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Impact of climate change on *Helicoverpa armigera* voltinism in different Agro-Climatic Zones of India

Kiran Gandhi Bapatla [a,*], Ajay Deep Singh [a], Vennila Sengottaiyan [b], Rajasekhara Rao Korada [c], Srujana Yeddula [d]

[a] ICAR-Indian Institute of Pulses Research, Kanpur, Uttar Pradesh, India
[b] ICAR- National Research Centre for Integrated Pest Management, New Delhi, India
[c] ICAR-National Rice Research Institute, Cuttack, Odisha, India
[d] ANGRAU-Regional Agricultural Research Station, Nandyal, Andhra Pradesh, India

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ABSTRACT

The Gram pod borer, *Helicoverpa armigera* (Noctuidae: Lepidoptera) is a cosmopolitan agricultural insect pest that prefers to feed on plant's protein biomolecules. Out of different density-independent factors, surface air temperature majorly affects the incidence and damage of the *H. armigera* on the crops. Early prediction of *H. armigera* generations (voltinism) in future climate years perhaps prevent additional damage in various crops and improve the farmers preparedness. In this study, future climate data that is temperature obtained for eleven Agro-Climatic Zones (ACZs) of India under four Representative Concentration Pathways (RCPs) scenarios in different climate years (2010, 2030, 2050, 2070, 2090) using weather file generator MarkSim web application. The accumulation of Growing Degree-days (GDD) by *H. armigera* at eleven ACZs in each climate year under different RCP scenarios was estimated using temperature data. The mean surface air temperature is predicted to 0.51 °C, 1.03 °C, 1.57 °C and 2.1 °C in climate years 2030, 2050, 2070 and 2090, which escalated annual *H. armigera* Gen. to 12.88, 13.33, 13.79 and 14.23, respectively over the baseline climate year 2010. Likewise, under RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios *H. armigera* Gen. is predicted to 12.86, 13.29, 13.23 and 13.97 per annum with mean surface air temperatures 27.4 °C, 27.92 °C, 27.86 °C and 28.72 °C, respectively. The Eastern Coastal Plains and Hills Zone (ACZ 11) across climate years and RCPs has experienced a considerable increase in mean surface air temperature minimum (25.22 °C) and maximum (34.61 °C), which likely favor the GDD accumulation (6319.91) and the Genrations (14.97) in *H. armigera*. Therefore, the Eastern Coastal Plains and Hills Zone of India could be identified as *H. armigera* risk zone in near future. The present predictions in various ACZs of India may be significant in planning *H. armigera* management.

1. Introduction

The Intergovernmental Panel on Climate Change projected global average surface temperature is likely to rise 1.5 °C between 2030 and 2050 (IPCC, 2018); thus, promoting indirect effect on inter-trophic interactions amid changing phenology and demography of terrestrial organisms (Parmesan 2007; Massad and Dyer 2010). Climate change may cause herbivory to increase two to four-fold (Coley, 1998) with associated pest outbreaks (Kurz et al., 2008). The development and distribution of insect pests are influenced by their thermal thresholds; though thermal requirements vary with species, climate warming can expand the survival boundary (Franco et al., 2006) and changes in temperature thresholds could cause extreme effects on the growth and development of insect pests (Honek et al., 2003).

Gram pod borer, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), is one of the most serious global insect pests characterized by high fecundity, polyphagy, facultative diapause, and high mobility (Firempong and Twine 1986; Wu and Guo 2005). In India, *H. armigera* incidence is common on cotton, pigeon pea, chickpea, sunflower, tomato, sorghum, millets, okra, and corn (Manjunath et al., 1989; Sharma 2001). Higher *H. armigera* moth activity and the capture of more moths have resulted from increased temperatures (Maelzer and Zalucki, 1999; Maelzer et al., 1996). Future climate years along with higher temperatures predicted one to two additional generations of *H. armigera* with

* Corresponding author. ICAR- NRRI, Regional Coastal Rice Research Station, Naira, Andhra Pradesh, India.,
E-mail addresses: kiran.baptala@icar.gov.in, bkg0530@gmail.com (K.G. Bapatla).

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Table 1
Agro-Climatic zones and locations with coordinates.

