Predicting the potential distribution of geographically-limited species, Apsylla cistellata *Buckton (Psyllidae: Hemiptera) on mango* (Mangifera indica) *under different climate change scenarios*

Gundappa Baradevanal, P. K. Shukla & S. Rajan

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ORIGINAL RESEARCH ARTICLE

Predicting the potential distribution of geographically-limited species, *Apsylla cistellata* Buckton (Psyllidae: Hemiptera) on mango (*Mangifera indica*) under different climate change scenarios

Gundappa Baradevanal[1] · P. K. Shukla[1] · S. Rajan[1]

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Abstract

The aim of present study was to predict the potential distribution of mango shoot gall psylla, *Apsylla cistellata* (Psyllidae: Hemiptera) under current and future climate scenarios of 2050 and 2070. This study was conducted across six states in India where their infestation and occurrence noticed. The study provided a deep insight on surveys of shoot gall psylla infestation that occurred between 2012 and 2018. Current and future climate change scenarios acquired from the WorldClim database and Maxent modeling technique was used to fit with occurrence points and current climate data to model potential shoot gall psylla distributions. The model performance was tested using area under the curve (AUC) of the receiver operating characteristic (ROC) values. Response curves depicted the relationships between bioclimatic variables and predicted probability of *A.cistellata* presence. MaxEnt model used to develop spatial map and their distributions for selected climate change scenarios (RCP2.6, RCP 4.5. RCP 6.0 and RCP 8.5) and mapped the habitat for *A.cistellata* suitability under current and future scenarios. Present study results suggested that under current climate change scenarios, the potential distribution of shoot gall psylla was noticed in Western and Central part of Uttar Pradesh and Eastern part of Madhya Pradesh. In future climate change scenarios predicted suitable habitat areas for *A.cistellata* was found mostly from regions of Western and Central Uttar Pradesh, Southern parts Himachal Pradesh and Uttarakhand. The predicted suitability maps developed from present study will be useful in planning and designing of pest management strategies to control pest effectively from designated areas. The study provides clutches of clues for understanding potential changes in distribution and activity of pest in designated areas in response to current and future climate change scenarios.

Keywords Shoot gall psylla · Mango pests · Climate change · MaxEnt · Species distribution models

Introduction

Plant feeding insects plays a key role in the structure and function of the ecosystem (Weisser and Siemann 2004). The agricultural crops ecosystem is very complex had various layers though several insect pest attacks on crops and causes devastating loss. Globally, crop loss was predicted due to insect pest is one third of the produce regardless of progress made in pest management strategies over the last five decades. Several studies highlighted that the climate change would favours spiking up of pests and diseases intensity in a incremental rate. The global mean surface air temperature is projected to rise by 1.8–4 °C by 2100 with additional changes in other drivers of climate change such as increased CO_2 levels and extreme weather events (IPCC 2007).

Insect habitat and survival hugely depends on climate change patterns, the major drivers of climate change viz.., increased CO_2, increased temperature and depleted soil moisture impacts on insect- pest population dynamics. Global climate change pattern could lead to a broader expansion of the geographical range of insect pests (Elphinstone and Toth 2008). Warmer temperature associated with climate change tend to influence insect population dynamics directly through effects on survival, generation time, fecundity and dispersal (Harrington et al. 2001). The most significant consequence of rising temperatures is the change in distribution in range of crops, pests and their

✉ Gundappa Baradevanal
Gundappa@icar.gov.in

1 ICAR- Central institute for subtropical Horticulture, Lucknow, U.P 226 101, India

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natural enemies (Bale et al. 2002). Insect pests that have greater mobility are likely to track the expansion in crop ranges as minimum temperature rather than maximum temperature plays an important role in determining global distribution of pest species (Hill 1987). Studies reported that marked changes in the distribution of insects in the Northern hemisphere in response to unusually hot summers (Parmesan et al. 1999). It is predicted that a 1 °C rise in temperature would enable species to spread 200 km northwards or 140 m upwards in altitude (Parry et al. 1989). The most crucial factors in the higher latitudes for population buildup and pest intensity due to higher survival rate of overwintering populations.

