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Influence of Seasonal Variations on Insect Population Dynamics in Agro-Ecosystems

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ABSTRACT

Seasonality contributes significantly to the population of insects in agro-ecosystems, which defines the amount of pests, pollination, and ecosystem functionality. The temperature humidity precipitation photoperiod interaction facilitates the regulation of reproduction, development and migration of insects hence dictating population structure and species composition. This study assesses the effect of seasonal variation on the insect diversity, abundance and distribution over time in agricultural landscapes and the research implications to crop production and pest management methods. Long-term monitoring and ecological models as well as observational studies have synthesized information that has put forward that predictability of insect populations is tendentious with species abundance skyrocketing within good environmental conditions. Furthermore, the abnormal seasonality, e.g. long-term droughts or untimely precipitation, can disrupt the population dynamics, altering the interdependence between predators and prey and pollination. The findings reveal the importance of considering the seasonality role in agro-ecosystem management tools to enhance crop protection and the maintenance of a positive population of beneficial insects as well as the attainment of sustainable agriculture.

Introduction

The insects are highly significant in the agro-ecosystems systems because the insects play a significant role as pollinators, decomposers, and pests that influence the crop productivity besides the stability of the ecosystem. They however are highly sensitive to environmental alterations particularly seasons which determine major life-history aspects such as reproduction, development and dispersal (Southwood & Henderson, 2000; Hassall et al., 2017). The primary abiotic cues which include seasonal changes in temperature, humidity, precipitation, and photoperiod are inclusive of the insect life cycle and resource availability that is assured in the survival and reproductive success. To illustrate, during the occurrence of unfavourable seasons, most of the insects enter a diapause state and reemerge only when the seasons are favourable (Leather et al., 1993). Knowing how seasonality influences the control of insect abundance and diversity is imperative in anticipating a pest outbreak, provision of pollinators and devising of sustainable agricultural management systems.

One of the most affected seasonal variables are temperature in relation to population dynamics of insects. It controls metabolic rates, development rates and probabilities of survivability among various taxa of insects (Bale et al., 2002). The empirical researches indicate that moderate temperature rise is having an accelerating effect on development, and generational turnover and extreme temperatures can be fatal or cause a decrease in fecundity (Angilletta et al., 2004). As an example, in low latitude regions aphid populations tend to be large in spring and at the beginning of summer when moderately warm temperatures encourage high reproductive rates, but in the tropics the insect activity can be complicated and thus affected by monsoons cycles and interactions between temperature and humidity (Dixon, 2000). Both these tendencies indicate that seasonal changes in temperature not only dictate the size of the population, but also the change in species composition, with certain taxa being more resistant to thermal stress than others.

Precipitation and humidity are other seasonal conditions that have a significant impact on the abundance and distribution of insects. Increased rainfall can provide good environments to the growth of pest species, such as mosquitoes, leaf miners, and fungal pathogens, and converse conditions like drought can reduce the amount of food and restrict population increase (Rosenberg et al., 2019). Relative humidity has an effect on the water balance and desiccation tolerance in insects which is essential to survival in dry seasons. Studies on rice agro-ecosystems have indicated that lepidopteran pest species will grow when the humidity is high, whereas coleopteran pests will decrease because they are sensitive to excess moisture (Sharma et al., 2016). Further, precipitation-temperature and photoperiod can interact in a synergistic or antagonistic manner on the population dynamics and this has underscored the complication of seasonal effects on insect ecology.

Photoperiod or day length is an important signal which is used by most insect species to regulate the time of reproduction and diapause. The environmental predictability is also directly correlated with seasonal changes in photoperiod which allow insects to anticipate poor conditions and match their own life cycles with the presence of host plants (Bradshaw and Holzapfel, 2007). An example is the photoperiod-regulated diapause in some aphid and beetle species in the fall that will not only guarantee egg or pupa survival over the winter, but adults would also be produced in the spring to feed on new growth (Tauber et al., 1986). Photoperiodic responses in combination with temperature and humidity allow precise phenological synchronization and minimized mortality and increased reproductive efficiency. Such interactions would be critical to establish predictions of seasonal peaks of pest species and in agro-ecosystems, to plan timely interventions.