Zone No.	Zone Name	Location	Latitude (°N)	Longitude (°E)
3	Lower Gangetic Plain Region	Murshidabad	24.1759	88.2802
		Purulia	23.3322	86.3616
4	Middle Gangetic Plain Region	Gaya	24.7914	85.0002
		Mirzapur	25.1337	82.5644
5	Upper Gangetic Plains Region	Aligarh	27.8974	78.088
		Kanpur	26.4499	80.3319
6	Trans-Ganga Plains Region	Jajjar	28.6055	76.6538
		Jind	29.3255	76.2998
7	Eastern Plateau and Hills	Kalahandi	19.9137	83.1649
		Rajnandgoan	21.0972	81.0338
8	Central Plateau and Hills	Hamirpur	31.6862	6.5213
		Narsinghpur	22.9473	79.1923
9	Western Plateau and Hills	Kalburgi	17.3297	76.8343
		Yavatmal	20.3899	78.1307
10	Southern Plateau and Hills	Dharmapuri	12.1211	78.1582
		Kurnool	15.8281	78.0373
11	Eastern Coastal Plains and Hills	Prakasam	15.3485	79.5603
		Thiruvallur	13.2544	80.0088
13	Gujarat Plains and Hills	Kachchh	23.7337	69.8597
		Vadodara	22.3072	73.1812
14	Western Dry Region	Alwar	27.553	76.6346
		Jaisalmer	26.9157	70.9083

reduced generation time (Srinivasa Rao et al., 2016). A higher incidence of *H. armigera* larvae on pigeon pea was found associated with the rise in temperature across the locations and seasons (Bapatla et al., 2020). Porter et al. (1991) stated that climate change may result in a higher population growth rate and an increased number of generations. The pest activity could be predicted from the number of degree days accumulated above the specified base temperature for 24hrs period (Srinivasa Rao et al., 2016; Bapatla et al., 2020).

Over time, climate change projections are continuously evolving and the Coupled Model Inter Comparison Project Phase 5 (CMIP 5) models include advances in the parameterization of physical processes and representation of new physical processes (Srinivasa Rao et al., 2020). Climate projections are generally more reliable at the global scale than at smaller regional scales (Taylor et al., 2012). However, CMIP 5 based temperature projections for India are far more reliable (Chaturvedi et al., 2021). MarkSim General Circulation models (GCM) is a stochastic climate simulation platform that creates annual charts of a) daily rainfall, air temperatures (maximum and minimum), and solar radiation and b) annual data files that are compatible with the Decision Support System for Agrotechnology Transfer (DSSAT) crop modeling system (Srinivasa Rao et al., 2015). Climate projection with MarkSim web application is available with 17 GCM and four Representative Concentration Pathways (RCPs) *viz.,* RCP 2.6, RCP 4.0, RCP 6.0, and RCP 8.5 (Jones and Thornton, 2013). The present study presumed linking evidence between climate change phenomena on the incidence of *H. armigera* across Agro-Climatic Zones (ACZs). This study aims to identify the potential *H. armigera* risk areas in future climate projections using surface air temperature (henceforth temperature) and degree days accumulation.

