Impact of Climate Change on Insect Pests and Their Management Strategies

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Introduction

Climate change is an important determinant of abundance and distribution of species. It is concerned with everyone since it posess potential threat to environment, and agricultural productivity and production throughout the world. It has implications for livelihood and survival of human beings. According to Intergovernmental Panel on Climate Change (IPCC, 2001), it is defined as "Change in climate over time, either due to natural variability or as a result of human activity." As described by IPCC, the most of global warming observed over last 50 years is attributed to the human activities. The rise in global climate temperature is the result of the enhanced green house effect that is caused due to the increased levels of green house gasses (GHG) like Carbon-dioxide (CO_2), Chlorofluorocarbon (CFC), Methane (CH_4) and Nitrous oxide (N_2O) in the atmosphere. Over past hundred years, CO_2 concentration in the atmosphere has increased drastically from 280 ppm to 370 ppm and is likely to be doubled in 2100. Likewise, the global temperature has increased by 0.6 + 0.2ºC and is expected to reach 1.1-5.4ºC by the end of next century (IPCC, 2007). According to IPCC, if temperatures rise by about 2°C over the next 100 years, negative effects of global warming would begin to extend to most regions of the world and directly affect most of the organisms on the earth. The climatic variability, together with increase in atmospheric temperature and carbon dioxide, change in precipitation pattern, extended period of drought do have lot of implication in agriculture sector. These climatic variables interact with plants in numerous ways with diverse mechanisms and affect directly in terms of tissue and organ-specific photosynthetic allocation. Such changes in climate also profoundly affect the population dynamics and the status of insect pests (Woiwod, 1997). These effects could either be direct, through the influence of weather on the insects' physiology and behaviour (Samways, 2005, Parmesan, 2007 and Merrill *et al.,* 2008), or may be mediated by host plants, competitors or natural enemies (Harrington *et al.,* 2001 and Bale *et al.,* 2002). In addition, the impacts include changes in phenology, distribution and community composition of ecosystem that finally leads to extinction of species (Walther *et al.,* 2002).

For species to survive in the changing climates, they must either adapt *in situ* to new conditions or shift their distributions in pursuit of more favourable ones. Many insects have large population sizes and short generation times, and their phenology, fecundity, survival, selection and habitat use can respond rapidly to the climate change. These changes to insect life-history may in turn produce rapid changes in their abundance and distribution. Increased temperature will cause insect pests to be more abundant and almost all insects will be affected by changes in temperature (Bale *et al.*, 2002). Porter *et al.* (1991) listed various effects of temperature on insects, including: changes in geographical range, overwintering, population growth rates, number of generations per annum, crop–pest synchronization, dispersal and migration, and availability of host plants and refugia. In-season effects of warming include the potential for increased levels of feeding and growth, including the possibility of additional generations in a given year (Cannon, 1998). This will alter the crop yield, and also influence the effectiveness of insect-pest management practices. Increased global temperature will also influence the phenology of insects including early arrival of insect pests in their agricultural habitats and emergence time of a range of insect pests (Dewar and Watt, 1992; Whittaker and Tribe, 1996, 1998). This will require early and more frequent application of insecticides to reduce the pest damage. Increased temperatures will also increase the pest population, and water stressed plants at times may result in increased insect populations and pest outbreaks. This will affect the crop yield and availability of food grains and threaten food security. The climatic change impacts on pests may include:

- Changes in diversity and abundance of insect pests
- Changes in geographical distribution of insect pests
- Increased overwintering insects
- Rapid population growth and no. of generations
- Changes in synchrony between insect pests and their host crops
- Introduction of alternative hosts plants

- Changes in host plant resistance
- Changes in insect biotypes
- Changes in tritrophic interactions
- Impact on extinction of species
- Changes in activity and relative abundance of natural enemies
- Increased risk of invasive pest species
- Reduced efficacy of crop protection technologies.

Climate change will also result in increased problems of 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 behaviour, particularly in identifiably sensitive regions, may provide some of the first indications of a biological response to climate change. The impact of climate change will vary across regions, crops and species. A large number of models and protocols have been designed to measure the effects of climate change for different species and in different disciplines. There is a need for interdisciplinary cooperation to measure the effects of climate change on the environment and food security. It will be important to keep ahead of undesirable pest adaptations, and consider global warming and climate change for planning research and development efforts for integrated pest management (IPM) in the future (Sharma, 2010).

Climate Change and Indian Agriculture

The Indian climate has undergone significant changes showing increasing trends in annual temperature with an average of 0.56°C rise over last 100 years (IPCC, 2007; Rao *et al.* 2009; IMD, 2010). Warming was more pronounced during post monsoon and winter season with increase in number of hotter days in a year (IMD, 2010). Even though, there was slight increase in total rainfall received, number of rainy days decreased. The rainfed zone of the country has shown significant negative trends in annual rainfall (De and Mukhopadhyay, 1998; Lal, 2003, Rao *et al.*, 2009). The semi arid regions of the country had maximum probability of prevalence of droughts of varying magnitudes (20-30%), leading to sharp decline in water tables and crop failures (Lal, 2003; Rao *et al.*, 2009;). By the end of next century (2100), the temperature in India is likely to increase by 1-5ºC (De and Mukhopadhyay, 1998; Lal, 2003; IPCC, 2007; IMD, 2010). According to the estimates of NATCOM (2004), there will be 15-40% increase in rainfall with high degree of variation in its distribution. Apart from this, the country is likely to experience frequently occurring extreme events like heat and cold waves, heavy tropical cyclones, frosts, droughts and floods (NATCOM, 2004; IPCC, 2007).

Being a tropical country, India is more challenged with impacts of looming climate change (Chahal *et al.,* 2008). Already, the productivity of Indian agriculture is limited by its high dependency on monsoon rainfall which is most often erratic and inadequate in its distribution (Chand and Raju, 2009). The country is experiencing declining trend of agricultural productivity due to fluctuating temperatures (Samra and Singh, 2004, Aggarwal, 2008; Joshi and Viraktamath, 2004), frequently occurring droughts and floods, problem soils, and increased outbreaks of insect-pests (Joshi and Viraktamath, 2004; Srikanth, 2007; Dhawan *et al.,* 2007; IARI News, 2008; IRRI News, 2009) and diseases. These problems are likely to be aggravated further by changing climate which put forth major challenge to attain a goal of food security.

