CLIMEX simulated predictions of Oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) geographical distribution under climate change situations in India

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An attempt was made to understand the influence of climate change on future potential distribution of Oriental fruit fly (OFF), *Bactrocera dorsalis* (Hendel), a polyphagous pest on a wide variety of fruit crops in India. Prediction of the potential distribution of OFF was done for different time-frames (2030, 2050, 2070 and 2090) under the A1B climate change scenario (CSIRO-Mk3.0, a global climate model) using CLIMEX software. The model predicted an overall gradual decrease in terms of area suitability for OFF in India by 2090 due to increase in various stress factors to the pest. In temperate regions of the north and northeastern parts, incidence of the pest may increase due to rise in temperature coupled with decrease in cold stress. In North India, the model predicts the regions of Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Haryana and Punjab to be more climatically suitable for OFF by 2030 and there is an expected steady increase in suitability by 2050, 2070 and 2090. The CSIRO model for North East indicated that by 2090, Assam, Arunachal Pradesh and Manipur would become highly suitable for the pest. The projected range expansion in terms of area suitability was recorded up to 100 km in temperate regions. Central and western India are projected to become progressively less suitable by 2030, 2050 and totally unsuitable by 2090. In South India, there was a slight reduction in climatic suitability for OFF in terms of ecoclimatic index over time-frames 2030, 2050, 2070, 2090 as highly suitable, optimal, suitable and marginally suitable respectively. Regression analysis was carried out using growth index obtained from CLIMEX and pest trap counts. Additionally, field level validation of the model was carried out for selected locations.

Keywords: *Bactrocera dorsalis*, climate change, geographical distribution, Oriental fruit fly.

THE Oriental fruit fly (OFF), *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) is a destructive polyphagous pest on a range of wild and cultivated fruit crops[1,2]. It is a major pest on mango and causes up to 31% fruit loss in India[3]. Further, these fruit flies are also of quarantine importance due to their restricted geographical distribution and up to 26,902 million rupees economic loss has been reported[4]. The risk of its spread to new areas is mainly through infested fruits facilitated by its concealed nature of infestation, wide host range, high fecundity, food adaptability of the larvae[5], short life cycle, rapid dispersal ability (can fly 50–100 km) and possible influences of climate change[2,6]. Studies indicate an increase in global average temperatures leading to regional climate changes that may have immediate effects mainly on the population dynamics and distribution of poikilotherms like insects whose internal body temperature depends on external environment.

Climate model projections of the fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC) indicated an increment in the global surface mean temperature of 1.1–2.9°C (2–5.2°F) for their lowest emission scenario and 2.4–6.4°C (4.3–11.5°F) for their highest by the end of the century[7]. Aforesaid drastic change in climate can have adverse effects on the population dynamics as well as status of the insect pests of crops[8] and in particular on global agriculture[9]. Some pests which are already present in small areas, or at low densities may be able to exploit the changing conditions by spreading more widely and reaching damaging population densities and vice versa[10,11]. Increase in temperature due to climate change causes poleward migration or expansion in the ranges of many organisms[12] and also allows higher rates of growth and reproduction in insects[3]. Studies on aphids and moths have revealed that due to increase in temperature, the minimum flight temperature required by the insect is attained sooner, aiding in dispersal capacities[13–16]. Climate change may also result in pest species replacement and rendering many places unsuitable for the survival of the existing pest[17]. Increase in temperature has resulted in the migration/expansion/shift of the insects towards north as observed in Ediths checkerspot butterfly[12].

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Models (ecological niche models or bioclimatic models) to predict potential distribution of a range of species are widely used to examine the climatic suitability of species under current and future climate change conditions[18]. Most bioclimatic models use the known ecological and climatic factors of poikilotherms in their native habitats to predict their potential distribution elsewhere[19]. One such bioclimatic software is the CLIMEX, which enables the user to estimate the potential geographical distribution and seasonal abundance of a target pest species in relation to observed climate. The modelling technique works on the assumption that if we know where a species lives we can infer what climatic conditions it can tolerate[20]. Using this principle, potential distribution maps can be generated under both present and future climate change scenarios which will have high implications in pest management in both agricultural and horticultural ecosystems. The multifunctional software CLIMEX has been widely used in more than 40 countries for illustrating the potential distribution of flora, fauna, vector-borne diseases, crop pests and their natural enemies[21–24]. Perusal of the literature reveals an array of prediction models based on possible impact of climate change on the distribution of OFF for different regions in the world[25–28]. The diverse geo-climatic conditions of India are expected to change in various regions of the country due to predicted climate change and may influence the distribution of OFF. Predicting the potential geographic distribution of quarantine pests like OFF is pivotal in managing the risk of its spread to new areas under climate change situations[21]. However, studies to understand the future potential distribution of OFF in India are not available. Thus, the present study was taken up with the objective of identifying changes in the potentially suitable regions for the establishment of OFF in India under future climate change situations, based on its present distribution.

