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ORIGINAL PAPER

Insect pest scenario in Uttarakhand Himalayas, India, under changing climatic conditions

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Abstract

The Himalayan mountains are early indicators of climate change, wherein slight changes in climate can lead to a drastic variation in faunal diversity, distribution, invasion of fauna into higher altitudes, rapid population growth, shortening of life cycle and increased number of overwintering species. The insects best represent the faunal diversity. In recent years, due to variation in pattern of rainfall and temperature regimes, several insect pests have moved northwards and are posing great threat to hill agriculture. Few among them are greenhouse whiteflies, thrips and mites in protected cultivation system; blister beetles on flowers of cereals, pulses and oilseeds; invasive insect pests like fall armyworm of maize and tomato pin worm and sporadic pests like grasshoppers that are reaching a status of major key pest in various crops. Keeping in mind the phenomenon of climate change and associated changes in pest population, the present article focuses on emerging insect pest problems in cereals, millets, pulses, oilseeds and vegetables of Indian Himalayas, along with their changing population density with respect to different climatic parameters, the per cent increase in the pest damage over the years and their potential of gaining the status of major pests in near future and causing huge economic losses to hill agriculture.

Keywords Climate change · Indian Himalayas · Hill agriculture · Insect pest scenario · Northward invasion

Introduction

The Indian Himalayas cover approximately 18% of India's geographical area and accounts for more than 50% of India's forest cover (Raina et al., 2014). Agriculture contributes a minor land use in this forest ecosystem with a net sown area of only 10% of total area and supporting livelihood of 115 million mountain people (Singh et al., 2008). The traditional subsistence system of crop-livestock farming is the basis of livelihood to local communities and is the backbone of rural economy (Rao and Saxena 1996; Tripathi and Sah 2001; Semwal et al. 2004). Climate change is an undeniable fact of present day and its impacts are felt all over the world (Knappenberger et al. 2001; IPCC 2007), but mountains are early indicators of climate change (Singh et al. 2010). The rise in air temperature, alterations in precipitation and faster melting of the glaciers have led to increased discharge in rivers and consequent rise in sea level (Karl et al. 1996; Fallot et al. 1997; Zhai et al. 1999; Crowley 2000; IPCC 2001). Conforming to the global trends, the mountainous areas of Alps, the Rockies, the Andes and the Himalayas have also warmed significantly (Vuille et al. 2003; Rebetez and Dobbertin 2004). Although, pre-monsoon (March to May) and summer cooling have been reported in some portions of the western Himalayas (Yadav et al. 2004). Additionally, overall annual temperatures in the Himalayas have recorded significant rise in the last century (Sharma et al. 2000; Bhutiyani et al. 2007).

Agriculture is a gamble with the weather, and changes in weather cycle have major effect on crop yield and food supply. Mountain agriculture is mostly rainfed (approximately 85%) and driven by biomass energy of surrounding

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forests and mostly confined to terraces carved out of hill slopes (Negi et al., 2012). The small holdings (< 1 ha in majority of cases) are distributed over small parcels of land, and the agricultural productivity is very low (6–13 q ha^{-1}). The mean minimum and maximum temperatures in North Western Himalayan region have increased by 0.25–1 ºC respectively, and the rainfall and snowfall have decreased by about 7 cm and 12 cm respectively, in 1990s as compared to 1880s (Vishvakarma et al. 2003). Some of the documented impacts on mountain agriculture that are linked with climate change in the Uttarakhand, Himalayan region are (i) reduced availability of water for irrigation; (ii) extreme drought events and shifts in the rainfall regime resulting in failure of crop germination and fruit set; (iii) invasion of weeds in the croplands; (iv) increased frequency of insect-pest attacks (whitefly in greenhouse and open field conditions, introduction of exotic pests like *Tuta absoluta* in tomato) and (v) decline in crop yield (Negi and Palni 2010). Apart from causing direct impacts on crop productivity, climate change is threatening food production in hill agriculture through increasing pest population and their damage potential by expanding distribution, enhancing survivability and allowing adaptability of insect pests to temperate climate (Bebber et al. 2013). In comparison to insect pest species found in tropical and temperate regions, the change in climate has significant effects on species found in temperate regions (Shrestha 2019). The increase in temperature and decrease in amount of precipitation is leading to altitudinal shift and intrusion of insect pests into high-altitude agriculture lands (Bhutiyani et al. 2007; Kumar et al. 2008). According to Stoeckli et al. (2012), the climate change is also associated with several changes in insect pest physiology and population dynamics like:

a. Changes in diversity, distribution and abundance of insect pests
b. Changes in geographical distribution of insect pests
c. Increased number of overwintering insects
d. Rapid population growth and increase in number of generations
e. Invasion on new alternative host plants
f. Changes in host plant resistance to insect pests
g. Increased risk of invasive pest species
h. Emergence and dissemination of vector-borne diseases

In the present article, we attempt to give elaborate information regarding emerging pest outbreaks, secondary pest outbreaks and shift in the pest population dynamics over a period of 6 years (2015–2020) in the Uttarakhand, Himalayan region, due to changing climatic conditions. Furthermore, we also correlated the changing population density of insect pests with minimum and maximum temperature, average rainfall and relative humidity of the mid-hill regions of Uttarakhand Himalayas, India, with the help of two-tailed correlation test at 1% and 5% level of significance.

Materials and methods

Survey and surveillance

Regular field surveys were carried out at monthly interval at six locations in the mid-hill regions (1200 to 1800 amsl) of Uttarakhand Himalayas, India, for a period of 6 years (2015–2020). The study locations included an Experimental Farm, Hawalbagh, Almora (29°64′97.0″N, 79° 61′49.4″E, 1250 amsl) and farmers' fields at Bhagarthola, Almora (29°65′18.9″N, 79° 87′80.7″E, 1690 amsl); Darima, Nainital (29°46′65.1″N, 79° 64′15.2″E, 1760 amsl); Lakhani, Bageshwar (29°87′94.1″N, 79°65′82.2″E, 1335 amsl); Someshwar, Bageshwar (29°78′74.4″N, 79°54′53.0″E, 1530 amsl) and Gwaldam, Chamoli (30°00′86.9″E, 79°55′73.8″E, 1720 amsl). The insect pest surveillance was taken up in general field conditions, which included both rainfed and irrigated fields. The per cent pest damage in various crops in different locations was recorded through random method of sampling, wherein a minimum of 10 ha of land in each location was surveyed by randomly traversing in the fields and recording the per cent pest damage per unit area of the cultivated crop. Care was taken to maintain a minimum of 50-km distance between two survey locations.

Climatic data

The weather parameters like average monthly minimum and maximum temperature, average rainfall and relative humidity of mid-hill regions of Uttarakhand Himalaya, India, were collected from the agro-meteorology station established at ICAR-VPKAS, Experimental Farm, Hawlabagh, Almora (29º38′01″ N and 79º37′49″ E, altitude 1242 amsl). As all the survey locations were under the mid-hill regions (1200 to 1800 amsl), not much variation in weather parameters was noticed.