Mango (*Mangifera indica* L.: Anacardiaceae) is grown in tropical and subtropical regions of the world. The delicious taste, excellent flavour and attractive fragrance are most common consumer's preference traits found in mango fruit grown in India. Besides all these, mangoes are rich in vitamin A and C. All these constituents present in mango along with higher production and wider area named mango as "King of fruits". India ranks first among world's mango production accounting 45 percent of its share in total world's mango production. In India, mango thrives well in Kanyakumari region which is located at tropical south (30 m) to the submountainous North regions up to 1400 m (Rajan 2012). Air temperature and rainfall are considered to be the most important factors influencing on suitability for commercial cultivation of mango (Legave et al. 2013; Rajan et al. 2013). Rajan (2012) also reported that global climate change has led to significant changes in the mango flowering and fruiting patterns in subtropical climatic conditions. Apart from climate change constraints, insect pests and diseases are also became potential threats to mango cultivation in India (Reddy et al. 2018). Among the insect pest, mango shoot gall psylla, *Apsylla cistellata* is regarded as one of the most noxious pest affecting the mango production (Singh et al. 2015; Gundappa et al. 2018). *Apsylla cistellata* converts the apical buds of mango into hard conical galls within which nymphs are nourished and developed into adults. Due to transformation of reproductive and vegetative buds into galls, no fruit is set on affected shoots. The occurrence of this pest was geographically limited to the certain states of India (Rahman et al. 2007). Recently, geographical expansion of this pest has been noticed (Gundappa et al. 2014). With respect to *A. cistellata* geographical distributions and suitability, no systematic study has been undertaken to decipher its interactions with environment under current-future climate change scenarios. Hence, present study was carried out to predict the potential distribution of *A.cistellata* under different climate change scenarios.

Materials and methods

Pest occurrence records

Data on geographic coordinates (i.e., latitude and longitude) of pest occurrence is the primary requirement for ecological niche modeling. For this study, occurrence data of *A. cistellata* were collected by conducting the roving survey during 2012–2018 in different states of India wherever pest occurrence was observed. Geographic coordinates for each point were collected by Global Positioning System (GPS) during the survey. In accordance with the requirements of MaxEnt, duplicate records and neighbouring occurrence points were removed. Finally, 86 valid occurrence points were used in the study to predict the potential distribution of *A.cistellata* under different climate change scenario (Fig. 1).

Current and future climate data

Current climatic conditions (1970–2000) of 19 'bioclimatic' variables data were collected from the WorldClim database, version 1.4 (http://www.worldclim.org/) at a spatial resolution of 2.5 min. Data were processed as per the requirement of the study using ENM tools version 1.4.4 (Warren et al. 2011). Multicollinearity among the environmental variables which hinder the species environmental relationships was assessed. We used the Pearson correlation coefficient to classify and remove highly correlated variables each pair wise comparisons of 19 bioclimatic variables. When two variables had a value of Pearson's coefficient $|r|\geq 0.80$, only one variable from pair considering its relative importance in determining *A. cistellata* distribution and their predictive power (i.e. percent contribution and Jackknife gain) was selected for model development. Based on importance, best describing only 10 environmental variables were further processed: Annual Mean Temperature (BIO1), Mean Diurnal Range (Mean of monthly (max temp - min temp)) (BIO2), Isothermality (BIO2/BIO7) (* 100) (BIO3), Max Temperature of Warmest Month (BIO5), Annual Precipitation (BIO12), Precipitation of Driest Month (BIO14), Precipitation Seasonality (Coefficient of Variation) (BIO15), Precipitation of Driest Quarter (BIO17), Precipitation of Warmest Quarter (BIO18) and Precipitation of Coldest Quarter (BIO19).

To predict the future potential distribution of *A.cistellata* in India, the future climate projection data were downloaded from the World Climate Database, version 1.4 (http://www.worldclim.org/) at a spatial resolution of 2.5 arc minutes on a global scale. The global climate model (GCM), Geophysical Fluid Dynamics Laboratory (GFDL) representing simulations for four representative concentration pathways RCP (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) from the fifth assessment of the Intergovernmental Panel for Climate Change (CMIP5)