Materials and methods

Potential distribution model

In the present study, 'compare location' function of CLIMEX version-3 was used to generate distribution models of OFF for present and possible future climate change conditions with special reference to India. CLIMEX uses two constraints to estimate the potential growth and survival of a population at a given location, i.e. growth (mainly temperature and soil moisture) and stress indices (cold, heat, wet and dry stress). The values of these two indices are clubbed to generate the ecoclimatic index (EI), generally scaled between 0 and 100. An EI close to 0 indicates location not favourable for long-term survival of a species and EI nearer to 100 as highly suitable. As EI of 100 is not possible under natural systems, in the present study an EI of >20 was considered as highly suitable for survival and establishment of the pest, based on the present distribution of the pest.

The 'compare location' function uses meteorological database consisting of monthly long-term average climatic variables, viz. maximum and minimum temperatures, rainfall, rainfall patterns, relative humidity (RH) and soil moisture for any number of locations worldwide. An iterative process comparing the known and predicted distributions for the same region was adopted to arrive at the parameter fitting. After adjusting the parameter values, the data were used to run the model for predicting the potential distribution of the species.

Present and future climate data

A global climate model (GCM), CSIRO-Mk-3.0 (hereafter CS), from CLIMOND 30′ gridded climate data, was used to obtain current and future climate data for the study[29]. The model was run with the A1B group of A1 storyline of IPCC-SRES[7] for four future time-frames, i.e. 2030, 2050, 2070 and 2090 as against the base (average of 1961–1990).

Known distribution of OFF

OFF is widely distributed throughout the world, particularly in Asia (more than 20 countries, including India with high infestation records), North America (Hawaii, eradicated in California and Florida), and the Pacific islands (Mariana Islands and Tahiti)[2].

Climatic preference of the pest

Fifty-one locations with known distributions of OFF around the world were used in DIVA GIS to find the climatic factors preferred by the pest, i.e. climate envelope which is considered as a further validation of temperature parameters being used to run the CLIMEX software (Table 1). Most of the pest distribution records (around 27) lie between annual mean temperatures of 21.7°C and 28.6°C, lower and upper threshold temperatures as 11°C and 36°C respectively, and preferred annual precipitation range of 200–2800 mm (Figure 1).

Fitting CLIMEX parameters

Data on present distribution of OFF (Figure 2) were obtained from published historic data (CABI)[2,30,31] and subsequently the CLIMEX model for OFF was fitted to the geographic range within India and confirmed with its worldwide distribution for the reference climate (1961–1990). CLIMEX parameter values (Table 1) that agreed with the known native distribution of the species were

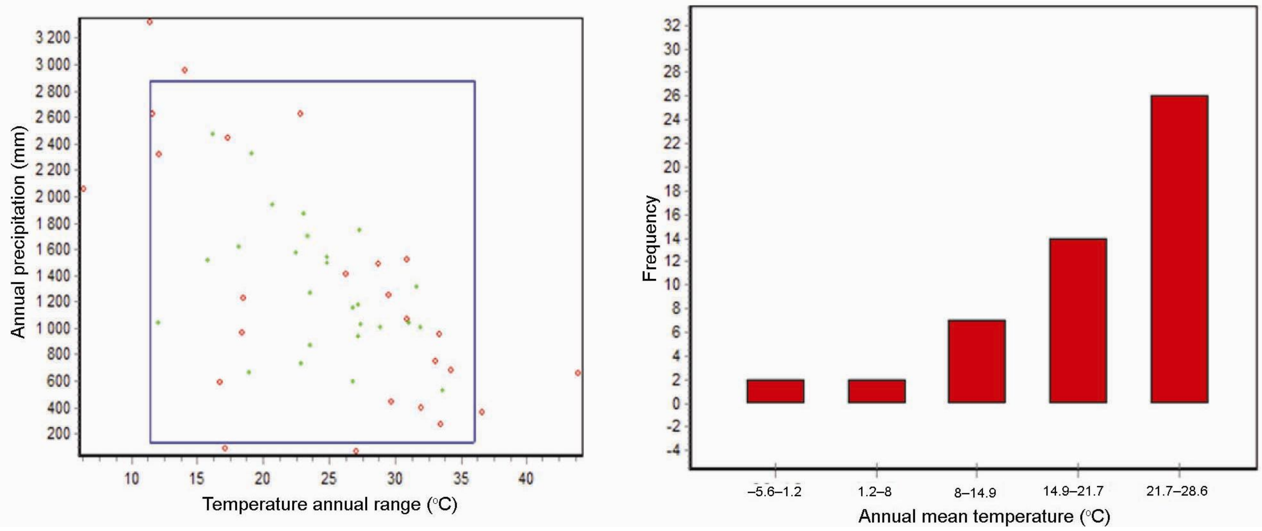

Figure 1. Climatic envelope obtained from DIVA GIS for 51 locations.

