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CLIMATE-DRIVEN SHIFTS IN AGRICULTURAL INSECT PEST DYNAMICS: PROJECTED IMPACTS AND IMPLICATIONS FOR ECOSYSTEM MANAGEMENT

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Abstract

Climate change is altering the biology, ecology and distribution of important insect pests and transforming agricultural systems at the global scale. Rapid increase in pest development, geographic ranges are expanding and natural enemy-pest interactions are being disturbed with increasing temperatures, rising atmospheric CO_2, and unpredictable precipitation patterns. The result is that these changes are ultimately threating crop production and food security by leading to an earlier infestation, overwinter, and an outbreak of pests. Although the high CO_2 concentration changes the nutritional quality of plants and influences the feeding behavior and performance of insects, the high temperatures may increase the metabolic rate, reduce the development stages, and enhance the reproductive capacity. It also highlights how fluctuations in rainfall influence both soil dwelling and aerial pests by modifying host availability, microhabitat conditions, and predator prey dynamics. Also, climate change undermines the power of biological control programs and exacerbates the transmission of plant diseases vectors by insects. This review presents an overview of the latest studies on the changes in the physiology of pests, population dynamics and ecosystem interactions under the influence of the changing environment associated with climate changes. The study emphasizes adaptive management strategies, such as ecofriendly crop protection methods, advanced predictive modeling tools, and climate smart integrated pest management systems. To develop resistant agricultural systems that can minimize the emergence of new pest threats to agriculture in the future under climatic conditions, understanding of these mechanisms is necessary.

1. INTRODUCTION

Throughout the past, Human's life is continuously facing changes in different fields of life; either it's related to values, knowledge, discipline, the economy or farming techniques. Agriculture itself has undergone many revolutions due to advanced livelihood, industrial spreads, and overall human growth. But place in recent past is having drastic effects because human population and food production are directly related to one another (Skendžić et al., 2021). Increasing competition for food, land and energy and severe changes in climatic conditions are highly affecting biotic and abiotic factors (Godfray et al., 2010).

Climate change harms both crops and their pests. Directly, it affects the growth or reproduction of

pests, change their life cycle due to which insect may start producing a greater number of generations in a specific time, alters the host and pest relationship or the synchronization they have (Fig. 01). On the other hand, it affects the relationship among pests and other environmental factors like predators or those organisms that are living in a mutual relationship with those pests as an indirect harm (Prakash et al., 2014).

The alteration in the climate variables may increase or reduce the pest population. Those species that are able to defy the end of the limits of climatic conditions and adapt to the altered atmosphere can preserve its population and, as a result, feast on crop vegetation. Compared with the insect species existing in tropical and temperate areas, changing temperature have severe impacts on insects in the temperate regions. Those felt in the temperate parts of the world have been the altitudinal shift, and intrusion of insect pests, in greater altitudes. This has come with fresh challenges of sustainability of agriculture (Shrestha, 2019).

Insects are also used as being significant keystones species in the health and. services of the ecosystem. The population of insects is decreasing drastically in all parts of the world due to the adverse effects of the changing climate. As such, one should design good pest control strategies that will be effective in future due to global warming. Host-plant resistance, natural plant products, biopesticides, natural enemies & agronomic techniques offer a potentially practical option for integrated pest management. Further studies are required in connection with climatic change of insects and mitigation measures (Bhagarathi & Maharaj, 2023). This review aims to analyze ongoing and anticipated climate change impacts, particularly elevated CO_2 concentrations, droughts, and temperature, on insect pest biology and ecology. Additionally, the paper presents modern pest monitoring technologies and prediction tools to create modified integrated pest management strategies that can effectively combat or manage pest adaptation and pressure on crops while considering the effects of climate change, ultimately ensuring adequate food production (Subedi et al., 2023).

