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Climate change and insect pests: a review

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Abstract: Modern scientific research and agronomy are focused on climate change and related phenomena rising global temperature and atmospheric carbon dioxide concentrations, heat waves, flooding, intense storms, droughts and other extreme weather events. A plant pest, hereafter referred to as a "pest", is any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products. Historic and current examples clearly show the extensive damage that can be caused by pest outbreaks. Warming facilitates the introduction of unwanted organisms; a single, unusually warm winter may be sufficient to assist the establishment of invasive pests, which otherwise would not be able to establish. Climate change will also result in increased problems with insect transmitted diseases. These changes will have major implications for crop protection and food security, particularly in the developing countries, where the need to increase and sustain food production is most urgent. Higher concentrations of CO2 with the rise in temperatures in the atmosphere have direct effects on plant metabolism and affect the distribution, abundance and productivity of insects that feed on plants. All these have led to the reduced efficacy of crop protection technologies, huge crop losses, thereby, food insecurity. Although concerted efforts have been made and simulation models have been developed to mitigate the climate change effects on plants, still, most simulation models fail to account for losses due to pests, weeds and diseases. In addition, the monitoring data of insect pests are not available in most of the developing countries and the software models developed for prediction analysis are not effective against insect- pests. This review highlights the possible impacts of climate change on phytophagous insects, chemical ecology, and plant pest interactions leading to food insecurity and the strategies thereof.

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Introduction

The growing world population has rising demands for crop production and accordingly, by 2050, global agricultural production will very likely need to be doubled to meet that kind of increasing demand (Razzaq et al., 2022; Haroon et al., 2022; Zafar et al., 2022; Sahar et al., 2021). For food security, numerous studies have recommended that enhancing crop yield, rather than clearing more land surface for crop production, is the most sustainable approach (Haroon et al., 2022). Modern scientific research and agronomy are focused on climate change and related phenomena—rising global temperature and atmospheric carbon dioxide concentrations, heat waves, flooding, intense storms, droughts and other extreme weather events (Zafar et al., 2021). Therefore, more attention to the aforementioned abiotic factors is given in agricultural science, as the tendency to reduce yield loss due to such conditions increases (Zafar et al., 2022; Zhang et al., 2022). Regarding crop production, changes in precipitation patterns may potentially have higher importance than temperature rise, especially in areas where dry seasons present a limiting factor for agricultural production (Safdar et al., 2022; Zafar et al., 2022). A plant pest, hereafter referred to as a "pest", is any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products. Historic and current examples clearly show the extensive damage that can be caused by pest outbreaks. Warming facilitates the introduction of unwanted organisms; a single, unusually warm winter may be sufficient to assist the establishment of invasive pests, which otherwise would not be able to establish (Tulu, 2022). In fact, the increased market globalization of recent years, coupled with increased temperatures, has led to a situation that is extremely favorable to pest movement and establishment, with concomitant increases in the risk of severe forest and crop impact. By affecting both plants and insects in various ways, climate change is predicted to be one of the major drivers of change in crop–pest interactions worldwide, along with agricultural intensification. While climate change can impact plant physiology in multiple ways, therefore, though changes in plant defenses, directly or indirect impact insect herbivores or their predators (Schneider et al., 2022; Zafar et al., 2022; Zafar et al., 2021; Zafar et al., 2020). Insects are ectothermic, tend to generally have a short life cycle, and are more mobile than plants. As a consequence, insect species can potentially react faster to climatic variations than plants. A warmer and changing climate is thus likely to stimulate plant consumption by pest species, in turn reducing crop yields in the future. Despite the wealth of studies on climate-change biology, there are still prominent gaps in research into the impact of climate change on pests and on hence on plant health (Zafar et al., 2022; Zafar et al., 2021; Farooq et al., 2020; Manan et al., 2022). These gaps include the effect of climate change on the effectiveness of management strategies, on below-ground pests, and on forestry and unmanaged systems. A long-term, multidisciplinary approach is needed that addresses the issues of developing as well as industrialized countries. International cooperation needs to be enhanced and investment should also be directed to capacity building, to ensure strong systems for pest risk analysis, surveillance and monitoring. However, insect pest severity may not be uniformly increased by warming temperatures, given the narrow environmental niche requirements, physiological tolerances of insects, and the variable effects of temperature on their phenology and life history. Because of these sensitivities, regional climate warming could in fact lead to local population declines or extinctions (Thackeray *et al*. **2016**). This uncertainty about pest responses to rising temperatures needs to be addressed in order to develop effective pest management strategies. Policies based on a universally anticipated, generic increase in pest severity will be misguided; rather, a more detailed understanding of insect pests' responses to climate warming is essential to inform effective allocation of public and private resources for pest management efforts in the future. Unfortunately, information about how most insect pests will respond to increased temperatures is scarce. Climate-change impacts are already emerging for natural and human systems, including changes in water quantity and quality, and shifts in geographical ranges, seasonal activities, migration patterns, species abundance and interactions for many terrestrial, freshwater and marine species (Shukla et al., 2019), with more negative than positive impacts on the yields of most crops. There is evidence that climate change is affecting biological systems at multiple scales, from genes to ecosystems. According to Scheffers et al. (2016), anthropogenic climate change has impaired 82 percent of 94 core ecological processes recognized by biologists, from genetic diversity to ecosystem function.