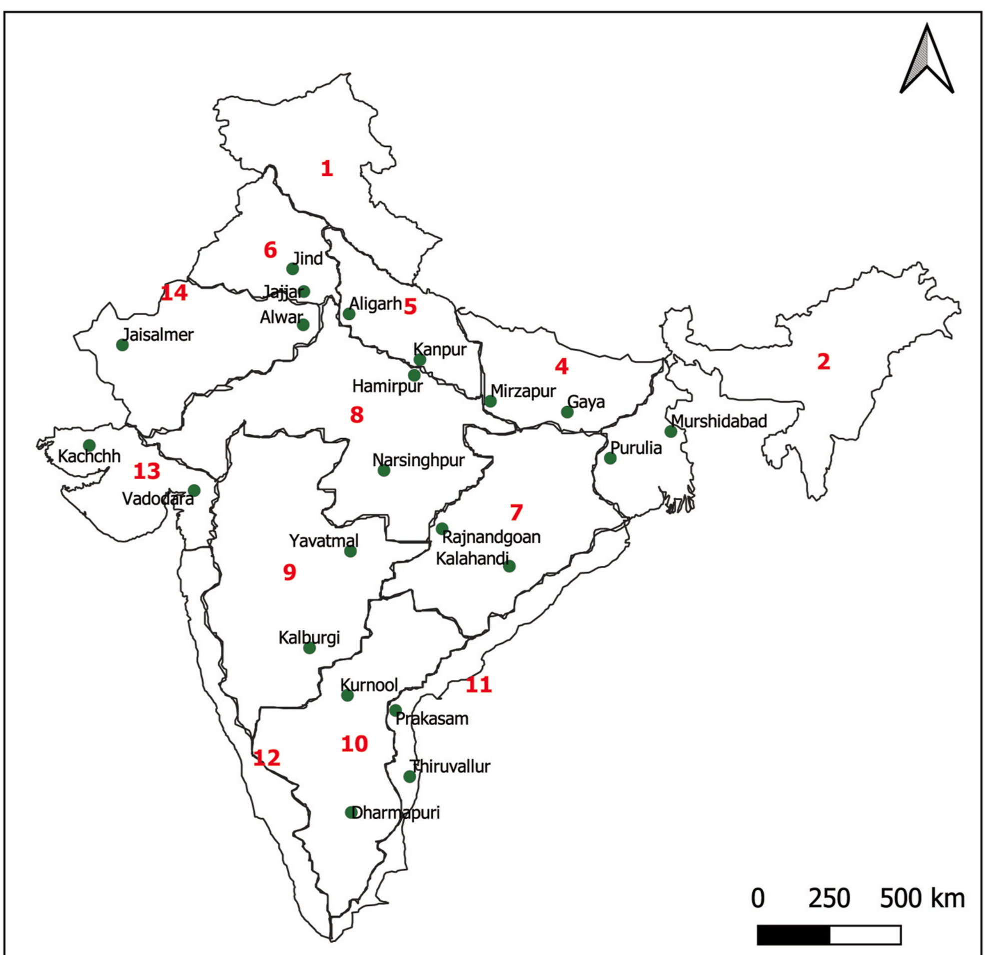

Fig. 1. Map illustrating Agro-Climatic Zones of India and twenty-two sampling locations.

2. Materials and methods

2.1. Climate data

Temperature maximum and minimum data were downloaded using MarkSim weather file generator through MarkSim web version from IPCC Assessment Report 5 data (CMIP5) (http://gismap.ciat.cgiar.org/MarkSimGCM/). Jones et al. (2011) provided detailed information on MarkSim. The planning commission of India during the VII five-year plan (1985–90) classified the country into fifteen ACZs based on physiographic and climate conditions (Ahmad et al., 2017). Out of fifteen ACZs, *H. armigera* host plants (Cotton, Pigeon pea, Chickpea, Corn, Tomato) were significantly cultivated from eleven ACZs of India. Therefore, the climate data i.e., annual surface air temperature data were obtained for five independent years with twenty-year intervals namely 2010, 2030, 2050, 2070, and 2090 (henceforth climate years) from eleven ACZs (two locations in each ACZ) (Table 1 and Fig. 1). The near (2030 and 2050) and far near (2070 and 2090) climate years are viewed as future climate years compared with the 2010 baseline climate year for annual temperatures and *H. armigera* number of Generations (Gen.) and Generation Time (GenT.). Projected temperature data was downloaded from the MarkSim web application by selecting ten different general circulation models (BCC-CSM-1.1, BCC-CSM-1.1 m, CSIRO-MK3-6.0, FIO-ESM, GFDL-ESM2G, GFDLESM2M, IPSL-CM5A-LR, IPSL-CM5A-MR, MRI-CGCM3, MIROC-ESM-CHEM) under four RCPs scenarios, namely RCP 2.5, RCP 4.0, RCP 6.5 and RCP 8.0. The simulated weather data (Tmin. and Tmax.) was downscaled from 30 replications at each location.

2.2. Variations in projected temperature and insect phenology

Daily Accumulated Growing Degree Days (GDD) were calculated by selecting a single sine horizontal cut-off method using 12.6 °C and 33.3 °C as lower and upper threshold temperatures, respectively (http://ipm.ucanr.edu/PHENOLOGY/ma-h_zea.html). The Gen. and GenT. of *H. armigera* was worked out using Degree-days (DD) calculator, an interactive tool developed by the University of California Agriculture and Natural Resources (http://ipm.ucanr.edu/WEATHER/index.html). In this study, 422.3 GDD accumulation (from egg to adult) was adopted for calculating *H. armigera* Gen. and GenT. (Hartstack et al., 1976).

$$Number\ of\ Generations = \frac{Cumulative\ ADD\ per\ annum}{DD\ accumilation\ from\ egg\ to\ adult\ stage}$$

$$Generation\ Time = \frac{Number\ days\ in\ an\ year}{Number\ of\ Generations}$$

The Gen. and GenT. of *H. armigera* were projected from estimated GDD in future and baseline climate years. Mean Gen. and GenT. of *H. armigera* were compared between AZCs, RCPs, and climate years.