Impact of Climate Change and Insects-Pests

Rising Temperature

Temperature is identified as dominant abiotic factor directly affects herbivorous insects. Insects being poikilothermic, have temperature of their bodies is approximately the same as that of the environment. Therefore, the developmental rates of their life stages are strongly dependent on temperature. Almost all the insects will be affected to some degrees by changes in temperature and there may be multiple effects upon insect life histories. Laboratory and modeling experiments support the notion that the biology of insect pests are likely to respond to increased temperatures (Fye and McAda, 1972, Cammell and Knight, 1991 and Fleming & Volney, 1995). With every degree rise in global temperature, the life cycle of insect will be shorter. The quicker the life cycle, the higher will be the population of pests. In temperate regions, most insects have their growth period during the warmer part of the year because of which, species whose niche space is defined by climatic regime, will respond more predictably to climate change while those in which the niche is limited by other abiotic or biotic factors will be less predictable (Bale *et al.,* 2002). In the first case, the general prediction is that if global temperatures increase, the species will shift their geographical ranges closer to the poles or to higher elevations and increase their population size (Sutherst, 2000, Harrington *et al.,* 2001, Bale *et al.,* 2002 and Samways, 2005).

The increase in temperature associated with climatic change, would impact crop pest insect populations in several complex ways like (a) extension of geographical range (b) increased over-wintering (c) changes in population growth rate (d) increased number of generations (e) extension of development season (f) changes in crop pest synchrony (g) changes in interspecific interactions (h) increased risks of invasions by migrant pests and (i) introduction of alternative hosts and over-wintering hosts.

i) Changes in insect- Pests diversity

Increased realization of the deterioration of biological systems over the last couple of decades has led to a better appreciation of the loss of genes, species and ecosystems. Insects comprise the largest group of animal kingdom and play vital role in providing various ecosystem services (Kremen *et al.* 1993; Kannan and James, 2009). The insect diversity in a habitat indicates the health status of an ecosystem as they are very good indicators of environmental change (Gregory *et al.,* 2009), play an important role in food chains. About 6.83% of world insect species are inhabitant in India (Alfred, 1998). The climate change may affect the relative abundance of different insect species and the species unable to adapt the changes may be lost in the due course of time (Thomas *et al.,* 2004). The Western Ghats in India is the only habitat to many rare, endemic and exotic species of colourful butterflies in the world (Hampson, 1908; Anand and Pereira, 2008). In the present day scenario, many butterfly species are under a real threat due to depletion of the natural vegetation for various anthropogenic developmental activities (Costanza *et al.* 1987; Sachs, 2008; Sidhu and Mehta, 2008). There is a need to increase functional diversity in agro-ecosystems vulnerable to climate change to improve system resilience, and decrease the extent of losses due to insect pests (Newton *et al.,* 2009). However, changes in cropping patterns as a result of climate change will drastically affect the balance between insect pests and their natural enemies. Main effects of climate change on insect pests and natural enemies communities result in decreased abundance of decomposers and predators, and increased herbivory, which may have negative consequences for structure and services of the entire ecosystems. Responses of insect pests and natural enemies depend on both temperature and precipitation, and ecosystem-wide adverse effects are likely to increase under predicted climate change (Zvereva and Kozlov, 2010). Consequences of temperature increases of 1 to 2°C will be comparable in magnitude to the currently seen climate change in the Antarctic region (Bokhorst *et al.,* 2008). Increase in rainfall in the Pampas region of Argentina will largely affect the species with poor dispersal capabilities, which will limit their ability to expand their home range. The most affected among the beetle species are the habitat specialists

(Xannepuccia *et al.,* 2009). Large scale changes in rainfall due to climate change will have a major effect on the abundance and diversity of both insect pests and natural enemies. In case of extreme drought due to climate change are likely to decrease multi-trophic diversity and change the composition of ecosystem (environment and organisms). Habitat fragmentation results in the subdivision of habitats into smaller units resulting in their increased insularity as well as loss of total habitat area. Such fragmentation changes the microenvironment at the fragmented edges and edges effects include microclimate, changes in light, temperature and humidity and each of these can have a significant impact on the vitality and composition of the species in the fragment. Speciation takes between 100 and 1,000,000 years, providing between 10 and 10,000 new species per annum. Nearly 99.9% of all species that ever existed have become extinct. Due to climate change the current extinction rates are 100 to 1,000 times greater than what has happened earlier, and nearly 45 to 275 species are becoming extinct everyday (Sharma, 2010).

ii) Expansion of geographical ranges

The geographic distribution and abundance of plants and animals in nature is determined by species specific climate requirements essential for their growth, survival and reproduction. Any increase in temperature is bound to influence the distribution of insects. It is predicted that a 1^{o}C rise in temperature would enable speed 200 km northwards (in northern hemisphere) or 40 m upward (in altitude). The areas that are not favorable at present due to low temperature may become favorable with rise in temperature. Minimum temperature rather than maximum temperature plays an important role in determining the global distribution of insect species, hence any increase in temperature will result in a greater ability to overwinter at higher altitudes, ultimately causing a shift of pest intensity from south to north. Many insect species have geographic ranges that are not directly limited by vegetation, but instead are restricted by temperature. Earlier researches have shown that with rise in temperature, the insect-pests are expected to extend their geographic range from tropics and subtropics to temperate regions at higher altitudes along with shifts in cultivation areas of their host plants (Hill and Dymock, 1989; Kuchlein *et al.*, 1997; Parmesan and Yohe, 2003; Logan *et al.*, 2003; Elphinstone and Toth 2008; Sharma *et al.*, 2005; 2010). This may lead to increased abundance of tropical insect species (Cannon, 1998; Patterson *et al.* 1999; Bale *et al.* 2002; Diffenbaugh *et al.* 2008) and sudden outbreaks of insect-pests can wipe out certain crop species, entirely (Kannan and James, 2009). At the same time; warming in temperate region may lead to decrease in relative abundance of temperature sensitive insect population (Petzoldt and Seaman, 2010: Sharma, 2005; 2010). Mostly the Polar Regions are constrained from the insect outbreaks due to low temperature and frequently occurring frosts (Volney and Fleming, 2000). In future, projected climate warming (Carroll *et al.,* 2004) and increased drought incidence (Logan *et al.,* 2003) is expected to cause more frequent insect outbreaks in temperate regions also.