Effects on Insect-pests:

Geographical distribution of insect pests confined to tropical and subtropical regions will extend to temperate regions along with a shift in the areas of production of their host plants, while distribution and relative abundance of some insect species vulnerable to high temperatures in the temperate regions may decrease as a result of global warming. These species may find suitable alternative habitats at greater latitudes (Zhang et al., 2022). Many species may have their diapause strategies disrupted as the linkages between temperature and moisture regimes, and the day length will be altered. Genetic variation and multi-factor inheritance of innate recognition of environmental signals may mean that many insect species will have to adapt readily to such disruption. Climate change will also result in increased problems with insect transmitted diseases. These changes will have major implications for crop protection and food security, particularly in the developing countries, where the need to increase and sustain food production is most urgent. Long-term monitoring of population levels and insect behavior, particularly in identifiably sensitive regions, may provide some of the first indications of biological response to climate change (Skendžić et al., 2021). In addition, it will also be important to keep ahead of undesirable pest adaptations, and therefore, itis important to carefully consider global warming and climate change for planning research and development efforts for pest management and food security in future. Incidence of pest and diseases is most severe in tropical regions due to favorable climate/weather conditions, multiple cropping and availability of alternate pests throughout the year. Therefore, in the south Asia, pests and diseases deleteriously affecting the crop yields are prevalent. Climate factors are the causative agents in determining the population fluctuations of pests. They influence plant disease establishment, progression and severity. In fact, a clear understanding of population dynamics, as influenced by abiotic and biotic parameters of environment, is of much help in pest forecasting and to formulate control measures. The global warming may affect growth and development of all organisms including insect-pests themselves. Among all the abiotic factors, temperature is the most important one affecting insect distribution and abundance in time and space, since these are cold-blooded animals (Secretariat et al., 2021). The insects cannot regulate their body temperature and thereby, ambient temperature influences their survival, growth, development and reproduction. Global mean annual precipitation may increase as a result of intensification of the hydrological cycle. This will alter the habitat specification of many insect pests, which may find suitable alternative habitats at greater latitudes. Many species may have their diapause strategies disrupted as the linkages between temperatures or moisture regimes and day lengths are altered. Genetic variation and multi-factor inheritance of innate recognition of environmental signals may mean that many species can adapt readily to such disruption. The direct effects of global climate change on the dynamics of pest populations in the tropics depends on the relative lengths of the wet and dry seasons, and on temperature (Lehmann et al., 2020). Changes in precipitation are possibly of greater importance in regions where lack of rainfall may be a limiting factor for crop production. The extent to which insect species are able to withstand the climatic factors will depend on the life history characteristics. The distribution of insect pests that are fast growing and nondiapausing will expand, while the ones with low temperature required for diapause will show shrinking of ranges. The latter are more prone to extinction due to climate change. The important factors that affect the range shifts include day length, natural enemies and the competitors, predators or parasitoids. Slower rate of spread of host plant species limit the expansion range of specialist insect pests (Halsch et al., 2021).