2.3. Statistical analyses

Levene's test was conducted to observe the homogeneity of variances in Tmin., Tmax., Gen., and GenT mean data. Shapiro-Wilk test confirmed normality of Tmin., Tmax., Gen. and GenT. data. The contribution of each factor (location, zone, climate years, RCPs, and their interactions) towards variation in Gen. and GenT. of *H. armigera* were estimated. Correlation and regression analyses were carried out to understand the type of relation and dependency of GDD with/on Gen., and GenT of *H. armigera*. All the statistical analyses were done in SPSS Ver. 25.0 (IBM Corp 2017). The shapefile of India was obtained from Global Administrative Areas (GADM) ver. 3.6 data. The choropleth maps illustrating *H. armigera* Gen. in different ACZs of India were developed in QGIS Desktop 3.16.4.

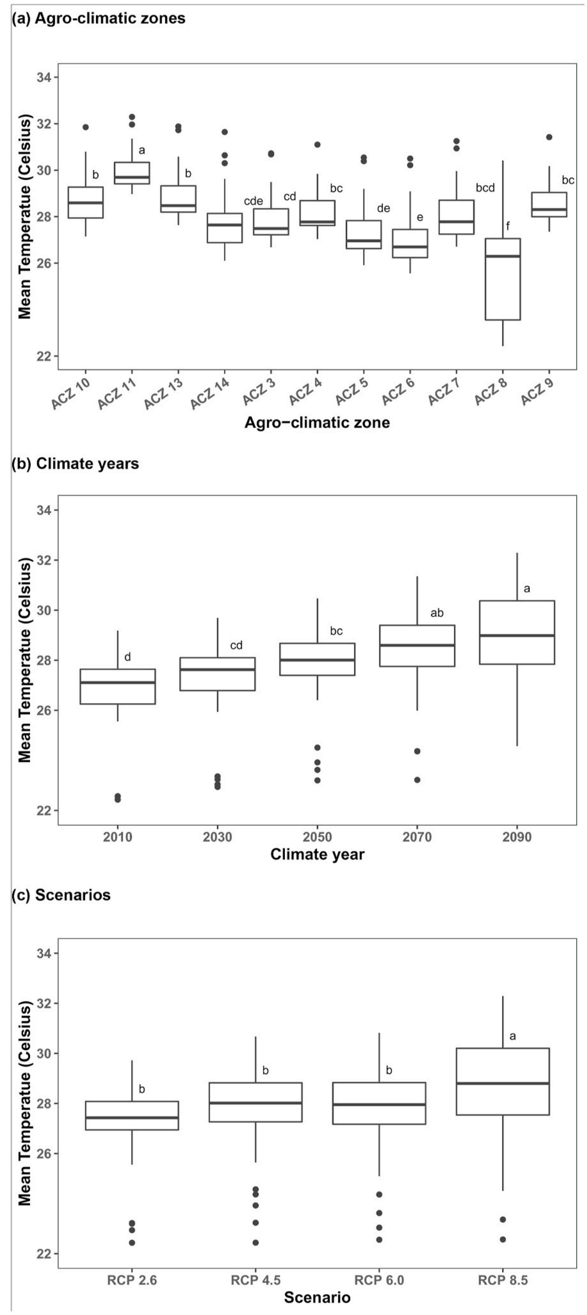

Fig. 2. Differences in mean surface air temperature across (a) Agro-Climatic Zones (b) Climate years and (c) Scenarios.

3. Results

Based on levene's test of significance ($p < 0.05$) equal variances was observed in Tmin., Tmax., Gen. and GenT. data. Normality of Tmin., Tmax., Gen. and GenT. data was confirmed from Shapiro-Wilk test of significance [Tmin. - W (440) = 0.995, $p > 0.05$, Tmax. - W (440) = 0.927, $p > 0.05$, Gen. - W (440) = 0.964, $p > 0.05$, GenT. - W (440) = 0.915, $p > 0.05$] values.

3.1. Variation in climate and insect phenology

The weather data differed significantly among RCPs [Tmin. – $F_{3,436}$ = 12.302, $p < 0.05$ and Tmax. – $F_{3,436}$ = 10.3, $p < 0.05$], climate years [Tmin. - $F_{4,435}$ = 20.479, $p < 0.05$ and Tmax. - $F_{4,435}$ = 28.117, $p < 0.05$], ACZs [Tmin. - $F_{10,429}$ = 64.432, $p < 0.05$ and Tmax. - $F_{10,429}$ =

