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Impact of climate change on insect pests, plant chemical ecology, tritrophic interactions and food production

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Abstract

Climate change is a major concern for agriculture globally. Dynamic climatic parameters including increased temperature and carbon dioxide have greatly affected crop production. As a consequence of climatic uncertainties, new insect pests have emerged, the crop cultivation practices have changed, and drought and floods have created havoc around the globe. Besides, plant and insecticidal resistance against insects and diseases has got compromised, the diversity and abundance of arthropods has changed, geographical ranges of insect pests have extended far beyond their existing limits and new biotypes have evolved. 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.

Keywords: *Climate change, increased CO_2, plant insect-interactions, food security, pest management*

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Introduction

Increased population has led to an ever increasing demand for agricultural production and poses a high risk on food security. Food availability is greatly influenced by occurrence of storms, drought and flooding, precipitation, increased Carbon dioxide (CO_2) and increased temperatures [1-3]. Evidences suggest that anthropogenic activities lead to an increase in greenhouse gas concentrations especially of carbon dioxide which ultimately leads to climate change. Plant physiological processes directly respond to the various climatic factors such as air and soil temperature, solar radiation, precipitation, relative humidity and wind speed [2,3]. Climate change exerts maximum influence on pests, diseases and weeds [2,4-8].

Insects have very short life cycles, are ectothermal, possess population size variation, are highly responsive to climate change and are greatly influenced by temperature [2,9]. Effects of climate change on insect pests is of greater importance as the insects are involved in many biotic Interactions such as plants, natural enemies, pollinators and other organisms, which are the key players for the ecological functioning [7, 10-12]. Over 10,000 insect species damage agricultural crops and account for about 13.6 percent annual loss globally [13], of which 23.3 percent occurs in India [14, 15]. Agricultural crops such as cotton, rice, maize, sugarcane, rapeseed-mustard, groundnut, pulses, coarse cereals, and wheat suffer annual losses of about 17.5 percent, which accounts for US$17.28 billion [14, 15]. It is anticipated that climate change is likely to exert a substantial effect on various insect pest management programs including host-plant resistance, natural plant products, bio-pesticides, natural enemies, and efficacy of synthetic chemicals. The increased global mean precipitation will have significant effect on crop production and disrupt the cropping systems, diversity and abundance of biota [16-18]. Moreover, the expansion of geographical horizons of insect pests will have broader effect on crop productivity [8,10,11]. Latest report of Inter- Governmental Panel on Climate Change [19] shows an increase of 0.85 °C [0.65 to 1.06 °C] in temperature between 1880 and 2012. Further, the CO_2 concentration has increased from 280 ppm (pre-industrial value) to 401 ppm in 2015 (Mauna Loa Observatory: Hawaii). This has resulted in shifting of geographical ranges, seasonal activities, migration patterns and abundances, and intra- and inter-specific interactions among insects [10,19].

Climate change: Possible effects on insect pests

Insect pests cause significant losses to agricultural production worldwide. As a result of global climate change, pest populations may become unstable, leading to outbreaks in some areas, causing greater losses; while in others, losses due to pests may decline. Agro-ecosystems are expected to respond to climate change in several ways: 1) shifts in geographical distribution of insect pests; 2) temperature limits of pest and natural enemy species; 3) selection of new strains with varying virulence; 4) differential effects on pest-natural enemies, thus causing decoupling of natural control mechanisms; 5) changes in food availability resulting in pest shifts and 6) changes in competitive interactions between crops and weeds. All this may result in the disappearance of some pest species and niches and a potential wider distribution of secondary pests and surviving species [2, 7,8]. Higher temperature and precipitation due to climate change strongly influences the insect growth, development, reproduction and survival [8]. To what extent the temperature affects the pests will differ among species depending on the environment, life history, and their ability to adapt.

