (Table 1) and the next two periods (2041–2060 and 2061–2080) (Brown, 2014; Fick & Hijmans, 2017; Liu et al., 2023). On the assumption of anticipated future concentrations of gases and aerosols, the IPCC (International Panel on Climate Change) designed multiple potential scenarios (indicated as shared socio-economic pathways, or SSP): SSP126, SSP245, SSP370, and SSP585 (Reisinger et al., 2011; Poloni et al., 2022). For the study, only one GCM (Global Climate Model) was selected: BCC-ESM2-MR (Beijing Climate Center and China meteorological Administration, China), as this future climate model is quite suitable for the targeted study area and favourable estimation for precipitation and temperature patterns (Sime & Dibaba, 2023). We considered all combinations of the four shared socioeconomic pathways (SSP126, green; SSP245, intermediate; SSP 370, High; SSP585, very high) which resulted in 4 climate change scenarios. We used ArcGIS software (Ver. 10.8.2; http://www.arcgis.com) for data processing and generate maps.

The Pearson correlation coefficients of 19 variables for the current period (1970–2000) were calculated using the ENM tool to reduce any biases caused by multicollinearity. Based on the current understanding of ecology of these two cicada species in India, one of the two variables was eliminated when the absolute value of Pearson's correlation exceeded 0.85 (Elith et al., 2006; Xue et al., 2022a). After the eliminations, only 7 environmental variables (BIO4, BIO5, BIO6, BIO9, BIO10, BIO15 & BIO18) for *P. octoguttata* and 7 environmental variables (BIO5, BIO6, BIO9, BIO10, BIO14, BIO18, BIO19) for *L. apicalis* were used into the modelling (Table 1). MaxEnt software has three resampling methods (i.e., bootstrapping, cross validation, and subsampling) and the correlation coefficient among these modelling results are different depending upon the selected model (i.e., suitability values). We selected the subsample method for the modelling.

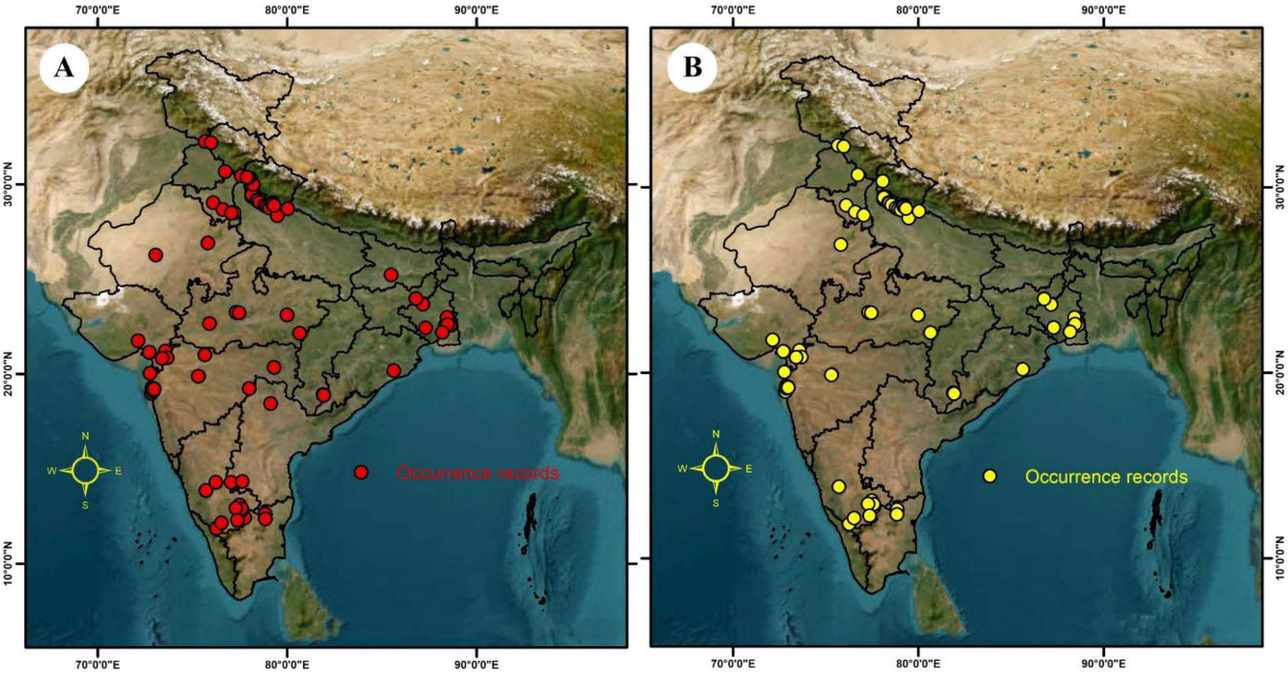

Fig. 1. Occurrence records of *P. octogutta* (A) and *L. apicalis* (B).

MaxEnt model parameter settings

The potential distribution of *P. octoguttata* and *L. apicalis* was predicted using MaxEnt software (Ver. 3.4.4, http://biodiversity-informatics.amnh.org/open_source/maxent/, accessed on 20 December, 2020) under current and future climate scenarios. The Maxent algorithm employs presence-only data to forecast distribution suitability models and demonstrates effective performance with smaller sample sizes compared to alternative modeling techniques. The model quantifies distribution suitability for the species on a scale from 0, indicating low suitability, to 1, indicating high suitability. Additionally, it generates a response curve for each predicted climate variable (Elith et al., 2006). We used the ArcGIS software's "extract by mask" function to clip the bioclimatic variables and future model layers to align with the study area's dimensions. We then converted these layers into an ASCII grid format to utilise them in the Maxent software.

The MaxEnt model was developed by using subsample replication run type method and replication was set as 10 times (maximum iterations: 5000; max. number of background points: 10,000) based on environmental factors and distribution data. Based on the occurrence records, 30% of the distribution data were randomly set for the purpose of testing the model. Jackknife test (Fig. S2) and responses curves were checked at the same time to see the key environmental variables affecting the *P. octoguttata* and *L. apicalis* distribution (Phillips et al., 2006; Naroue-Khandan et al., 2016; Xue et al., 2022a; Chi et al., 2023).

We evaluated the MaxEnt model using a threshold–independent receiver operating characteristic (ROC) curve, and the area under the curve (AUC) was shown to have a positive correlation with the performance of the prediction model (Peterson & Soberon, 2012). We selected threshold as equal training sensitivity

Table 1. Environmental variables (in bold) were selected in model building.

Variable	Description	Percent contribution for *P. octoguttata*	Percent contribution for *L. apicalis*
BIO1	Annual mean temperature		
BIO2	Mean diurnal range (mean of monthly [max temp _min temp])		
BIO3	Isothermality (BIO2/BIO7) (_100)		
BIO4	Temperature seasonality (standard deviation _100)	11.2	
BIO5	Max temperature of warmest month	16.3	16.9
BIO6	Min temperature of coldest month	8.7	6.5
BIO7	Temperature annual range (BIO5–BIO6)		
BIO8	Mean temperature of wettest quarter		
BIO9	Mean temperature of driest quarter	12.9	12.8
BIO10	Mean temperature of warmest quarter	8	11.7
BIO11	Mean temperature of coldest quarter		
BIO12	Annual precipitation		
BIO13	Precipitation of wettest month		
BIO14	Precipitation of driest month		12.8
BIO15	Precipitation seasonality (coefficient of variation)	6.9	
BIO16	Precipitation of wettest quarter		
BIO17	Precipitation of driest quarter		
BIO18	Precipitation of warmest quarter	36.6	41.3
BIO19	Precipitation of coldest quarter		5.5