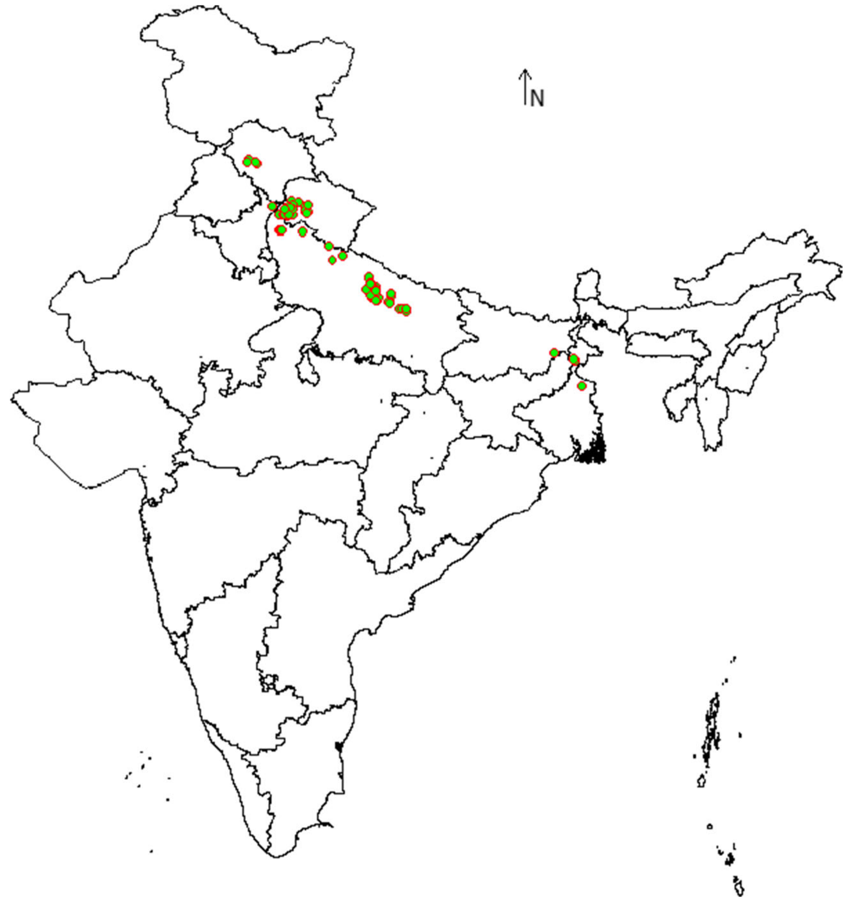

Fig. 1 Incidence records of mango shoot gall psylla in India

was selected for representing the future climatic conditions of the years 2050 and 2070. For mapping the potential geographic distribution of *A.cistellata* in India, MaxEnt (Maximum entropy species modeling), Version 3.3.3 k was used. MaxEnt estimates the probability distribution of species occurrence and randomly generated background points of environmental conditions by finding the maximum entropy distribution of species. The model settings were employed as convergence threshold (10 − 5), maximum iterations (5000) and maximum number of background points (10000) to run the model. Based on background data, MaxEnt can compare the environmental characteristics of presence records. Similarly, a Jackknife test was also used to estimate the relative importance of each of the variable to the model development.

Model development, validation and visualization

The model performance was tested using area under the curve (AUC) of the receiver operating characteristic (ROC). AUC values in model output ranges from 0 to 1 (unsuitable to highly suitable). When AUC shows the values below 0.5 then it can be interpreted as a random prediction. An AUC value between 0.5 and 0.7 indicates poor model performance, 0.7 to 0.9 indicates reasonable performance, and > 0.9 indicates high model performance (Peterson et al., 2011). Response curves were used to study the relationships between bioclimatic variables and the predicted probability of presence of *A.cistellata*. We projected final MaxEnt model in to spatial map for each of the selected climate scenarios (RCP2.6, RCP 4.5. RCP 6.0 and RCP 8.5) to visualize current and future habitat suitability for *A.cistellata*. Data were then imported into Diva-GIS, version 7.3 to produce suitability maps.

Results

Apsylla cistellata is one of the most noxious pest of mango confined to the Indo-Gangetic Plains and lower valleys of the Himalaya.

Current climate

The potential distribution of *A.cistellata* in India based on the current climate and occurrence. The relative contributions of the environmental variables to the predicted model were higher with precipitation seasonality (54.6%), annual precipitation (17.3%), precipitation of the coldest quarter (12.2%)

precipitation of the driest quarter (8.6%) and isothermality (6.1%) (Table 1). In the Jackknife test precipitation seasonality was found as a very important variable with highest gain in the model (Figs. 2 and 3). MaxEnt model predicted potential distribution of pest in western and central part of Uttar Pradesh as highly suitable areas for *A.cistellata* occurrence. Southern parts of the Himachal Pradesh, Southern part of the Uttarakhand, Eastern part of Madhya Pradesh were predicted as highly suitable environmental conditions for pest occurrence. Mango growing belts of Jharkhand, Orissa and West Bengal were predicted with moderately to low suitability areas for pest distribution (Fig. 4). Predicted model revealed that among temperature-related variables isothermality was found to be the important factor in determining the climatic suitability of *A.cistellata*. Among the precipitation related variables such as annual precipitation, precipitation seasonality, precipitation of the driest quarter, precipitation of the coldest quarter were found as important factor in determining the climatic suitability of *A.cistellata* .