Climate change strongly affects the geographic distribution of insect pests, and this distribution is determined more by low temperatures than high temperatures [7-12]. Research in the area of global climate change has made extensive use of crop growth simulation models. However, most simulation models fail to account for losses due to pests, weeds and diseases [12]. Effects of global climate change on pest and disease epidemics are crucial in predicting future spread and development, which ultimately affect the global crop production. Rising temperatures are likely to result in the availability of new pests and pest niches. The development of insects depends on the temperature to which they are exposed as they cannot regulate the body temperature, and any deviation in temperature will have direct effect on insect development.

Insects respond to climate change in various ways, ranging from changes in phenology and distribution to influencing community dynamics and composition [10,12]. Whilst some influences of climate change may be good in protecting the crops and forest health, many effects will be quite damaging [12]. Forest communities occur over a wide range of climatic conditions indicating that forests have the ability to persist under altered climatic conditions. However, the changeover of pests into new territories without any checks and balances by natural enemies, or invasion of a new host species or the expansion of host species, might result in the pest outbreaks, reduced forest growth and tree mortality. Furthermore, specialist insect pests inhibiting a narrow niches in extreme environments are more likely to be adversely affected than the polyphagous insect pests that show phenotypic and genotypic plasticity and occur across a range of environments [9,12]. Increase in pest damage to crops will result in significant economic losses. Long-term monitoring of population levels and pest behavior, particularly in identifiably sensitive regions, may provide some of the first indications of a biological response to changes in the climate [10,12]. In addition, no substantive body of information is available on how long-term changes in CO_2 and temperature, singly and in conjunction, will interact with other agronomic management variables (water and nutrients) in affecting crop interactions in the tropics and subtropics. Thus, it is critical that possible climatic changes should be considered as an integral component in research on pest management systems.

Climate change can have a remarkable effect on the incidence and intensity of pest populations [8, 15]. Climate change can lead to higher densities of *Helicoverpa armigera* (Hub.) and *Maruca vitrata* (Fab.) populations and the shifting to the temperate regions, which will have drastic effect on legumes and related crops [20,21]. Occurrence of *H. armigera* as an invasive pest in Brazil and North America has been attributed to the climate change [22,23]. *Spodoptera litura* (Fab.) has been reported emerging as a serious pest under higher levels of CO_2 [24]. The woolly aphid, *Ceratovacuna lanigera* Zehntner has emerged as a serious pest in Maharashtra due to climate change [25]. Earlier reported in West Bengal in 1958, it has now invaded Central and South India. Further, planting dates corresponding to different temperatures and relative humidity also affect the pest incidence in grain legumes. It has been reported that chickpea and pigeonpea sown in different months showed differential incidence of insect pests [26]. For example, pigeonpea sown in August had maximum incidence of insect pests than the one sown in September [26]. Similar results have been observed for chickpea, with maximum leaf damage by *H. armigera* and

Spodoptera exigua Hub. in October sown crop and lowest in January sown crop [26]. Further, stress in plants on account of climate change will result in pest outbreaks as the plant defense system is lowered due to changes in physiological processes [12,27,28].

Global mean annual precipitation may increase as a result of intensification of the hydrological cycle [29]. 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 [2,30]. 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 [10,12]. Changes in precipitation are possibly of greater importance in regions where lack of rainfall may be a limiting factor for crop production [6,31].

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 non-diapausing will expand, while the ones with low temperature required for diapause will show shrinking of ranges [9]. The latter are more prone to extinction due to climate change [12,32]. The important factors that affect the range shifts include day length, natural enemies and the competitors, predators or parasitoids [33]. Slower rate of spread of host plant species limit the expansion range of specialist insect pests [12,34].

Effect of climate change on chemical ecology and tritrophic interactions

Tropics are most vulnerable to climate change. Climate change leads to the alteration of plant phenology, which influences herbivore growth, abundance, and availability of prey and hosts for natural enemies [7,12,30,33,35]. When grown under increased CO_2 and temperature extremes as well as decreased precipitation, plant nutrition quality for herbivores changes and influences the fitness of predators and parasitoids feeding on these hosts [7,12,30,35]. Pest-natural enemy interaction will depend on the herbivore tolerance of environmental extremes relative to their herbivore hosts as well as their movement rates. Increase in temperature due to climate change will affect insect pest populations in several complex ways [12,34]. The insect population is likely to be decreased, however, most researchers are of the opinion that warmer temperatures in temperate climates will result in outbreak of insect pests due to the alteration of chemical ecology of plants [12,36].