Table 1. CLIMEX parameter values for Oriental fruit fly modelling

Parameter	Mnemonic	Value
Limiting low temperature	DV0	11.8°C
Lower optimal temperature	DV1	22°C
Upper optimal temperature	DV2	28°C
Limiting high temperature	DV3	35°C
Limiting low soil moisture	SM0	0.1
Lower optimal soil moisture	SM1	0.5
Upper optimal soil moisture	SM2	1
Limiting high soil moisture	SM3	2
Minimum degree-day cold stress threshold	DTCS	10°C-day
Degree-day cold stress rate	DHCS	–0.00025 week^{-1}
Heat stress temperature threshold	TTHS	35°C
Heat stress temperature rate	THHS	0.0002 week^{-1}
Dry stress threshold	SMDS	0.1
Dry stress rate	HDS	–0.0001 week^{-1}
Wet stress threshold	SMWS	2
Wet stress rate	HWS	0.009 week^{-1}
Degree-days per generation	PDD	358

subsequently verified to ensure that they were biologically reasonable with exceptions in a few places like Sikkim, where though pest was recorded, its presence was not reflected in the present distribution, even after iteratively adjusting various parameters.

CLIMEX parameters

Parameters pertaining to the distribution of OFF used for the study were slightly modified from earlier studies[27,28]. In the present modelling only rainfed factor was considered for simulations.

Temperature index

The lower temperature threshold was set as 11.8°C (DV0), optimum range between 22°C (DV1) and 28°C (DV2) and lethal upper temperature as 35°C (DV3) for matching the current distribution of the pest.

Moisture index

Soil moisture plays a pivotal role in the survival of OFF, as the mature maggots from infested fruits drop down to the soil for pupation. A soil moisture range of 10–70% is best suited for the maggot to pupate[32]. Thus the soil moisture threshold (SM0), optimum lower/higher soil moisture (SM1 and SM2) and upper soil moisture (SM3) values were set at 0.1, 0.5, 1.0 and 2 respectively. SM3 was set as 2.0 so as to include most of the wet regions of North East India and the Western Ghats where OFF is known to exist.

Dry stress

The dry stress threshold was set to 0.1 (SMDS, proportion of soil moisture holding capacity) with an accumulation rate of –0.0001 week^{-1} (HDS). These parameters were set to accommodate the dry regions of Gujarat and Rajasthan where the incidence of OFF was observed.

Wet stress

The wet stress threshold was set at 2 (SMWS) and wet stress rate was set to 0.009 week^{-1} (HWS) to include wet regions of the North East and parts of Kerala with OFF occurrence.

Cold stress

Cold stress degree day threshold was set to 10°C (DTCS) and cold stress degree day rate was set to 0.00025 week^{-1}