Future climate

2050 scenario

Potential distribution of mango shoot gall psylla was also predicted at different future climate change scenario of (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) of 2050 and 2070. In the future climate 2050, RCP 2.6 scenario potential distribution model was predicted with the AUC of 0.998. The highest relative contributions of the environmental variables to the predicted model were precipitation seasonality (47.70%), annual Precipitation (21%), precipitation of the driest month (14.30), precipitation of the coldest quarter (7.2%) and precipitation of the driest quarter (5.9%) (Table 2). In RCP 2.6 scenario, *A.cistellata* occurrence was predicted as like current climate, However, higher suitability areas were also predicted in Southern parts of Bihar and western parts of Jharkhand (Fig. 5). In future climate scenario of RCP 4.5 potential distribution of model maximum relative contribution of the environmental variables were precipitation seasonality (46.80%), precipitation of the coldest quarter (16.3%), annual precipitation (15.90%), maximum temperature warmest month (10%), isothermality (7.10%) and precipitation of the driest month (3.30%) (Table 2). In RCP 4.5 scenario high suitability areas for the *A.cistellata* occurrence was predicted in western Uttar Pradesh, Eastern Madhya Pradesh and Western Jharkhand (Fig. 5). In RCP 6.0 scenario the environmental variables precipitation seasonality (55.5%), precipitation of coldest quarter (19.9%), precipitation of wettest quarter (11.9%), annual precipitation (10.40), isothermality (7.7%) and Precipitation of the driest quarter (6.10%) were contributed maximum to the model (Table 2). In RCP 6.0 scenario model predicted higher vulnerable areas for occurrence of *A.cistellata* were in Western and central parts of Uttar Pradesh and Eastern parts of the Madhya Pradesh (Fig. 5). In RCP 8.5 scenario, the maximum relative contribution to model by the environmental variables were precipitation seasonality (53.4%), precipitation of the driest quarter (10.9%) precipitation of the coldest quarter (10.8%), annual precipitation (10.2%), isothermality (6.9%) and maximum temperature of the warmest month (5.6%) (Table 2). In RCP 8.0 scenario, it is predicted the most suitable areas for *A. cistellata* occurrence was predicted in Eastern Madhya Pradesh and medium suitable areas were predicted in western and central Uttar Pradesh. Low suitability areas predicted by the model are in Northern Bihar, Northern Jharkhand and some parts of Orissa (Fig. 5).

2070 Scenario

The potential distribution of *A.cistellata* was also predicted under different climate change scenario of 2070. In the RCP 2.6 scenario important bioclimatic variables contributed for the model were precipitation seasonality (48.2%), annual precipitation (16.3%), precipitation of the coldest quarter (15.0%), maximum temperature of the warmest month (9.5%), isothermality (5.7%) and precipitation of the driest Quarter (5.0%) (Table 3).Under RCP 2.6 scenario high suitable areas for *A.cistellata* occurrence was predicted in western Uttar Pradesh and other vulnerable areas were predicted in Jharkhand, Himachal Pradesh and Uttarakhand (Fig. 6). In RCP 4.5 scenario the important environmental variables

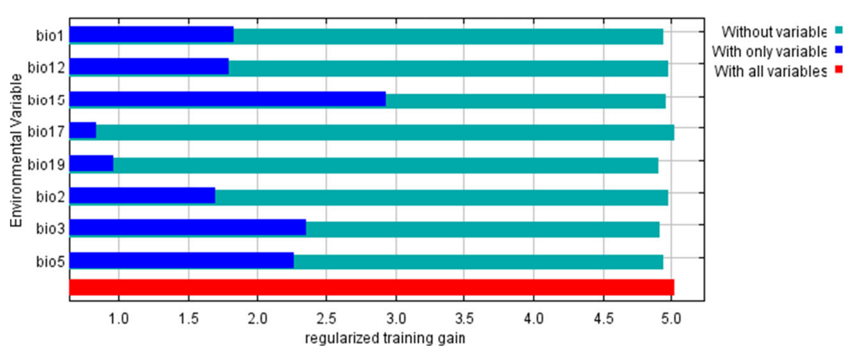

Fig. 2 Jackknife test of variable importance for *A.cistellata* under current climatic conditions (1970–2000)