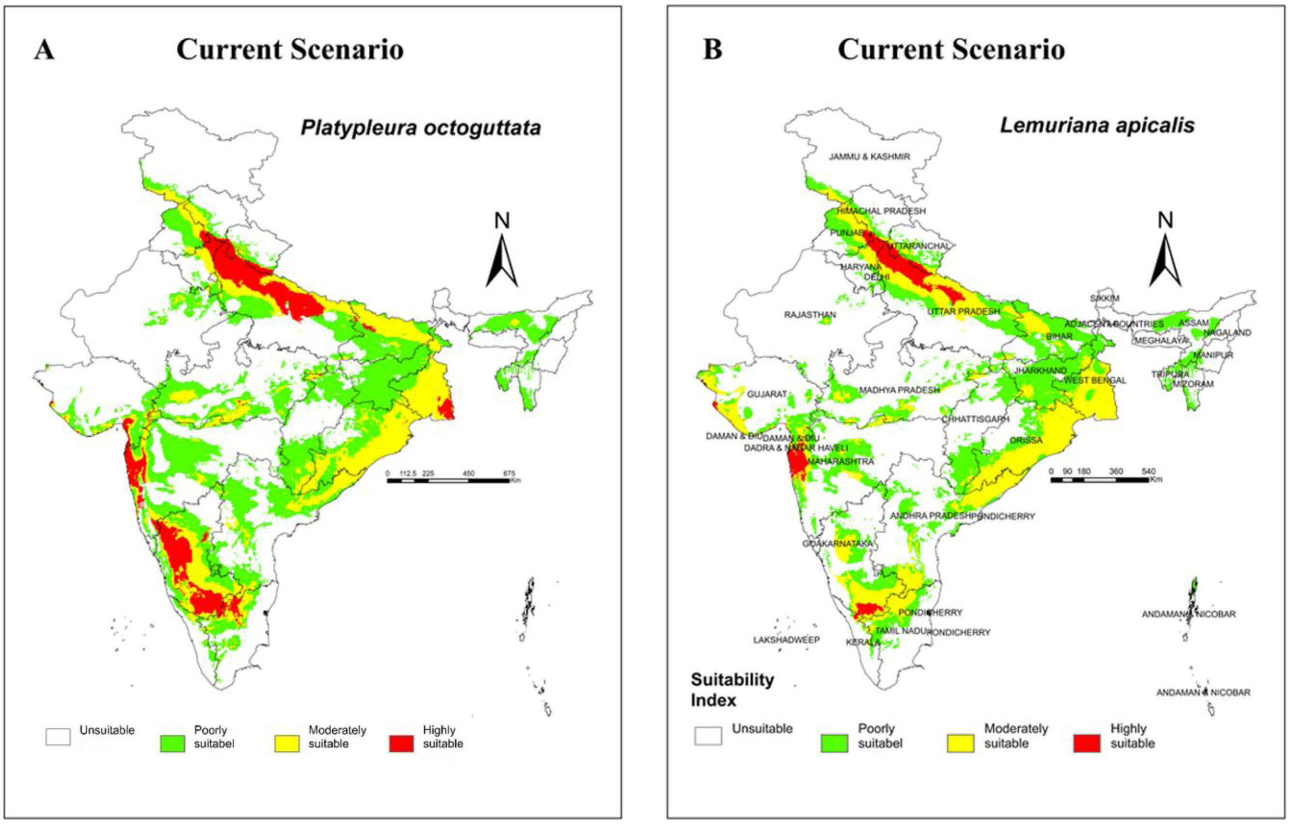

Fig. 2. Potential suitable areas for *P. octoguttata* (A) and *L. apicalis* (B) under the current climate scenario.

and specificity (ETSAS) to determine the suitable and unsuitable areas.

Classification of suitable distribution areas

We used ArcGIS and SDM Toolbox to visualise distribution changes of *P. octoguttata* and *L. apicalis* under future climate scenarios. Based on the output of ETAS threshold, the distribution results were classified into four categories for *P. octoguttata* and *L. apicalis*: unsuitable areas (0–0.3), poorly suitable areas (0.3–0.64 and 0.3–0.64), moderately suitable areas (0.64–0.78 and 0.64–0.78), and highly suitable areas (0.78–1) (Table S1).

Distribution change and centroid shifts estimation

The potential distributions of *P. octoguttata* and *L. apicalis* were compared using various methods to assess how these two species respond to climate change. The zonal statistics tool in ArcGIS 10.8.2 was utilised to determine the potential habitats for the two species under various climate scenarios and habitat suitability types. Next, we compared the current suitable distribution with the suitable distribution under different future climate scenarios to determine how the distribution will change (range contraction, range expansion, no change, and no occupancy). It was done using binary models, which are distribution maps that classify habitats as suitable or unsuitable. The distribution changes between current and future projections were analysed using the distribution changes between binary SDMs tool in the SDM toolbox (Brown, 2014). In addition, in order to demonstrate the varying directions and distances of distribution area shifts of the two species, the distributional centroid shifts of the predicted distribution in different periods under future climate scenarios were measured separately using the centroid changes (lines) tool through SDM toolbox in ArcGIS 10.8.2 (Brown, 2014; Xue et al., 2022b).

RESULTS

Maxent model performance and significant environmental variables

The AUC values obtained were 0.811 and 0.866 after a model run for *P. octoguttata* and *L. apicalis*, respectively, which predicted that the model's performance was greater than 8 for both species and was excellent (Fig. S1). The findings of our validation demonstrated that the predictions of the distribution of *P. octoguttata* and *L. apicalis* were reliable and could be utilised to forecast the suitable areas (Fig. S1). Table 1 shows MaxEnt model contributions for seven environmental variables of *P. octoguttata* and *L. apicalis*. Precipitation of hottest quarter (Bio18, 36.6%), max temperature of warmest month (Bio5, 16.3%), mean temperature of driest quarter (Bio9, 12.9%) and temperature seasonality (standard deviation _100) (Bio4, 11.2%) were the four key environmental variables which had the highest contribution rate, and these four environmental variables contributed a cumulative contribution of 77% to the total model construction for *P. octoguttata* (Table 1). However, precipitation of hottest quarter (Bio18, 41.3%), max temperature of warmest month (Bio5, 16.9%), precipitation of driest month (Bio14, 12.8%) and mean temperature of driest quarter (Bio9, 12.8%) were the four environmental variables which had the highest contribution rate, and these four environmental variables contributed a cumulative contribution of 83.8% to the total model construction for *L. apicalis* (Table 1).

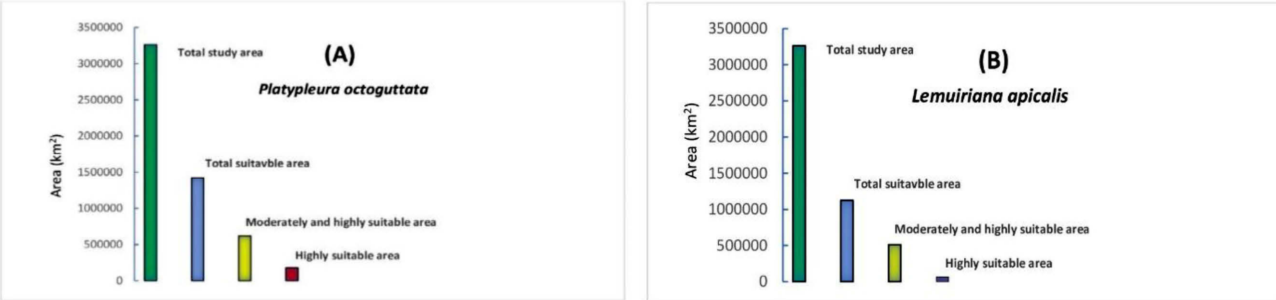

Fig. 3. Comparison of potential suitable areas estimated for *P. octoguttata* (A) and *L. apicalis* (B) in India under the current scenario.