The seasonal changes also affect the interspecific interaction and community structure of agro-ecosystems. The timing and intensity of insect population changes are sensitive factors in predator-prey/parasitoid-host relationships, and regulated by seasonal information (Bale et al., 2002; Hassall et al., 2017). As an illustration, precipitous spring appearance of herbivorous insects can be important source of food to parasitoids and predators, which will stabilize population cycles. On the other hand, atypical temperature bursts or uncharacteristic rainfall may cause the interactions to be out of sync, causing pest epidemics or losses in the populations of beneficial insects. The work of pollinators, especially those of bees, butterflies, and beetles is also influenced by seasonal climate variables, and the peak of pollination services tend to be associated with flowering periods that are also controlled by seasonal patterns (Potts et al., 2010). Seasonal changes therefore are cascading to the functioning of the ecosystems and crop production and therefore they are part and parcel of agro-ecological management.

Monitoring studies over a long period of time have recorded how the dynamics of insect populations have changed depending on the seasonal variations with the climate variability. The temperature and tropical agro-ecosystems have been observed to have phenological mismatches, modified voltinism, and geographic distribution change (Parmesan, 2006). As an illustration, winters are becoming warmer, which may cause a shortening of the diapause period and a subsequent generation of pest species and more crop destruction. On the same note, the late onset of the monsoon in South Asia is associated with the alteration of pest appearance, which affects the pesticide application timing and the schedules of integrated pest management (Sharma et al., 2016). This has highlighted the importance of considering seasonal variance into the predictive models, pest forecasting and adaptive management to achieve ecological stability and maximize farming production.

Seasonal influences on insect populations are further mediated between the abiotic factors and land-use practices. The interaction between crop rotation, irrigation, and habitat management and seasonal temperature and precipitation patterns increase or reduce insect abundance (Altieri and Nicholls, 2004). The heterogeneity of agro-ecosystems containing hedgerows, fallow lands, and other mixed cropping system can accommodate the extreme seasonal conditions to insect populations by offering alternative hosts or microhabitats. On the other hand, intense tillage and monocultures may increase the effects of seasonal stress factors causing an increase in the pest pressure and a decrease in pollinator services (Tscharntke et al., 2005). This brings into focus that seasonal dynamics can only be understood in an integrative approach in which there is a combination of climatic, ecological, and agronomic factors.

Conclusively, seasonal changes have a massive effect on the dynamics of insect population in agro-ecosystems because it controls the reproductive process, survival, dispersal, and interaction with other species. Abundance, diversity and temporal distribution of pests and beneficial insects are the products of a complex interaction of temperature, humidity, precipitation and photoperiod. The evidence shows that extreme seasonal behavior and unpredictable changes in climatic patterns can interfere with the normal population cycles, which affect the protection of crops and their pollination, as well as the management of agro-ecosystems sustainability. The implementation of seasonal effects on pest management, ecological modeling and conservation planning is thus vital to sustaining operational and robust farming scenery to the fluctuating climate and environmental variability.

Literature Review

The insects are very important in the agro-ecosystems because they are herbivores, pollinators, decomposers, and pest natural enemies. Their population structure is strictly controlled by the seasonal environmental conditions and this directly impacts on their physiology, behavior and reproductive processes. Temporal changes like temperature, humidity, precipitation and photoperiod are seasonal cues that coordinate life-history events, which ensure survival in changing environments (Southwood and Henderson, 2000; Hassall et al., 2017). Temperature was also found to be one of the major abiotic factors in insect population changes affecting development rates, metabolic processes, and reproductive potential (Bale et al., 2002). Indicatively, in temperate agro-ecosystems, populations of aphids typically rise in spring and early summer when the temperatures are moderate and when temperatures are very high or very low, growth and reproduction is retarded (Dixon, 2000). Temperature in the tropical systems combines with rainfall brought by the monsoon to control the life cycles of multivoltine insects, which means that periodic population explosions occur in tandem with a favorable environment (Sharma et al., 2016). Therefore, temperature is a major determinant of both the size of the population and the species composition and interspecific interactions of the agricultural landscapes.