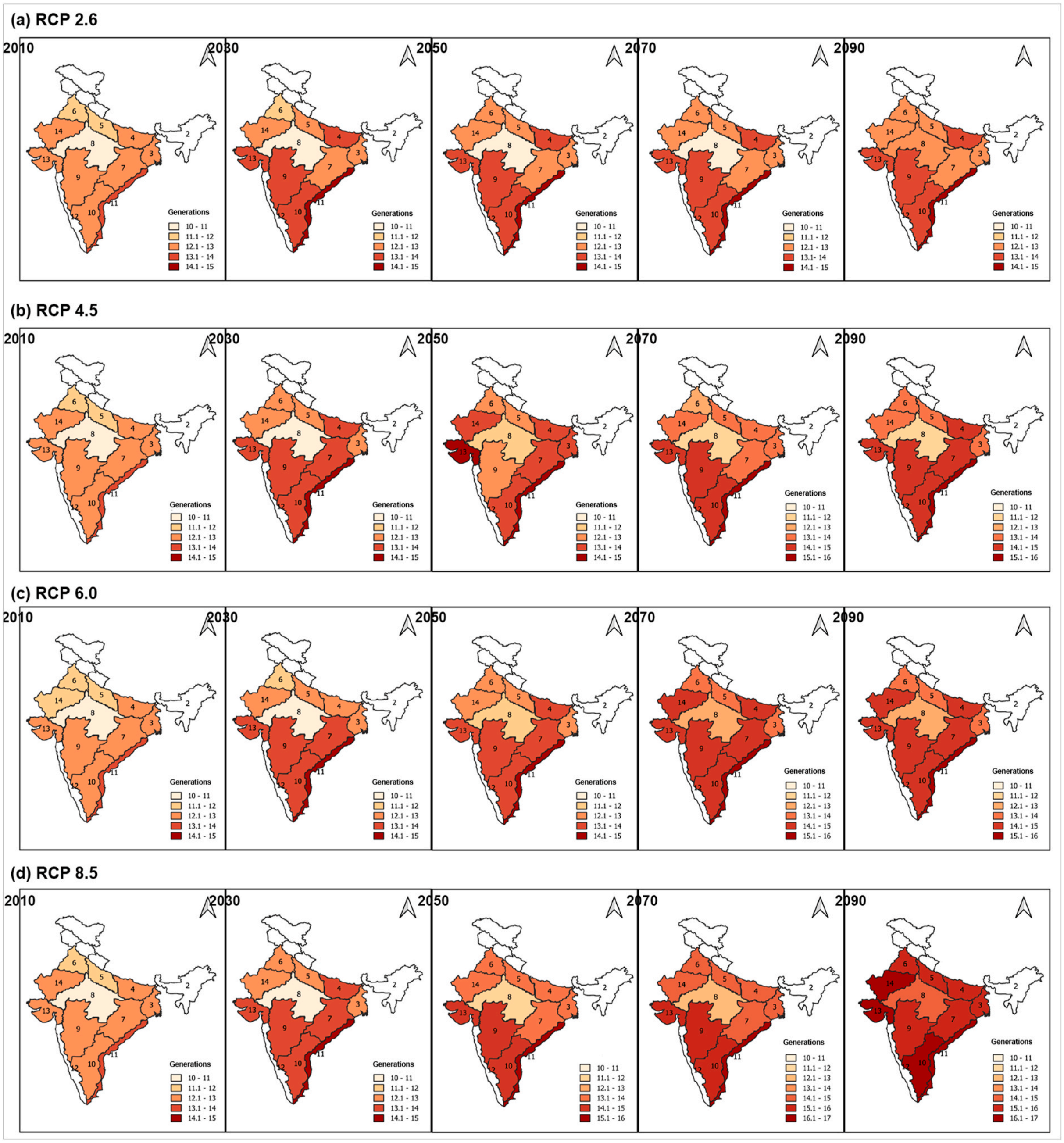

Fig. 3. GCM ensemble mean number of generations of *H. armigera* projected under four representative concentration pathways in different climate years from various Agro-Climatic Zones.