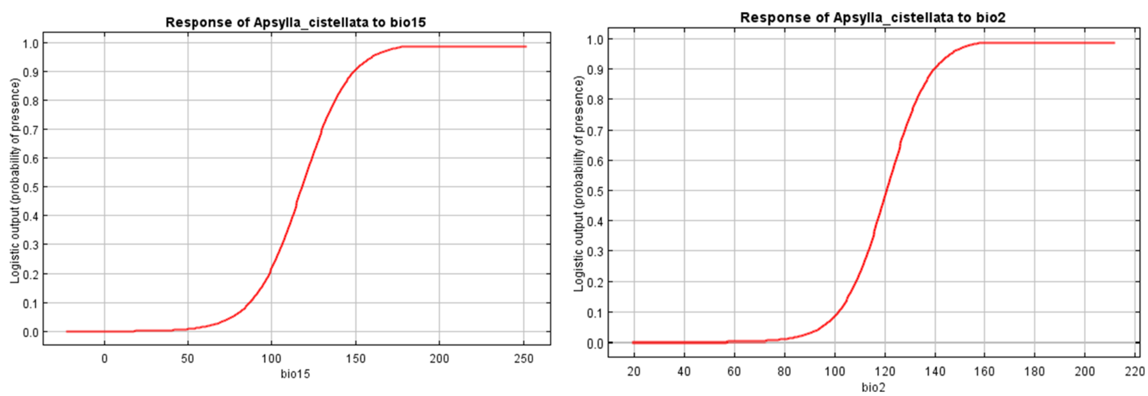

Fig. 3 Response curves of the important bioclimatic variables contributing to the model

contributed for the model were precipitation seasonality (42.2%), annual Precipitation (16.5%), precipitation of coldest quarter (15.2%), maximum temperature of the warmest month (11.50%, isothermality (8.5%) and precipitation of the driest Quarter (4.9%) (Table 3). In RCP 4.5 higher suitability areas for occurrence of *A.cistellata* was predicted in Western Uttar Pradesh, the areas relatively lesser vulnerable to attack are eastern Uttar Pradesh and Madhya Pradesh (Fig. 6). In RCP 6.0 scenario important bioclimatic variables relative contribution to the model were precipitation seasonality (51.6%), precipitation of coldest quarter (19.7%) and annual precipitation (16.30%) (Table 3). In RCP 6.0 scenario highly suitable areas for the potential distribution of *A.cistellata* was predicted in western Uttar Pradesh, Eastern Uttar Pradesh and Eastern parts of Madhya Pradesh. Other relatively less vulnerable areas for the pest occurrence was predicted in Uttarakhand, Bihar, Jharkhand and Orissa (Fig. 6). In RCP 8.5 scenario, relative contribution of the bioclimatic variables to the model were precipitation of precipitation seasonality (42.7%), annual precipitation (15.40%), maximum temperature of the warmest month (12.50%), precipitation of the driest Quarter (10.8%) and isothermality (7.4%) %) (Table 3). In RCP 8.0 scenario model predicted higher suitability areas for the occurrence of the pest in Western Uttar Pradesh, Eastern Madhya Pradesh,

Fig. 4 Geographical distribution of mango shoot gall psylla under current scenario (1970–2000)

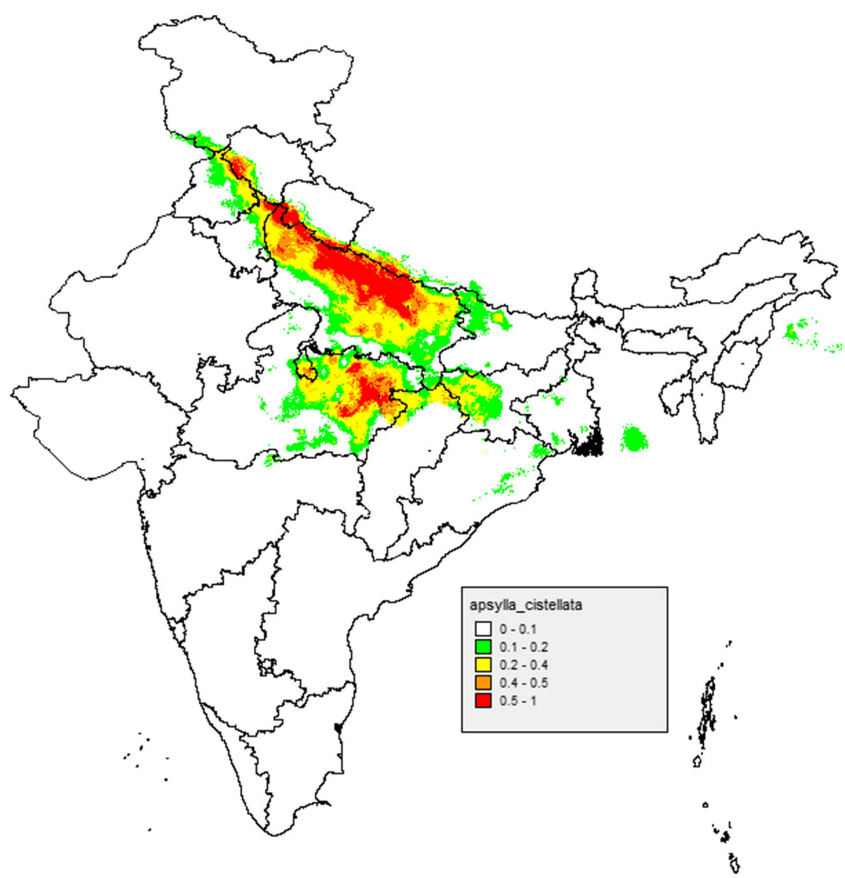

Table 1 Percent contribution of bioclimatic variables for fitting the model

Bioclimatic Variable	Current
Precipitation Seasonality (BIO15)	54.6
Precipitation of Driest Quarter (BIO17)	8.6
Isothermality (BIO3)	6.1
Precipitation of Coldest Quarter (BIO19)	12.2
Annual Precipitation (BIO12)	17.3