As the species richness of insect tends to increase with temperature, it is presumed that with an increase in temperature more species will be gained than lost. Overwintering survival and timing of the commencement spring are important at higher latitudes, leading to population build-up of, for example, global warming results altitude wise range expansion and increased overwintering survival of corn earworms *Heliothis zea* (Boddie) and *Helicoverpa armigera* (Hubner) may cause heavy yield loss and put forth major challenge for pest management in maize, a staple food crop of USA (Diffenbaugh *et al.,* 2008). Range extension in migratory species like *Helicoverpa armigera* (Hubner), a major pest of cotton, pulses and vegetables in North India is predicted with global climate warming (Sharma *et al.,* 2005; 2010). Subsequently, these ongoing shifts in insect-pest distribution and range due to changing climate may alter regional structure, diversity and functioning of ecosystems (IPCC, 2007).

iii) Changes in Insect Phenology

In addition to the shift in space of species distributions, climate change has led to an ecological shift in time, with changes in species' phenology (timing of life history stages insects). It is one of the easiest impacts of climate change to monitor and is by far the most documented in this regard for a wide range of organisms (Root *et al.,* 2003). With increased temperatures, it is expected that insects will pass through their larval stages faster and become adults earlier. Therefore, expected responses in insects could include an advance in the timing of larval and adult emergence and an increase in the length of the flight period (Menéndez, 2007). Members of the order Lepidoptera are the best examples of such phenological changes. Changes in butterfly phenology have been reported in UK, where 26 of 35 species have advanced their first appearance (Roy and Sparks, 2000). Early adult emergence and an early arrival of migratory species have also been reported for aphids in the UK (Harrington *et al.,* 2007). Gordo and Sanz (2005) investigated climate impacts on four Mediterranean insect species *viz.* butterfly, bee, fly and beetle and indicated that all species exhibited changes in their first appearance date over the last 50 years, which was correlated with increases in spring temperature.

For insects, changes in phenology can be studied through long-term experiments with variable sowing dates for observing the appearance of pests on crops. Likewise, the timing of arrival of insect species can also be recorded through light traps, suction traps or pheromone traps. Analysis of long-term data on phenology would reveal changes in the timings of pest appearance under the climate change (Pathak *et al.*, 2012). Suction traps are being used to monitor aphids at The Rothamsted Insect Survey since 1964. Analysis of suction trap data has revealed that spring flights of the potato aphid (*Myzus persicae* (Sulzer) started two weeks earlier for every 1ºC rise in combined mean temperature of January and February. Likewise, long-term data from several insect-recording schemes in Europe and North America have provided evidence for species becoming active, migrating or reproducing earlier in the year due to increases in temperatures that lead directly to increased growth rates or earlier emergence from winter inactivity (Roy and Sparks, 2000). Increasing temperatures have also allowed a number of species to remain active for a longer period during the year or to increase their annual number of generations.

Under the All India Coordinated Rice Improvement Programme (AICRIP) of ICAR, there is also widespread network of the Coordinating Centres all over India that collect light trap insect data round the year. Analysis of historical light trap data vis-à-vis current data can provide important information on the impacts of climate change on rice pests.

iv) Increased Overwintering Survival

Being poikilotherms, insects have limited ability of homeostasis with external temperature changes. Hence they have developed a range of strategies such as behavioural avoidance through migration and physiological adaptations like diapause to support life under thermally stressful environments (Bale and Hayward, 2010). Diapause is a period of suspended developmental activities, the manifestation of which is governed by environmental factors like temperature, humidity and photoperiod. As an adaptive trait, diapause plays vital role in seasonal regulation of insect life cycles because of which the insects have better advantage to survive great deal of environmental adversities. There are two main types of insect diapause; aestivation and hibernation to sustain life under high and low temperature extremes respectively (Chapman, 1998). The studies have shown that, global warming is occurring notably in winter than in summer and is greatest at high latitudes (IPCC, 2007, IMD, 2010). Looking at the past 100 years climate profile of India, warming was more pronounced during winter season and it was the minimum and not the maximum temperature where significant increase was observed (IMD, 2010). Thus, insects undergoing a winter diapause are likely to experience the most significant changes in their thermal environment (Bale and Hayward, 2010).

Accelerated metabolic rates at higher temperatures shorten the duration of insect diapause due to faster depletion of stored nutrient resources (Hahn and Denlinger, 2007). Warming in winter may cause delay in onset and early summer may lead to faster termination of diapause in insects, which can then resume their active growth and development. This gives an important implication that increase in temperature in the range of 1°C to 5°C would increase insect survival due to low winter mortality, increased population built-up, early infestations and resultant crop damage by insect-pests under global warming scenario (Harrington *et al.,* 2001; Sharma *et al.,* 2005; 2010).

v) Increase in Number of Generations

Some crop pests are "stop and go" developers in relation to temperature. They develop more rapidly during periods of time with suitable temperatures. Increased temperatures will accelerate the development of these types of insects possibly resulting in more cycles of generations per year (Awmack *et al.,* 1997). It has been estimated that with a 2°C temperature increase, insects might experience one to five additional life cycles per season (Yamamura and Kiritani, 1998). Warming could decrease the occurrence of severe cold events, which could in turn expand the over-wintering area for insect pests (Patterson *et al.,* 1999). Thus, global increase in temperature within certain favourable range may accelerate the rates of development, reproduction and survival in tropical and subtropical insects. Consequently, insects will be capable of completing more number of generations per year (Yamamura and Kiritani 1998; Petzoldt and Seaman, 2010).