Effect of temperature on insect pest and plants

The global average temperature is expected to increase by at least 4°C by the end of the 21st century, due to the increased frequency and intensity of drought and heat waves. Temperature has a strong effect on insect growth, survival and reproduction and enrols a major role in controlling the development and growth of their host plants. In addition, the development of plant secondary chemicals as well as the structural characteristics used to protect against herbivores are influenced by temperature (Halsch et al., 2021). Thus, for both insects and plants, temperature has potentially significant consequences. Phytochemical and morphological changes in host plants are caused by changes in temperature. For example, at night temperatures of 17°C, the concentration of catecholic phenolics (chlorogenic acid and rutin) in tomatoes was significantly higher than at other temperatures (Zafar et al., 2020). Also, Zandalinas et al. (2022) reported low polyphenol oxidase (PPO) activity of peroxidase (POX) at 35°C in tomatoes; it has been also reported that there is a substantial decrease in protease inhibitor activity in tomato at temperatures below 22°C. At elevated temperatures, the thickness of leaf trichomes normally rises.

Effect of carbon dioxide (CO2) on insect pest and plants

Higher concentrations of CO2 with the rise in temperatures in the atmosphere have direct effects on plant metabolism and affect the distribution, abundance and productivity of insects that feed on plants. The behavior of phloem-feeding insects, when supplied with plants grown under increased CO2, increases compared to leaf chewing insects. When leaf chewing insects like grasshoppers and caterpillar larvae feed on plants that are grown under higher CO2 levels, more leaf area is eaten than they actually eat. Spodoptera litura has been reported to grow under higher levels of CO2 as a serious pest. The larvae of Helicoverpa, grown under high CO2 ate much more leaf tissue than those under ambient CO2. However, under elevated CO2, adult moths increased and lived longer and laid considerably few eggs (Pokharel et al., 2021).

The change in CO2 concentration also influences the plant biochemistry, along with the synthesis of secondary metabolites. The higher concentration of CO2 is subjected to increased ratio of carbon to nitrogen in plants (Kumar et al., 2021). Insects are allowed to consume more in order to achieve sufficient dietary nitrogen, resulting in slower larval growth and increased mortality. Phytophagous insects can become more susceptible to changes in atmospheric CO2 concentration by CO2 cascading effects on plant biochemistry, as certain plant feeding insect species produce their pheromone molecules on the basis of compounds taken from the host plants (Tonnang et al.,2022). Example: Bark beetles use the mevalonate pathway to generate pheromones, where certain components of aggregation pheromones originate from the hydroxylation of secondary metabolites derived from tree. Besides affecting the plant biochemistry, along with the synthesis of secondary metabolites changes in CO2 concentration could also affect the plant yield (Bazinet et al., 2022).

EFFECT OF CLIMATE CHANGE ON THE EFFECTIVENESS OF PEST MANAGEMENT TECHNOLOGIES

Host-plant resistance to insects is one of the most environmentally friendly components of pest management. However, climate change may alter the interactions between insect pests and their host plants (Sharma, 2016). Resistance to sorghum midge, Stenodiplosis sorghicola (Coq.), observed in India, breaks down under high humidity and moderate temperatures in Kenya. Sorghum midge damage in the midge-resistant lines ICSV 197, TAM 2566 and AF 28 decreased with an increase in open pan evaporation, maximum and minimum temperatures, and solar radiation, while no significant effect was observed on the susceptible cultivars ICSV 112 and CSH 5 (Sharma, 2010). There will be an increased impact on insect pests which benefit from reduced host defences as a result of the stress caused by the lack of adaptation to suboptimal climatic conditions. Some plants can change their chemical composition in direct response to insect damage to make their tissues less suitable for growth and survival of insect pests (Sharma, 2002).

Generally, CO_2 impacts on insects are thought to be indirect. Impact on insect damage will result from changes in nutritional quality and secondary metabolites of the host plants. Increased levels of CO_2 will enhance plant growth, but may also increase the damage caused by some phytophagous insects (Matzrafi, 2019). In the enriched CO_2 atmosphere expected in the 21st century, many species of herbivorous insects will confront less nutritious host plants that will induce both lengthened larval developmental times and greater mortality. The effects of climate change on the magnitude of herbivory and direction of response will not only be species-specific, but also specific to each insect–plant system.