Northern Orissa, Northern parts of Jharkhand and Southern parts of Bihar (Fig. 6).

Discussion

Under current-future-climate change scenarios (RCP 2.6. RCP 4.5, RCP 6.0 and RCP 8.5) predicted using MaxEnt model for mango shoot gall psylla *A.cistellata* distribution, indicated that there is potential shift towards Northern plains region of the country. Across the different representative concentration pathways, precipitation-related parameters viz.., annual precipitation, precipitation

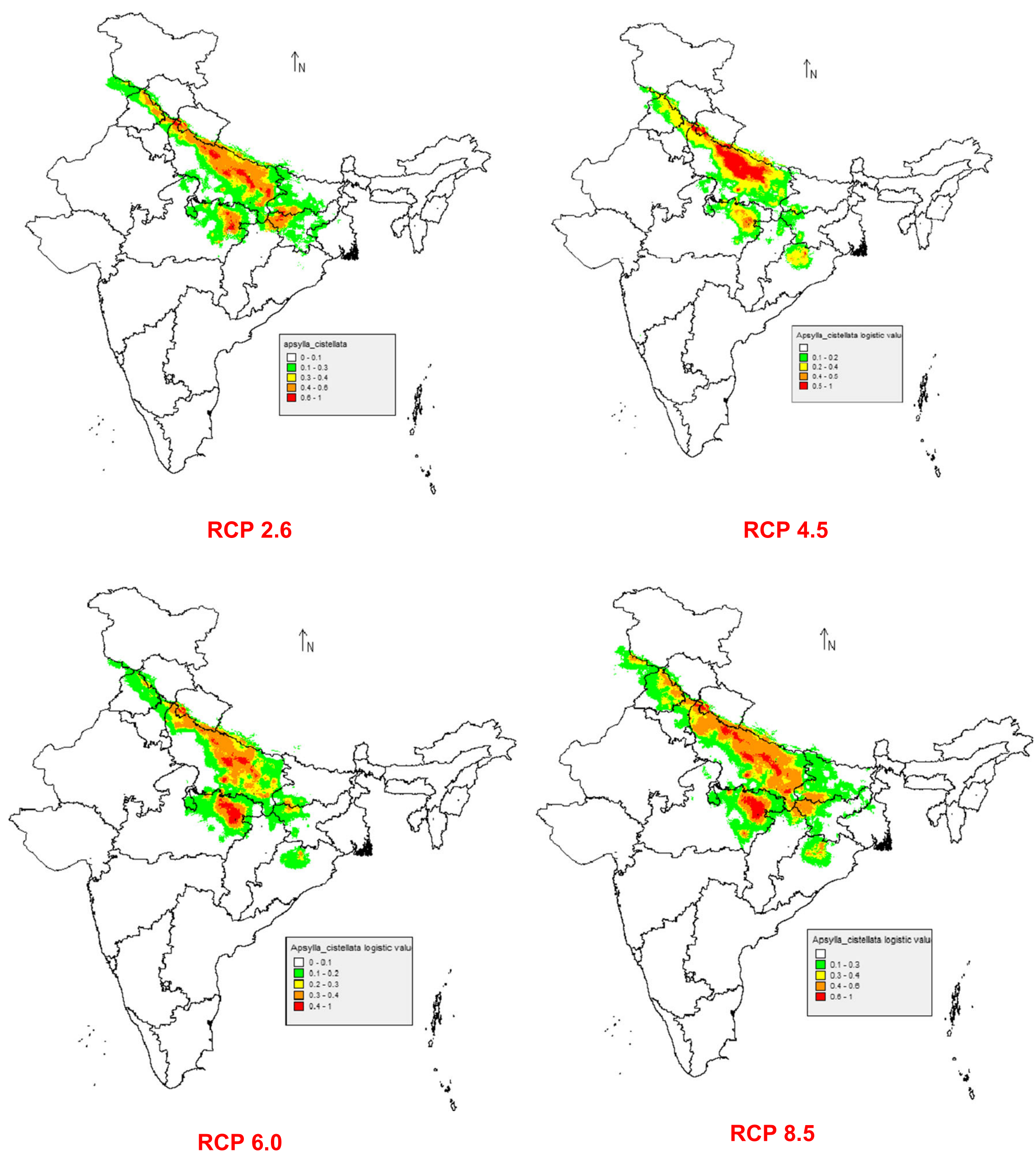

Fig. 5 Geographical distribution of mango shoot gall psylla under different future climate change scenario of 2050