vi) Introduction of invasive alien species

Climate change can as well promote arrival and establishment of the exotic species. Risk of introduction invasive alien species, increase with global climate change. Even though the causes of biological invasions are manifold and multifaceted, changes in abiotic and/or biotic components of the environment (climate change, biological control) are recognised as primary drivers of species invasion (Dukes and Mooney, 1999; IPCC, 2007). Globalization and liberalization of world agricultural trade coupled with the rapid transport and communication means nowadays, have substantially and plausibly increased the chances of exotic introductions. According to the Convention on Biological Diversity (CBD), invasive alien species are the greatest threat to loss of biodiversity in the world and impose high costs to agriculture, forestry and aquatic ecosystems by altering their regional structure, diversity and functioning (Mooney and Hobbs, 2000; Sutherst, 2000; Timoney, 2003).

It is expected that global warming may exacerbate ecological consequences like introduction of new pests by altering phenological events like flowering times especially in temperate plant species (Fitter and Fitter, 2002; Parmesan and Yohe, 2003; Willis *et al.,* 2008) as several tropical plants can withstand the phenological changes (Corlett and LaFrankie, 1998). Invasion of new insect-pests will be the major problem with changing climate favouring the introduction of insect susceptible cultivars or crops (Gregory *et al.,* 2009).

vii) Pest population dynamics and outbreaks

The population dynamics is the aspect of population ecology dealing with factors affecting changes in population densities. The seasonal effects of weather and ongoing changes in climatic conditions will directly lead to modifications in dispersal and development of insect species. The changes in surrounding temperature regimes certainly involve alterations in development rates, voltinism and survival of insects and subsequently act upon size, density and genetic composition of populations, as well as on the extent of host plant exploitation (Bale *et al.,* 2002). It may result in upsetting ecological balance because of unpredictable changes in the population of insect-pests along with their existing and potential natural enemies (Rao *et al.,* 2006; IPCC, 2007).

Changes in climatic variables have led to increased frequency and intensity of outbreaks of insect-pests. Outbreak of sugarcane woolly aphid *Ceratovacuna lanigera* Zehntner in sugarcane belt of Karnataka and Maharashtra states during 2002-03 resulted in 30% yield losses (Joshi and Virakamath, 2004; Srikanth, 2007). These situations of increased and frequent pest damage to the crops have made another big hole in the pockets of already distressed farmers by increasing the cost of plant protection and reducing the margin of profit.

viii) Crop-pest interactions

The capacity of an herbivore insect to complete its development depends on the adaptation to both, the environmental conditions and the host plant. The global change of climate have been found to exert both bottom-up and top-down effects on the tri-tropic interactions between crops, insects and natural enemies by means of certain physiological changes especially related to host-suitability and nutritional status (Hare, 1992; Roth and Lindroth, 1995; Coviella and Trumble, 1999; Gutierrez, 2008). This has been shown by gypsy moth attacking the Red maple (*Acer rubrum* L.) and Sugar maple (*A. saccharum*) which had reduced larval weight, increased feeding time and prolonged development (Williams *et al.,* 2000). The large outbreaks observed in the expansion areas on the new hosts may be explained either by the high susceptibility of the hosts or by the inability of natural enemies to locate the moth larvae on an unusual hosts or environment (Stastny *et al.,* 2006).

Temperature and photoperiod have been found to affect profoundly the critical events such as stem elongation, flowering and fruiting in the life cycle of plants (Cleland *et al.,* 2007). Global warming lead increased temperatures may accelerate the life cycles in some of the plant species (Parmesan and Yohe, 2003: Fitter and Fitter, 2002: Willis *et al.,* 2008) which may affect significantly, feeding and reproduction patterns in associated insect-pests like aphids, jassids, mealybugs, etc. Such increases can greatly exacerbate the negative ecological and economical consequences (Timoney, 2003, Millennium Ecosystem Assessment, 2005).

ix) Increased incidence of insect vectored plant diseases

Climate change may lead to more incidence of insect transmitted plant diseases through range expansion and rapid multiplication of insect vectors (Petzoldt and Seaman, 2010; Sharma *et al.*, 2005; 2010). Increased temperatures, particularly in early season, have been reported to increase the incidence of viral diseases in potato due to early colonization of virus-bearing aphids, the major vectors for potato viruses in Northern Europe (Robert *et al.,* 2000).

Increased Level of CO_2

One of the most studied aspects of climate change is the effect of increasing concentrations of CO_2 on plants. Plants consist primarily of carbon and elevated CO_2 levels allow them to grow more rapidly because they can assimilate carbon more quickly. Greenhouse growers have known this for decades and add CO_2 to encourage plant growth. Similarly, because CO_2 increases the photosynthetic rates of most crop plants, scientists initially thought that increasing CO_2 would be a solution for the world's food supply (LaMarche *et al.,* 1984). In addition to enhanced growth, many crop plants become more drought-tolerant due to CO_2 enrichment. This is because openings in the leaves (stomata) that let CO_2 in and also let water vapor out. If there is high CO_2 concentration in the vicinity of leaf then the stomata need not open as much. It was suggested that under conditions of elevated CO_2, plants will produce better yields even when conditions are harsh (LaMarche *et al.,* 1984). Unfortunately, such optimistic predictions have not proven accurate. One reason for this is that insects also eat more when plants are grown under elevated levels of CO_2 to compensate their low nutritional quality.