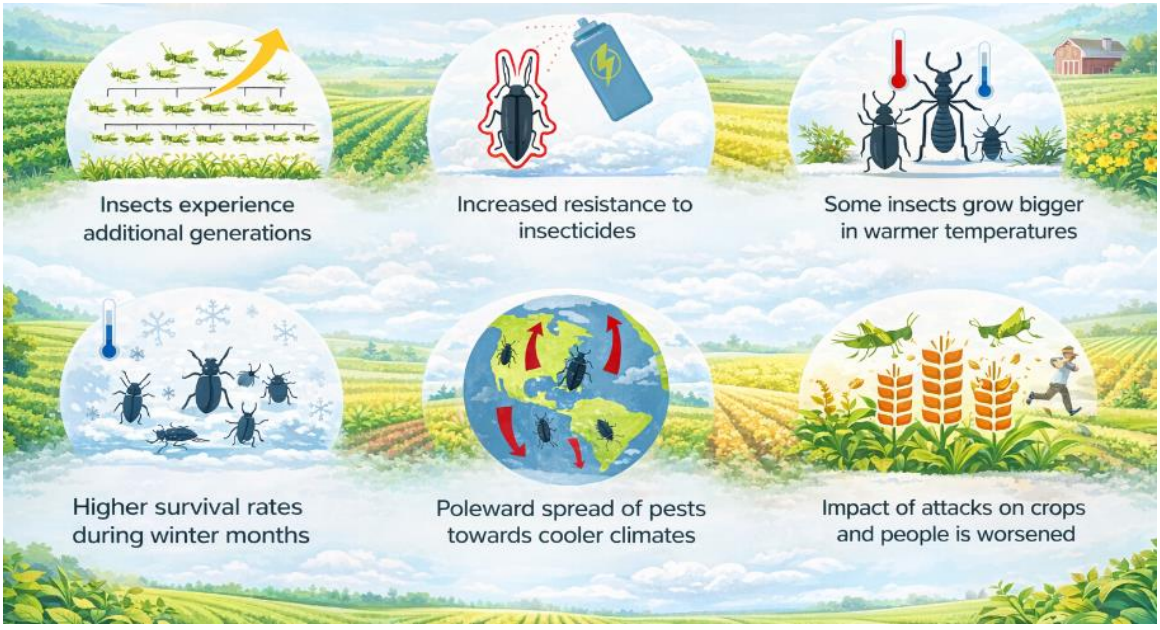


Fig. 01. Climate driven shifts in agricultural insect pest dynamics

2.1. Mechanisms That Influence Agricultural Insect Pests

The major effect of environmental changes on agricultural pests is change in reproduction, behavior, dispersal, migration and more no of offsprings per year. Increase in universal temperature can change the insect phenology. It will cause the arrival of insects in the crops before time. Water strained plants may promote the more pest's outbreak that will affect both crop yield as well as food security (Pareek et al., 2017). As the climates keep on changing, the species will either have to adapt to the changing conditions in the present location or they will have to relocate and seek better ones. The insects are numerous and reproduce quickly, and their fecundity, phenology, survival, selection and habitat use are highly responsive to the climate change because of their high population and short generation times. Such insect life-history alterations can in turn result in rapid alterations in abundance and distribution (Shrestha, 2019). Changes in climate can alter the insect physiology directly or indirectly. Natural enemies and the pest of host plant may respond to changing environmental conditions differently (Prakash et al., 2014).

Increased temperature will increase the abundance of insect pest and practically all species of insect are influenced by varying temperature. The effects of warming in season are that it could also result in greater levels of feeding and growth including the possibility of an extra generation in one year. This has dire consequences on crop development and also in the pest management scheme. Global warming will also have an effect on the phenology of insects such as introduction of insect pests into their agricultural areas and the hatching of various insect pests (Shrestha, 2019).

2.1.1. Elevated temperatures

The organisms and ecosystem of earth is going under stress because of drastic elevation in temperature. Extremeness in temperature can have impact on the pests by altering their lifestyle, it can disturb their rate of growth, survival and number of offspring by altering their environment. It can fasten their metabolism with every temperature rise of 10 degrees. Changes in temperature can change the behaviors of insect pests like how they forage, find their mates and responds to changing conditions. All the species show different responses towards changing climate so it may change the interactions between species and causes a disturbance in the number of their population and their role in the environment (Ma & Ma, 2016).

Despite of being sensitive to the climate warming, how they will respond to the upcoming change is still not clear because the reactions of insect pests are complicated and keep varying. A study on 31 major pest species tells us that some species give more arm in a warmer environment but some species show mixed responses like they show changes in their life cycle, reproduction and range. It means that a pest specie can either increase or decrease due to a change in climate. Mixed responses of insect pests are totally depended on their traits and their habitat where they live in. (Lehmann et al., 2020). Wheat pests' population will increase with a rise in temperature and vice versa for rice pests. Climate change will affect those insect pests more that live above the ground because they do not have any insulator on them in the form of soil which is available for the pests living under the ground that keep them save from climate warming (Skendžić et al., 2021).