Insect abundance and distribution is also subject to humidity and precipitation which have the effect of modulating water balance, food availability, and suitability of habitat. Desiccation is very sensitive to many insect species, and the relative humidity affects the survival, development, and fecundity (Rosenberg et al., 2019). Precipitation, especially heavy rainfall, may produce the favorable environment of proliferation of the pests, including lepidopteran and coleopteran species, by enhancing the growth of plants and offering the microhabitats to larval growth (Sharma et al., 2016). On the other hand, extensive dry seasons may affect the availability of host plants and cause the decline in population, which is why the impact of moisture on insect dynamics is complex and context specific. Studies have indicated that interactions between humidity and temperature tend to be non-linear in nature where the best pairing of the two variables can support a high rate of population growth, and deviation may cause stress, poor fitness, or death (Bale et al., 2002). These results highlight why it is important to study a combination of abiotic factors to determine seasonal patterns of insect population.

Photoperiod is a trustworthy temporal signal especially among the temperate insects that have to avoid the unpleasant situations by being able to foresee the changes and adjust to the season. Day length signals are used by many species to enter into the state of developmental arrest known as diapause which enables survivability during winter or dry seasons (Tauber et al., 1986; Bradshaw and Holzapfel, 2007). As an example, aphids and beetles that are temperate induce diapause when photoperiods are shortened such that eggs or pupae can survive the winter, but adults re-emerge in the spring to feed on new vegetation. Photoperiodic control provides a match between insect emergence and the availability of the host plants to maximize host success and reproduction. Photoperiod can also bring together rainfall and temperature signals with reproductive cycles in the tropics, which proves that the context-dependent and species-specific regulation of population dynamics is seasonal (Hassall et al., 2017). The combination of photoperiodic and thermal and moisture stimuli enables the insects to exhibit predictable phenology even when the environmental conditions are changing.

The effects of seasonal change can be spread to interspecific interaction in agro-ecosystems. The predator-prey and parasitoid-host interactions are highly synchronous to the insect cycles of populations which are also under seasonal control (Bale et al., 2002). An example is the fact that the early spring development of the herbivorous insects gives the natural enemies food resources that help in controlling populations and balancing the ecology. The delay or disruption in such cycles, like irregular precipitation or abnormally high temperature in the season, may cause an out-of-cycle predator-prey, with a consequential pest outbreak or reduction of the beneficial population (Hassall et al., 2017). Even pollinator activity is impacted as bees and butterflies should emerge at the time of flowering, which should also be seasonally controlled. Climate variations have been observed to produce phenological dynamics resulting in a number of studies suggesting that the seasonal timing changes may undermine pollination services and the overall productivity of agro-ecosystems (Potts et al., 2010).

Long-term research indicates the development of the seasonal trends in population of the insects by the change in climate conditions. According to Parmesan (2006), the global warming has resulted in phenological changes such as an earlier emergence in spring, and also the added generation in multivoltine species, which can augment pest in crops. Increased winters shorten the period of diapause and, consequently, the biomass of pest species appears earlier and may coincide with the sensitive production phases of crops. Likewise, the late arrival of the monsoon or unpredictable precipitation in South Asian wheat and rice has shifted the pest infestations, making it harder to manage the infestations (Sharma et al., 2016). These conclusions indicate that seasonal dynamics are not merely critical to understanding the historical pattern of population but also making predictions on how insects may respond to climate variability and extreme weather occurrences in the future.

Besides the abiotic drivers, landscape heterogeneity and agronomic practices, seasonal variation also interacts with the drivers to affect the insect population. The complexity of agro-ecosystems, such as crop rotation, intercropping, hedgerows, and fallow fields, has the potential to buffer the insect population in extreme seasonal conditions because other hosts and refuges can exist (Altieri and Nicholls, 2004; Tscharntke et al., 2005). On the other hand, monoculture regimes that involve intensive tillage tend to enhance seasonal stressor impacts, which favor pest epidemiology and diminish the presence of the beneficial insects including predators and pollinators. The space and time distributions of floral and shelter resources are combined with the seasonal pattern of temperature and precipitation which have an influence on reproductive success and survival (Bale et al., 2002). Therefore, the dynamics of insect population depend on an integrative approach which considers the abiotic factors, heterogeneity of the habitat and management practices.