A rise in CO_2 in atmosphere generally increases the carbon to nitrogen ratio due to accumulation of non- structural carbohydrates of plant tissues thereby reducing the nutritional quality for protein limited insects diluting the nitrogen content by 15-25% in the tissues (Coviella *et al.,* 1999). The expected reactions from herbivores to the increase in carbon to nitrogen ratio are compensatory feeding, concentrations of defensive chemicals in plants and competition between pest species. Insects may accelerate their food intake to compensate for reduced leaf nitrogen content (Holton *et al.,* 2003), although this is not always the case (Knepp *et al.,* 2005). However, the response of plants to increased CO_2 varies among species. Increased carbon to nitrogen ratios in plant tissue may slow insect development and increase the length of life stages vulnerable to attack by parasitoids. O' Neill *et al.* (2008) found that the life span of Japanese beetle, *Popillia japonica*, a major pest of soybean (*Glycine max*), is prolonged by 8.25% when fed on foliages developed under elevated CO_2. Besides, females fed on such foliages laid approximately twice as many eggs as compared to females fed on foliages grown under normal ambient conditions. A higher level of sugars like glucose, sucrose, and fructose in soybean foliages grown under higher CO_2 is considered to be a preferential factor for Japanese beetle, *P. japonica* to feed on them. Though, Casteel *et al.* (2008) showed in soybean a low level of deterrent phytochemicals under high ambient CO_2 that allows the insects, particularly the Japanese beetle to feed voraciously on the plants. Chen *et al.* (2004) also reported a higher fecundity in aphids with higher carbohydrate levels in food plants grown under elevated CO_2 level. Phytophagous insects may also develop adaptations to overcome higher carbon to nitrogen ratios, for example the pine sawfly, *Neodiprion lecontei*, showed an increase in the efficiency of nitrogen utilization when reared on plants treated with high CO_2 concentration (Williams *et al.,* 1994). However, other insect species seem unable to compensate the lower nutritional quality of the plants by increasing the efficiency of nutrient utilization (Brooks and Whitekar, 1999). The experiments of Lindroth *et al.* (1993) on three species of saturnid moths showed that the performance of caterpillars is only marginally affected when the nitrogen content of the leaves is reduced by 23% and the carbon to nitrogen ratio increased by 13-28%.

Impact of CO_2 on insect population via host plants can be studied through open top chambers (OTCs) and free air carbon dioxide enrichment (FACE). The OTCs are essentially plastic enclosures placed around a sample of an ecosystem. Air is drawn into a box by a fan, enriched with CO_2, and blown through the chamber. Open-top chambers are relatively inexpensive to build because they consist simply of an aluminum frame covered by panels of polyvinyl chloride plastic film.

Temperature control is affected by air movement and differential between inside and outside air temperatures has been found less than 1°C. Relative humidity within the open tops is directly related to transpiration rate and is always higher than in the external air. OTCs have long been known to modify the environment by altering light intensity, relative humidity, wind speed and direction, and other environmental factors. This is considered a shortcoming for studies on insect and disease occurrence as chambers may interfere with the dispersal of organisms or alter the plant's susceptibility to a given pest. Therefore, to separate out the effect of higher temperature and humidity on insect development from CO_2 effect on it, control should also be in an OTC at ambient CO_2 concentration. Rao *et al.* (2009) have conducted feeding trials with two foliage feeding insect species, *A. janata* and *S. litura* using foliage of castor plants grown under three concentrations *viz.*, 700 ppm, 550 ppm, 350 ppm (ambient) of CO_2 inside open top chamber (OTC) and 350 ppm CO_2 in the open. Biochemical analysis of the foliage showed that plants grown under the elevated CO_2 levels had lower N-content, and higher C-content, C/N ratio and polyphenols. Compared to the larvae fed on the ambient CO_2 foliage, the larvae fed on 700 ppm and 550 ppm CO_2 foliage exhibited higher consumption. The 700 ppm and 550 ppm CO_2 foliage was more digestible with higher values of approximate digestibility. The relative consumption rate of larvae increased, whereas the efficiency parameters, viz. efficiency of conversion of ingested food (ECI), efficiency of conversion of digested food (ECD) and relative growth rate (RGR) decreased in the case of larvae grown on 700 ppm and 550 ppm CO_2 foliage. The consumption and weight gain of the larvae were negatively and significantly influenced by the leaf nitrogen, which was found to be the most important factor affecting consumption and growth of larvae.

On the other hand, in FACE, plants are grown in open without any enclosure. The FACE technology facilitates modification of the environment around growing plants to future concentrations of atmospheric CO_2 under natural conditions of temperature, precipitation, pollination, wind, humidity, and sunlight. Therefore, FACE field data represent plant responses to concentrations of atmospheric CO_2 in a natural setting. FACE facilities have been developed and deployed ranging from the scale of 1–2m for low-stature crops or ecosystems to those of 10–20m diameter for field crop evaluation to those for young-to medium-aged forest stands and finally to mature trees of basically any size. Hamilton *et al.* (2005) used the FACE technology to create an atmosphere with CO_2 and O_2 concentrations similar to those predicted for the middle of the 21st century. During the early season, soybean grown under the elevated CO_2 atmosphere had 57% more damage from the insects like Japanese beetle, potato leafhopper, western corn rootworm and Maxican bean beetle than those grown under the ambient conditions and even required an insecticide treatment to continue the experiment. Measured increases in the levels of simple sugars in the soybean leaves might have stimulated the additional insect feeding.