As the global temperature increases by one degree, it will reduce the life cycle of insect. The faster the life cycle, the more the population of pests will be. The majority of insects in the temperate regions grow in the warmer half of the year due to which, the species whose niche space is determined by the climatic regime will change in response to the change in climate more predictably whereas those species, the niche of which is constrained by other factors of abiotic or biotic nature will be less predictable. It is predicted that if the temperatures will rise the same way, the species will move their geographical ranges towards the poles or towards the elevations and will enlarge their number (Pareek et al., 2017).Global warming can cause pest infestation and crop damage before the time.

For example, whitefly population rises with an increase in moisture & temperature as well as the outburst of bark and timber boring pests also get severe. Climate change decreases the efficiency of biological control of cereal leaf beetles by changing the harmonization between the pests and its natural predators. These alterations in insect pests' behavior can result in many new problems for the landowners because the pests will migrate towards new areas where their host plants are growing (Subedi et al., 2023).

2.1.2. Increased levels of CO_2

Carbon dioxide is a notorious gas which is always linked to climatic change. The carbon dioxide participates in the augmentation of the insect population increment by meddling with plant nutritional make-up. Carbon dioxide increase is commonly perceived as carbon dioxide increase in photosynthetic rate and it is believed that plant becomes well adapted to drought in higher carbon dioxide concentration. This makes it possible to have the availability of host even in severe conditions guaranteed to insects. As such, it triggers the state in which pest infestation is plentiful (Shrestha, 2019). An increased number of crop foliage and thicker foliage will cause increased relative humidity due to increased CO_2 level in the atmosphere and this will make the micro-environment conducive to the pests. The rises in the quality of food i.e. increase in the nitrogen content of the plants with high temperature may lead to sudden resurgence of the population of pests. In addition, defensive systems of plants, during the condition of stress, are less effective and are more vulnerable to pest attack illustrated in fig. 02 (Das et al., 2011).

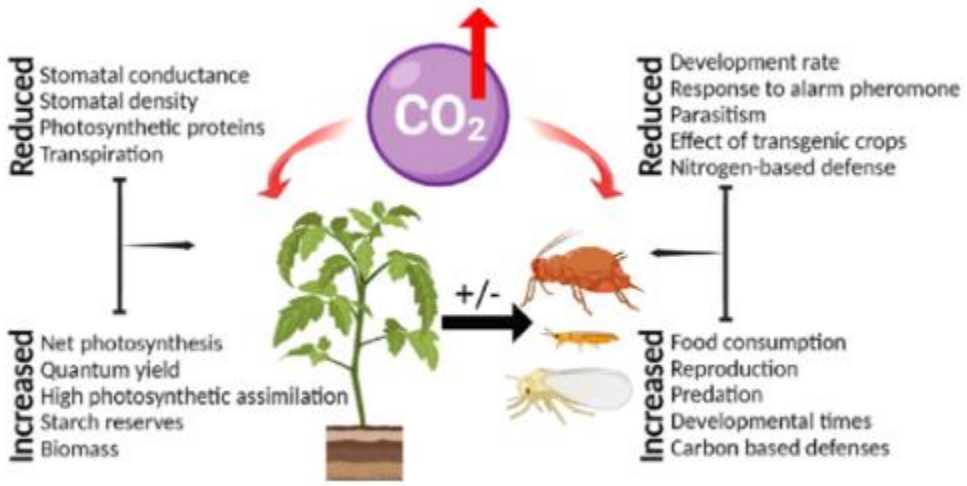


Fig. 02. Effect of elevated CO_2 on insect pests

Increasing CO_2 levels accelerate the growth of the bean pod borer of the family Crambidae and change the nutritional content of chickpea and consequently enhances food consumption and larval weight gain, pupal weight gain, and the overall larval period. CO_2 fertilization affects differently depending on the nature of pest feeding. The thrips numbers are increasing. Whiteflies and aphids are examples of phloem-feeding insect pests where the rates of population growth and the population density decrease. It is unanimous on whether rising CO_2 will have any impacts on the sucking of insects even though in other situations abundance and fecundity can be boosted (Bhagarathi & Maharaj, 2023). Due to CO_2's cascade effects on plant biochemistry, phytophagous insects may be more vulnerable to variations in atmospheric CO_2 concentrations. This is because some bug species that feed on plants make their pheromone molecules using substances that they obtain from their hosts. For instance, the mevalonate pathway is used by bark

beetles to produce pheromones. Hydroxylation of the secondary metabolites obtained from trees is the source of some components of aggregation pheromones (Karthik et al., 2021)