Data analysis

The per cent insect pest damage data of six study locations was combined, and an average data was obtained through Microsoft Office Excel 2019 (Microsoft corp., USA), and the values were presented graphically for 6 consecutive years. However, for analysing the population dynamics of nine major white grub beetle species, the number of adult beetles collected through in situ method of sampling from six locations during a 10-year period (2011–2020) was averaged and presented graphically. Moreover, the per cent pest damage of various insect pests in different crops and population dynamics of adult beetles was correlated with climatic variables of the mid-hill regions of Uttarakhand with the help of two-tailed correlation test at 1% and 5% level of significance through SPSS-16 statistical tool (SPSS Inc., Chicago). Additionally, the principal component analysis was performed to ascertain the pest population density in different months of *kharif* and *rabi* season respectively, over a period of 6 years.

Results and discussion

A. Emerging insect pests of cereals

Cereals are important field crops covering an area of 3.8 lakh ha in *kharif* and 1.7 lakh ha in *rabi* season in Uttarakhand, Himalayan region (Indiastat-2021). The major cereals and emerging insect pest outbreaks in respective crops are mentioned below. The per cent pest damage has also been represented graphically to understand the variation in pest population density over a period of 6 years (2015–2020).

1. Pests of paddy/rice: The insect pest damage has been increasing over the years in paddy cultivated in hilly regions of Uttarakhand, and the per cent damage is either positively or negatively correlated with climatic conditions. The minor pests are gaining the status of major pest over the years (Table 1; Fig. 1).

   (a) Paddy grasshoppers (*Oxya* spp., *Hieroglyphus* spp. and *Chrotogonus* spp.): Grasshoppers have recently gained the status of major pest in paddy in hill agriculture. Variation in amount and fre-

Table 1 Correlation between insect pest population density of cereals v/s climatic conditions of *kharif* season from 2015 to 2020 (6 years)

Pest type	*Rainfall (mm)*	*Max temp*	*Minimum temp*	*Avg. temp*	*RH (%)*
Paddy grasshoppers	0.355	−0.18	0.30	0.22	0.32
Rice leaf roller	0.215	0.03	0.34	0.31	0.31
Brown plant hopper	0.482**	−0.030	0.398*	0.341	0.503**
Stem borer	0.063	−0.396*	0.162	0.026	0.335
Wheat shoot fly	−0.433**	−0.143	−0.395**	−0.281	0.027
Wheat aphids	0.258	0.613**	0.697**	0.682**	−0.330*
Helicoverpa armigera	0.268	0.653**	0.738**	0.724**	−0.368*
Aphid	−0.671**	−0.203	−0.564**	−0.568**	−0.286
Blister beetles	−0.395*	−0.390*	−0.444*	−0.517**	−0.119
Fall army worm	−0.173	0.079	−0.119	−0.080	0.012

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

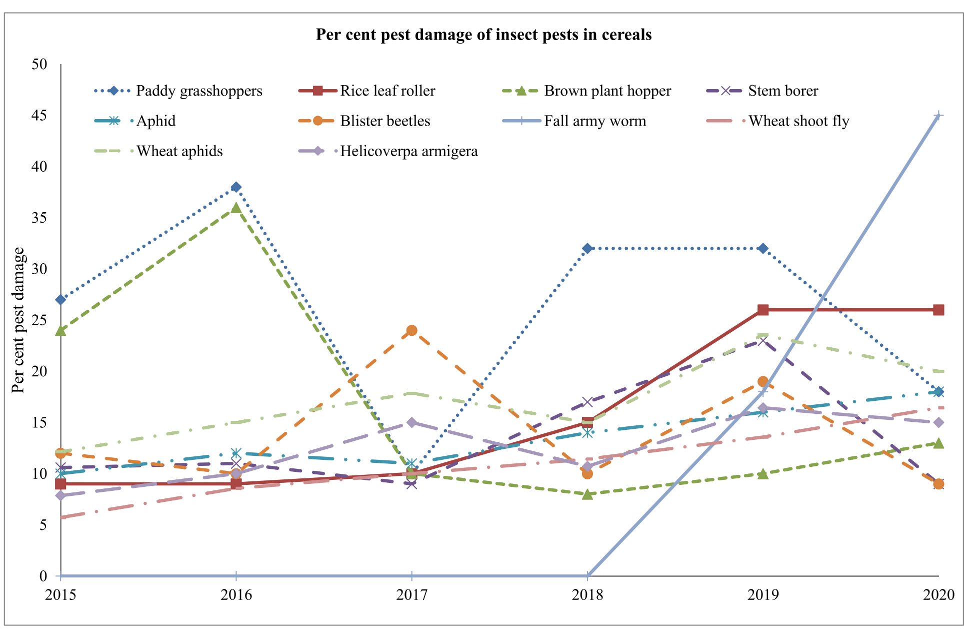

Fig. 1 Per cent damage by insect pests in cereal crops over a period of 6 years (*kharif/rabi* 2015–2020)

quency of rainfall, late onset of monsoon, moderate temperature in *kharif* season (22–28 °C) favours faster multiplication (Leksono et al., 2020). The infestation is very severe during *kharif* season, and in *kharif*-2016, 2018 and 2019, the severe outbreak of grasshoppers was observed in parts of Almora, Bageshwar and Nainital districts of Uttarakhand and the per cent pest damage up to 60% was recorded in severely infected fields. Although the pest population is fluctuating over the years, the prevailing favourable environmental conditions like optimum rainfall, average temperature and relative humidity are positively correlated, but are not significantly affecting the population density of grasshoppers, and these climatic conditions can accentuate the grasshopper population in the near future (Hussain et al., 2017; Adhikari et al., 2021).

(b) Rice leaf roller (*Cnaphalocrocis medinalis*): The pest population of leaf roller is exponentially increasing over the years in upland and broadcast sown paddy fields in the Indian hills due to deficit rain fall, increasing gap between two consecutive rainy days and high temperatures in cropping season (> 22 °C average during vegetative stage). The pest population density is positively correlated with minimum and maximum temperature, relative humidity and rainfall. But, they do not significantly influence the population density of the pest. However, the increase in population density and per cent pest damage over the years poses an alarming pest situation in the near future (Haq et al., 2010; Padmavathi et al. 2013; Amer Rasul et al. 2019; Morshed et al., 2020).

(c) Brown plant hoppers in rice (*Nilaparvata lugens*): Brown plant hopper (BPH) is a major sucking pest of rice in plains, causing extensive damage to rice cultivation. Till 2008, the pest was not observed in Himalayan states but made its first appearance in *kharif*, 2009, in the foot hills of Uttarakhand Himalayas. In the following year, i.e. *kharif*, 2010, the pest reached the mid hills of Uttarakhand Himalayas and appeared in severe form. The damage levels ranged from 30 to 50%. This was a clear evidence of pest migration/expansion in respect of temperature alleviations, more precisely increase in minimum temperature coupled with rain fall observed during the years (Stanley et al. 2009). In addition, delay in sowing time due to late monsoons during the season also aggravated the pest damage. Studies also reported elevated temperatures positively affect the fecundity, multiplication and growth parameters of BPH (Pandi et al. 2018), and although the pest is evident in further years, no noticeable damage was observed. Moreover, the pest population density and per cent pest damage have shown significantly positive correlation with average rainfall, minimum temperature and relative humidity, thus indicating that the favourable climatic conditions like optimum rainfall and relative humidity coupled with moderate temperature conditions would escalate the pest damage in the near future (Prasannakumar and Chander 2014; Ali et al. 2014).