33.17, $p < 0.05$] and locations [Tmin. - $F_{21,418} = 40.477$, $p < 0.05$ and Tmax. - $F_{21,418} = 33.926$, $p < 0.05$] (Fig. 2). The *H. armigera* Gen. and GenT. between ACZs [Gen. – $F_{10,429} = 34.374$, $p < 0.05$ and GenT. $F_{10,429} = 36.793$, $P < 0.05$] and locations [Gen. – $F_{21,418} = 26.495$, $p < 0.05$ and GenT. $F_{21,418} = 36.995$, $P < 0.05$] differed significantly. However, *H. armigera* Gen. alone showed a significant difference between RCPs [$F_{3,436} = 12.603$, $p < 0.05$] and climate years [$F_{4,435} = 21.391$, $p < 0.05$]; whereas no considerable difference was found for GenT. between RCPs [$F_{4,436} = 1.037$, $p > 0.05$] and climate years [$F_{4,435} = 0.81$, $p > 0.05$]. Among different RCP scenarios, the highest and most significant mean number of *H. armigera* generations (13.96 y^{-1}) was predicted from RCP 8.5. The RCP 2.6, RCP 4.5 and RCP 6.0 scenarios projected ≥14 *H. armigera* generations per annum only at ACZ 11; whereas, RCP 8.5 projected ≥14 *H. armigera* generations in six different ACZs (ACZ 4, ACZ 7, ACZ 9, ACZ 10, ACZ 11, ACZ 13). In future climate year 2090 alone a significant and more number of *H. armigera* Gen. (14.08) was projected. During all four climate years (2010, 2030, 2050, 2070, 2090) ACZ 11 experienced ≥14 Gen. of *H. armigera* followed by ACZ 13 in three climate years (2050, 2070, 2090); while ACZ 9 and ACZ 10 showed ≥14 *H. armigera* Gen. in two climate years (2070, 2090), and a similar trend was noticed at ACZ 4, ACZ 7 and ACZ 14 but only during 2090 climate year (Fig. 3). Across the ACZs and RCP scenarios, *H. armigera* Gen. was predicted to rise 3.2% (12.88), 6.5% (13.33), 9.6% (13.79), 11.5% (14.23) in future climate years 2030, 2050, 2070 and 2090, respectively compared to baseline climate year 2010 (12.46). Tukey's HSD pairwise comparison test among ACZs revealed, ACZ 11 (Eastern Coastal Plains and Hills Zone) showed significant and more *H. armigera* Gen. (14.96) with reduced GenT. (24.45 days) followed by ACZ 13 (14.03 & 26.1 days), ACZ 10 (13.94 & 26.68 days), ACZ 9 (13.77 & 26.57 days), ACZ 4 (13.48 & 27.17 days), ACZ 7 (13.4 & 27.34 days),