2.1.3. Unusual pattern of precipitation

Various studies on climate change have predicted the regional changes in the rainfall pattern that was caused by the climate change (Fig. 03). The increase in population of wireworms in the upper soil is brought about by the enhanced summer rainfall and drought conditions on the soil which harbors wireless worms. Migratory patterns of the desert locust in Sub-Saharan Africa are being influenced by the rainfall patterns. The rainfall deviation in monsoon and November and its correlation to the level of *Helicoverpa armigera* infestation also indicated that the higher was the rainfall in November and the stronger the infestation (Karuppaiah & Sujayanad, 2012).

On the other hand, heavy rainfall may be of an advantage since it may help to cleanse off minute pests like aphids, mites and whiteflies. A change in the amount of precipitation may also affect the nutritional value of plants that herbivores feed on affecting their performance. Extreme droughts may boost the population of the bark beetles, whereas trees that are moderately stressed may become resistant to the bark beetles. It has been found that water stress will cause a reduction in the biological processes of plants leaving them vulnerable to attacks by diseases and pests (Subedi et al., 2023)

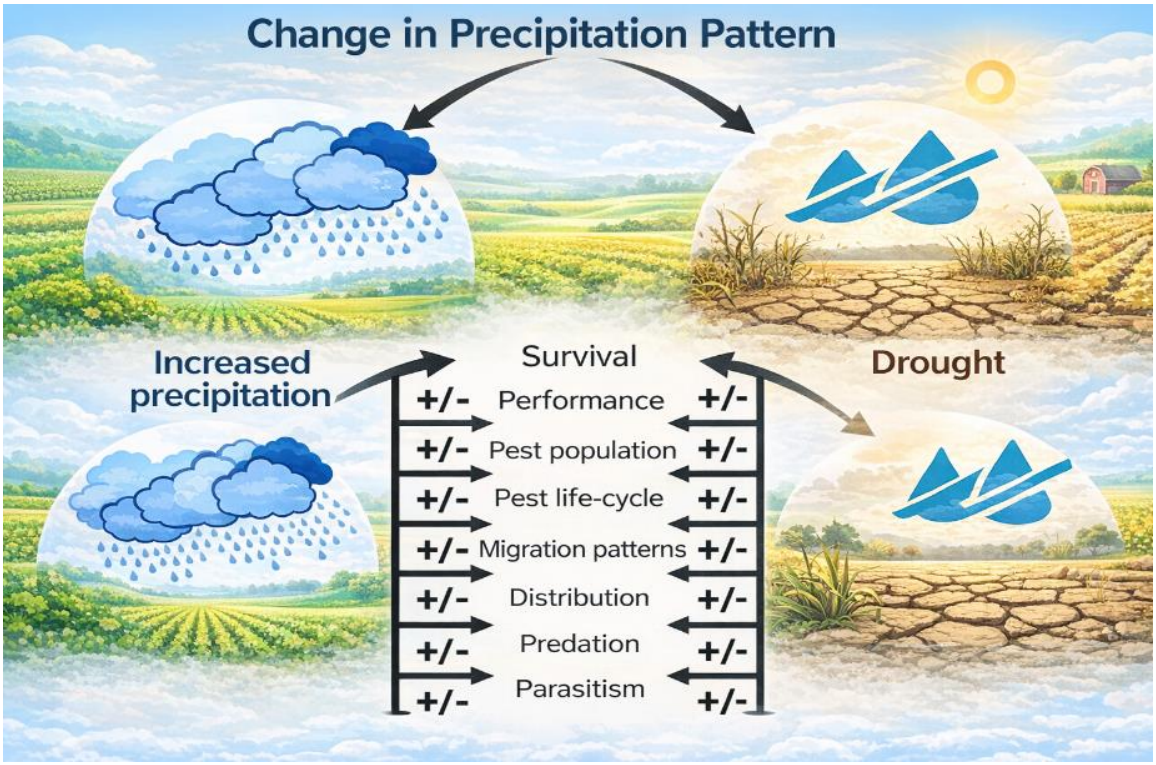


Fig. 03. Effect of unusual precipitation patterns on insect pests

It has also been reported that rainfall, relative humidity and temperature influence the emission of volatile plant metabolites. Alterations in the emissions of volatiles of plants might in effect alter the capacity of insect herbivores to locate host plants in case the alterations pertain to particular cues that influence foraging behavior. Moreover, it can also influence the foraging behavior of higher trophic-level arthropods that is mediated by volatiles released to signal herbivory, including predators and parasitoids. Therefore, the alteration of the abiotic factors can

significantly influence the interaction between the species (Chen et al., 2019).