(d) Paddy stem borer (*Scirpophaga* spp.): Three different species of stem borers infect paddy crop in the hills of Uttarakhand. Although the pest damage is very severe in plains and foot hills of Himalayas, the damage in hilly regions is very low. The stem borer damage crossed the ETL levels only once (2019) during 2015–2020. The possible reason might be the favourable climatic conditions like optimum rainfall, average temperature and relative humidity. However, based on correlation studies, it was observed that the maximum temperature (> 35 °C) significantly reduced the population of stem borers in rice. The recent shift towards cultivation of high-yielding rice varieties and changing climatic conditions may offer a favourable condition for stem borers to feed, breed and multiply in large numbers in Indian Himalayas (Nag et al., 2018; Mandal and Mondal 2018).

2. Pests of wheat and barley: Wheat and barley are very important *rabi* crops in the cropping system of Indian Himalayas (Das et al. 2018). These crops were almost pest free in the past. But, the shift in cultivation of high yielding varieties has exposed these crops to insect pest damage over the years. Several minor and sporadic pest damages have been observed in these crops, and few insects are adapting to wheat and barley as their alternate hosts during winter off seasons (Table 1; Fig. 1).

   (a) Wheat shoot fly (*Atherigona naqvii*, *Atherigona orientalis* and *Atherigona varia*): More than six species of shoot flies are known to infect wheat and barley crops in seedling stage, and they are minor pests. The per cent pest infestation of shoot flies in wheat ranged from 10 to 15% and in barley from 5 to 10% in both *rabi* 2019 and 2020. However, in few high-yielding varieties, up to 35% damage was recorded, where monoculture of wheat was practiced on a large area. Moreover, delayed onset of winter (later than November, second fortnight), extended dry spells in early crop season and lack of irrigation facilities in the Indian Himalayas are aggravating the shoot fly infestation over the years. However, increase in rainfal during north-western monsoon (October and November months) and early onset of winter (first fortnight of October) shows significantly negative correlation with population density of shoot flies. Moreover, the recent observations have shown the drastic increase in per cent damage by shoot flies in wheat and barley due to cultivation of advanced high-yielding, insect-susceptible crop varieties (Jambagi et al., 2021).

(b) Wheat aphids (*Macrosiphum miscanthi* and *Sitobion avenae*): The infestation of aphids begins from the second fortnight of January. The aphid infestation in the *rabi*-2018 varied between 10 and 15%, while in *rabi*-2019, the incidence rose to 25% due to extended winters, i.e. cold weather continuing till the end of March month and lower average night temperature (< 19 °C) significantly increased the aphid population (Zhang et al., 2019). However, excessive relative humidity affects the aphid spread and significantly reduces the aphid population in wheat. Although March and April receive optimum rainfall in Indian Himalayas, they do not affect the population density of aphids in these crops (Ahmad et al., 2016; Bajwa et al., 2020).

(c) Maize cob worm (*Helicoverpa armigera* and *Heliothis* spp.,): The infestation of *Helicoverpa* in wheat and barley is observed in recent years. The early-stage caterpillars feed on leaves by scraping the chlorophyll content, while the later-stage caterpillars are found feeding on ear heads. The infestation is severe during milky and dough stage of the crop. Although the per cent infestation of the pest has not crossed 15% in the last 2 years, the chance of *Helicoverpa* reaching pest status is not far because of changing environmental conditions like non-availability of alternate host in the months of March, April and May; high pre-monsoon temperatures and reduced frequency of pre-monsoon rainfall. However, the pest population reduces drastically due to biological control agents like parasitoids, predators and granulosis virus infection in the Indian Himalayas. But, there are several points needed to be considered beforehand: minimum and maximum temperature conditions are significantly positively correlated with the pest population density, while excessive relative humidity in negatively correlated (Akbar et al., 2016; Hussain et al., 2021).

3. Pests of maize: Maize is an important *kharif* crop in Uttarakhand Himlayas, and it is mainly less affected by insect pests. But, the recent invasion of alien fall army worm has created havoc and distress among the farming community. The details of emerging pests of maize and their possible correlation with climatic condition are elaborated below (Table 1 and Fig. 1).

(a) Maize aphid (*Rhopalosiphum maidis*): The infestation of aphids has increased recently in maize due to erratic rainfall and increase in summer temperatures. The pest infestation during favourable seasons (months of low rainfall and high temperature) usually crosses 20% or more. The pest population density is significantly negatively correlated with average rainfall, minimum temperature and average temperature. However, the maximum temperature and relative humidity do not significantly influence the population density of aphids in maize (Hulle et al., 2010; Abdallah and Youssef, 2017).

(b) Blister beetles (*Mylabris pustulata*, *M. phalerata*, *Lytta* spp.): They are sporadic pests on Maize, whose infestation is observed every alternate year. The beetles feed on silk of cobs and tassels, thus, reducing pollination and per cent seed set. The infestation is mainly due to non-availability of alternative hosts. The pest in severe cases causes up to 20% yield loss and results in empty cobs without seeds. The beetles mostly prefer climatic conditions that are less humid, less rainy and with optimum climatic conditions. Excessive rainfall and lower or higher temperatures significantly affect the beetle multiplication and thus reducing the pest damage in maize. The pest outbreak although is sporadic can gain a potential pest status in Indian Himalayas in the future (Govind et al., 2015).

(c) Fall army worm (*Spodoptera frugiperda*): The infestation of FAW in state of Uttarakhand was first reported in 2019 in the foothills of Himalayas (Paschapur et al., 2021). In a span of 1 year, the insect traversed a long distance and reached mid and high hills of Himalayas in *kharif*-2020. In few locations of Uttarakhand, the per cent infestation reached up to 80%. It is expected to be a potential threat to maize crop in hill agriculture, and it necessitates immediate action from the government agencies and farmers. Monitoring and early management of the pest is necessary for containing its damage in hill agriculture. Although limited data is available to compare the climatic conditions and pest population density of FAW, the average rainfall and minimum temperature are negatively correlated, while maximum temperature and relative humidity are positively correlated with the pest population of FAW in maize in Uttarakhand (Ramirez-Cabral et al., 2017; Nurzannah et al., 2020).

B. Emerging insect pests of millets

Millets are among the major field crops cultivated in hill agriculture after cereals. They cover approximately 1.66 lakh ha in *kharif* season and provide livelihood for poor and marginal farmers practicing subsistence traditional farming (Indiastat-2021). The major millets cultivated in Uttarakhand Himalayan region are Finger millet, Proso millet, Kodo Millet and Barnyard Millet. Few important emerging pests are listed below along with climatic conditions influencing the population dynamics of these insect pests (Table 2; Fig. 2).