Climate change will have substantial effect on insect-plant interactions and the physiology of both insect pests and plants will be modulated. The production of plant secondary metabolites and other plant defensive traits will be affected. Increasing temperature, CO_2, relative humidity, precipitation etc., will modify both plant and herbivore systems [11,37-41]. Increases in global temperature, atmospheric CO_2, and the length of the dry season are all likely to have ramifications for plant/herbivore interactions in tropics with important implications for food security and natural ecosystems [11,37,39,40]. There will be an increase in the impact of pests, which benefit from reduced host defenses as a result of stress caused by a lack of adaptation to sub-optimal climatic conditions. Also, there will be mismatches between plants and insect pollinators. Climate change may favor non-resistant crops or cultivars, which will lead to the greater insect pest infestation [18,39,41]. However, as suggested by many researchers, plants grown under elevated temperature or CO_2 will be less nutritious, and the insects feeding on them will have lengthened larval period and greater mortality [42,43]. Increased CO_2 may also cause reduction in nitrogen-based defenses (e.g., alkaloids) and an increase in carbon-based defenses (e.g., tannins) [43]. Further, Sharma et al. [43] showed that the healthy chickpea plants grown under elevated CO_2 exhibited increased levels of carbohydrates, as compared to insect-infested plants. This was attributed to increased photosynthesis in the former, and reduced chlorophyll levels on account of foliage damage and increased C-based defensive secondary metabolites.

Climate change lowers the plant defense system against insect pests, thereby making them vulnerable to attack [11,14,15]. Early onset of infestation by *H. armigera* in cotton and pulses in Northern India is one such example [8,21]. Lower foliar nitrogen due to elevated CO_2 causes an increase in food consumption by the herbivores up to 40 percent, and unusually severe drought appears to cause herbivore populations to explode [43,44]. Further, the lower N content reduces the overall protein content of the plant [43-46]. Carbon dioxide has been found to reduce the plant defense against insect pests [19,40]. For example, the signaling of plant defensive pathways mediated by jasmonic acid (JA) in soybean do not work out under increasing levels of CO_2 [40]. The production of defensive cysteine proteinase inhibitors (CystPIs) is reduced and renders plants vulnerable to insect pests such as the Japanese beetle (*Popillia japonica* Newman) and the western corn rootworm (*Diabrotica virgifera* LeConte). Further, higher temperature and CO_2 affect the herbivore induced volatile organic compound emission (HIPVs) [47,48]. Any changes in HIPVs will have direct effect on the efficiency of the biological control [49]. Temperature will reduce the olfactory perception of the volatiles and thus, host location ability of the natural enemies [50-52]. In addition, increased CO_2 levels alter the levels of oxalic and malic acids in chickpea, thus influencing its resistance against herbivores [43,35].

To take advantage of the new environmental conditions the introduction of new crops and cultivators is one of the adaptive strategies suggested as a possible response to climatic changes [11-15]. These will show a shift in the rates of plant and insect developments, which may either increase or decrease herbivory. It may however, increase the generation turnover in many insects, thus causing greater damage to plant communities.

The understanding of the response of insect pests and their natural enemies to climate change is very important for effective biological control of insect pests. The effect of climate change on natural enemies is highly complex. Relationships between pests and their natural enemies will change as a result of global warming; resulting in both increases and/or decrease in the status of individual pest species. Effect of temperature and CO_2 on plants will affect the herbivore quality, which in turn will affect the fitness of natural enemies [7,15,35,41-43]. There may be a decrease in parasitism and predation of herbivores by natural enemies due to increase in plant foliage and changes in herbivore life cycle due to phenological changes in plants [12,41-43]. The increased foliage may hinder the pest location by natural enemies. Quantifying the effect of climate change on the activity and effectiveness of natural enemies will be a major concern for the future pest management programs.