3. Biological Responses of Insects Due to Climate Change

3.1. Expansion in geographic ranges of insect pests

Due to change in the temperature regimes, pests could be introduced in newer regions which are not favorable to insect development and multiplication. The help of oriental fruit fly, *Bactercera dorsalis*, which is a major pest in South East Asia as well as in some pacific Islands can be used to explain the situation. Climatically warming will permit most of the temperature insects' species to expand to higher latitudes and highest elevations. Minimal temperature instead of maximum temperature plays a role in global distribution of insects. Recent decades in a study of the species of 35 non-migrating butterflies in Europe, that two-thirds have increased by 20-150 miles and many plants flower a week earlier than they used to 50 years ago. Thus, with the increase in temperatures, seasonal signaling change and life changes both in space and time (Nitta et al., 2024). The researchers discovered that climatic factors have a dramatic impact on the occurrence and fecundity of insect pests of radish crop in the Eastern Himalayas. Increase in temperatures was more likely to raise the activity and density of the population of the pests through faster development and more generations per season. Conversely, an increased rainfall and an increased relative humidity tended to lower the number of pests, heavy rain or frequent rain has the potential of washing off pests and decreasing the survival of eggs and larvae. The microclimate is influenced by the seasonal changes in temperature, rainfall, humidity, to find out when and where pest outbreaks will occur (Ela et al., 2023).

Alterations in the frost pattern can affect the distribution of frost sensitive insect pests. When the temperature increases, spring frost become less and result in longer summer periods which increases the number of pest outbreaks. Even if the farmers plant their crops earlier, these crops will be available for the pests to feed on. As a result, pests will give more harm and their reproductive growth may increase (Skendžić et al., 2021).

3.2. Increased overwintering survival

The cold temperature is a major problem to the insects, which affects their physiological processes and kills them. In order to counteract the impact of the low temperatures, insects have developed an overwintering behavior including overwintering by diapause that lowers their physiological rates so as to endure the low temperatures or freeze avoidance where insects remove their potential nucleates to prevent freezing. Climate change is however affecting the overwintering patterns of insects by changing the photoperiod, caused by changes in temperatures and precipitation leading to the distortion in diapause timing and an elevated threat of severe cold conditions in case insects go into diapause later in life cycle (Subedi et al., 2023).

For instance, the fully grown green stink bugs in Japan can survive during winters by entering diapause at proper time but the immature bugs can die if they are not fully grown before arrival of winters. if the temperature is high during time of diapause it can reduce the time and frequency of that state in some insect species. A study shows that if the European bluebottle beetles grow at 20 degrees, they will produce a smaller number of offspring that will undergo diapause than the beetles that are reared at 15 degrees. Insects will face cold stress if they do not enter in diapause at proper time due to warm temperature. This is because the insects do not have fully developed mechanisms to survive winters (Skendžić et al., 2021).

Insects that are going through a diapause are probably going to see the most changes in their temperature environment. Insects' diapause lasts for less time at higher temperatures because their stored nutrients are used up more quickly. Warming in winter may cause a delay in commencement, whereas early summer may result in a speedier end of diapause in insects, allowing them to resume active growth and development (Rehman & Kumar, 2018). Chances of insects' survival is more in the warm

temperatures. It is expected if the temperature increases from one to five degrees in winter the survival rate of insects can be improved. If the winter temperature becomes too high and insects have less snow-cover then it can lead to the death of many insect pest species. But the insects that have the ability to survive in extreme winter temperature can get a chance to enjoy a long summer period if they have less snow cover or if there is early snow melting happens. It is important to keep in sight how increase in temperature is having effect on these phases of diapause (Bale & Hayward, 2010).

3.3. Increase in number of pest generations

As previously said, temperature is the most essential regulating factor for insects. Tropical and subtropical insects experience faster development, reproduction, and survival rates as global temperatures rise within a suitable range. Insects will be able to reproduce more frequently, causing more agricultural damage (Rehman & Kumar, 2018).