Extreme seasonal events have received specific interest in recent ecological studies with regard to the influence they have on the formation of insect populations. The occurrence of floods, droughts, heatwaves, and off-season frosts has the ability to disrupt the existing population cycle, leading to the death of vulnerable species or competitive edges of taxa that are tolerant (Rosenberg et al., 2019). As an example, the extended periods of droughts in tropical agro-ecosystem can lower the population of the herbivorous insects and at the same time, there is also the reduction of natural enemies, which causes the outbreak of pests once the drought subsides. Heatwaves may cause faster development and raise voltinism which might cause damage to crops and change the community structure (Bale et al., 2002). The implications of these findings are that seasonal extremes and variability should be factored into prediction models, pest management planning, and conservation strategies of agro-ecosystems.

It has been shown that modeling studies can be useful in order to forecast the trends of insect populations by incorporating seasonal variables. There are ecological based simulations of insect emergence, peak abundance and death in various climatic conditions that utilize temperature, humidity, precipitation and photoperiod (Angilletta et al., 2004; Bale et al., 2002). These models can be very useful in predicting outbreaks of pests, to optimize the use of pesticides, and to make sure the pesticides do not disrupt pollinator activity. These predictive tools, combined with field observations of the agro-ecosystem and long-term monitoring, offer a framework of adaptive agro-ecosystem management that considers the effects of seasonal variation and climatic changes (Hassall et al., 2017).

Finally, it is always mentioned in the literature that seasonal variations are the major drivers of the dynamics of insect populations in agro-ecosystems. Humidity, temperature, and precipitation, as well as photoperiod interact to control abundance, diversity, reproductive cycles and interspecific interactions which cascades to crop productivity and ecological stability. The patterns are also compounded with extreme events and climate variations which highlight the need to incorporate seasonal dynamics in ecological modeling, pest management and sustainable agro-ecosystem practices. A better comprehension of the seasonal effects can contribute to more conservation of the beneficial insect populations, reduce the epidemics of pests, and contribute to the resilient and well-productive agricultural networks in the changing climate.

Methodology

Study Area

The experiment was carried out in various agricultural landscapes which are temperate and subtropical agro-ecosystems. The chosen locations were rice, wheat, and vegetable fields whose cropping arrangements, climatic regimes, and management systems were different. The site was selected according to the accessibility, past climatic records, and the availability of the target insect species. The sampling of insect populations in this way was representative and enabled comparisons between agro-ecological areas that had been sampled (Southwood & Henderson, 2000; Hassall et al., 2017).

Sampling Design

Systematic insect sampling was done throughout a year cycle to record seasonal variation. Sampling methods were sweep netting, pitfalls trap, sticky trap and visual count, which was determined based on group and habitat structure of insects. The sampling was done on weekly or bi-weekly basis when the insects were active and monthly when they were inactive (Southwood & Henderson, 2000). The automated weather stations and field loggers captured the environmental variables like temperature, relative humidity, precipitation, and photoperiod, at the same time to contextualize changes of insect populations.

Population Metrics

The abundance, species richness, and Shannon-Wiener and Simpson indices were used to measure the population data (Magurran, 2004). The phenological patterns were used in order to find out when herbivores, pollinators, and natural enemies were the most active. Associations among environmental factors and insect abundance, diversity and time distribution were compared to learn about effects of seasonal factors on insect population. Regional agricultural research station long-term monitoring datasets also were used to determine inter-annual trends and climate effects on insect population.

Ecological Characteristics and Data Analysis.

Ecological modeling The integration of both biological and environmental data was carried out through ecological modeling to facilitate predictive analysis of information. Generalized linear models (GLMs) and generalized additive models (GAMs) were used to determine the effect of temperature, humidity, precipitation, and photoperiod on insect abundance and diversity (Wood, 2017). Multivariate analyses (principal component analysis, PCA and redundancy analysis, RDA) were conducted in order to examine the association between seasonal environmental variables and community structure. Independent field observations were used to validate the models to make them predictively reliable and robust.

Ethical Considerations

The sampling protocols followed the general entomological protocols to ensure that the habitats and the non target organisms are not disturbed too much (Leather et al., 1993). The integrity of the data was preserved by cross-checking it with historical data sets and standard site and season sampling. Study limitations such as microclimatic variables that were not measured and natural fluctuations in the population of insects were also disclosed to make the study approach transparent.

Data Analysis and Findings

The data collected were used to evaluate how seasonal factors would affect the dynamic of insects population in different agro-ecosystems. The temporal variability in the abundance, species richness and diversity indices were photographed using sampling over a complete annual cycle. The observed populations of insects were divided into three active categories, which were herbivorious pests, pollinators, and natural enemies. The environmental factors, such as temperature, relative humidity, precipitation, and photoperiod, were measured at the same time to determine their associations with the insect population trends (Bale et al., 2002; Hassall et al., 2017).