1. Shoot flies (*Atherigona* spp.): A minimum of four shoot fly species infect different millet crops. The infestation of shoot flies has increased exponentially in the recent years due to favourable environmental conditions like delayed onset of monsoon, extended dry spells in early crop season and lack of irrigation facilities and lack of knowledge regarding the pest damage. The pest infestation is severe in seedling stages, and finger millet is very susceptible to the pest damage than barnyard millet. The per cent damage of 20% or more was recorded in finger millet, while 15% or less was recorded in barnyard millet in *kharif*-2019 and 2020. Moreover, the minimum and average temperatures are significantly positively correlated with the population density of shoot flies in millets (Kundra et al., 2020).
2. Stem borer complex (*Chilo* spp., *Saluria* spp., *Sesamia inferens*, *Scirpophaga* spp.): The infestation of stem borers begin 30–35 days after sowing, and the per cent damage in *kharif*-2018 crossed 20%; from then, the pest damage has not crossed ETL. But, the damage is expected to increase in the future due to cultivation of traditional as well as high-yielding varieties that are susceptible to stem borer damage, low rainfall during tillering stage, cultivation of millets under rainfed condition

Table 2 Correlation between insect pest population density of millets v/s climatic conditions of *kharif* season from 2015 to 2020 (6 years)

Pest type	*Rainfall (mm)*	*Max temp*	*Min temp*	*Avg. temp*	*RH (%)*
Shoot flies	0.297	0.316	0.436*	0.491**	0.103
Stem borers	−0.161	−0.372*	−0.115	−0.218	0.020
Grass hoppers	−0.031	−0.475**	0.136	−0.024	0.431*
Aphids	−0.573**	−0.129	−0.440*	−0.438*	−0.265
Cetonid beetles	−0.700**	−0.218	−0.657**	−0.657**	−0.325

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

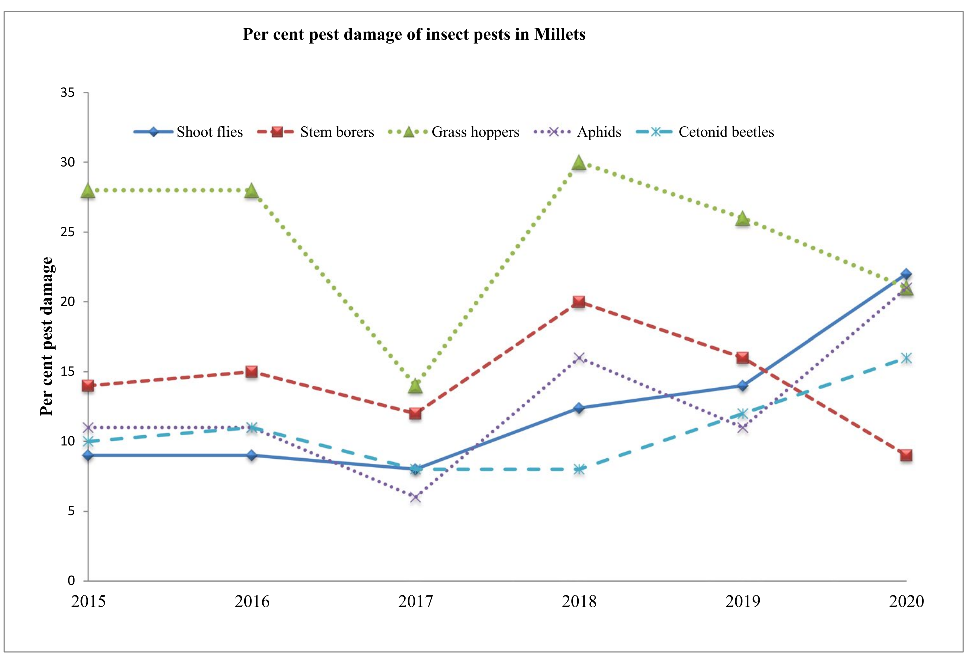

Fig. 2 Per cent damage by insect pests in millets over a period of 6 years (*kharif* 2015–2020)

and following traditional pest management strategies in millets. Moreover, drastic increase or decrease in temperature and increase in amount of rainfall during crop period is known to negatively influence the population of stem borers in millets (Ntiri 2015; Kalaisekar et al. 2016).

3. Grass hoppers (*Chrotogonus* spp., *Acrida* spp., *Melanoplus* spp., *Sphingonotus* spp.): There are more than eight species of grasshoppers infecting various millets in hill agriculture. During severe infestations, the per cent damage reached 30% or more in *kharif*-2016 and 2018. The nymphs and adults defoliated the plants, nibble the growing buds and feed on grains of millets during milky stage of the crop and cause severe yield losses. The pest damage has increased due to hot summer weather and erratic non-frequent rainfalls in the Indian Himalayas. Consequently, extensive rainfall and high temperature during cropping season negatively affects the grasshopper population, while optimum relative humidity positively influence the population and pest damage in millets (Axelsen 2009; Bal et al., 2015).
4. Aphids: Although aphids were minor pests of millets in the past, recently, their infestation has increased drastically in millets due to erratic non-frequent rainfall and increase in summer temperatures. The pest infestation during *kharif*-2020 (due to low rainfall and high temperature) crossed 20%. The pest population density is significantly negatively correlated with average rainfall, minimum temperature and average temperature. However, the maximum temperature and relative humidity do not significantly influence the population density of aphids in millets (Sharma 2016).
5. Cetonid beetles: Cetonids are minor pests of millets, and their damage usually ranges between 5 and 15%. They mainly attack the crop during flowering stage and feed on floral parts. Due to their damage, the seed set is drastically affected. Their damage is noticed only during the periods of low rainfall and high temperature seasons. The rainfall and minimum temperature conditions are significantly negatively correlated with the beetle population, while maximum temperature negatively influences the beetle population (Sharma and Davies, 1988). Due to changing rainfall and temperature regimes over the year, the pest population density is crossing ETL levels (> 10%) and necessitating the use of insecticides for their management in Indian Himalayas.

C. Emerging pests of pulses

Pulses are minor but important crops in Uttarakhand Himalayas covering an area of 0.24 lakh ha in *kharif* and 0.13 lakh ha in *rabi* season (Indiastat-2021). Few important pulses cultivated in hill agriculture are soybean, garden peas, rajma, French bean, red gram and lentil. Important and emerging pests of pulses and the per cent pest damage caused in different crops with respect to climatic condition are furnished in Table 3 and Fig. 3.