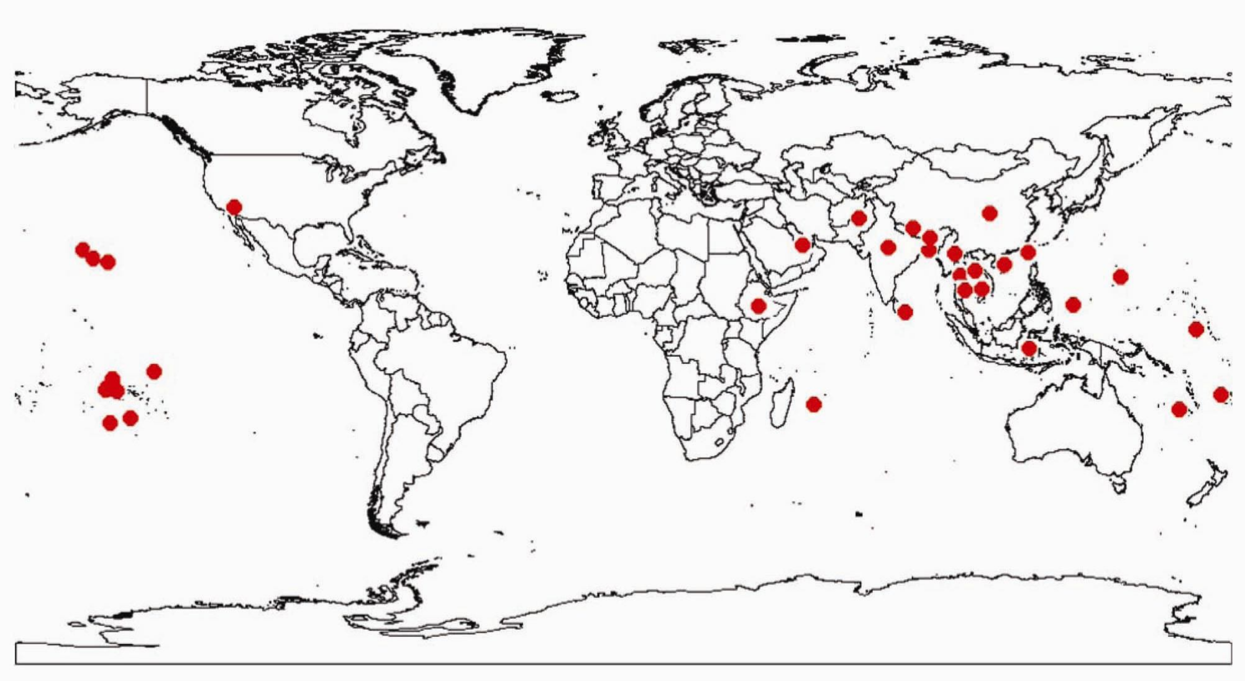

Figure 2. Global known distribution of Oriental fruit fly (OFF)[2].

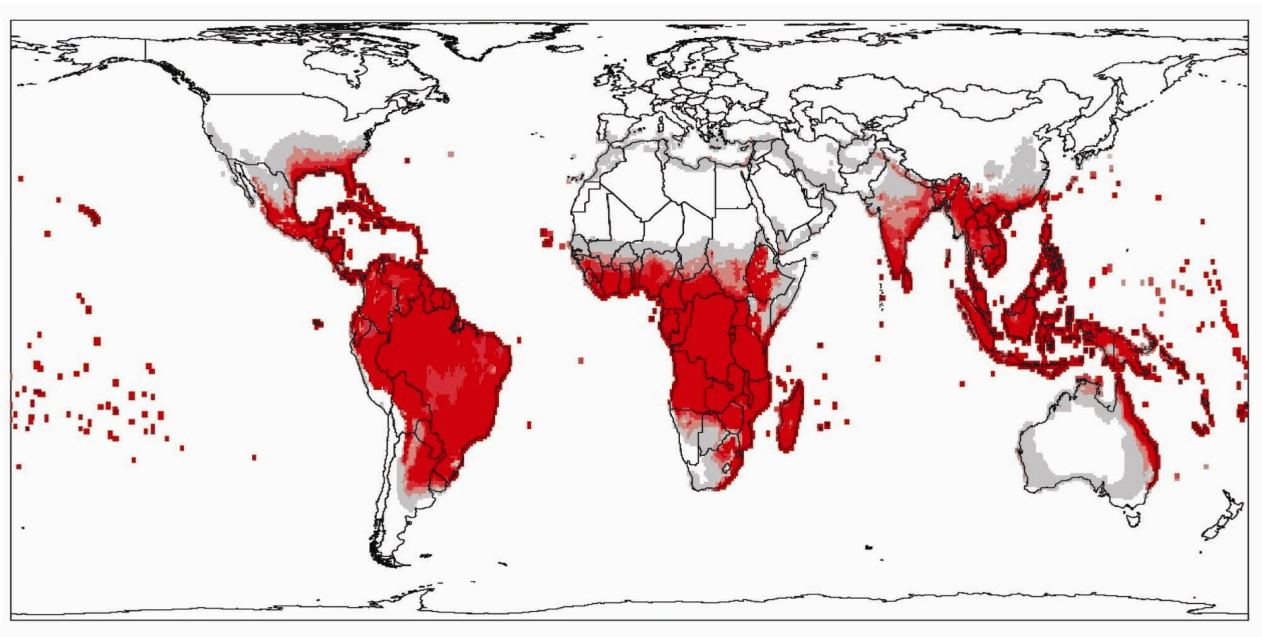

Figure 3. Current global distribution of OFF as modelled using CLIMEX. Ecoclimatic Index (EI) values: ☐ Unsuitable (0–0.99); ☐ Marginal (1–7.35); ☐ Suitable (7.35–13.7); ☐ Optimal (13.7–20); ☐ Highly suitable (20 +).

(DHCS) to include places in the cold regions of Jammu & Kashmir, Uttarakhand and Manipur with OFF incidence.

Heat stress

Heat stress temperature threshold was set at 35°C (TTHS) as OFF is known to exist in hot regions like Rajasthan as well as Gujarat and heat stress temperature rate was set at 0.0002 week^{-1} (THHS) to have largely uniform distribution in central and western India.