Predicted potential distribution of *P. octoguttata* and *L. apicalis* under current climate scenarios

Based on the ETSAS threshold, it is predicted that both *P. octoguttata* and *L. apicalis* have a lot of possible areas that would be good for them in the current climate (Fig. 2). The highly suitable and moderately suitable areas of *P. octoguttata* were mainly distributed in the North, South, and East India, including the mountainous regions of Uttarakhand, Himachal Pradesh, and Jammu and Kashmir, and the protected areas of the Western Ghats (Fig. 2). However, the highly and moderately suitable areas of *L. apicalis* were primarily located in the North, West, and South-East India and the South parts of Karnataka Province (Fig. 2), including the provinces located close to the Bay of Bengal region. The key factors that lead to the development of highly and moderately suitable areas for both species in those areas are the advantageous environment and the host plants. Moreover, certain species within the genus *Platypleura*, such as *P. octoguttata*, are ectothermic, depending on external heat sources like sunlight to manage their body temperature. They favour the habitats found in North, West, and Southeast India, as well as the southern regions of Karnataka Province. The potential suitable areas of *P. octoguttata* and *L. apicalis* were projected to be 1,421,140 km^2 and 1,124,560 km^2 in India, respectively, under the current climate scenario (Table S2). The potential suitable areas of *P. octoguttata* and *L. apicalis* were projected to occupy 43.54% and 34.46% of India's total area, respectively (Table S2). The highly suitable areas of *P. octoguttata* and *L. apicalis* were projected to be 178,580 km^2 and 65,220 km^2, respectively (Table S2), which were estimated to occupy 5.48% and 1.99% of India's total area, respectively (Figs 3A–B and Table S2). The moderately and highly suitable areas of *P. octoguttata* and *L. apicalis* were projected to be 617,500 km^2 and 512,240 km^2 in India, respectively (Fig. 2), which were estimated to occupy 18.92% and 15.7% of India's total area, respectively (Figs 3A–B and Table S2).

Predicted potential distribution of *P. octoguttata* and *L. apicalis* under future climate scenarios

The potential suitable areas of *P. octoguttata* and *L. apicalis* show significant variations across different SSPs under future climate scenarios (Figs 4, 5 and Table S3). Under all the climate scenarios (i.e., 2041–2060, SSP126; 2041–2060, SSP245; 2041–2060, SSP370; 2041–2060, SSP585; 2061–2080, SSP126; 2061–2080, SSP245; 2061–2080, SSP370; 2061–2080, SSP585) (Figs 4, 5 and Table S3), there was a continuous decrease in the suitable areas of *P. octoguttata* and *L. apicalis*. In addition, the area considered moderately-to-highly suitable for both species has notably decreased, particularly in the southwestern and southern regions of India close to the coast (Fig. 4 and Table S3). The decline may be attributed to the excessively high temperatures, as cicada species typically avoid extreme warmer and more humid climatic conditions.

Under 2041–2060 climate scenario, the potential suitable areas of *P. octoguttata* were estimated to be 926,240 km^2 (SSP126), 886,280 km^2 (SSP245), 879,720 km^2 (SSP370), and 1,402,480 km^2 (SSP585) in India (Figs 4A, 5A and Table S3). The potential suitable areas of *P. octoguttata* were correspondingly estimated to occupy 28.38% (SSP126), 27.16% (SSP245), 26.96% (SSP370), and 42.97% (SSP585) in the country (Table S3). However, the potential suitable areas of *L. apicalis* were estimated to be 862,060 km^2 (SSP126), 820,640 km^2 (SSP245), 801,580 km^2 (SSP370), and 764,620 km^2 (SSP585) in India (Figs 4B, 5B and Table S3). The potential suitable areas of *L. apicalis* were correspondingly estimated to occupy 26.42% (SSP126), 25.15% (SSP245), 24.56% (SSP370), and 23.43% (SSP585) in the country (Fig. 4B and Table S3).

Under 2061–2080 climate scenario, the potential suitable areas of *P. octoguttata* were estimated to be 931,760 km^2 (SSP126), 943,060 km^2 (SSP245), 931,320 km^2 (SSP370), and 861,540 km^2 (SSP585) (Fig. 4A and Table S3). The potential suitable areas of *P. octoguttata* were compatibly estimated to occupy 28.55% (SSP126), 28.90% (SSP245), 28.54% (SSP370), and 26.40% (SSP585) (Table S3) in the country. However, the potential suitable areas of *L. apicalis* were estimated to be 809,900 km^2 (SSP126), 772,660 km^2 (SSP245), 799,700 km^2 (SSP370), and 750,720 km^2 (SSP585) (Fig. 4B and Table S3). The potential suitable areas of *L. apicalis* were correspondingly estimated to occupy 24.82% (SSP126), 23.68% (SSP245), 23.68% (SSP370), and 23% (SSP585) in the country (Table S3). The evaluation reveals a significant decline in potential suitable areas for *P. octoguttata*, from 43.54% in the current climate scenario to 26.40% in the SSP585 scenario for the 2061–2080 period. Similarly, the current climate scenario reduces the total suitable area for *L. apicalis* from 34.46% to 23% in the SSP585 scenario during the same timeframe.