1. Blister beetle (*Mylabris* spp.): The blister beetles are sporadic pests in pulses. The infestation is severe during *kharif* season when there is prolonged drought and lack of alternative hosts. The adult beetles feed on flowers of rajma, horse gram, soybean and red gram, due to which pod formation is hindered. The economic yield of crop is drastically reduced during periods of severe infestation due to direct feeding on flowers. The per cent pest population usually ranges between 10 and 40% in all the pulses. Majorly, the red gram and horse gram are severely infected by this pest. Erratic and infrequent rainfalls in the last few years in Himalayas can be considered the major cause for blister beetle outbreak. However, its damage in *kharif*-2019 was less than 10% in pulses due to optimum and timely rainfall. Moreover, optimum rainfall coupled with minimum and maximum temperature show negative correlation with the pest population density of blister beetles (Sahay et al., 1999; Jat et al., 2017).
2. Red spider mite (*Tetranychus* spp.): The population of mites is compounding year after year due to cultivation of crops under protected cultivation system (especially French bean) and prolonged drought period during crop growth stages. The nymphs and adults of the mites suck

Table 3 Correlation between insect pest population density of pulses and oilseeds v/s climatic conditions of *kharif* season from 2015 to 2020 (6 years)

Pest type	*Rainfall (mm)*	*Max temp*	*Min temp*	*Avg. temp*	*RH (%)*
Blister beetles	−0.369*	−0.093	−0.205	−0.209	−0.117
Red spider mites	−0.388*	−0.278	−0.363*	−0.408*	−0.131
Leaf miners	−0.305	−0.360	−0.330	−0.404*	−0.041
Thrips	−0.483**	−0.168	−0.301	−0.320	−0.099
Mustard aphids	0.512**	−0.036	0.306	0.141	0.026
Soybean leaf bug	−0.086	−0.200	−0.061	−0.120	0.297
Platypria hystrix	−0.357	−0.157	−0.250	−0.269	0.060

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

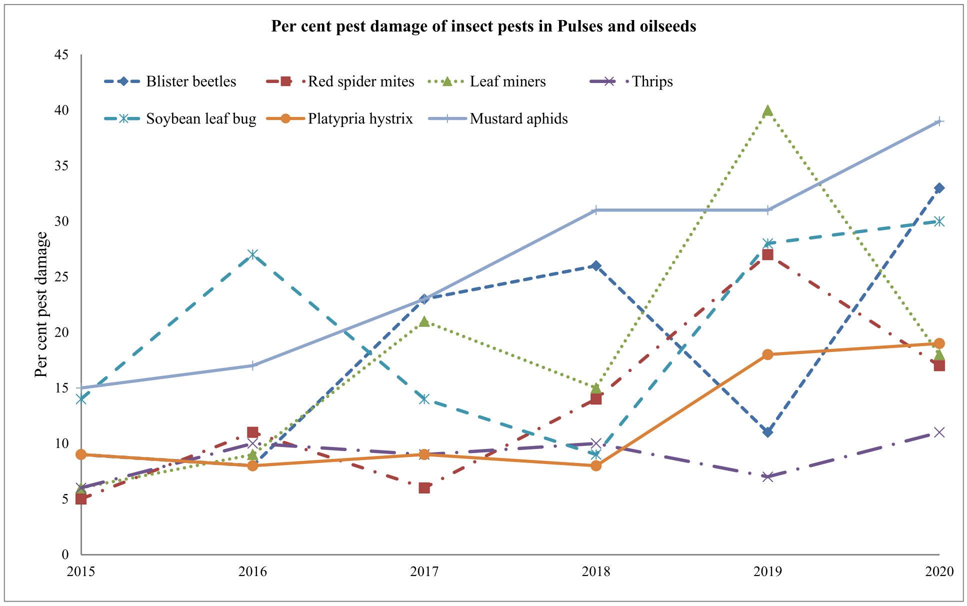

Fig. 3 Per cent damage by insect pests in pulses and oilseeds over a period of 6 years (*kharif/rabi* 2015–2020)

the sap from the underside of the leaf by constructing webs, and the infected leaf surface turns coppery colour with downward curling and crinkling. During periods of severe infestation, the entire crop dries up bearing no flowers and pods. The damage of mites is seen in rajma, French bean and garden peas, and the per cent mite damage ranged from 5 to 30% under protected cultivation. Optimum rainfall and timely onset of winter can significantly reduce the pest population. While, excessive relative humidity and high temperature conditions negatively influence the pest population density over the years (Khan et al., 2011; Choudhary 2016).

3. Leaf miners (*Liriomyza* spp. and *Chromatomyia* spp.) in pulses and vegetables: Recently, the leaf miner damage has increased exponentially in garden peas and horse gram. The leaf miners are usually hard-to-manage pests due to their concealed feeding habits, as the maggots tunnel inside the leaf and feed on chlorophyll content. The damaged leaf droops and dries up. The damage due to leaf miners in peas alone ranged from 20 to 60% in *rabi-2019* due to cultivation of crops in greenhouses and prolonged drought period during crop growth stages. Moreover, good winter showers followed by optimum relative humidity and temperature conditions are known to negatively affect the population of leaf miners in pulses (War et al., 2016).
4. Thrips (*Scirtothrips* spp.) in pulses and vegetables: The infestation of thrips also increased due to increased cultivation of crops under protected conditions, providing favourable microclimatic conditions for the multiplication of thrips. The damage is very severe in rajma and garden peas due to hot weather conditions and lack of regular irrigation schedules. But, over the years, the pest infestation is constant and is expected to increase due to increased cultivation of pulses under protected cultivation systems. Moreover, exposure of pulse crops cultivated in open fields to timely rainfall conditions reduces the thrips populations significantly (Choudhary 2016).

D. Emerging pests of oil seeds

Mustard and soybean are two important oil seed crops cultivated in hill agriculture (Kolte 2018), but the area under oilseed cultivation is very meagre in Uttarakhand. There are several insect pests infecting these oilseed crops, but the economic damage is caused only in mustard crop. Few important and emerging pests of oilseeds are explained in brief along with per cent pest damage and correlation with climatic conditions (Table 3; Fig. 3).

1. Mustard aphid (*Lipaphis erysimi*): Aphids in mustard are key and persistent pests. Due to feeding of aphids, seeds shrink, and yield is drastically reduced. Up to 80% yield loss can be observed in case of severe infestations (Patel et al., 2004). Late sown crop is severely infected. The per cent pest damage is increasing over the years, and the per cent damage in *rabi*-2020 was recorded to be more than 40%. Decrease in frequency of north-eastern monsoon and winter rains favours its population build up. Moreover, the extended winters (cold weather continuing till the end of March month) make the environmental conditions unfavourable for natural enemies and provide suitable conditions for aphid multiplication. However, the climatic conditions recorded over a period of 6 years had no significant effect on aphid population, but heavy rainfalls during early cropping season and

minimum temperature during flowering season reduce the coccinellid population and influence the aphid population positively, thus creating favourable environment for aphid multiplication in mustard (Singh et al., 2007; Bavisa et al., 2018).

2. Soybean leaf bug (*Chauliops choprai*): The leaf bug is sporadic pest of soybean in hilly areas of Uttarakhand, and its damage fluctuates over the years. The nymphs and adults suck the sap from under the surface of the leaf and cause white patches thus reducing photosynthetic activity. The insects prefer shady areas near the bunds. Erratic and infrequent rainfalls combined with high temperatures favour faster multiplication of the pest. However, the pest population density declines with respect to the amount and frequency of rainfall and minimum and maximum temperature conditions. But, optimum relative humidity during cropping period positively influences the pest population build up in soybean (Rajendran and Singh, 2016).
3. Soybean spiny beetle (*Platypria hystrix*): This is a regular pest of soybean in Himalayas. The grubs mine the leaves and feed on the epidermal layer of the leaf. Excessive damage leads to defoliation and reduction in pod set. Reduced rainfall during cropping season and optimum temperature regimes provide favourable climatic condition for pest multiplication. However, excessive rainfall and minimum and maximum temperature negatively affect the pest population, while relative humidity during cropping season has positive correlation with the population density of spiny beetle in soybean.