Field data validation

The simulation models for the present distribution of OFF were validated using field data of seasonal incidence of the pest from four different locations worldwide, based

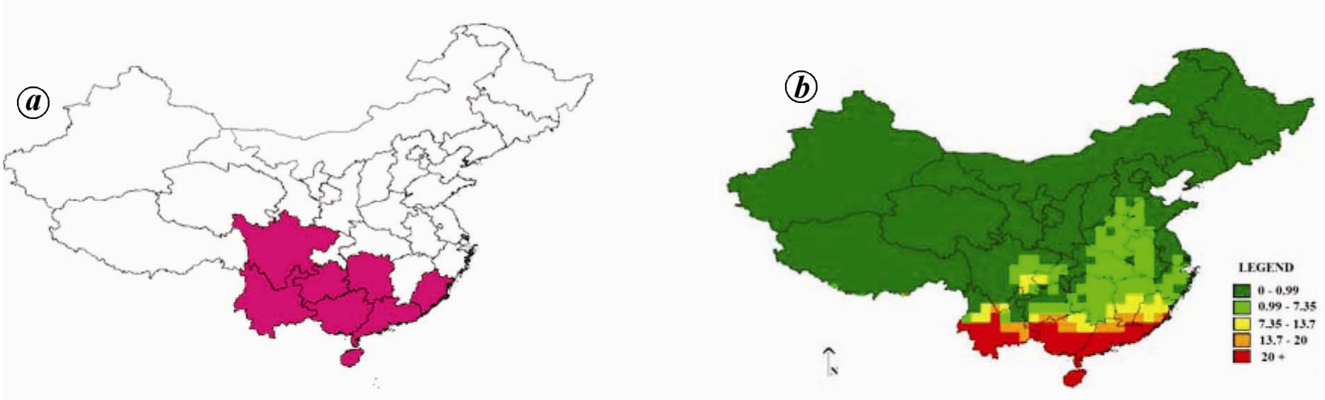

Figure 4. ***a***, Known distribution of OFF in China[37,38]. ***b***, Potential distribution of OFF in China for current climate using CLIMEX, based on EI values.

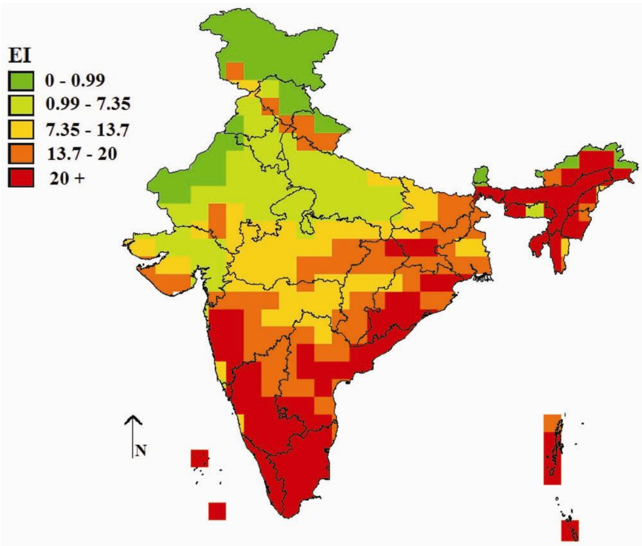

Figure 5. EI-based climate suitability for OFF under the reference climate (1961–1990 average) projected using CLIMEX for India.

on pest distribution data[33–36]. Additionally, model validation was attempted through regression analysis of weekly trap counts and growth indices for Baoshanba, China as validation outside the country.

Results

Current climate – global distribution of OFF

The potential worldwide distribution of OFF modelled in this study is shown in Figure 3 and closely agrees with known potential distribution (Figure 2) stretching from the tropics to the subtropics. Based on the EI values, various regions were identified as unsuitable (0–0.99), marginal (1–7.35), suitable (7.35–13.7), optimal (13.7–20) and highly suitable (20 +). OFF is prevalent in southern China in most parts of Fujian, Hainan, Guangdong, Guangxi, Hunan, Guizhou, Yunnan and Schuian[37,38]. In the present study, CLIMEX predicted southern China as being suitable/highly suitable for OFF and is in close agreement with the known distribution of the pest (Figure 4). Further, optimal climate conditions for OFF occur in large parts of South America, Central America, Sub-Saharan Africa, Queensland, most of the Pacific islands and with marginally suitable areas in southeastern USA. Climatic conditons in many of the warm areas such as Southern Mediterranean Europe and northern New Zealand are projected to be marginally suitable.

Current climate situation – distribution of OFF in India

The model closely resembles the known distribution of OFF in India representing its presence in all the suitable regions. However, the climatic unsuitability for OFF was observed in hotter regions of northwestern Rajasthan (with dry and heat stresses) and northern Jammu & Kashmir, Himachal Pradesh and Uttarakhand (with cold stress). Climatic conditions are projected to be marginally suitable to OFF in many warm areas such as parts of Gujarat, Rajasthan, Haryana, Punjab, Uttar Pradesh and northern Madhya Pradesh (Figure 5).