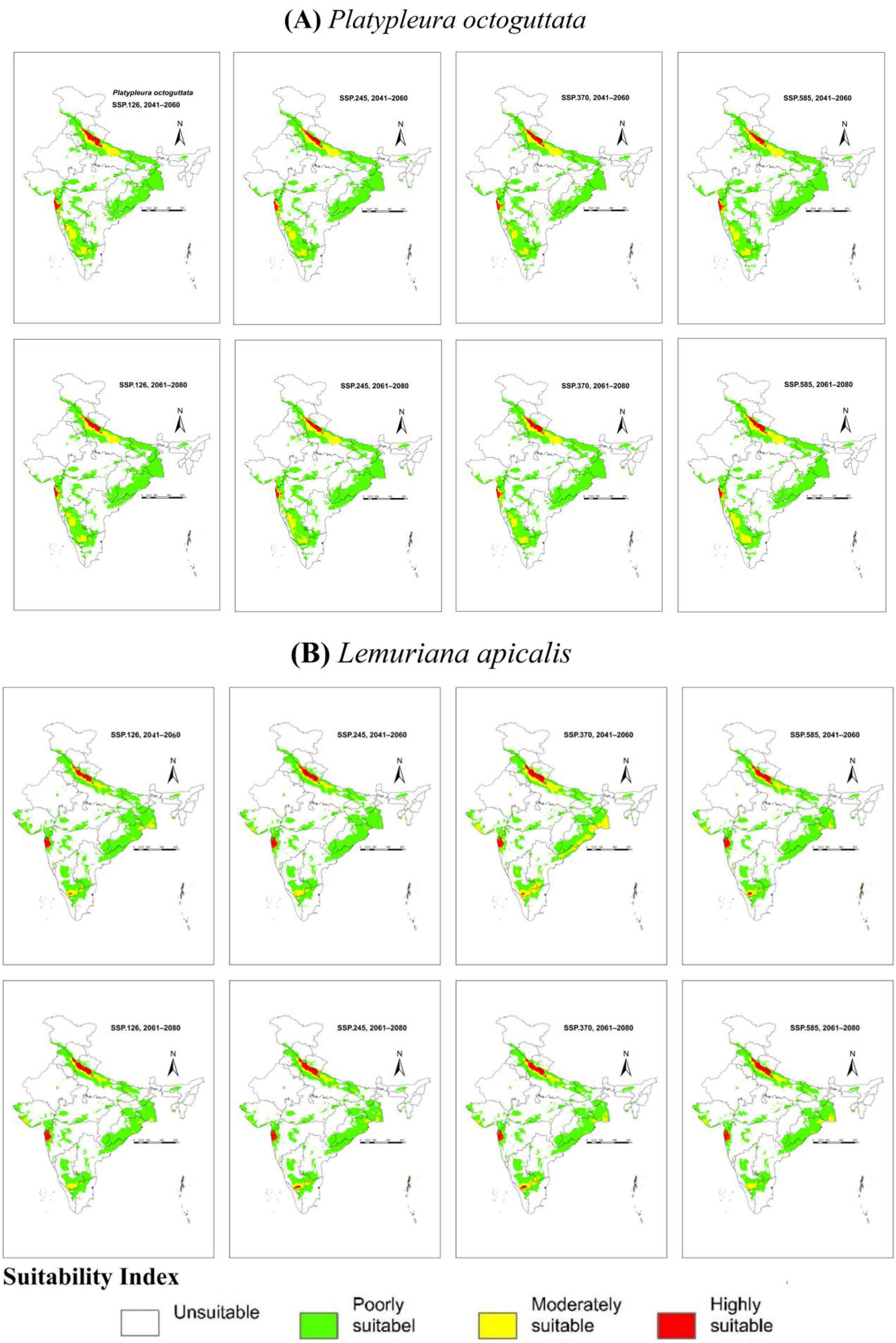

Fig. 4. Potential suitable areas of *P. octoguttata* (A) and *L. apicalis* (B) under future climate scenarios (SSPs).

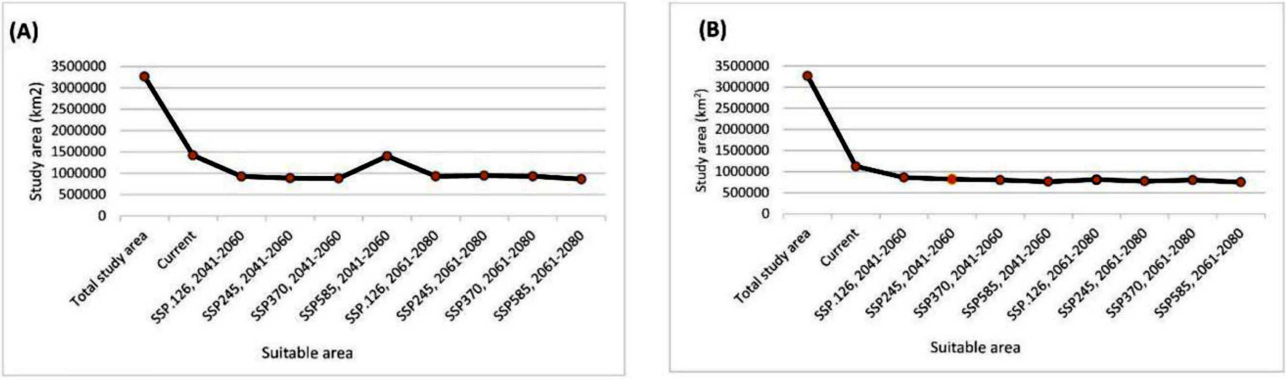

Fig. 5. Comparison of potential suitable areas of *P. octoguttata* (A) and *L. apicalis* (B).

Potential distribution changes under future climate scenarios

Our study revealed that moderately suitable and highly suitable areas of *P. octoguttata* under future climate scenarios were primarily distributed in the mountainous areas of the North (i.e., Uttar Pradesh, Uttarakhand, and Himachal Pradesh provinces) and coastal west regions of India (i.e., Maharashtra Province) (Fig. 4A). However, the moderately suitable and highly suitable areas of *L. apicalis* under future climate scenarios were primarily distributed in the mountainous areas of the North (i.e., Uttar Pradesh, Uttarakhand, and Himachal Pradesh provinces), coastal west part (i.e., Gujrat and Maharashtra provinces), and small plain regions of East India (i.e., Odisha Province), followed by Western Ghats (i.e., Karnataka Province, Fig. 4B). Under future climate scenarios, the distribution of both *P. octoguttata* and *L. apicalis* were predicted to have a decreasing trend compared to the current climate scenario (Fig. 5). This study revealed that environmental conditions may no longer remain suitable for *P. octoguttata* and *L. apicalis*, and their distribution will be greatly impacted by future climate scenarios in India.

Under all future climate scenarios, a trending decrease was predicted in the potential suitable areas of *P. octoguttata* and *L. apicalis* in India (Figs 4, 5 and Table S3). Under 2041–2060 climate scenario, the suitable distribution ranges of *P. octoguttata* were estimated to be decreased 494,900 km^2 (SSP126), 534,860 km^2 (SSP245), 541420 km^2 (SSP370), and 18,660 km^2 (SSP585) in the country (Fig. 6A and Table S4). The potential suitable distribution of *P. octoguttata* were correspondingly estimated to be decreased 34.83% (SSP126), 37.64% (SSP245), 38.09% (SSP370), and 1.32% (SSP585) in the country (Fig. 6A and Table S4) compared to current potential suitable distribution. However, under the 2041–2060 climate scenario, the potential suitable distribution of *L. apicalis* were estimated to be decreased 262,500 km^2 (SSP126), 303,920 km^2 (SSP245), 322,980 km^2 (SSP370), and 359,940 km^2 (SSP585) (Fig. 6B and Table S4). The potential suitable distribution of *L. apicalis* were similarly estimated to be decreased 23.35% (SSP126), 27.03% (SSP245), 28.73% (SSP370), and 32.01% (SSP585) in the country (Table S4) compared to current potential suitable distribution.

Under 2061–2080 climate scenario, the potential suitable distribution of *P. octoguttata* were estimated to be decreased 489,380 km^2 (SSP126), 478,080 km^2 (SSP245), 489,820 km^2 (SSP370), and 559,600 km^2 (SSP585) (Fig. 6A and Table S4). The potential suitable distribution of *P. octoguttata* were compatibly estimated to be decreased 43.52% (SSP126), 42.52% (SSP245), 43.56% (SSP370), and 49.77% (SSP585) in the country (Fig. 6A and Table S4) compared to current potential suitable distribution. However, under the 2061–2080 climate scenario, the potential suitable distribution of *L. apicalis* were estimated to be decreased to 314,660 km^2 (SSP126), 351,900 km^2 (SSP245), 324860 km^2 (SSP370), and 373,840 km^2 (SSP585) (Fig. 6B and Table S4). The potential suitable distribution of *L. apicalis* were correspondingly estimated to be decreased to 27.99% (SSP126), 31.29% (SSP245), 28.89% (SSP370), and 33.24% (SSP585) in the country (Fig. 6B and Table S4) compared to current potential suitable distribution.

Centroid shifts between current and future distribution

The shifts in the distributional centroid of suitable areas for *P. octoguttata* and *L. apicalis* provide valuable insights into the potential changes in their distribution over time. This emphasises the species responses to future climate change (Fig. 7 and Table S5). The distributional centroid of *P. octoguttata* and *L. apicalis* were situated in Laksar County (103.2N, 28.8E) of Uttarakhand (Uttaranchal) Province and Bijnor County of Uttar Pradesh Province, respectively, under the current conditions. However, it was projected to move towards the north-west in all future climate scenarios (Fig. 7 and Table S5). The simulated changes in the distributional centroids of these two species showed a consistent trend of moving in a north-westward direction across all future periods under the four climate scenarios (SSP126, SSP264, SSP370, and SSP585) (Fig. 7), except for SSP370 in the case of *L. apicali*s, which showed the direction of overall migration towards north–eastwards over time. However, the migration direction and distance varied between periods (Fig. 7 and Table S4).