Precipitation

Distribution and frequency of rainfall may also affect the incidence of pests directly as well as through changes in humidity levels. It is being predicted that under the climate change, frequency of rainfall would decline while its intensity would increase. This would lead to heavy showers and floods on one hand and drought spells on the other. Under such situations, incidence of small pests such as aphids, jassids, whiteflies, mites, etc. on crops may be reduced as these get washed away by the heavy rains (Pathak *et al.,* 2012). The deviation of rainfall during monsoon and November and its relationship with level of *Helicoverpa armigera* (Hub.) damage severity showed higher November rainfall favoured higher infestation. Average rainfall is predicted to decrease in several regions and the occurrence of summer droughts is likely to increase. Root herbivore species responded differently to the summer rainfall manipulations. The larvae of dominant root chewing species, *A. lineatus*, were more numerous under enhanced rainfall, in contrast, abundance of the *Coccoidea lecanopsis formicarum* was unaffected by the rainfall manipulations (Karuppaiah and Sujayanad, 2012). Crops such as groundnut, cotton, chillies and coriander before, after and along with tobacco lead to higher incidence of *S. litura*. Resistance to pesticides, favourable weather conditions such as cyclonic weather and heavy rainfall followed by dry spell also contributed to its outbreak (Chari *et al.,* 1993). Lever (1969) analysed the relationship between outbreaks of armyworm, *Mythimna separate* (Walker) and to a lesser extent *Spodoptera mauritia* (Boisd.) and rainfall from 1938 to 1965 and observed that all but three outbreaks occurred when rainfall exceeded the average 89 cm. The effect of rainfall on pests can be studied by simulating various rainfall intensities through sprinklers. Aphid population on wheat and other crops was adversely affected by rainfall and sprinkler irrigation (Daebeler and Hinz, 1977; Chander, 1998). Masters *et al.* (1998) have carried out novel manipulations of local climate to investigate how warmer winters with either wetter or drier summers would affect the homopteran insects a major component of the insect fauna of grasslands.

Impact of Climate Change on Pollinators and Pollination

Insects play vital role in providing various ecosystem services. One of the very important is pollination as they are excellent pollinators for many of the economically important crops (Murugan, 2006; Sidhu and Mehta, 2008). Approximately 73 per cent of the world's cultivated crops are pollinated by bees, 19 per cent by flies, 6.5 per cent by bats, 5 per cent by wasps, 5 per cent by beetles, 4 per cent by birds, and 4 per cent by butterflies and moths (Abrol, 2009). The pollinators in turn benefit by obtaining floral resources such as nectar, pollen or both. This mutualism has evolved over centuries and been helping both natural terrestrial ecosystems as well as man-made agro-ecosystems. Thus the entomophilies pollination is a fundamental process essential for the production of about one-third of the world human food (Klein *et al.,* 2007).

Climate change, an emerging global phenomenon, with a potential to affect every component of agricultural ecosystems, is reported to impact insect pollinators at various levels, including their pollination efficiency. According to Millennium Ecosystem Assessment report 2005, pollination is one of the 15 major ecosystem services currently under threat from mounting pressures exerted by growing population, depleting natural resource base and global climate change (Costanza *et al.,* 1987; Sachs, 2008). Earlier studies have clearly shown that the population abundance, geographic range and pollination activities of important pollinator species like bees, moths and butterflies are declining considerably with changing climate (FAO, 2008). The climatic factors like temperature and water availability have been found to affect profoundly the critical events like flowering, pollination and fruiting in the life cycle of plants (Cleland *et al.,* 2007). Many pollinators have synchronised their life cycles with plant phenological events. Impending climate change is expected to disrupt the synchrony between plant-pollinator relationships by changing the phenological events in their life cycles and may thus affect the extent of pollination (Kudo *et al.,* 2004; Ricketts *et al.,* 2008). The quality and the quantity of pollination have multiple implications for food security, species diversity, ecosystem stability and resilience to climate change (FAO, 2008).

Although pollination is a critical issue it appears to be neglected and overlooked for other ecosystem services such as water and air quality, climate regulation and food availability. The pollination services and associated risks are not addressed properly in determining the actions needed for conserving pollinators. The high degree of uncertainty regarding the risks related to pollination services implies the need for well focused research to understand scientifically the pollination processes.

Impact of Climate Change on the Pest Management Strategies

a) Breakdown of host plant resistance

Host plant resistance is one of the most environmental friendly components for managing harmful insect-pests of crops wherein the plant can lessen the damage caused by insect-pests through various mechanisms like antixenosis, antibiosis and tolerance (Painter, 1968; Dhaliwal and Dilavari, 1993). Expression of the host plant resistance is greatly influenced by environmental factors like temperature, sunlight, soil moisture, air pollution, etc. Changes in these climatic factors may alter the interactions between insect pests and their host plants (Sharma *et al.*, 2010). Under stressful environment, plant becomes more susceptible to attack by insect-pests because of weakening of their own defensive system resulting in pest outbreaks and more crop damage (Rhoades 1985). With global temperature rise and increased water stress, tropical countries like India may face the problem of severe yield loss in sorghum due to breakdown of resistance against midge *Stenodiplosis sorghicola* (Coq.) and spotted stem borer, *Chilo partellus* Swinhoe (Sharma *et al.*, 2005). 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. 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 (Coviella and Trumble, 1999). 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. Bark beetles, wood borers, and sap sucking insects benefit from severe drought (Bjorkman and Larsson, 1999; Huberty and Denno, 2004; Koricheva *et al.*, 1998), while *Spodoptera exigua* (Hub.) exhibited a reduced ability to feed on drought-stressed tomato leaf tissue, which contained higher levels of defense compounds as a result of the abiotic stress (English-Loeb *et al.*, 1997). In atmospheres experimentally enriched with CO_2, the nutritional quality of leaves declined substantially due to a dilution of nitrogen by 10–30% (Coley and Markham, 1998). Increased CO_2 may also cause a slight decrease in nitrogen-based defences (e.g. alkaloids) and a slight increase in carbon-based defences (e.g. tannins). Lower foliar nitrogen due to CO_2 causes an increase in food consumption by herbivores. Increase in amounts of simple sugars and down-regulation of gene expression for a protease-specific deterrent to coleopteran herbivores may have resulted in greater insect feeding (Zavala *et al.*, 2008). Elevated CO_2 decreases the induction of jasmonic acid and ethylene related transcripts (*lox7*, *aos*, *hpl*, and *acc1*) in soybean plants causing decreased accumulation of defenses (polyphenol oxidase, protease inhibitors, etc.) over time compared to plants grown under ambient conditions, suggesting that CO_2 exposure might have resulted in increased insect damage (Casteel, 2010). Problems with new insect pests will occur if climatic changes favour the introduction of nonresistant crops or cultivars into new areas. The introduction of new crops and cultivars could be one of the methods to take advantage of climate change (Parry, 1990; Parry and Carter, 1989).