Future climate projections – distribution of OFF in India

Climate change is expected to affect the distribution of OFF in India as it is expected to spread northwards into areas that are currently too cold and unsuitable. In North India, the CS model predicts the regions, viz. Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Haryana and Punjab to be more climatically suitable for OFF by 2030. This expansion is expected to steadily increase through the time-frames 2050, 2070 and 2090 (Figure 6), whereas central and western India are projected to become progressively less suitable by 2030, 2050 and totally

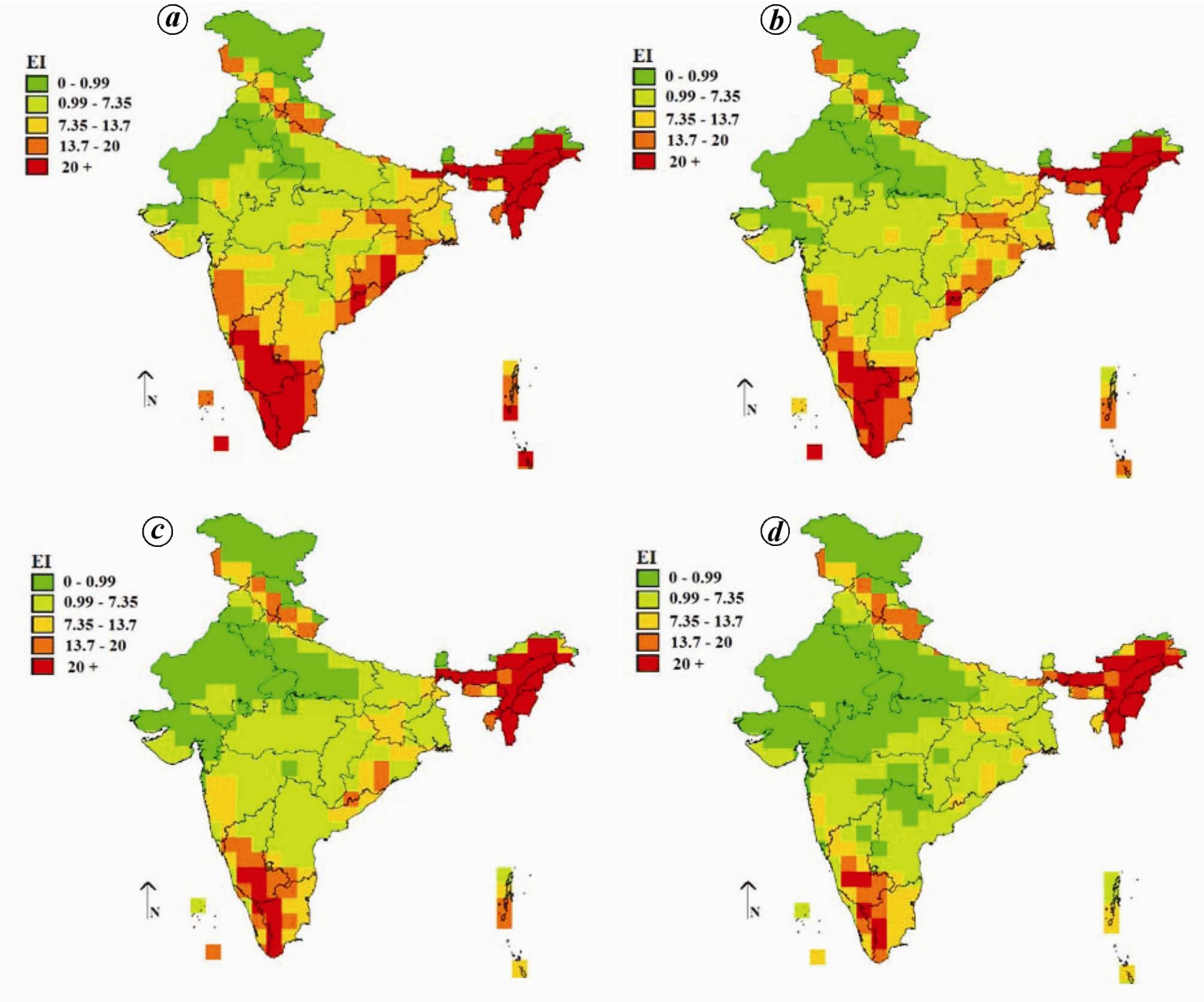

Figure 6. EI-based climate suitability of *Bactrocera dorsalis* under future climate scenarios as projected by CLIMEX: ***a***, 2030; ***b***, 2050; ***c***, 2070; ***d***, 2090.

unsuitable by 2090. The CS model for the North East indicated that by 2090, Assam, Arunachal Pradesh and Manipur would become highly suitable for the pest. In South India, there is a slight reduction in climatic suitability for OFF in terms of EI over time-frames, 2030, 2050, 2070 and 2090 (highly suitable, optimal, suitable and marginally suitable respectively).