E. Emerging pests of vegetables

Vegetables in hill agriculture are cultivated mostly during offseason, and the cultivation has shifted from open fields to greenhouses to obtain better yields. The cultivation of crops in controlled environmental conditions with optimum fertilization and irrigation has exposed the crops to multitude of insect pests. Few of the major vegetables cultivated in Uttarakhand, Himalayan region are tomato, capsicum, chilli, brinjal, cabbage, cauliflower and green leafy vegetables. The important and emerging insect pests of vegetables are elaborated in brief along with climatic conditions influencing their population density over the years (Table 4; Fig. 4):

1. Greenhouse whitefly (*Trialeurodes vaporariorum*): The whitefly infects a wide variety of crops including pulses and vegetables. Recently, due to increased cultivation of crops in greenhouses, the pest population has shoot up rapidly. Temperate climate with temperatures between 18 and 28 °C is most ideal for whitefly survival and multiplication (McDougall 2009). Whiteflies are hard-to-control pests that infect tomato, capsicum, chilli, French bean, cauliflower and brinjal in Uttarakhand, Himalayas. The pests also transmit a large number of viral diseases in plants, thus causing severe yield losses (Navas-Castillo et al., 2011). The years from 2016 to 2019 have seen severe outbreaks of whiteflies with per cent infestation raging between 25 and > 40% in Almora and Bageshwar districts of Uttarakhand, wherein farmers had to fumigate the polyhouses to get rid of the pest. Although increase in temperature in polyhouses significantly reduces the whitefly population, optimum relative humidity due to excessive irrigation positively enhances the pest load in polyhouse condition (Al-Ajlan 2007; Gamarra et al., 2020).
2. South American tomato pin worm (*Tuta absoluta*): It is an introduced pest, causing havoc all over the country and causing severe yield losses in tomato. The pest has become severe in hills from *kharif*-2018. The per cent pest damage is increasing year after year, and in few polyhouses, as high as 60% yield loss was recorded (Sharma and Gavkare, 2017). In general, the damage is

Table 4 Correlation between insect pest population density of vegetables v/s climatic conditions of *kharif* season from 2015 to 2020 (6 years)

Pest type	*Rainfall (mm)*	*Max temp*	*Min temp*	*Avg. temp*	*RH (%)*
Greenhouse whitefly	−0.209	−0.469**	−0.287	−0.402*	0.047
Tuta absoluta	−0.164	−0.066	−0.093	−0.100	0.025
Black cut worm	0.283	0.482**	0.345	0.462*	−0.102
Mites	−0.519**	−0.173	−0.424*	−0.436*	−0.149
Aceria lycopersici	−0.162	0.129	−0.089	−0.038	−0.011
Aphids	−0.439*	−0.214	−0.392*	−0.417*	−0.112
Thrips	−0.545**	−0.296	−0.495**	−0.540**	−0.174
Leaf miners	−0.296	−0.288	−0.287	−0.343	−0.194
Pieris spp.	−0.326	−0.566**	−0.391*	−0.529**	−0.070
Red pumpkin beetle	−0.374*	0.172	−0.076	−0.015	−0.121
Cucurbits Fruit flies	−0.415*	−0.263	−0.313	−0.358	−0.042

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

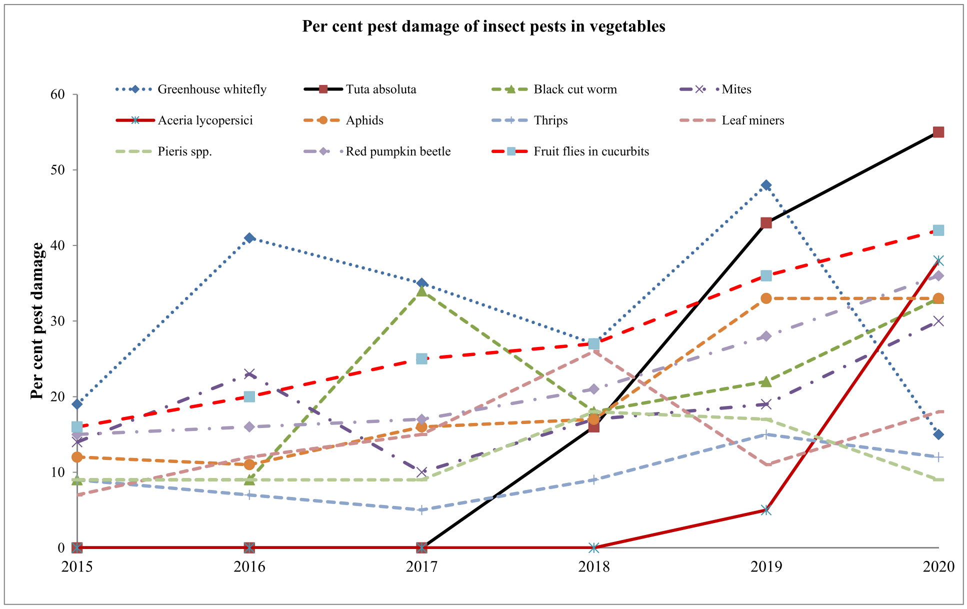

Fig. 4 Per cent damage by insect pests in vegetables over a period of 6 years (*kharif/rabi* 2015–2020)

more severe in polyhouse conditions than in open fields. The excessive rainfall and high- and low-temperature conditions during cropping season in open fields reduce the population build-up of *T. absoluta*. Wherein, optimum relative humidity due to excessive irrigation in polyhouse conditions positively enhances the pest load (Guimapi et al., 2016; Campos et al., 2021).

3. Black cut worm or army worm (*Agrotis segetum*): It is an endemic pest infecting all the vegetable and field crops in nursery in Himalayas. The caterpillars cut the young seedlings at the collar region at night time and defoliate the plants. The damage is severe in uplands, rain fed areas and sandy soils. The damage in nursery may sometimes reach up to 100%, while in broadcast sown rajma crop, the pest damage up to 60% was recorded in various villages of Chamoli district. The crucifers also incur early damage of up to 35% in both open fields and polyhouses (Sharma 2014). Delayed monsoon, extended dry spells in early crop season and lack of irrigation facilities are the possible reasons for faster multiplication of cut worm in the Indian Himalayas. Moreover, optimum rainfall during crop germination and high temperature conditions during early crop growth period can positively favour faster multiplication of cut worm (Thakur et al., 2012; Hayat et al., 2021).
4. Mites in tomato, chilli and capsicum (*Aceria lycopersici, Tetranychus* spp. and *Polyphagotarsonemus* spp.): The infection of mites is severe in greenhouse conditions. The nymphs and adults of mites suck the sap from under the surface of the leaf and cause downward curling and crinkling of the leaves. Early crop infestation can cause crop mortality and 100% yield loss. Recently in *kharif*-2019, an eryophid mite (*Aceria lycopersici*) damage was recorded in cherry tomato for the first time, and it caused excessive curling of leaves, blackening of stem, hardening and cracking of fruits. Within a span of 1 year, the per cent crop damage reached up to 40% in tomato. However, its damage was confined to cherry tomato, but the possibility of its host expansion cannot be neglected. It was observed that the average daily temperatures between 22 and 32 °C during crop season and more than 21 days of gap between two consecutive rainfalls are the possible reasons for rapid population build-up of mite pests (Premalatha et al., 2016). However, under open field conditions, optimum timely rainfall can drastically reduce the mite population. But, increased cultivation of vegetables under protected cultivation system provides very favourable climatic condition for pest multiplication (Monica et al., 2014).
5. Aphids in cabbage and cauliflower (*Brevicoryne brassicae*): Sucking pests have gained the status of major pests very recently due to erratic rainfall and elongated periods of dry spells in late winter and early summer months. The decline in amount of pre-monsoon rains has also favoured their rapid multiplication in both open field and polyhouse conditions. In the last 3 years, up to 30% yield loss was recorded in crucifers due to infestation of aphids. Timely rainfall during cropping season and prolonged winter months (up to end of march) significantly creates hurdles for aphid multiplication in Himalayas (Embaby and Lotfy, 2016; Sampaio et al., 2017; Mishra and Kanwat 2018).
6. Red pumpkin beetle in cucurbits (*Raphidopalpa foveicollis*): Cucurbits form an important component of vegetable cultivation system of Indian Himalayas. Their cultivation is usually practiced during off sea-