DISCUSSION

The prediction of species distribution under climate change scenarios is crucial for risk analysis, early detec-

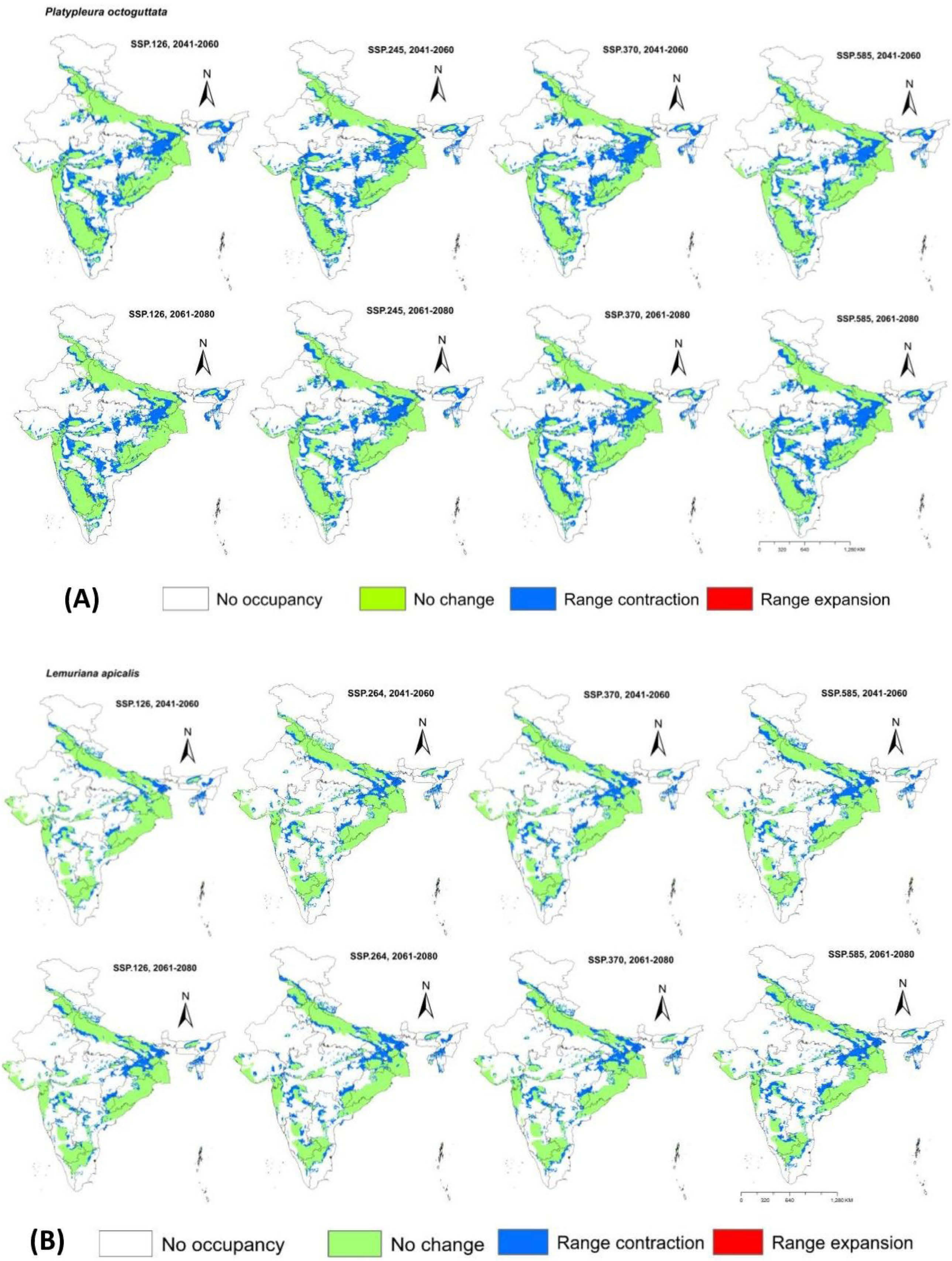

Fig. 6. Predicted distribution area changes for *P. octoguttata* (A) and *L. apicalis* (B) in India under future climate scenarios compared with the Current climate scenario. (SSP – shared socioeconomic pathway).

tion, and prevention or control management of related species (Beaury et al., 2020; Xue et al., 2022a). Endemic insects often have a greater chance of becoming extinct due to habitat destruction, because they have limited ranges and rely significantly on specific habitats (Burlakova et al., 2011; Raina et al., 2021; Parrey et al., 2022). It has been revealed that habitat changes can have a significant impact on the endangered butterfly *Teinopalpus aureus*.

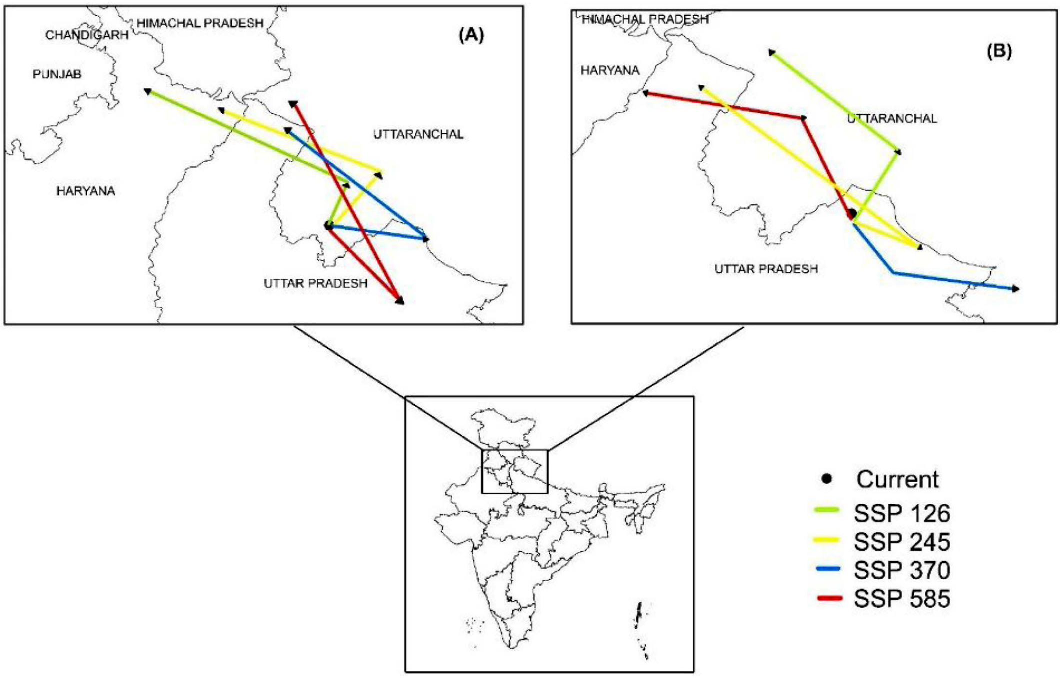

Fig. 7. Distributional centroid shifts of suitable areas for (A) *P. octoguttata* and *L. apicalis* (B) under the future periods (2041–2060 and 2061–2080).

These changes can result in a decline in the butterfly population and even lead to the extinction of the local population (Zeng et al., 2012). In a study conducted by Wang et al. (2019), it was found that the cicada *Subpsaltria yangi* experienced local extinction in certain habitats in Shaanxi Province of China. SDM (Species Distribution Model) are being utilised more frequently in biogeographic research to forecast changes in insect distribution due to global warming and habitat destruction (Mainali et al., 2015; Uden et al., 2015; Wang et al., 2019; Wang & Wei, 2020; Xue et al., 2022a). This study focused on building MaxEnt models to estimate the impact of climate change on the potential distribution for two cicada species, *P. octoguttata* and *L. apicalis*. The models were constructed using occurrence data and various environmental variables, both for current and to predict future conditions. Based on the information available for us, this study is the first of its kind to predict the potential distribution in suitable habitats for these two species or any cicada species in India under both current and future climate scenarios. Therefore, our findings hold significance in advancing our comprehension of distribution of these two species in India. It will also enhance our capacity to understand their biogeography, ecology, and impact of climate on their potential distribution.