The majority of insects are benign to agro-ecosystems, and there is much evidence to suggest that this is due to population control through interspecific interactions among pests and their natural enemies–pathogens, parasites and predators [7,8,35,53]. Oriental armyworm (*Mythimna separate* Walker) populations increase when extended periods of drought (which is detrimental to the natural enemies) are followed by heavy rainfall [54]. Changes in interspecific interactions could also alter the effectiveness of natural enemies [7,8]. Climate change reduces the control of insect pest through natural enemies and increases the plant susceptibility to herbivores. For example, mealybug parasitism in cassava is reduced under drought conditions leading to water stress, because under water stress conditions, immune response of mealybugs is improved [55] . Elevated CO_2 reduced the aphid parasitoid *Diaeretiella rapae* (M'Intosh) population by about 50 percent and also resulted in short lived adults [56]. Furthermore, *Cotesia melanoscela* (Ratz.) exhibited high larval and pupal mortality and reduced performance under elevated CO_2 [57]. However, the effectiveness of some natural enemies might also get increased under climate change conditions. For example, elevated levels of CO_2 decreased the development time of the aphid parasitoid *Lysiphlebia japonica* (Ashmead) [58] and lepidopteran parasitoid *Cotesia plutellae* (Kurd.) [59].With reduced levels of nitrogen, *H. armigera* larvae showed reduced growth and were easily preyed by pentatomid bug, *Oechalia schellenbergii* Guérin [60]. It has been reported that higher CO_2 could make generalist predators more effective in controlling pests than the specialists. The coccinellid predator, *Leis axyridis* (Pallas) Mulsant feeding on *Aphis gossypii* Glover showed higher consumption of prey under conditions of higher CO_2 [44]. Chen et al. [61] reported no significant impact of elevated CO_2 on feeding of coccinellid predator, *Harmonia axyridis* (Pallas) on aphid pest, *Sitobion* *avenae* Fab., however, braconid parasitoid, *Aphidius picipes* (Nees) showed increased aphid parasitism under elevated CO_2. The emergence of parasitoids is very critical and the earlier emergence of parasitoids than the host, since their development shows a sharper response to temperature, a marked decrease in pest population would occur, but could eventually cause extinction of the parasitoid population [62]. The host availability at the vulnerable stage will be decreased and the mismatch between host and natural enemies would lead to death of the natural enemies. This variability on emergence patterns of the hosts or parasitoids due to climate change will have drastic effects on the host plant [15,35,51]. A number of studies regarding poor synchrony between a parasitoid and its host have been documented [61, 62]. The earlier emergence of hibernating parasitoids of leaf miners in absence of hosts results in a low level of parasitism in horse chestnut leafminers, *Cameraria ohridella* Deschka & Dimić under field conditions [62]. Forest pests are also likely to be influenced by climate change [12,63]. The influence of increased temperature on the association of forest insect pests with symbiotic fungi has been studied [12,63,64]. Decoupling of symbiotic association between insect pests and fungi has been reported due to the asymmetrical effect on hosts and symbionts [12,63,64].

Effect of climate change on crop production

Temperature increases associated with climatic changes could result in major implications for food security, particularly in the developing countries of the semi-arid tropics, where the need to increase and sustain food production is most urgent [6,8,11,12]. In developing countries situated at lower latitudes having lower adaptive ability, climate factors can have negative effect on the crop yield and will worsen as the warming proceeds [6,15]. Every degree increase in temperature above 32℃has been found to reduce the crop production in wheat and rice by 5 percent [65]. The reduction in crop productivity was been proposed to increase up to 10-40% by 2100 in India [65]. Maize, wheat and rice have been proposed to be the worst sufferers of climate change in terms of productivity in dry/rainfed areas especially in Africa [18,65,67]. Rate of photosynthesis, respiration and grain filling are influenced by increased temperature and CO_2, decreased precipitation, prolonged dry periods, resulting in increased development rate in plants, but the shortening of duration and reduced yield [2,18,68]. There will be an increase or decrease in net photosynthesis (photosynthesis-respiration) which may lead to the increase in the saturation vapor pressure of air. This will affect the water-use efficiency as the loss of water by plants per unit carbon gain will be more [18,69]. Plants normally respond to such conditions by closing their stomata, however, this is accompanied by the reduced photosynthesis rates, increase in plant canopy temperature, which leads to further heat-stress on the plants.