Opportunities and Challenges for Using Bt Crops in IPM

Over the past 30 years, traits have progressed from single events with one mode of action against one insect order, to pyramided and stacked events containing multiple modes of action against the same or different pest orders, respectively. GE crops have also progressed from insect protection traits expressing proteins from Bt to new traits based on RNAi or expressing proteins from non-Bt sources (Barros et al., 2019). There are many widely accepted benefits of using GE crops for insect control, including the ability to reduce the use of less effective and/or less environmentally friendly insecticides, high specificity toward pests, and a more convenient insect pest management strategy for growers (Razzaq et al., 2021). An additional benefit seen in some systems, such as with Bt maize in the US and Bt cotton in China and the US, has been area-wide suppression of key target pests that has reduced pest pressure and input costs for both growers adopting Bt crops and non-adopters in the same area (Razzaq et al., 2021). Nevertheless, there remain several challenges for sustainable use of this technology and successful implementation in an IPM approach for many Bt crops and regions.

One of the biggest challenges for sustainable use of the technology is the evolution of resistance. Over-reliance on Bt crops without appropriate IRM or IPM practices has led to a growing number of cases of target pest resistance (Zafar et al., 2022). Examples include field-evolved resistance to Cry1Ab-expressing maize in the African stalk borer, Busseola fusca (Fuller) (Lep.: Noctuidae), in South Africa; resistance to Cry1F-expressing maize in the fall armyworm, Spodoptera frugiperda (J. E. Smith) (Fuller) (Lep.: Noctuidae), in Puerto Rico, Brazil and Argentina, and the mainland US; resistance to Cry1Ac-expressing cotton in the pink bollworm, Pectinophora gossypiella (Saunders) (Lep.: Gelechiidae), in India; and resistance to Cry3Bb1-expressing maize in the western corn rootworm, Diabrotica virgifera virgifera LeConte (Col.: Chrysomelidae), in the US (Ren et al., 2019).

To address the risk of insect resistance, IRM programs have been proactively implemented wherever Bt crops have been commercialized, with these programs being mandatory in some countries including the USA, Canada, Australia, the EU, the Philippines and South Africa (. Central to these IRM programs is the concept of a “refuge,” which is an area of plants (typically of the crop of interest) that do not contain any Bt protein and thereby support the production of Bt-susceptible insects (Rehman et al., 2022). Refuges represent a short-term cost to growers because they incur greater pest damage and require additional management, and thus refuge adoption by growers is generally much higher in countries where IRM is a regulatory requirement e.g., Australia, Canada and the US. The Australian cotton industry represents one success story for adoption of IRM. In the 1990s, Australian cotton-growers faced near catastrophic levels of Lepidoptera resistance to insecticides, which almost led to the end of the cotton industry (Wang et al., 2019). High awareness of the need for IRM by growers, the availability of different refuge options, and appropriate education and training has resulted in refuge adoption that is consistently near 100% in Australia. Similarly, intensive education together with auditing of growers have helped to maintain high levels of refuge adoption in other countries like Canada (91%) and, to a lesser extent, the US Corn Belt (68–72%). In areas where IRM is not a requirement, disincentives are very high, or growers are not as aware of the costs of resistance, it remains a challenge to educate growers, demonstrate the long-term value of the refuge strategy, and identify other tools to balance the short-term costs. The absence of robust IRM programs can have major consequences; for example, in all the cases of field-evolved resistance described above, one of the primary causes was determined to be low refuge compliance. Examples of countries where IRM management programs are not mandated include Argentina, Brazil, and China (Safdar et al., 2022). In addition to the lack of refuge compliance, other factors contributing to the evolution of resistance include less-than-high-dose technologies and diverse pest complexes. Overall, regulating IRM and integrating GE crops within the context of a larger IPM plan can help to ensure success, particularly with technologies that are not high dose, but will not be sufficient to do so without extension that leads to broad stakeholder support. Demonstrating the value of IRM within the context of IPM, for example showcasing how GE crops and refugia can better support populations of natural enemies (Anderson et al., 2019), or positioning IPM strategies as solutions to greater pest damage in refuges and for non-adopters of