This study revealed that the highly suitable and moderately suitable areas of *P. octoguttata* and *L. apicalis* were mainly distributed in the protected areas of India. The potential suitable areas of *P. octoguttata* and *L. apicalis* show significant variations across different SSPs under future climate scenarios. Under all the climate scenarios, there was a continuous decrease in the suitable areas of *P. octoguttata* and *L. apicalis*. The simulated changes in the distributional centroids of these two species showed a consistent trend of moving in a north-westward direction across all future periods under the four climate scenarios (SSP126, SSP264, SSP370, and SSP585), except for SSP370 in the case of *L. apicali*s, which was showing the direction of overall migration towards north-eastwards over time. This study provides valuable insights for establishing conservation areas, designing land management strategies, and setting priorities to restore natural habitat. These efforts are crucial for the effective conservation of endemic insects and other invertebrates that are restricted to specific geographical areas and habitats in India.

Role of protected and natural areas in the conservation in India

Protected areas have increased tremendously in the last 25 years, especially in developing nations with the most biodiversity. The goal of protected areas has evolved from biodiversity conservation to human wellbeing (Naughton-Treves et al., 2005). Most conservationists and environmentalists applaud biodiversity and protected area growth. Nevertheless, the selection of geographic locations for many protected areas worldwide is not primarily based on species conservation but rather on other factors such as the beauty of their surroundings and non–arable landscapes. In India, several protected areas are characterised by their small size, lack of connectivity, or existing vulnerability to significant threats. India's protected areas cover 173,629.52 km^2 as of January 2023, or 5.28% of its total area. Our results suggest that protected natural areas in the Western Himalayas (cover around 2533.44 km^2), a small part (cover around 1125 km^2) of Eastern India, and a little part (cover around 825 km^2) of Southern India cover highly suitable areas for *P. octoguttata* and *L. apicalis* and, therefore, may be suitable as a strategy to provide habitat that supports cicada diversity. The Rajaji National Park, Dehradun, Kedarnath Wildlife Sanctuary, Uttarakhand, Pilibhit Tiger Reserve, and the Pipli Van Uttar Pradesh contributed the most to the highly suitable areas of these two cicadas according to current and future climate scenarios. A small fraction of Western Ghats which is well known for Indian biodiversity hotspots will also support highly suitable habitats, according to future climate scenarios. The creation of a new protected natural area at the border of Bijnor District in Uttar Pradesh Province and Haridwar District in Uttarakhand Province would be greatly helpful in future for the conservation of these two species because this region also has high biodiversity of invertebrates and vertebrates.

CONCLUSION

These two cicada species displayed a distribution pattern that was both irregular and patchy. Their presence spanned across the Western Himalayan region, with a particular concentration in the mountainous areas of Northern (Uttar Pradesh, Uttarakhand and Haryana provinces) and Southern India (Western Ghats) under the future climatic scenarios, where the habitat was favourable. Climate change, particularly under the SSP585 scenario, will impact their distributions. Both species show sympatric distribution in India under current climatic conditions. However, they show migration towards the mountainous region under future climate scenarios. In this study we accurately predicted where *P. octoguttata* and *L. apicalis* might live and how their distributions might be impacted over time by using Maxent modelling. However, more research is needed to fully understand how these species adapt to extreme weather conditions and how genetic diversity affects population movement. Furthermore, exploring ways to effectively manage it, along with the creation of efficient early detection and rapid response systems, will be crucial areas of research.

CONFLICT OF INTEREST. The authors declare no conflicts of interest.

ETHICS STATEMENTS. No ethical statement was reported in this study.

AUTHOR CONTRIBUTIONS. Authors confirm their contribution to the paper as follows; Babu Saddam and Cong Wei: study conception and design, data collection, analysis and interpretation of results and draft manuscript preparation. Both authors critically reviewed the article and approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT. All of the data that support the findings of the study are available in the main text or Supplementary information. The supplementary files can also download at: https://figshare.com/s/0faffa6564cd4339a53e. Supplementary files contained distribution points, supplementary tables and supplementary figures.

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REFERENCES

Aidoo O.F., Souza P.G.C., Siqueira da Silva R., Santana P.A. Jr, Picanço M.C., Kyerematen R., Setamou M., Ekesi S. & Borgemeister C. 2022: Predicting the potential global distribution of an invasive alien pest *Trioza erytreae* (Del Guercio) (Hemiptera: Triozidae). — *Sci. Rep.* **12**: 20312, 14 pp.

Bajwa A.A., Farooq M., Al-Sadi A.M., Nawaz A., Jabran K., & Siddique K.H.M 2020: Impact of climate change on biology and management of wheat pests. — *Crop Prot.* **137**: 105304, 7 pp.

Beaury E.M., Fusco E.J., Jackson M.R., Laginhas B.B., Morelli T.L., Allen J.M., Pasquarella V.J. & Bradley B.A. 2020: Incorporating climate change into invasive species management: insights from managers. — *Biol. Invas.* **22**: 233–252.

Bellard C., Bertelsmeier C., Leadley P., Thuiller W. & Courchamp F. 2012: Impacts of climate change on the future of biodiversity. — *Ecol. Lett.* **15**: 365–377.

Brown J.L. 2014: SDM toolbox: a python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. — *Meth. Ecol. Evol.* **5**: 694–700.

Burlakova L.E., Karatayev A.Y., Karatayev V.A., May M.E., Bennett D.L. & Cook M.J. 2011: Endemic species: contribution to community uniqueness, effect of habitat alteration, and conservation priorities. — *Biol. Conserv.* **144**: 155–165.

Chi Y., Wang G.G., Zhu M., Jin P., Hu Y., Shu P., Wang Z., Fan A., Qian P., Han Y. & Jin S. 2023: Potentially suitable habitat prediction of *Pinus massoniana* Lamb. in China under climate change using Maxent model. — *Front. For. Glob. Change* **6**: 1144401, 14 pp.

Coope G.R. 1994: The response of insect faunas to glacial-interglacial climatic fluctuations. — *Philos. Trans. R. Soc. Lond. (B, Biol. Sci.)* **344**: 19–26.

Dahlhoff E.P., Dahlhoff V.C., Grainger C.A., Zavala N.A., Otepola-Bello D., Sargent B.A., Roberts K.T., Heidl S.J., Smiley J.T. & Rank N.E. 2019: Getting chased up the mountain: High elevation may limit performance and fitness characters in a montane insect. — *Funct. Ecol.* **33**: 809–818.

Distant W.L. 1906: Rhynchota. Heteroptera–Homoptera. In Bingham C.T. (ed.): *The Fauna of British India, including Ceylon and Burma.* Taylor and Francis, London. i–xiv, pp. 1–503.

Elith J., Graham C.H, Anderson R.P., Dudík M., Ferrier S., Guisan A., Hijmans R.J., Huettmann F., Leathwick J.R., Lehmann A. et al. 2006: Novel methods improve prediction of species distributions from occurrence data. — *Ecography* **29**: 129–151.

Fick S.E. & Hijmans R.J. 2017: WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. — *Int. J. Climatol.* **37**: 4302–4315.

Giri V.B., Chaitanya R., Mahony S., Lalrounga S., Lalrinchhana C., Das A., Sarkar V., Karanth P. & Deepak V. 2019: On the systematic status of the genus *Oriocalotes* Günther, 1864 (Squamata: Agamidae: Draconinae) with the description of a new species from Mizoram state, Northeast India. — *Zootaxa* **4638**: 451–484.