Table 2 Percent contribution of bioclimatic variables for fitting the model in 2050 scenarios

Bioclimatic Variable	Different climate change scenarios			
	RCP 2.6	**RCP 4.5**	**RCP 6.0**	**RCP 8.5**
Precipitation Seasonality (BIO15)	47.7	46.8	55.5	53.4
Precipitation of Driest Quarter (BIO17)	5.9	3.3	6.2	10.9
Isothermality (BIO3)	0.0	7.1	7.7	6.9
Precipitation of Coldest Quarter (BIO19)	7.2	16.3	17.9	10.8
Precipitation of Driest Month (BIO14)	14.3	0.0	0.0	0.0
Max Temp. of Warmest Month (BIO5)	0.0	10.0	0.0	5.6
Annual Precipitation (BIO12)	21.0	15.9	10.4	0.0

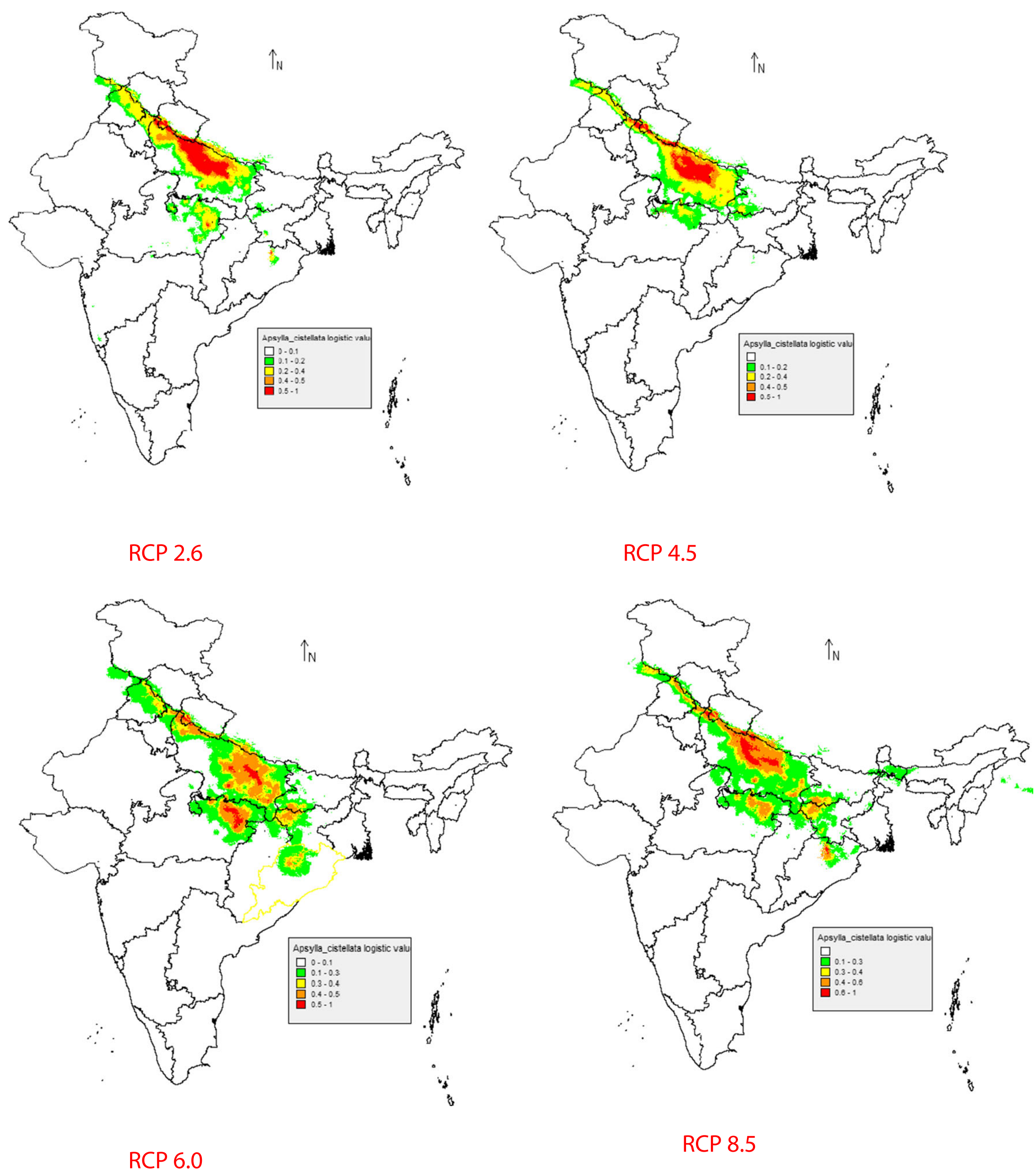

Fig. 6 Geographical distribution of mango shoot gall psylla under different future climate change scenario of 2070