Aphids are the best example to explain the influence of environment change on pests. When the temperature rises, aphid reproduction cycle increases 4 to 5 times in a year. That's why they are extremely delicate to climate change. High temperature also affects their growth rate by reducing the time period of larval and nymphal stages and make the aphids grow faster and spread around because the stages that are more susceptible to predation become shorter. (Skendžić et al., 2021)

Every insect species has their own optimal temperature series set for growth, development and reproduction. If the temperature suddenly increases or decrease it will affect the survival of the insects. For instance, the developmental time of *Matsumura tettix hiroglyphicus, a leafhopper that is the pest of sugarcane, is decreases from egg to adult due to increase in temperature. The quantity of male offspring is more at high temperature and number of female offspring is more at low temperature* (Kobori & Hanboonsong, 2017).

4. Ecological Responses of Insects Due to Climate Change

4.1. Surge in insect transmitted plant pathogens

Insect transmitted plant diseases are becoming a major challenge in improving the productivity of horticulture crops. Factors like climate change is one of the chief reasons in the emergence of plant diseases. Increase in the temperature and moisture level help the disease transmitting vectors to survive in those areas where they were unable to grow previously. These vectors transfer different viruses like *Potyvirus, Tospovirus* etc. to the plants and the infections become severe with changing climate. The import of plants is a big reason in the introduction of new disease-causing vectors. The survival, growth, reproduction of insect vectors and resistance development in host plants is highly influenced by change in climate (Krishnareddy, 2013). Climate change may increase the prevalence of insect-transmitted plant diseases by expanding insect ranges and multiplying vectors. High temperatures, especially during the early season, have been linked to an increase in viral infections in potatoes. This is due to the early colonization of virus-bearing aphids, which are the primary vectors of potato viruses in Northern Europe (Rehman & Kumar, 2018).

Insects of Hemipteran are significant facilitators of disease. Climate change can increase the occurrence of plant diseases that are spread by insect vectors by raising the geographical range of insect vectors and leading to an explosive growth in insect vectors. The spread of related diseases can be attributed to a rise in population and hazards due to insects that are related to the aphids (Bhagarathi & Maharaj, 2023).

The development and survival rates of pathogens and the alteration of host susceptibility due to predicted changes in climatic conditions are expected to change the effects of diseases on crops. Impact of such climatic changes will vary according to their pathosystem and geographical locations. Such changes do not necessarily only have effects on the optimum conditions of infection and may also influence host specificity and plant infection mechanisms. Alteration of the abiotic conditions will also have an impact on

the micro climate of the plants and the vulnerability of the plants to infection (Elad & Pertot, 2014).

4.2. Reduced efficiency of biological control agents

The effects of climate change on the natural enemies of the insect pest are quite numerous. The increase in temperature and CO_2 and decrease the precipitation of plants consequently results in plants with different nutritional opportunities, which leads to the fitness of the insect pest- feeding predators and parasitoids. Although there are a great number of host and parasitoid species, variability in precipitation is the most important reason to explain variant caterpillar parasitism. Concerning herbivores host and their mobility, natural enemies search their hosts depending on their vulnerability to host environments. It was discovered that predatory bugs are more useful in destroying the cotton bollworm larvae when the pea plants are grown under high CO_2 concentration (Karthik et al., 2021).

The migration of pests to the areas where they have no predators to control them will result an increase in number of pest population. New predators may not be as effective as the actual predators. Climate change severely affect the host plants, pests and their bio control agents. Farmers use different policies to overcome the losses due to climate change but it will change the synchronization between the host plant and pest and biological control will become less effective (Thomson et al., 2010)

Other research stated that concomitant rise in temperature and CO_2 content adversely impacted the nutritional value of alfalfa plants, which in turn caused the breakdown of the feeding generation of the parasitoid on the beet armyworm. It is not yet well known how an increase in CO_2 can affect the predator performance, but in one study the Asian lady beetle was found to be more attracted to aphids under the high CO_2 but no difference was found in the real predation performance of the beetle (Küçük & Tunca, 2024).

5. Case Studies

5.1. Effects of Climate Change and Crop Planting Structure on *Helicoverpa armigera*

The effects of alterations in climate and crop planting structure on the population dynamics of *H. armigera* was evaluated using a 25 years climate and crop planting structure dataset of Bachu County, south Xinjiang, China. The *H. armigera* exhibited a positive trend of population size with increasing climate and in the third generation. The percentage ratios of the first and the second generation declined, whereas, the third generation percentage ratio rose. Increasing temperature and precipitations created various effects on the growth of various generations. The *H. armigera* populations grow with the non-Bacillus thuringiensis cotton area that was planted. There was asynchrony of the sudden shifts between climate changes, the day of crop flowering, and *moth H. armigera* phenology. Asynchronous reactions in the phenology and dates of crop flowering of *H. armigera* to climate warming would be extended in future (Huang & Hao, 2020).