Hajong S.R. & Yaakop S. 2013: *Chremistica ribhoi* sp. n. (Hemiptera: Cicadidae) from North-East India and its mass emergence. — *Zootaxa* **3702**: 493–500.

Hamann E., Blevins C., Franks S.J., Jameel M.I. & Anderson J.T. 2021: Climate change alters plant-herbivore interactions. — *New Phytol.* **229**: 1894–1910.

Hodkinson T.R., Jones M.B., Waldren S. & Parnell J.A. (eds) 2011: *Climate Change, Ecology and Systematics (Vol. 78).* Cambridge University Press, Cambridge, 544 pp.

Karban R. 1983: Sexual selection, body size and sex-related mortality in the cicada *Magicicada cassini*. — *Am. Mid. Nat.* 324–330.

Kellermann V. & Van Heerwaarden B. 2019: Terrestrial insects and climate change: adaptive responses in key traits. — *Physiol. Entomol*. **44**: 99–115.

Koenig W.D. & Liebhold A.M. 2013: Avian predation pressure as a potential driver of periodical cicada cycle length. — *Am. Nat*. **181**: 145–149.

Liu J., Xu Y., Sun C., Wang X., Zheng Y., Shi S., Chen Z., He Q., Weng X. & Jia L. 2022: Distinct ecological habits and habitat responses to future climate change in three east and southeast Asian *Sapindus* species. — *For. Ecol. Manag.* **507**: 119982, 12 pp.

Liu T., Liu H., Wang Y. & Yang Y. 2023: Climate change impacts on the potential distribution pattern of *Osphya* (Coleoptera: Melandryidae), an old but small beetle group distributed in the northern hemisphere. — *Insects* **14**: 476, 18 pp.

Mainali K.P., Warren D.L., Dhileepan K., McConnachie A., Strathie L., Hassan G., Karki D., Shrestha B.B. & Parmesan C. 2015: Projecting future expansion of invasive species: comparing and improving methodologies for species distribution modeling. — *Glob. Change Biol.* **21**: 4464–4480.

Narouei-Khandan H.A., Halbert S.E., Worner S.P. & van Bruggen A.H. 2016: Global climate suitability of citrus huanglongbing and its vector, the Asian citrus psyllid, using two correlative species distribution modeling approaches, with emphasis on the USA. — *Eur. J. Plant. Pathol.* **144**: 655–670.

Naughton-Treves L., Holland M.B. & Brandon K. 2005: The role of protected areas in conserving biodiversity and sustaining local livelihoods. — *Annu. Rev. Environ. Resour.* **30**: 219–252.

Parrey A.H., Raina R.H., Saddam B., Pathak P., Kumar S., Uniyal V.P., Gupta D. & Khan S.A. 2022: Role of bumblebees (Hymenoptera: Apidae) in pollination of high land ecosystems: A review. — *Agric. Rev.* **43**: 368–373.

Peterson A.T. & Soberón J. 2012: Species distribution modeling and ecological niche modeling: getting the concepts right. — *Nat. Conserv.* **10**: 102–107.

Phillips S.J., Anderson R.P. & Schapire R.E. 2006: Maximum entropy modeling of species geographic distributions. — *Ecol. Mod.* **190**: 231–259.

Poloni R., Iannella M., Fusco G. & Fattorini S. 2022: Conservation biogeography of high-altitude longhorn beetles under climate change. — *Insect Conserv. Diver.* **15**: 429–444.

Price B.W., Allan E.L., Marathe K., Sarkar V., Simon C. & Kunte K. 2016: The cicadas (Hemiptera: Cicadidae) of India, Bangladesh, Bhutan, Myanmar, Nepal and Sri Lanka: an annotated provisional catalogue, regional checklist and bibliography. — *Biodiv. Data J.* **4**: e8051, 156 pp.

Raffa K.F., Aukema B.H., Bentz B.J., Carroll A.L., Hicke J.A. & Kolb T.E. 2015: Responses of tree-killing bark beetles to a changing climate. — *Clim. Change Insect Pests* **7**: 173–201.

Raina R.H., Saddam B., Parrey A.H., Pathak P. & Chandra K. 2021: Mites: an emerging problem for bumblebees in the Indian Himalayan Region. — *Curr. Sci*. **121**: 581–585.

Raina R.H., Pathak P., Saddam B. & Parrey A.H. 2023: Role of mining bees (Hymenoptera: Andrenidae) in pollination ecology in India: A review. — *Agric. Rev*. **44**: 66–71.

Reisinger A., Meinshausen M. & Manning M. 2011: Future changes in global warming potentials under representative concentration pathways. — *Environ. Res. Lett.* **6**: 024020, 8 pp.

Saddam B., Idrees M.A., Kumar P. & Mahamood M. 2024: Biopesticides: Uses and importance in insect pest control: A review. — *Int. J. Trop. Insect Sci.* **44**: 1013–1020.

Sanborn A. 2014: *Catalogue of the Cicadoidea (Hemiptera: Auchenorrhyncha).* Elsevier, London, viii + 1001 pp.

Sarkar V. 2019: A note on the taxonomy and natural history of the Summer Clicker *Lahugada dohertyi* (Distant, 1891) (Insecta: Hemiptera: Cicadidae) along with its distribution in northern West Bengal, India. — *J. Threat. Taxa* **11**: 14128–14136.

Sime C.H. & Dibaba W.T. 2023: Evaluation of CMIP6 model performance and extreme precipitation prediction in the Awash basin. — *Heliyon* **9**: e21578, 15 pp.

Uden D.R., Allen C.R., Angeler D.G. Corral L. & Fricke K.A. 2015: Adaptive invasive species distribution models: a framework for modelling incipient invasions. — *Biol. Invas.* **17**: 2831–2850.

Wagner D.L., Grames E.M., Forister M.L., Berenbaum M.R. & Stopak D. 2021: Insect decline in the Anthropocene: Death by a thousand cuts. — *Proc. Natn. Acad. Sci.* **118**: e2023989118, 10 pp.

Wang D. & Wei C. 2020: Bacterial communities in digestive and excretory organs of cicadas. — *Arch. Microb.* **202**: 539–553.

Wang Z.-P., Peng S.-Z., He Z.-Q. & Wei C. 2019: Potential impacts of climate change on the distribution of *Subpsaltria yangi* (Hemiptera: Cicadidae), a rare cicada species in the Loess Plateau and adjacent areas in China. — *Acta Entomol. Sin.* **62**: 91–100.

Williams K.S. & Simon C. 1995: The ecology, behavior, and evolution of periodical cicadas. — *Annu. Rev. Entomol.* **40**: 269–295.

Xue J., Hu X., Hao Y., Gong Y., Wang X., Huang L., Lv S., Xu J., Li S. & Xia S. 2022a: Transmission risk predicting for schistosomiasis in mainland China by exploring ensemble ecological niche modeling. — *Trop. Med. Inf. Dis.* **8**: 24, 13 pp.

Xue Y., Lin C., Wang Y., Liu W., Wan F., Zhang Y. & Ji L. 2022b: Predicting climate change effects on the potential distribution of two invasive cryptic species of the *Bemisia tabaci* species complex in China. — *Insects* **13**: 1081, 13 pp.

Yadav S., Stow A.J. & Dudaniec R.Y. 2021: Microgeographical adaptation corresponds to elevational distributions of congeneric montane grasshoppers. — *Mol. Ecol.* **30**: 481–498.

Yoshimura J., Hayashi T., Tanaka Y., Tainaka K.I. & Simon C. 2009: Selection for prime-number intervals in a numerical model of periodical cicada evolution. — *Evolution* **63**: 288–294.