Northward range expansion in terms of area suitability is projected up to 100 km in temperate regions like Jammu & Kashmir by 2090 due to decrease in cold stress. In warm regions like the Kolar district, Karnataka (where mango is predominantly grown), because of increase in heat stress, the area may become unsuitable to OFF by 2090.

Field-data validation

The present distribution of OFF (Figure 5) was validated by seasonal incidence obtained from historic data. The CLIMEX generated growth index (Figure 7) for the selected location, viz. Baoshanba was in accordance with the seasonal incidence of OFF. Thus CLIMEX model gave reliable projections of the pest status in the present and future climate change scenarios. The regression analysis of weekly trap counts and growth indices was significant ($P < 0.05$; $F = 5.785$; d$f = 1$) with a R^2 value of 0.36 (Figure 8).

Discussion

Studies world over indicate that temperatures have been changing both at global and regional scales during the past century[7]. Considering the temperature as a vital climatic component that strongly influences the distribution of poikilotherms like insects, our research analysis outlines the shifts in suitable climatic areas for OFF under future climatic scenarios using CLIMEX.

CLIMEX predicted a mixed outcome pertaining to region-specific suitability in the northern and western states

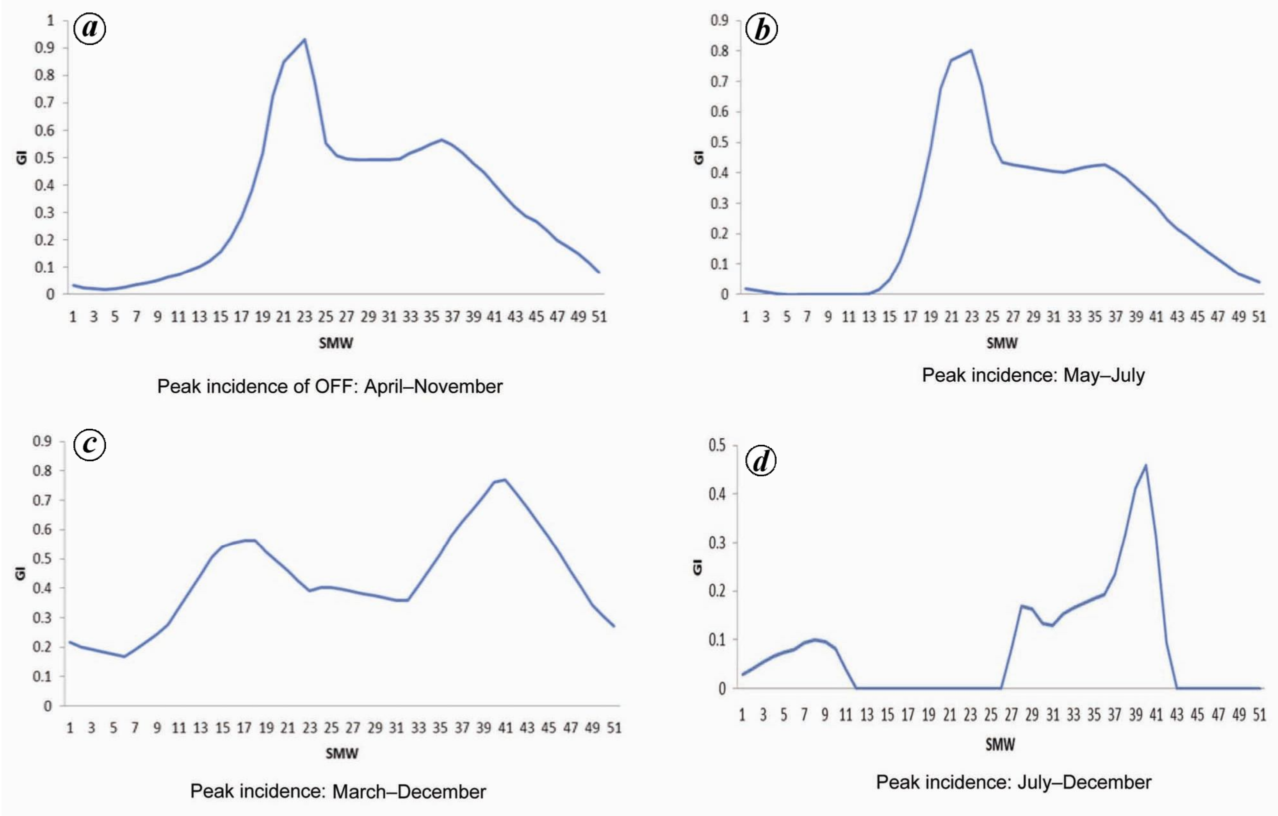

Figure 7. Growth index curve for *B. dorsalis* (base year 1961–1990): ***a***, Baoshanba, China; ***b***, Kunming region, China; ***c***, Taichung, Taiwan; ***d***, Ludhiana, Punjab.