Climate change will also have a prominent effect on cropping systems as the rates of changes to the timing, frequency, daytime and nighttime warming, and exposure to O_3, CO_2, and air pollution sources will differ regionally [12,41,53]. This will geographically shift the timing and length of the growing seasons thus changing the crop planting and harvesting dates. Thus crop varieties used for a particular area need to be changed. Furthermore, rise in sea level and desertification due to climate change will result in decreased cropping areas.

Strategies to mitigate the effects of climate change

Shifts in species abundance and diversity due to climate change may result in reduction in the efficacy of insect pest management programs; hence the need to sharpen existing monitoring tools and develop new ones to help detect potential changes in pest distribution, population ecology, damage assessment, yield loss and impact assessment [11,14,15]. Potential changes in pest survival strategies may need broader and stronger inter-center partnerships to develop new IPM options or disseminate existing ones to new areas where farmers may find these applicable. Current sensitivities on environmental pollution, human health hazards and pest resurgence are a consequence of improper use of synthetic insecticides [11]. Several botanically and biologically based products are presently used as environmentally friendly products. However, many of these methods of pest control are highly sensitive to the environment. Increase in temperatures and UV radiation, and a decrease in relative humidity may render many of these control tactics to be ineffective [38,39]. Therefore, there is a need to develop appropriate strategies for pest management that will be effective under situations of global warming in future.

Host-plant resistance, natural plant products, bio-pesticides, natural enemies, and agronomic practices offer a potentially viable option for integrated pest management. But, the relative efficacy of many of these control measures is likely to change as a result of global warming. Biological control which is considered as the important and effective component of IPM programs is severely affected by climate change, since the relationship between natural enemies and host pests will be affected.

Almost all the insect control methods including cultural practices, natural enemies, host plant resistance, biopesticides, and synthetic pesticides are highly sensitive to the environment. Thus a more robust and climate adaptable pest management technologies are needed for managing insect pests. For sustainable agriculture and to mitigate the climate effects on agriculture, evaluating the effects of climate change on crop production and development of climate smart crops is important. Climatic and crop models need to be developed for land use criteria, and soil productivity and the methods for tailoring insecticide/herbicide inputs to weather need to be developed. Further, advanced cropping methods and cropping systems is needed that would reduce the risk of attack/competition need to be explored.

The alarming point is the transition of insect pests to new territories in absence of natural enemies as it will lead to pest outbreaks. The main challenge ahead is to develop successful prediction models that would pave way for their management. An urgent need is felt to develop and adopt modeling strategies to predict the changes in geographical distribution and population dynamics of insect pests and the strategies to be adapted to reduce crop losses. The water deficiency and unpredictable weather changes may lead to decreased yield and shrinking of the cultivable area and may render the societies vulnerable to climate change effects. The pest forewarning systems based on weather are important decision support tools that help farmers to evaluate the risk of pest outbreaks under different climatic conditions. The information on weather, crop, and/or insects, is very important for the warning systems for taking necessary action to prevent pest outbreaks and avoid economic losses. If so, we can develop plants that are adapted to these extreme conditions when such conditions become extreme naturally and we do not need to wait for evolution to work its magic on crop production and thus can have plants with good yield.

Conclusion

Warmer temperatures, changes in precipitation, increased drought frequency and higher CO_2 concentrations due of climate change will have a devastating effect on abundance of insect pests, which might lead to the emergence of new pests. It is likely that if measures and global collaborative efforts are not undertaken, most pests will have a cosmopolitan range wherever the climate is favorable and the hosts are available. Further, pest control strategies such as host plant resistance, biological control, synthetic insecticides, etc., may be rendered less effective. Understanding insect-plant interactions, efficacy of natural enemies, host plant resistance, bio-pesticides and synthetic insecticides under climate change need to be studied carefully to devise appropriate methods for pest management.

Conflict of Interest

We declare that we have no conflict of interest

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