5.2. Evaluation of the effects of climate change on the existence of tomato invasive insect pests

Uganda has been experiencing the upsurge of new tomato invasive insect pests in the last century. The determination of how temperature, rain-fall, relative humidity and wind speed influence the incidence of invasive tomato insect pests, will provide a more realistic insight to control and reduce the bio-invasion process of tomato invasive insect pests in Uganda sustainably. Climate change is one of the drivers that promote the availability of bio-invasion of tomato invasive insect pest's occurrence in Uganda. It asks the policymakers and stakeholders to be aware of climate-wise pest management practices and policies in order to address bio-invasion (Ela et al., 2023).

6. Innovative Pest Management in an Evolving Climate

Agricultural pest control of insects has emerged as a burning issue that needs to be addressed

through development of effective and sustainable ways of controlling agricultural insects. Climate forecasting and development of climatic models to predict and control the effects of the climate change on the insect pests is one of such strategies. Climate forecasting is a statistical procedure that involves the application of models, statistical techniques, as well as data to project the future weather patterns and climate changes. These forecasts are useful in decision making in different fields including agriculture (Subedi et al., 2023).

In order to reduce the negative impacts of the climate change on the management of pests, a number of measures are being formulated and put in place. Incorporated Pest Management techniques which involve a combination of different pest control methods including cultural methods, biological control and the use of pesticides in moderation are becoming common. IPM focuses on preventive and monitoring control, less use of chemical pesticides, and the resiliency of the ecosystem. Such methods as remote sensing and predictive models are the precision agriculture techniques that help detect pests early and apply specific interventions to them to optimize resource use (Sen & Banerjee, 2023). Global warming and greater acceleration of international trade are adding to the rate of occurrence of the old as well as new pests. Hence, the improvement of the adaptability of insects to the fluctuation in climatic conditions acquires more significance. There are potential adaptation strategies that have been found to minimize the risk of emerging pests and the diseases that they can cause. The more common approaches are featured as modified integrated pest management practices, climate and pest population monitoring and application of modeling and forecasting tools (Küçük & Tunca, 2024).

Addressing the challenges of climate change and pests goes beyond just using technology. It requires policy support, building skills, and involving everyone from local communities to international organizations. Governments, research groups, NGOs, and communities must work together to create policies that promote sustainable farming, educate farmers, and help them use climate-friendly pest control practices (Chandana et al., 2024).

6.1. Modified IPM strategies

The key goal of integrated pest managing (Fig. 04) is to control the harmful pests like ticks, mites, aphids sustainably. In IPM, we use different physical, biological or cultural control methods to keep the pest population in a limited number. For example, crop rotation, trap cropping or using natural enemies of the pest before applying the chemical control in the form of pesticides. We should make IPM strategies by using latest techniques and tools like forecasting technique. Chemical control should only be applied when the pest population spreads at a dangerous level (Skendžić et al., 2021).

The IPM practices such as field monitoring, pest forewarning, record keeping and the choice of cost effective and sustainable control would assist in reducing the potential effects of climate change. It should be mentioned that the management of pests might be different. It depends on the local circumstances, yield, and the type of pest. Thus, it is important to take into consideration the specific conditions of particular farming system and consult it with the local knowledge and consultation with agricultural extension services may be very helpful to introduce the most appropriate practices of pest management (Sen & Banerjee, 2023). It is crucial to develop alternative eco-friendly strategies to control the pest outbreak (Gomez-Zavaglia et al., 2020). Knowledge of the effects of climate change on different pests, especially crop pests, will allow the agricultural scientists to devote some of their research time on possible future research solutions that can reduce and adapt to the dangers of estimated climate change (Sen & Banerjee, 2023).