b) Transgenic crops

In recent advancement of integrated pest management, insect resistant transgenics expressing the *Bacillus thuringiensis* (Berliner) (*Bt*) insecticidal protein (delta-endotoxin) were developed (Kranti *et al.* 2005). However, these transgenic plants showed a reduction in the level of toxin protein during periods of high temperature, elevated CO_2 levels, or drought, leading to decreased resistance to insect pests (Chen *et al.*, 2005; Chen *et al.*, 2005a; Dong and Li, 2007). Cotton bollworm, *Heliothis virescens* (F.), destroyed *Bt* cottons due to high temperatures in Texas, USA (Kaiser, 1996). Similarly, *H. armigera* and *H. punctigera* damaged *Bt*-cotton in the second half of the growing season in Australia because of reduced production of *Bt* toxins in the transgenic crops (Hilder and Boulter, 1999). Cry1Ac levels decrease with plant age, resulting in greater susceptibility of the crop to bollworms during the later stages of crop growth (Adamczyk *et al.*, 2001; Greenplate *et al.*, 2000; Kranthi *et al.*, 2005; Sachs *et al.*, 1998). Possible causes for the failure of insect control may be due to inadequate production of the toxin protein, the effect of environment on transgene expression, locally resistant insect populations, and development of resistance due to inadequate management (Sharma and Ortiz, 2000). It is therefore important to understand the effects of climate change on the efficacy of transgenic plants for pest management.

c) Natural enemies

Relationships between insect pests and their natural enemies will change as a result of global warming, resulting in both increases and decreases in the status of individual pest species. Changes in temperature will also alter the timing of diurnal activity patterns of different groups of insects (Young, 1982), and changes in interspecific interactions could also alter the effectiveness of natural enemies for pest management (Hill and Dymock, 1989). Quantifying the effect of climate change on the activity and effectiveness of natural enemies for pest management will be a major concern in future pest management programs. The majority of insects are benign to agro-ecosystems, and there is considerable evidence to suggest that this is due to population control through interspecific interactions among insect pests and their natural enemies–pathogens, parasites, and predators (Price, 1987). Oriental armyworm, *M. separata* populations increased during extended periods of drought (which is detrimental to the natural enemies), followed by heavy rainfall because of the adverse effects of drought on the activity and abundance of the natural enemies of this pest (Sharma *et al.*, 2002). Aphid abundance increases with an increase in CO_2 and temperature, however, the parasitism rates remain unchanged in elevated CO_2. Temperatures up to 25°C will enhance the control of aphids by coccinellids (Freier and Triltsch, 1996). Temperature not only affects the rate of insect development, but also has a profound effect on fecundity and sex ratio of parasitoids (Dhillon and Sharma, 2008 and 2009). The interactions between insect pests and their natural enemies need to be studied carefully to devise appropriate methods for using natural enemies in pest management.

d) Biopesticides and Synthetic Insecticides

There will be an increased variability in insect damage as a result of climate change. Higher temperatures will make dry seasons drier, and conversely, may increase the amount and intensity of rainfall, making wet seasons wetter than at present. Current sensitivities on environmental pollution, human health hazards, and, pest resurgence are a consequence of improper use of synthetic insecticides. Natural plant products, entomopathogenic viruses, fungi, bacteria, nematodes, and synthetic pesticides are highly sensitive to the environment. Temperature is a major factor affecting insecticide toxicity either positive or negative and, thus, efficacy. The response relationship between temperature and efficacy has been found to vary depending on the mode of action of an insecticide, target species, method of application, and quantity of insecticide ingested or contacted (Johnson, 1990). Increased temperature will increase the activity of some of the insecticides. Diflubenzuron (an insect growth regulator (IGR)) caused rapid mortality at higher temperatures and was more efficient at 35°C (Amarasekare and Edelson, 2004). This was probably because this IGR is only effective when the insect moults

(Ware, 2000), and the insect growth rate and moulting rate increase at higher temperatures (Lactin and Johnson, 1995). However, the biological activity of the entomopathogenic fungus, *Beauveria bassiana* (Balsamo), is reduced at temperatures >25°C (Amarasekare and Edelson, 2004; Inglis *et al.*, 1999). Increase in temperature and UV radiation, and a decrease in relative humidity, may render many of the pest control tactics to be less effective, and such an effect will be more pronounced on natural plant products and the biopesticides. Entomopathogens used as biocontrol agents suffer from instability after exposure to solar radiation, especially in the ultraviolet (UV) portion of the spectrum. Several studies have reported a significant decrease in biological activity of entomopathogens, viz. NPV, GV, *Beauveria* and *Bt* (up to 90%) within a few days (Broome *et al.*, 1974; Ignoffo *et al.*, 1977; Jones and McKinley, 1986). Another effect of increased temperature and UV radiation may be to slow down the activity even without the loss of activity due to UV radiation; as a result, more time may be required to achieve insect mortality (Moscardi, 1999; Szewczyk *et al.*, 2006). Larvae continue to feed and damage crops until shortly before death. Chen and McCarl (2001) estimated that pest treatment costs under the 2090 projections of climate exhibit increases of 3–10% for corn, soybeans, cotton and potatoes and mixed results for wheat, and show a $200 million per year projected loss to society due to climate change related pesticide treatment cost effects in the USA. Therefore, there is a need to develop appropriate strategies for pest management that will be effective under situations of global warming in the future. Farmers will need a set of pest control strategies that can produce sustainable yields under climatic change.

Implications for Food Security

The greatest challenge in the coming century is to double the present levels of food production to meet the needs of ever increasing population by sustainable use of shrinking natural resource base (Deka *et al.,* 2008). The aggravating pest problems under changing climate regimes are expected to intensify the yield losses; threatening the food security of the countries with high dependency on agriculture. The climate change is likely to affect the extent of entomophilies pollination by disrupting the synchrony between plant-pollinator life cycles (Kudo *et al.,* 2004), with an estimated risk of reduction in world food production by one-third (Klein *et al.,* 2007). This has major implication for food and nutritional security (FAO, 2008). This may have direct bearing on the livelihood of the rural poor as their survival is directly linked to outcomes from food production systems. The increased food prices resulting from declining food production may also impact negatively the urban population (IPCC, 2007; Chahal *et al.,* 2008).