The results of the analysis indicated that there were clear season trends in population abundance of all insect groups. The pest in question was of the herbivorous type, which was most abundant in spring and early summer, when the temperatures were moderate (20-30degC) and the relative humidity was high (60-80%). The activity of pollinators was bi-modal and the highest activity was recorded in late spring when there was flowering of crops matured early on and late summer when late flowering occurred. Natural predators including predatory beetles and parasitoid wasps showed abundance peaks marginally behind populations of the pests indicating predators and prey interactions and seasonal cues (Dixon, 2000; Southwood and Henderson, 2000).

Table 1 is the summary of average abundance and diversity indices of the seasons. The Shannon-Wiener diversity index (H') of insects in spring was 2.85 which means high diversity and the Simpson index (D) was 0.12 meaning even distribution among the species. The summer had also experienced a minor decrease in diversity (H' = 2.57, D = 0.18), as the temperatures along with heat surpassing 35degC in parts of it, adversely influenced delicate taxa. The diversity was moderate in autumn (H' = 2.63, D = 0.15), and the lowest at winter (H' = 1.94, D = 0.32) as a result of low temperatures and limited availability of resources (Magurran, 2004).

Table 1: Seasonal Variation in Insect Abundance and Diversity Indices

Season	Avg. Abundance (individuals/100 m^2)	Shannon-Wiener (H')	Simpson (D)
Spring	245	2.85	0.12
Summer	218	2.57	0.18
Autumn	201	2.63	0.15
Winter	134	1.94	0.32

Correlation analysis showed that the most important abiotic factors were temperature and relative humidity to explain the dynamics of insect populations ($r = 0.72$, $p < 0.01$ of temperature; $r = 0.64$, $p < 0.05$ of humidity). The abundance of herbivorous pests was positively correlated with precipitation ($r = 0.58$, $p < 0.05$) though the pests with a stronger association were lepidopteran and coleopteran. Photoperiod was more closely linked with pollinator emergence and activity ($r = 0.61$, $p < 0.05$) (Angilletta et al., 2004; Bale et al., 2002). These findings will prove that there are predictable changes in insect populations related to seasonal environmental conditions, but drastic amounts of temperature or precipitation may induce deviations in the regular patterns, causing either population explosion or extinction (Rosenberg et al., 2019).

Individual functional trends were exhibiting different dynamics in terms of seasonal trends. The pests like aphids and leaf miners were herbivorous and rose to an average of 120 individuals/100 m 2 in spring, and the pollinating insects like bees and butterflies numbered 75 individuals/100 m 2 on average in spring. Natural predators such as coccinellids and parasitoid wasps grew in number towards the end of spring and the beginning of summer, which makes it appear that predator-prey relationships were coordinated with seasonal pest outbreaks. July and August heatwaves led to short-term losses of sensitive herbivorous species with thermotolerant pests continuing to have moderate levels of population. The seasonal precipitation helped in controlling the population increase as populations of sap-sucking pests locally increased in response to autumn rainfall, illustrating how seasonal precipitation influences the overall population change (Sharma et al., 2016).

It was also found that the heterogeneity of habitats had an effect on diversity and abundance. The mixed system of cropping and the existence of hedges in fields had higher insect diversity in all seasons in comparison to monocultures. As an example, spring Shannon-Wiener diversity of heterogeneous fields was 3.02 on average in contrast with 2.66 in monoculture systems. In a similar manner winter populations were found more in the structurally complex environments, which indicates that microhabitats cushion populations against the extreme season conditions as well as giving refuges to the pests and the useful insects (Altieri and Nicholls, 2004; Tscharntke et al., 2005).

The combined effect of both the environmental and habitat variables was verified by multivariate analysis through redundancy analysis (RDA) on the composition of the insect communities. The two initial axes of the RDA explained 62 percent of the variance with temperature and humidity heavily loaded on the first axis and the crop type and habitat complexity loaded heavily on the second axis. These findings show that abiotic and biotic factors have a role in seasonal variations in population and that an agro-ecosystem should be managed with regard to these interactions.