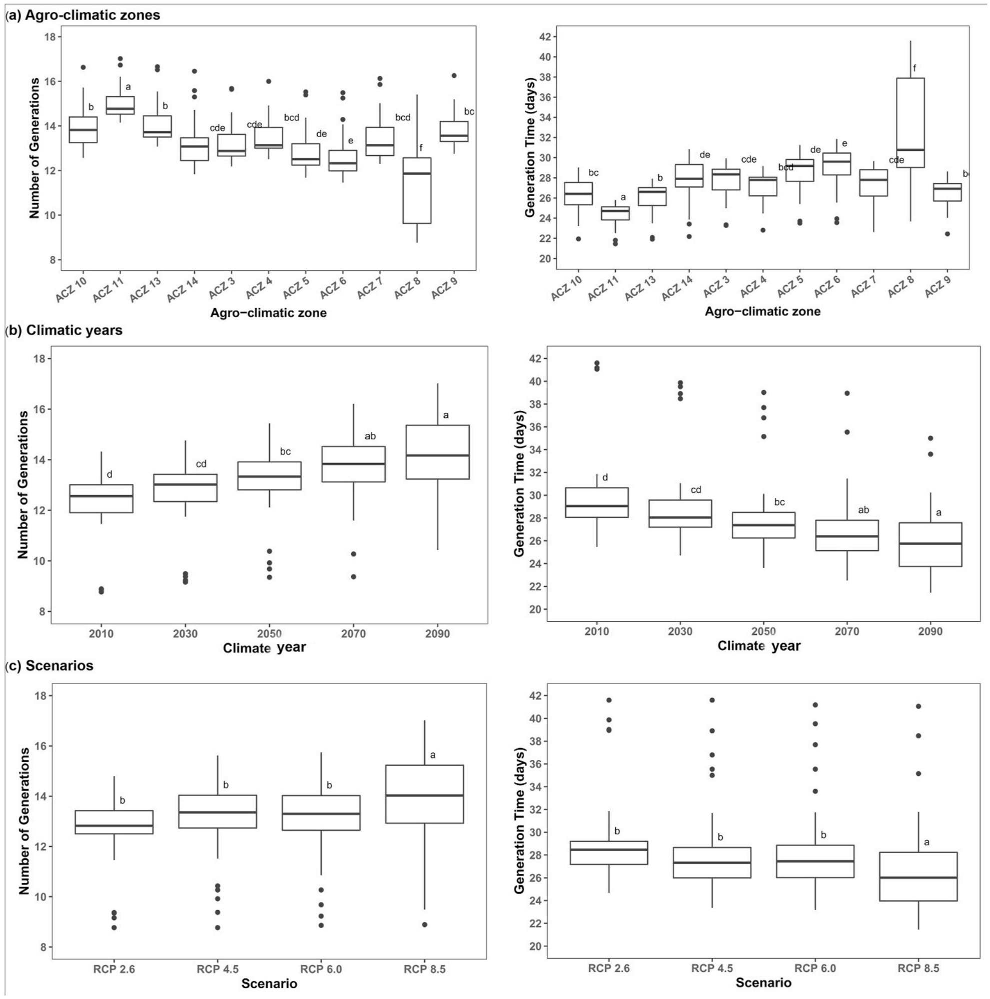

Fig. 4. Significant variation in *H. armigera* generations and generation time among (a) Agro-Climatic Zones (b) Climate years and (c) Scenarios.

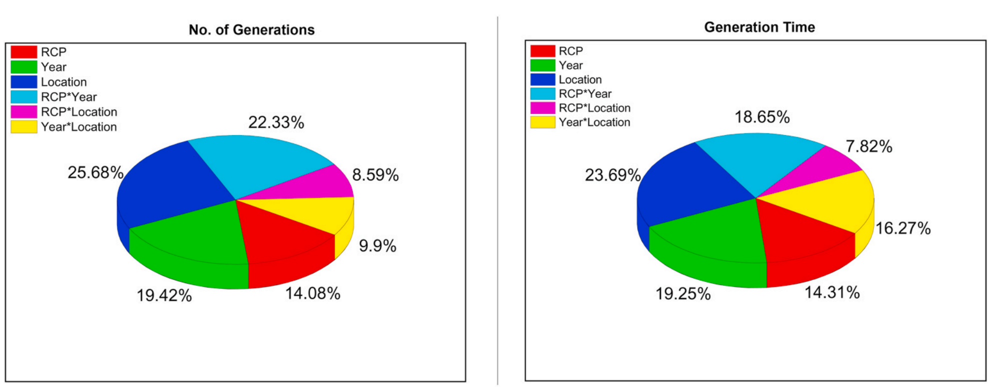

Fig. 5. Contribution of different factors for predicted *H. armigera* generations and generation time.

ACZ 14 (13.18 & 27.83 days), ACZ 2 (13.18 & 27.78 days), ACZ 5 (12.79 & 28.65 days), ACZ 6 (12.54 & 29.24 days) and ACZ 8 (11.39 & 32.79 days) (Fig. 4).

3.2. Effect of factors on H. armigera phenology

Test of subject effects revealed, geographical location alone explained 25.68% and 23.69% variations in *H. armigera* Gen. and GenT., respectively. RCP x Year (interaction), Year and RCP factors had contributed 22.32%, 19.42% and 14.08% variation in Gen., respectively. Likewise, 19.25%, 18.65%, 16.26% and 14.31% variations in *H. armigera* GenT. were explained by Year, RCP x Year (interaction), Year x Location (interaction) and RCP factors, respectively. However, other factors explained below 10% variation in *H. armigera* phenology (Gen. and GenT.) (Fig. 5).

3.3. Association of climate and insect phenology data

More *H. armigera* GDD accumulation was found during the 2090 climate year (6010.12) followed by 2070 (5821.78), 2050 (5628.38), 2030 (5440.78) and 2010 (5261.4); however, this increase in GDD was significant at a 1% level. It was also estimated cumulative increase in *H. armigera* GDD accumulation at the rate of 3.1°-days per every two decades. An incremental increase in GDD during climate years 2030, 2050, 2070 and 2090 at the rate of 3.29%, 6.52%, 9.62%, 12.45% would increase *H. armigera* Gen. to 3.2%, 6.5%, 9.6% and 12.4%, respectively over the baseline climate year 2010. Remarkably, the ACZ 11 experienced increased GDD that varied between 153 and 606°-days per two decades. Mean GDD was found positively and negatively associated with *H. armigera* Gen. and GenT., respectively.