GE crops, are important benefits to highlight to promote an integrated approach. For example, insect predator and aphid populations in Bt cotton fields in northern China were assessed over 20 years, from 1990 to 2010, to test the hypothesis that Bt crops can promote biocontrol services at a landscape level (Lu et al., 2012). Results from this study showed that Bt cotton fields with reduced insecticide application supported higher predator populations and decreased aphid abundance. This work supports the hypothesis that widespread adoption of Bt cotton may promote landscape level benefits due to increased generalist predator abundance, and reinforces how IPM strategies that utilize Bt crops and reducing insecticide application can achieve more effective biological control (Romeis et al., 2018).

An additional challenge associated with Bt crops can result if there is a pest shift (i.e., increased prominence of a secondary pest that was collaterally or incidentally controlled by broad-spectrum insecticides but is not controlled by the selective GE trait). For example, in China, widespread adoption of Bt cotton, and the associated decreased use of chemical insecticides, has led to increased abundance of mirid bugs (Hemiptera: Miridae) in some fields (Lu et al., 2010). Any time a primary pest is significantly reduced or eliminated by a technology including a GE trait, there exists the possibility that replacement inputs or other ecological factors will result in a pest shift that may require additional crop protection inputs. If those additional inputs are selective, the overall gains made by growers may still be very positive and IPM is strengthened. However, when new inputs are broad-spectrum, the benefits of adopting the GE trait could be significantly diminished both because of the new input costs and lost opportunities for environmental and human health benefits. A well-structured IPM approach should balance the use of one technology with other complementary approaches and avoid relying on only one solution for pest control. Genetic engineering is not a “silver bullet” for all problems and an agricultural production system will not automatically become a durable IPM strategy just by adding GE technology or, for that matter, host plant resistance developed through conventional means. Therefore, understanding the challenges for each crop, pest complex and region and acknowledging the limitations of GE crops is important for education, training and development of robust IPM strategies for future crops and traits.

Contribution to climate-smart agriculture

CSPM is designed to become a key component of CSA and will therefore contribute to the three main objectives that CSA aims to tackle: adapting and building resilience to climate change; reducing and/or removing greenhouse gas emissions; and sustainably increasing agricultural productivity and incomes. The following section outlines a few examples of how CSPM has the potential to support these goals.

Short-term and long-term adaptive measures

Adapting to climate change can be viewed as an ongoing process of implementing existing risk management strategies and reducing the potential risk posed by the consequences of climate change (Howden et al. 2007). With regards to pest management, CSPM recognises that adaptive measures to climate change can be short-term or long-term (Juroszek and von Tiedemann 2011; Olesen and Bindi 2002). Short-term adjustments include efforts to optimise production without major system changes, e.g. moving to adapted crop varieties that are more resilient to climate change-related stresses, or application of biological or synthetic pesticides to control certain pests. Long-term adaptations include major structural changes to overcome adversity caused by climate change (e.g. introducing crop rotation/intercropping to control pests, or changing to a novel crop) (Olesen and Bindi 2002). Regardless of whether measures are short- or long-term, CSPM acknowledges that input from multiple stakeholders will often be required for their identification, development and implementation.

Prediction and recognition of future pest outbreaks

An increasing number of (new) pests are being seen, especially in the northern hemisphere due to poleward movement, and at higher altitudes due to upslope movement. For example, the southern green stink bug (Nezara viridula (Linnaeus), Hemiptera: Pentatomidae) has expanded its range northward in temperate regions of Europe and Japan since the 1960s, most likely because of reduced mortality due to milder winter temperatures (Musolin 2007). Nandudu (2014) states that coffee leaf rust disease caused by the black coffee twig borer (Xylosandrus compactus (Eichhoff), Coleoptera: Curculionidae), which has normally only affected coffee plants at altitudes below 1400 m above sea level, has now reached 1800 m above sea level. This movement in altitude of black coffee twig borers has led to crop damage in far more elevated locations than the industry is accustomed to. Nandudu notes that 85% of the coffee farms in Uganda are family operated and are facing alarmingly low yields. CSPM highlights the importance of developing more effective diagnostic processes for the identification of pests and their natural enemies in order to be able to make pest management decisions going forward (Cock et al. 2017; Lamichhane et al. 2016; SciDevNet 2013). CSPM also recognises that quantitative modelling (including climate models, empirical models, population models and simulation models) is needed to investigate multiple interactions simultaneously (Coakley et al. 1999) and most importantly, model results need to be interpreted alongside social and ecological model outputs, in order to support countries in developing the most appropriate responses to future pest outbreaks.