Adaptation of agriculture to changing pest scenario due to climate

No doubt, understanding and dealing with the problem of abiotic stresses and crop insect pest interactions under the influence of changing climate is difficult task. Some of the strategies that we would feel useful in tackling the issue are pointed out below.

Sensitization of Stakeholders about Climate Change and its Impacts

Considering the impacts of future climate change on sustainability and productivity of agriculture, especially in the developing countries like India, there is an urgent need to sensitize the farmers, extension workers and other stakeholders involved in supply chain management about the climate change associated changes in incidence of pests and diseases of major crops in their regions and the different adaptation strategies to cope with the situation. This can be achieved through organization of awareness campaigns, training and capacity-building programmes, development of learning material and support guides for different risk scenarios of pest, etc.

Farmers' Participatory Research for Enhancing Adaptive Capacity

The decision making ability and adaptive capacity of farmers can be enhanced through the integration of a farmers' participatory and multidisciplinary research approach involving research and developmental organizations and farmers as equal partners. This will help to improve the channels of communication between researchers and farmers for dissemination of knowledge and information regarding the current advances in the provision of weather and climate information, weather based agro-advisory services for facilitating operational decisions at farm level. A decision support system (DSS) involving mechanisms for collection and dissemination of information on insect-pest data under diverse environmental conditions for improved assessments well in advance needs to be developed. In view of changing pest scenario due to climate, we recommend that our future research programmes should focus on the search for more general forms of resistance against various classes of insects or diseases under abiotically stressful environments.

Promotion of Resource Conservation Technologies (RCTs)

Shrinking resource base due to anthropogenic developmental activities is a major challenge ahead for humanity. Conservation of natural resources can be promoted by giving incentives to the farmers those who are adopting environmental conserving pest controlling activities such as organic farming, bio-control, integrated pest management, habitat conservation for important insect pollinators, etc. Strategies for adaptation and coping could benefit from combining scientific and indigenous technical knowledge (ITK), especially in developing countries where technology is least developed. ITK is helpful to adapt the adverse effects of changing climate. *e.g.* application of natural mulches helps in suppression of harmful pests and diseases besides moderating soil temperatures and conservation of soil moisture. Further more study towards integrating indigenous adaptation measures in global adaptation strategies and scientific research is required.

Climate Change : Challenge Ahead

In addition to the strategies discussed above, we need to decide the future line of research for combating the pest problems under climate change regimes.

Breeding Climate-Resilient Varieties

In order to minimize the impacts of climate and other environmental changes, it will be crucial to breed new varieties for improved resistance to abiotic and biotic stresses. Considering late onset and/ or shorter duration of winter, there is chance of delaying and shortening the growing seasons for certain Rabi/ cold season crops. Hence we should concentrate on breeding varieties suitable for late planting and those can sustain adverse climatic conditions and pest and disease incidences.

Rescheduling of Crop Calendars

Global temperature increase and altered rainfall patterns may result in shrinking of crop growing seasons with intense problems of early insect infestations. As such certain effective cultural practices like crop rotation and planting dates will be less or no effective in controlling crop pests with changed climate. Hence there is need to change the crop calendars according to the changing crop environment. The growers of the crops have to change insect management strategies in accordance with the projected changes in pest incidence and extent of crop losses in view of the changing climate.

GIS Based Risk Mapping of Crop Pests

Geographic Information System (GIS) is an enabling technology for entomologists, which help in relating insect-pest outbreaks to biographic and physiographic features of the landscape, hence can best be utilized in area wide pest management programmes. How climatic changes will affect development, incidence, and population dynamics of insect-pests can be studied through GIS by predicting and mapping trends of potential changes in geographical distribution (Sharma *et al.*, 2010) and delineation of agro-ecological hotspots and future areas of pest risk (Yadav *et al.*, 2010).

Screening of Pesticides with Novel Mode of Actions

It has been reported by some researchers that the application of neonicotinoid insecticides for controlling sucking pests induces salicylic acid associated plant defense responses which enhance plant vigour and abiotic stress tolerance, independent of their insecticidal action (Gonias *et al.,* 2003; Thielert, 2006, Horii *et al.,* 2007; Chiriboga *et al.,* 2009; Ford *et al.,* 2010). This gives an insight into investigating role of insecticides in enhancing stress tolerance in plants. Such more compounds needs to be identified for use in future crop pest management.

Conclusion

Climate change now a day is globally acknowledged fact. It has serious impacts on diversity, distribution, incidence, reproduction, growth, development, voltisim and phenology of insect pests. Climate changes also affect the activity of plant defense and resistance, bio-pesticides, synthetic chemicals, invasive insect species, expression of *Bt* toxins in transgenic crops. Considering such declining production efficiency due to depleting natural resource base, serious consequences of climate change on diversity and abundance of insect-pests and the extent of crop losses, food security for 21st century is the major challenge for human kind in years to come. Being a tropical country, India is more challenged with impacts of looming climate change. In India, pest damage varies in different agro-climatic regions across the country mainly due to differential impacts of abiotic factors such as temperature, humidity and rainfall. This entails the intensification of yield losses due to potential changes in crop diversity and increased incidence of insect-pests due to changing climate. It will have serious environmental and socio-economic impacts on rural farmers whose livelihoods depend directly on the agriculture and other climate sensitive sectors.

Dealing with the climate change is really tedious task owing to its complexity, uncertainty, unpredictability and differential impacts over time and place. Understanding abiotic stress responses in crop plants, insect-pests and their natural enemies is an important and challenge ahead in agricultural research. Impacts of climate change on crop production mediated through changes in populations of serious insect-pests need to be given careful attention for planning and devising adaptation and mitigation strategies for future pest management programmes. Therefore, there is a need to have a concerted look at the likely effects of climate change on crop protection, and devise appropriate measures to mitigate the effects of climate change on food security.

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