sons, i.e. pre-monsoon months (April to July), and during this period, they are exposed to a large number of insect pests. Few important among them include the red pumpkin beetles. Both the grubs and adults cause damage to the plants and lead to severe yield losses in early crop growth period. Their damage is increasing over the years, and pest damage in *kharif*-2019 and 2020 crossed 20% due to lack of pre-monsoon rainfalls, high temperature during crop germination and lack of irrigation facilities. However, timely rainfall is known to significantly reduce the pest population, and high humidity also affects their population growth negatively (Khan et al., 2012; Khursheed et al., 2013; Afroz et al., 2019).

7. Fruit flies (*Bactrocera* spp.): Fruit flies are important pests of many fruit crops, but, in Indian Himalayas, their damage is mainly recorded in tomato and cucurbits. Their damage is growing exponentially over the years, and in the year 2019 and 2020, the damage has crossed 30%. The fruit flies have reached the status of hard-to-manage pest in Indian Himalayas due to lack of their knowledge among farmers. The fruit fly population density is negatively correlated with rainfall, temperature and relative humidity. However, lack of pre-monsoon rainfalls and optimum temperature regimes during fruiting stage have favoured rapid multiplication of fruit flies in Indian Himalayas (Stanley et al., 2015; Shinde et al., 2018).

F. Polyphagous white grubs

White grubs are the most notorious polyphagous pests in the Indian Himalayan region (Subbanna et al., 2016). More than 80 species of white grubs infesting crops are recorded in the state of Uttarakhand, India (Subbanna et al., 2020). Both grubs and adults cause severe damage to cultivated crops and forest trees in the state and cause huge economic losses (Bhatt et al., 2015; Sushil et al., 2022). In the present study, we concentrated on nine dominant and economic white grub species infecting various crops in Uttarakhand and correlated their population dynamics of 10 years with weather

Table 5 Correlation between population dynamics of white grubs of Uttarakhand state v/s climatic conditions from 2011 to 2020 (10 years)

Pest type	*Rainfall (mm)*	*Max temp*	*Min temp*	*Avg. temp*	*RH (%)*
Xylotrupes gideon	0.439**	0.222	0.314*	0.254	0.178
Brahmina coriacea	0.418**	0.140	0.340*	0.286*	0.110
Holotrichia longipennis	0.097	0.250	0.149	0.243	−0.177
Holotrichia rosettae	0.169	0.239	0.174	0.268	−0.153
Holotrichia seticollis	0.249	0.431**	0.123	0.310*	−0.236
Lepidiota sticticoptera	0.239	0.361*	0.090	0.247	−0.170
Lepidiota stigma	0.235	0.590**	0.308*	0.444**	−0.186
Maladera similana	0.216	0.272	0.275	0.370**	−0.154
Anomala dimidiata	0.418**	0.287*	0.156	0.210	0.002

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed)

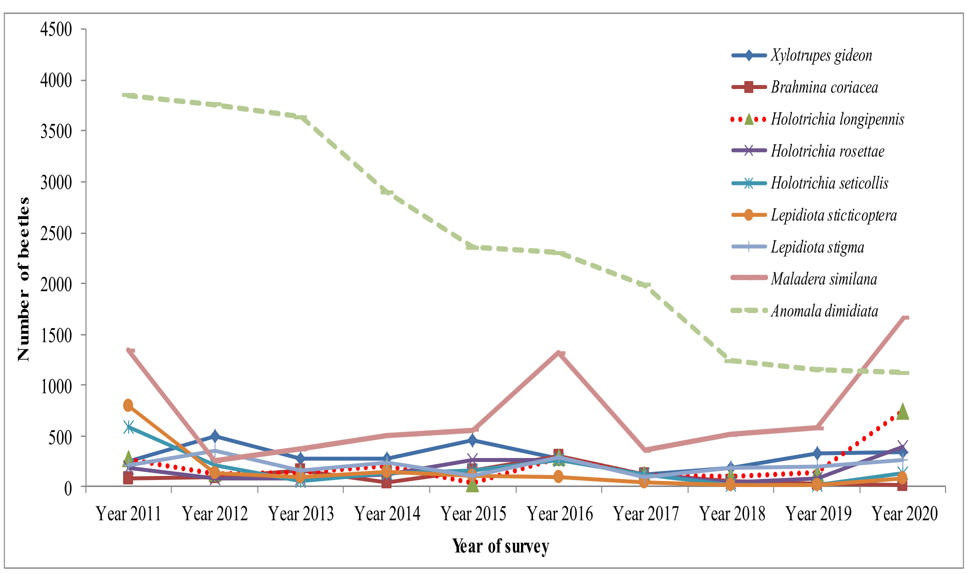

Fig. 5 Average population density of white grub beetles collected from six locations in Uttarakhand, India over a period of 10 years

parameters (2011–2020). It was observed that (Table 5; Fig. 5) pre-monsoon rainfalls during the months of April and May lead to significantly higher adult emergence of *Xylotrupes gideon, Brahmina coriacea* and *Anomala dimidiata.* While, maximum temperature of 35 °C or more during months of June and July showed positive correlation with the population density of *Holotrichia seticollis*, *Lepidiota sticticoptera* and *Lepidiota stigma.* However, the various weather parameters had no significant influence on the population dynamics of *Holotrichia longipennis* and *Maladera similana*. Our results formed close concurrence with the studies of Sushil et al. (2004) and Sushil et al. (2006). Moreover, the introduction of two pronged strategy of white grub management by Sushil et al. (2022) led to drastic decline in the population density of positively phototrophic *Anomala dimidiata* over the years and increase in the population of *Maladera similana*, which is negatively phototrophic. Further studies are also planned to develop a population prediction model of white grubs in the Indian Himalayas.