Suppression of pest outbreaks and pathogen transmission

Pests are expected to respond to changing climate conditions more rapidly than plants, so for a pest management system to be resilient it must be ready to withstand both pests that are moving into the area and outbreaks of existing populations. Therefore, CSPM encompasses (i) pest prevention, i.e. development and implementation of biosecurity action plans, raising awareness of threats at the local level and preventing arrival and spread; (ii) early detection and rapid response, i.e. development and implementation of surveillance and emergency action plans for detecting and eradicating listed species, and building capacity to implement these plans; and (iii) management, i.e. evaluating and scaling up existing management solutions, and developing and scaling up new solutions to ensure those living in rural communities have in place the best practice and locally adapted solutions.

Enhancement of health and pest resilience of farms and landscapes

It has been found that farms with higher levels of biodiversity show a greater resilience to climate disasters such as hurricanes and droughts (Altieri 2012; Altieri et al. 2015). For that reason, CSPM promotes crop diversification, a method of enhancing farm biodiversity, that also promotes the abundance of natural enemies (Lin 2011), and this can be achieved by diversifying production (e.g. from mono-cropping to strip-cropping) to provide refuges for natural enemies that will contribute to pest suppression. Alternatively, annual and perennial non-crop vegetation can be introduced, increasing crop diversity either in situ or ex situ (Lin 2011). Crop diversification can also reduce the risks of pests becoming more severe as a result of climate change (Juroszek and von Tiedemann 2011). Herbivore suppression, natural enemy enhancement and crop damage suppression effects were significantly stronger on diversified farming systems than on fields with no or fewer associated plant species (Altieri 2012). CSPM promotes many other methods that can be employed to increase a system's resilience to climate change, such as crop variety selection, planting dates, conservation tillage methods and mulching.

Strengthening of a climate-responsive extension system

Because of the difficulty of predicting biological responses of pests to climate change in terms of their distribution and population dynamics, it remains unlikely that in the short term any general models can be developed to predict climate change-induced pest outbreaks on a local scale (Lamichhane et al. 2015; Scherm 2004). Inevitably, this increases the vulnerability of farmers, who routinely have to make vital decisions in response to unpredictable conditions and unknown risks, and this can only worsen with the impacts of climate change. If farmers do not have access to the right information at the right time, this poses a great threat to crop production, agroecosystem functioning and livelihoods. One approach that is promoted by CSPM to increase resilience to such unpredictable events is the development of a more responsive national extension system and the promotion of functioning links between extension, research and farmers (Susko et al. 2013). This revitalisation of the rural advisory system plays a pivotal role and should lead to extension being able to fulfil the twofold role of:

Contributing to the early detection of changing pest threats, which requires that extension workers are skilled and linked to appropriate information and communications technologies (ICT)-based reporting and diagnostic systems and services (Heeb et al. 2016);

Repackaging and delivering farmer-friendly science-based pest management information directly into the hands of farmers, e.g. using ICT-based communication channels, such as mobile phones, radio or television, which are cost-effective and versatile solutions (Heeb et al. 2016).

To enable extension systems to fulfil these roles, CSPM recognises that there must be quantitative investment (e.g. increasing the ratio of extension workers to farmers and promoting digital development) and qualitative investment (i.e. revisiting extension training programmes and investing in building climate literacy), see 'costs, benefits and funding for climate-smart pest management' section for some examples. It is also important to consider and include private sector extension mechanisms when assessing investment requirements of national advisory systems since they already play an important role for semi-commercial and commercial-oriented smallholders. Repurposing extension services so that landscape considerations prevail over plot-based advice is also crucial.

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