Zeng J., Zhou S., Ding J., Luo B. & Qin K. 2012: Behavior characteristics and habitat adaptabilities of the endangered butterfly *Teinopalpus aureus* in Mount Dayao. — *Acta Ecol. Sin*. **32**: 6527–6534.

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Table S1. Four suitability levels of distribution regions were defined for *P. octoguttata* and *L. apicalis* based on the results of ETSAS threshold.

Different suitability levels of regions	Classified Value (*P. octoguttata*)	Classified Value (*L. apicalis*)
Unsuitable region	0–0.3	0–0.3
Lowly suitable region	0.3–0.64	0.3–0.64
Moderately suitable region	0.64–0.78	0.64–0.78
Highly suitable region	0.78–1	0.78–1

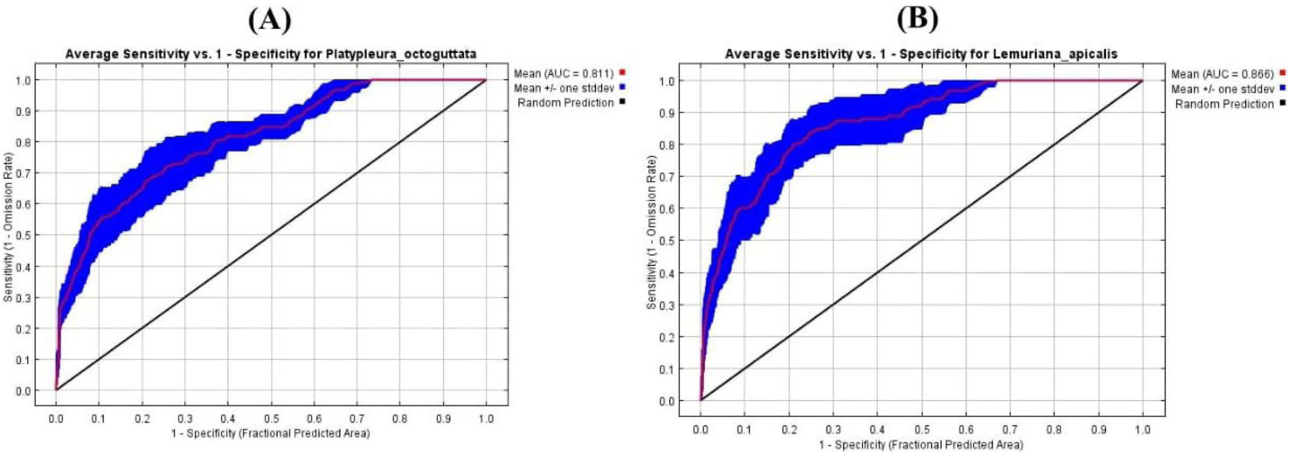

Fig. S1. Receiver operating characteristic (ROC) curves and the area under the curves (AUC) values of the final habitat suitability models of (A) *Platypleura octoguttata* and (B) *Lemuriana apicalis.*

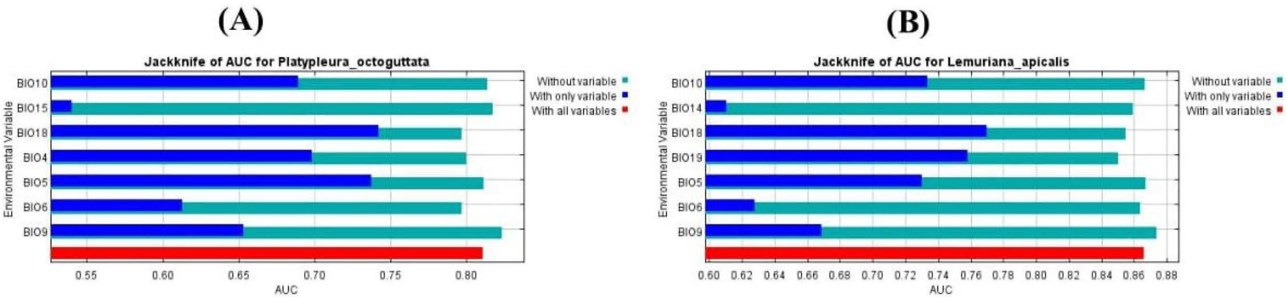

Fig. S2. Jackknife results of habitat distribution prediction of (A) *P. octoguttata* and (B) *L. apicalis.*

Table S2. Suitable habitat of *Platypleura octoguttata* and *Lemuriana apicalis* in India under current climate scenarios.

Cicada species	Areas of suitable regions (km²)		Total areas in India (%)	
	High suitability	Total suitability	High suitability	Total suitability
Platypleura octoguttata	178,580	1,421,140	5.48%	43.54%
Lemuriana apicalis	65,220	1,124,560	1.99%	34.46%

Table S3. The total suitable habitat of *Platypleura octoguttata* and *Lemuriana apicalis* under different climate scenarios.

Climate scenarios	*P. octoguttata* total suitable area (km²)	*L. apicalis* total suitable area (km²)
Current	1,421,140	1,124,560
2041–2060 SSP126	926,240	862,060
2041–2060 SSP245	886,280	820,640
2041–2060 SSP370	879,720	801,580
2041–2060 SSP585	1,402,480	764,620
2061–2080 SSP126	931,760	809,900
2061–2080 SSP245	943,060	772,660
2061–2080 SSP370	931,320	799,700
2061–2080 SSP585	861,540	750,720

Table S4. The decreased in the total suitable habitat of *P. octoguttata* and *L. apicalis* under different climate scenarios compared to total suitable habitat under current climate scenario.

Climate scenarios	*P. octoguttata* total suitable area [(km²) and (%)]	*L. apicalis* total suitable area [(km²) and (%)]
2041–2060 SSP126	494,900 (34.83)	262,500 (23.35)
2041–2060 SSP245	534,860 (37.64)	303,920 (27.03)
2041–2060 SSP370	541,420 (38.09)	322,980 (28.73)
2041–2060 SSP585	18,660 (1.32)	359,940 (32.01)
2061–2080 SSP126	489,470 (43.52)	314,660 (27.99)
2061–2080 SSP245	478,080 (42.52)	351,900 (31.29)
2061–2080 SSP370	489,820 (43.56)	324,486 (28.89)
2061–2080 SSP585	559,600 (49.77)	373,840 (33.24)

Table S5. The potential distribution ranges of *P. octoguttata* and *L. apicalis* under different climate scenarios.

Climate scenarios and periods	Coordinates (lat. & long.)	Distance (km)
P. octoguttata		
Current	29°45'N, 78°1'E	–
2041–2060 SSP126	29°59'N, 78°7'E	34.2
2061–2080 SSP126	30°41'N, 75°22'E	358.9
2041–2060 SSP245	30°1'N, 78°18'E	49.8
2061–2080 SSP245	30°20'N, 77°29'E	153.6
2041–2060 SSP370	29°41'N, 78°32'E	84.2
2061–2080 SSP370	30°13'N, 77°48'E	159.1
2041–2060 SSP585	29°20'N, 78°25'E	102.7
2061–2080 SSP585	30°5'N, 77°42'E	146.9
L. apicalis		
Current	29°40'N, 78°20'E	–
2041–2060 SSP126	29°58'N, 78°32'E	96.3
2061–2080 SSP126	30°23'N, 77°58'E	147.4
2041–2060 SSP245	29°33'N, 78°38'E	51.9
2061–2080 SSP245	30°13'N, 77°35'E	179.6
2041–2060 SSP370	29°25'N, 78°32'E	65.9
2061–2080 SSP370	29°23'N, 79°2'E	48.3
2041–2060 SSP585	30°7'N, 78°9'E	64.9
2061–2080 SSP585	30°12'N, 77°27'E	162.3