Fig. 04: Modified Integrated Pest Management strategies

Adaptive pest management strategies, such as biocontrol and Integrated Pest Management (IPM), should be emphasized in farmer education programs. Extension services and digital platforms may spread information about precision agriculture equipment, climate-resilient crops, and environmentally friendly pest management techniques. Initiatives to increase capacity will enable farmers to successfully reduce pest concerns (Tiwari, 2024)

It is necessary to understand how environment affect the crops and their pests. For instance, if plants present in resource less or stressed environment it will be more susceptible to the pests. If the temperature gets higher, it will cause an increase in pest development and damage will result earlier in a drastic way. So, controlling strategies should be start at low level to prevent yield from damage (Lamichhane et al., 2015). We should study how the climate warming is affecting insecticides and for how much time it remains in the environment and causing harm into both crops and pests (Vadez et al., 2012).

6.2. Assessing population size & spatial distribution

It is essential to monitor and analyze the insect distribution and abundance because they have small size and they are highly sensitive to climatic changes and act as bioindicator of environmental health. It is one of the most important steps to check if the change in climate is affecting insect population dynamics or not. For example, due to increase in temperature the distribution of dragonfly and butterfly is altering (Thomson et al., 2010). One of the most critical conditions of assessing the impact of climate change on changing the population of pests is tracking its density and distribution. In the absence of such vital long term datasets, changes in pest populations in relation to changing climate regimes or predicting future trends in population are very hard to evaluate fully. The ability to

monitor pest populations and their behavior over time especially in climate sensitive areas can give some of the first signs of biotic response to climate change. It is the same way as the dynamics of vectors, diseases, and hosts are under surveillance in their countries of origin, changes in the geographic location of pest species should also be monitored accordingly (Küçük & Tunca, 2024). By tracking both climate and pest data, along with risk predictions, farmers can take early action with pest prevention strategies to minimize future pest issues. This monitoring helps scientists and conservationists detect early signs of ecological imbalance and develop strategies to mitigate issues affecting biodiversity (Skendžić et al., 2021).

6.3. Innovations in climate predicting models

Climatic changes are highly affecting the pest populations so there is a huge need to use the adaptive managing strategies for deal with the upcoming threats. Development of predictive models can help us to do the risk management and make guidelines according to it. Such models deal with the pest abundance, life cycle, and changes in population at different sites and at different times. Models are made by keeping in mind the economic value of the pests and then preventive measures are taken to control the insect pests within limits at local as well as at large scales (Sutherst et al., 2011). To overcome those issues, interdisciplinary cooperation between scientists, conservationists and policymakers is necessary to come up with adaptive management measures to incorporate climate resilience into conservation policies. The research ought to concentrate on long term studies in the future to have a better predictive analysis of the impacts of climate change on insects as well as take proactive steps to conserve biodiversity. Together with a set of technological innovations, policy strategies and community involvement, we can find some sustainable ways of reducing negative consequences of climate change on the population of insects and guarantee further functioning of environments that humans and other species depend on (Yadav et al., 2024).

Considering the critical importance of climatic models in learning and predicting the risk level of climate change, a thorough examination of the meteorological science offers a requisite background in understanding the complexity and utility of the climatic models. They provide the basis to foresee the consequences, direct the adaptation actions, and set the mitigation goals. This innovative plan can result in the generation of massive scientific knowledge that is needed to enhance ambitions in mitigation and adaptation efforts in the coming decades. With the promotion of collaboration and improvement in climate modelling, we will have an easier time trying to cope with the intricacies of climate change and to move towards a sustainable future (Khan & Srivastava, 2025).

7. Conclusion

The agricultural pest complexes are sweeping redefining the climatic change by changing the physiological and population structure of insects, their distribution range, association with host plant and natural enemies. Increasing temperatures, changing rainfalls, and CO_2 levels are also enhancing pest growth, more generations per season, overwintering survival, and pest outbreaks of large-scale cropping systems. At the same time those shifting climatic conditions are weakening the resistance of plants and disrupting ecological balance making crops more susceptible to insect feeding and diseases they carry. In order to protect future agricultural output, pest-management models should change to be proactive, climate-resilient models that should be based on the conventional reactive methods. These involve the incorporation of predictive modeling, changing of planting time, the introduction of resistant and climate-resistant crop varieties, farm biological control, and also, cropping system diversification to upset colonization. Precise tools, enhanced extension services, and enhanced monitoring networks are much needed otherwise early detection and quick response. Finally, the problem of pest risks under the conditions of changing climate will involve the concerted actions of the researchers, farmers, policymakers, and international organizations. It

is important to develop sustainable, flexible, ecologically informed pest-management systems that would guarantee long-term food security and resiliency of agriculture in a more unpredictable climate.

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