G. Principal component analysis of insect pests of kharif and rabi

The PCA analysis was performed to ascertain the pest population density in different months of *kharif* and *rabi* season respectively, over a period of 6 years (Figs. 6 and 7). The principal component 1 and 2 accounted for ~ 64.2% of total variance in *kharif* and ~ 88% in *rabi* with various insect pests in 12 different months from years 2015–2020, respectively. An angle of zero or 180° reflects a correlation of 1 or – 1, respectively. It was observed that in *kharif*, only cut worm and shoot flies infected the crop during early growth period (June and July), while few pests like grasshoppers, plant hoppers, FAW, *Tuta absoluta*, leaf roller, pumpkin beetle and mites infected the crop during vegetative period of the crop (August). Moreover, during the 2 months, September and October, the highest pest population density was recorded in various crops with insect pests like blister beetles, fruit flies, grasshoppers, stem borers, leaf miners and aphids etc. infecting crops during this favourable climatic condition. The observations recorded in *rabi* showed that only the months of February, March and April recorded the highest pest population densities in *rabi* season. Wheat shoot fly was the only insect pest known to infect crop during early crop growth stages. After November, the onset of severe winters drastically reduced the insect population, and pre-monsoon or winter showers during the months of February and March initiated the insect activity. Mustard aphid population was found at peak during late February and early March months, while peak infestation of insect pests of wheat and barley was recorded only in April. This PCA analysis study indicates the importance of favourable environmental conditions required for the insects to multiply in large numbers and cause damage to crops.

Conclusion

The list of above-mentioned insect pest infestation in various crops cultivated in hill indicates the altitudinal shift of insects to temperate regions, due to changing climatic conditions. The insects have gained the status of

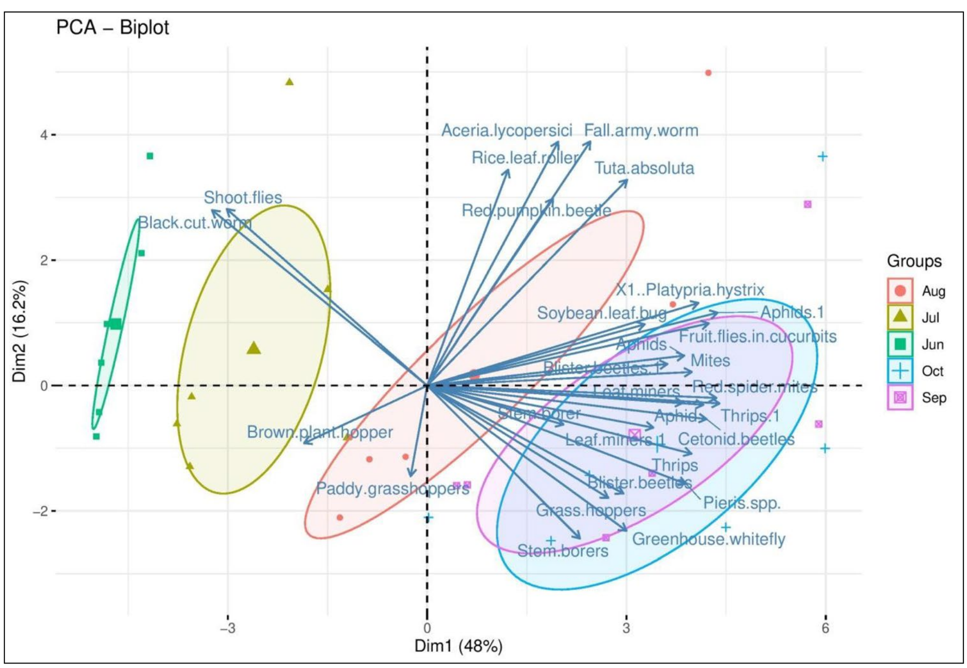

Fig. 6 PCA analysis of *kharif* pests (month wise pest population density over a period of 6 years 2015–2020)

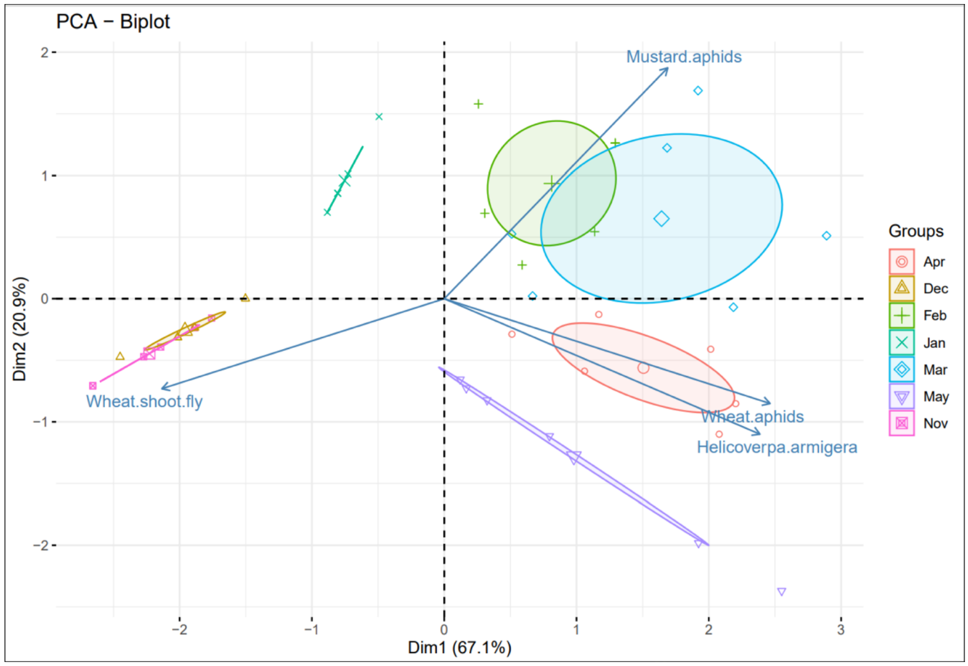

Fig. 7 PCA analysis of *rabi* pests (month wise pest population density over a period of 6 years 2015–2020)

pest in recent years, and it is due to decrease in amount and frequency of rainfall, high summer temperatures that expose the crops to infestation by insect pests of tropical climates and increased area of crops under protected cultivation, which provide favourable climatic condition for insect pests to multiply in large numbers. Especially the sucking pests like aphids, thrips, mites and whiteflies have multiplied rapidly and reached the status of hard-to-manage pests. Moreover, the introduction of exotic pests like tomato pin worm, fall armyworm and eryophid mite in cherry tomato are known to cause severe threats to hill agriculture in years to come and need proper monitoring and forecasting technologies to check their spread before they establish in a new favourable climate. The farmers in Uttarakhand, Himalayas, rely mainly on natural control strategies and seldom use low-grade, locally available, conventional insecticides, which pave path for faster resistance development by insects against insecticides. So, use of novel and safer insecticides with different modes of action can help farmers in managing the pests successfully in an eco-friendly way.

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Declarations

All the authors have thoroughly reviewed the article and given their consent for publication of the article to "International Journal of Biometeorology".

Conflict of interest The authors declare no competing interests.

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