Table 3 Percent contribution of bioclimatic variables in 2070 scenarios

Bioclimatic Variable	Different climate change scenarios			
	RCP 2.6	**RCP 4.5**	**RCP 6.0**	**RCP 8.5**
Precipitation Seasonality (BIO15)	48.2	42.2	51.6	42.7
Precipitation of Driest Quarter (BIO17)	5.0	4.9	0.0	10.8
Isothermality (BIO3)	5.7	8.5	9.0	7.4
Precipitation of Coldest Quarter (BIO19)	15.0	15.2	19.7	9.9
Max Temp. of Warmest Month (BIO5)	9.5	11.5	0.0	12.0
Annual Precipitation (BIO12)	16.3	16.5	16.3	15.4

seasonality, precipitation of wettest month, precipitation of the driest quarter found as major determining factors in potential distribution of *A.cistellata*. Among the temperature- related variables isothermality and minimum temperature of the warmest month are key drivers for potential distribution of *A.cistellata* under future climate change scenarios. The study revealed that the bud initiation in mango influenced by cold temperature of the month. Temperature and rainfall (precipitation) considered to be major bioclimatic variables which directly influence on infestation of *A.cistellata* in mango. There is strong evidence to suggest that, the psyllids are highly effective dispersers over short and long distances, although dispersal through wind-assisted mechanisms (Hodkinson 2009). A possible reason for the localized incidence of *A. cistellata* found in India due to annual rainfall is more than 1100 mm and more than 30 °C temperature difference between the maximum and minimum (Singh 2003). The present study findings in accordance with previous work which implicated differential impact of climate change on *A.cistellata* expansion to the new areas. Earlier, the pest was thought to be the endemic to '*Tarai*' regions of Uttar Pradesh, however recently it has been observed that pest spreading towards Lucknow region which is major mango growing belt. In the past, the pest caused severe damage to mango crop in Faizabad, Sitapur and Barabanki districts of Uttar Pradesh was noticed (Gundappa et al. 2014).

Psyllids evolved at greater extent to exploit a variety of host plants vis-a vis that have also diversified their physiognomy, physiology and phenology over evolutionary period of time acclimatized for adaptation to the varying global environmental conditions (Hodkinson 2009). The occurrence, growth, and spread of pest depends not only on the biological characteristics of pest but also on the host plants, farming systems, management levels and environmental conditions. Meteorological variables are extremely important factors. If these factors relatively consistent would incisive pest to outbtreak at larger scale leading to epidemic (Monteith 2000; Qin et al. 2017). Findings of the present study are in agreement with the fact that wherever adult emergence of *A.cistellata* coincided with the bud initiation phenomenon of mango and there is more chances of the high infestation of the pest. Since the bud initiation starts during February –March in North India, may be the main reason for the localized occurrence and severity of the pest. During the results interpretation from the present study at most caution has to be taken because MaxEnt model prediction based on uncertainties due to the quality of occurrence data, sampling bias, resolution of spatial data layers, species characteristics, and spatial autocorrelation (Dormann et al. 2008; Jarnevich et al. 2015). The MaxEnt model accuracy depends on the adjustments with respect to selection of background points and extent, value of regularization multiplier, and selection of feature types (Kumar et al. 2014). The present study included available current climate conditions from 1970 to 2000. Considering the potential drawbacks from the past works in the modeling process, we took utmost care in model calibration and thus generating accurate predictive models that are consistent with the current distribution of the pest (Figs. 1 and 4).

This study provides deeper insight on potential distribution of *A.cistellata* using a MaxEnt model. The results from present study can be used in planning and designing pest management strategies to prevent introduction and establishment of pest in newer areas and to develop forewarning strategies. The suitability maps developed from study can be efficiently used for formulating pest management policies to suppress pest from conventional areas and to avoid reoccurrence in those areas. The study also serves as an important tool in understanding potential changes in distribution and activity of pest in response to current-future climate change scenarios. Findings of the study also provide a deeper insight on the climatic factors that affect *A.cistellata* distribution in India.

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