4. Discussion

The phenology of various ecological processes was potentially sensitive to climate change as influenced by temperature (Bartomeus et al., 2011) and advances the phenology of the *H. armigera* (Huang and Hao, 2018). Akbar et al. (2016) regarded elevated temperatures as induced changes in insect metabolism by enhancing the activity of proteases and carbohydrates in the insect midgut, which influence the survival and growth and development of *H. armigera*. Nonlinear and discontinuous climate systems (Huang and Hao, 2018) evidenced the considerable variation in one of the climate drivers (Tmin. and Tmax.) between zones. This study projected highest mean surface temperature (30.02 °C) at the ACZ 11 namely, Eastern coastal plains and hills zone (location - Prakasam), which envisaged spatiotemporal variations in climate or abrupt climate change (Fu and Wang 1992). Ten GCM models from four different RCPs scenarios have estimated average increased Tmin. (0.53 °C 20^{-y}) and Tmax. (0.51 °C 20^{-y}). However, mean surface air temperature was projected to increase at 0.53 °C 20^{-y} in different climate years. A similar trend was noticed by Arora et al. (2005), where the mean temperature could increase at the rate of 0.42 °C 100^{-y}. Though, there was frightening upsurge in surface air temperature at 0.53 °C per two decades, Gen. and GenT. of *H. armigera* increased and reduced at the rate of 3.26% and 3.37%, respectively in slow pace. Moreover, there was an addition of one *H armigera* generation for every forty years period; that may contribute for population build-up and crop damage. The slow rate of increase in *H. armigera* generations per two decades can be attributed to - several other components like biotic and abiotic factors, host plants, pest management practices, insecticide resistance etc. could influence *H. armigera* Gen., however, temperature alone may have little effect on the *H. armigera*. Present findings were confirmed by Mironidis and Savopoulou-Soultani (2008) and Srinivasa Rao et al. (2016) reports, wherein *H. armigera* showed shorter mean generation time with a higher number of generations with increased temperatures.

Geographical regions impact various reproductive and life history aspects of populations (Papadopoulos et al., 2002); accordingly, the present study found geographical location as the major and only factor that contributed 25.68% and 23.69% variations in *H. armigera* Gen. and GenT., respectively. Likewise, Srinivasa Rao et al. (2016) envisaged geographical location accounted for a higher percentage of the variability in the number of generations of *H. armigera*. Our study found a positive and linear association between GDD and Gen. of *H. armigera*, which could be attributed to direct consequences in metabolic rates, activity patterns, and developmental rates with increased ambient temperature in ectoderms (Altermatt, 2010).

The present study predicted the multiple generations (multivoltine) of *H. armigera* in different ACZs of India; however, such an increased number of generations not only promote population growth but also speed up the evolutionary process and adapt (Altermatt, 2010) to damage many economically important crops, including cotton, pigeon pea, chickpea, sunflower, tomato, sorghum, millets, okra, and corn in India (Manjunath et al., 1989; Sharma 2001). Under all future climate years ACZ 11 was predicted for less generation time (24 days per generation) and increased generations (15 per annum) of *H. armigera*; wherein the changes in voltinism may amplify the outbreak of pest species (Steinbauer et al., 2004) and negatively influence the plant communities (Porter et al., 1991). Food suitability, availability of oviposition and pupation sites (Fitt, 1989 and Sequeira, 2001), topography, farming practices, and climate change (Bapatla et al., 2020) would influence the *H. armigera* abundance over different host crops. The rise in mean surface air temperature at 0.41 °C per two decades in the East Coastal and Plain Zone (ACZ 11) has favored the *H. armigera* growth and development by accumulating 151.73 additional GDD per two decades over other zones, and this situation could be attributed to the rising Tmin. (0.53 °C) and Tmax. (0.51 °C) and the availability of multiple hosts. Therefore, the prediction of *H. armigera* phenology in different ACZs could be significant in planning pest management (Srinivasa Rao et al., 2015). This study finding showed that temperature alone brought a little change in the *H. armigera* Gen. and GenT., so, a new opinion may be formulated that future temperature changes have lesser effects on *H. armigera*.

5. Conclusion

The surface air temperature loses its equilibrium state due to continuous climate change. The change in surface air temperature during the course of global warming, alter the *H. armigera* phenology and thus change in GenT. and Gen., which has a significant impact on agriculture production. The future climate data under different RCP scenarios showed high GDD accumulation in *H. armigera* that minimised the GenT. and increased the Gen. in the majority of ACZs of India. Under climate change background, various ACZs of India would encounter an inevitable leap in Tmin. (0.53 °C 20^{-y}) and Tmax. (0.51 °C 20^{-y}), which affects the *H. armigera* phenology by reducing GenT. to 3.37% and increasing Gen. up to 3.26% with an additional accumulation of 463 GDD per two decades. Favorable changes in *H. armigera* phenology would escalate the damage and cause potential economic losses to various crops. The circumstances in future climate years with respect to *H. armigera* Gen. and GenT. are alarming at different ACZs of India.

Authors' contributions

KGB conceived and designed the concept. KGB and ADS curated the data. KGB and SY analysed the data. KGB wrote the manuscript. KGB, VS and RRK edited the manuscript. All authors approved the manuscript.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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