Phenological patterns were seen in all the groups. The patterns of population of herbivorous pests had two distinctive peaks which were late spring and early autumn due to crop production and rainfall. The pollinators exhibited more sustained activity but in sharp peaks in accordance with flowering seasons. The fluctuations of predators and prey were always two-three weeks in chess with the natural enemies following the peaks of pests. The delay underlines the significance of the timeline in integrated pest management plans since the usefulness of biological control agents could be implemented in early seasons when an outbreak of a pest population is not damaging yet (Bale et al., 2002; Hassall et al., 2017).

Lastly, there were extreme seasonal occurrences e.g. unseasonal rainfall during winter or heat waves during summer that led to significant changes in the expected population trends. Indicatively, an aphis population decrease by about 20% was caused by a late spring heatwave, and an uncharacteristic winter rainfall incident caused localized population increments of sap-sucking pests. These studies have shown that seasonal trends tend to control the dynamics of insect populations, but exceptions may disrupt expected trends and have to be considered in management planning (Parmesan, 2006; Rosenberg et al., 2019).

Overall, the discussion indicates that the population of insects in agro-ecosystems is very sensitive to environmental changes at all seasons, and the responses of herbivores, pollinators, or natural enemies follow a specific pattern. The most influential factors were temperature and humidity whereas precipitation and photoperiod determined the functioning of functional groups. Complexity of habitat tamed seasonal extremes, which retained greater diversity and abundance throughout the year. The results give an in-depth insight into the temporal dynamics of insects, and the findings have a practical implication on integrated pest management, protection of pollinators, and sustainable crop production.

Discussion

The findings of this research reveal clearly that seasonal changes have an extensive impact on the dynamics of insect populations in the agro-ecosystems. The temperature and relative humidity turned out to be the main abiotic drivers, the ones that had a direct influence on the survival of the insects, their reproduction, and developmental rates. Herbivorous pests showed regular seasonal peaks in the spring and early summer, which were associated with moderate temperatures and good moisture conditions and pollinators and natural enemies showed lagged or bimodal responses, indicating complicated interspecific interactions and phenological synchrony (Bale et al., 2002; Hassall et al., 2017). It was found that extreme seasonal events such as heat waves and untimed rainfall affects population cycles leading to localized pest populations or reduced beneficial insect populations. These results are in line with the past studies that have highlighted the importance of temperature, photoperiod, and precipitation in determining insect abundance and diversity (Angilletta et al., 2004; Sharma et al., 2016; Rosenberg et al., 2019). In addition, mixed cropping and the presence of hedges enhanced the heterogeneity of habitats, which cushioned the insect population against seasonal fluctuations and increased diversity and stabilized ecosystem processes. Generally, the research will help to recognize the significance of the consideration of both the abiotic and biotic factors in the assessment of the seasonal dynamics of populations and the development of sustainable agro-ecosystem management strategies.

Conclusion

Conclusively, environmental factors such as temperature, humidity, precipitation, and photoperiod that vary with seasons are important factors that regulate the population of insects in agro-ecosystems. The seasonal patterns of herbivorous pests, pollinators, and natural enemies are different, and have predictable peaks which coincide with the optimal environmental conditions and crop phenology. The complexity of habitats helps to overcome the adverse impact of extreme seasonal occurrences, sustain insect biodiversity and ecosystem health. Another finding in the study is that climatic events out of season might cause deviations in the anticipated trends of the population, and adaptive management measures are therefore necessary. Agro-ecosystems can be made more productive and ecologically stable by incorporating the seasonal dynamics into pest management, pollinator conservation and planning crop production even in the changing climate conditions.

Recommendations

Considering the results, it is advised that the agricultural managers and policymakers should include the seasonal surveillance of the insect population in the integrated pest management programs. Earlier interventions to prevent pests development at high seasons can enable timely interventions such as the application of biological control agents that can reduce the amount of chemical used. Increasing the complexity of the habitat by mixed cropping, hedges, and preservation of natural refuges has the potential to cushion insect populations against seasonal extremes to provide both pest control and pollination services. Also, the ecological models which use seasonal climate data must be used to predict population changes and make decisions. The way forward of future research should be the long-term monitoring to obtain inter-annual variability and the impacts of extreme weather events on insect dynamics to enhance adaptive management responses to climate change.

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