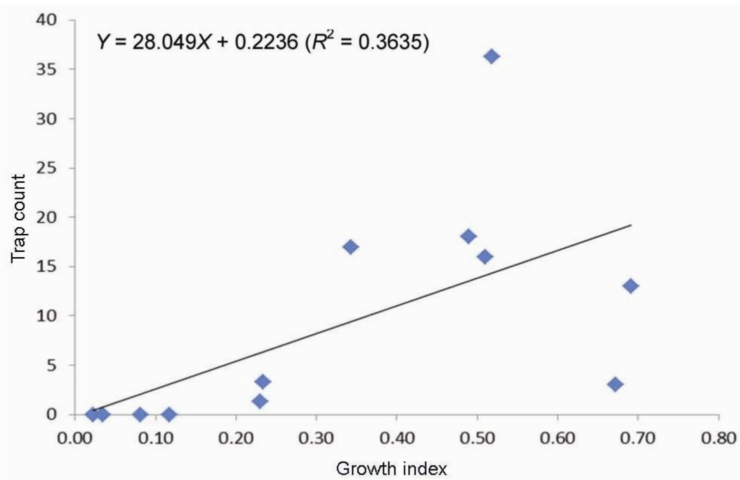

Figure 8. Scatter plot of trap counts against growth index for test location, Baoshanba.

of India. An increase in the climatic suitability of OFF is expected to shift towards north in parts of Jammu & Kashmir by 2090. This predicted spread is attributed to the expected increase in temperature and decrease in cold stress. A similar trend is expected in Himachal Pradesh and Uttarakhand, where new areas were found becoming suitable for the establishment of the fruit fly. In Punjab, a slight decrease in suitable areas is expected. Most of the regions in Haryana are expected to become less suitable by 2090. In Uttar Pradesh, much of the marginally suitable regions are expected to become unsuitable by 2090 with a significant decrease in EI, due to the increased heat stress. An increase in dry and heat stresses in areas like Rajasthan, parts of Madhya Pradesh (particularly, northern and western regions) and entire Gujarat (except parts of some districts, like Junaghad, Amreli, Bhavnagar and Porbhandar) will make survival of the pest difficult by 2090 (Figure 6). Though our studies are confined to A1B scenario, predictions made elsewhere for A2 and B1 climate change situation for global[26] and New Zealand conditions[25] using CLIMEX reported differential suitability for OFF, which is mainly attributed to different stress factors in different climatic zones against the pest.

Suitability for OFF in most parts of the southern states is expected to decrease from highly suitable to marginal, gradually from 2030 to 2090, except for projected optimal conditions in a few parts, viz. southern Karnataka, Kerala and regions in Tamil Nadu (Figure 6). In the NE states, the expected congenial conditions for OFF remain highly suitable because of decrease in various stresses. Exceptions are observed in a few places in Assam and Arunachal Pradesh, with a slight decrease in EI due to the increase in wet stress (Figure 5).

From the results, it is evident that majority of the currently suitable areas such as southern and NE states would continue to remain suitable for OFF, with few exceptions.

The present study provides an indication of the possible change in the potential distribution of OFF in future as a consequence of predicted climate change. However, in the present study, while deciding the regional climatic suitability for OFF, main emphasis was given to climatic variables, viz. temperature, soil moisture, heat/cold stress and dry/wet stress. Other factors that decide the survival of OFF, viz. presence of suitable hosts, host fruiting phenology, interspecies competitions, etc. were not considered. As climate changes, most of the areas where OFF currently occurs may turn climatically unsuitable. The present modelling would therefore be useful in planning future strategies in regions that may be positively or negatively impacting the pest. Several such studies on the impact of climate change on insect pests need to be undertaken to tackle the pest problem associated with Indian agriculture. However, possible errors while extrapolating the climate change scenarios based on existing climatic conditions may occur and need constant emphasis of climate change predictions. From the pest management perspective, the potential distribution maps of pest species will enable the policy makers at both national and international levels to make quick rational decisions about distribution of pests and their natural enemies both under current and future climate change situations. From a pest risk analysis perspective, the application may indicate areas vulnerable (highly suitable) for an exotic (invasive) pest species under climate change situation which will help in the prevention of their introduction.

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ACKNOWLEDGEMENTS. This study is part of the ICAR sponsored project 'National Initiative on Climate Resilient Agriculture (NICRA)'. We thank the Director, Indian Institute of Horticultural Research, Bangalore for encouragement and providing us with the necessary facilities.

Received 12 December 2013; revised accepted 30 April 2014