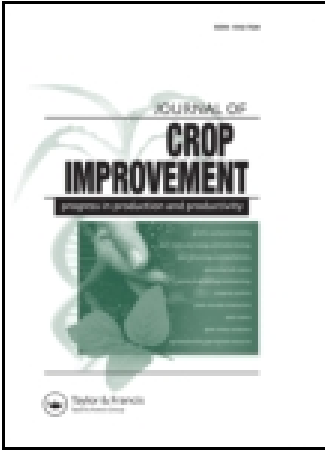


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Climate Change Effects on Insects: Implications for Crop Protection and Food Security

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Climate Change Effects on Insects: Implications for Crop Protection and Food Security

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Global warming and climate change will trigger major changes in diversity and abundance of arthropods, geographical distribution of insect pests, insect population dynamics, insect biotypes, herbivore-plant interactions, activity and abundance of natural enemies, species extinction, and efficacy of crop protection technologies. Changes in geographical range and insect abundance will increase the extent of crop losses and, thus, will have a major bearing on crop production and food security. Distribution of insect pests will also be influenced by the changes in cropping patterns triggered by climate change. Major insect pests, such as cereal stem borers (Chilo, Sesamia, and Scirpophaga), pod borers (Helicoverpa, Maruca, and Spodoptera), aphids, and whiteflies may move to temperate regions, leading to greater damage in cereals, grain legumes, vegetables, and fruit crops. Host-plant resistance, biopesticides, natural enemies, and synthetic chemicals are some of the potential options for integrated pest management. However, the relative efficacy of many of these pest control measures is likely to change as a result of global warming. 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 developing countries where the need to increase and sustain food

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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 a biological response to climate change.

KEYWORDS *bioiversity, biopesticides, global warming, host-plant resistance, marker-assisted selection, pollinators, species extinction, synthetic insecticides*

INTRODUCTION

Current estimates of changes in climate indicate an increase in global mean annual temperatures of 1°C by 2025 and 3°C by the end of the 21st century. The amounts of CO₂ will double between 2025 and 2070, depending on the level of emission of greenhouse gasses (UNFCCC 2007). Mean annual temperature changes between 3°C and 6°C are estimated to occur across Europe, with the greatest increases occurring at high latitudes. Global warming and climate change will have major implications for ecosystem services, water availability, crop production, and food security. Increased temperatures have drastically affected rice (*Oryza sativa* L.) production because of reduced crop duration in Philippines (10% reduction in rice yield per 1°C rise in temperature) (Peng et al. 2004). An increase of 6°C in temperature and a precipitation deficit of 300 mm reduced maize (*Zea mays* L.) yield by 36% in the European Union (Ciais et al. 2005). Crop plants used as food by human beings are damaged by over 10,000 species of insects, which cause, globally, an estimated annual crop loss of 13.6% (Benedict 2003). In India, the average annual losses caused by insect pests have been estimated to be 17.5% (valued at US\$17.28 billion) in eight major field crops, including cotton (*Gossypium* spp.), rice, maize, sugarcane (*Saccharum* spp.), rapeseed-mustard (*Brassica* spp.), groundnut (*Arachis hypogea* L.), pulses, coarse cereals, and wheat (*Triticum aestivum* L.) (Dhaliwal et al. 2004, 2010). Losses attributable to insect damage are likely to increase as a result of decreased crop diversity and increased incidence of insect pests resulting from global warming.

The world population will increase by 25% to 7.5 billion by 2020, and nearly 73 million people are added annually, of which 97% live in developing countries (Pinstrup-Andersen and Cohen 2000) (Figure 1). The amount of land available for crop production continues to decrease, and the trend is expected to be much more dramatic in developing countries than in developed ones. The decrease in the amount of land available for crop production will have major implications for food security in the future. The situation will become more serious with impending shifts in fauna and flora associated with climate change. Therefore, there is a need to focus on technologies that will help in increasing crop productivity on the available arable lands with minimum adverse effects on the environment. There

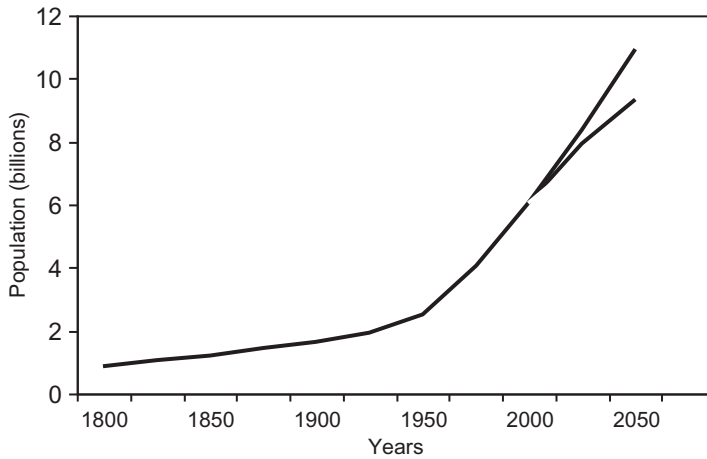


FIGURE 1 Expected population increase over the next 50 years.

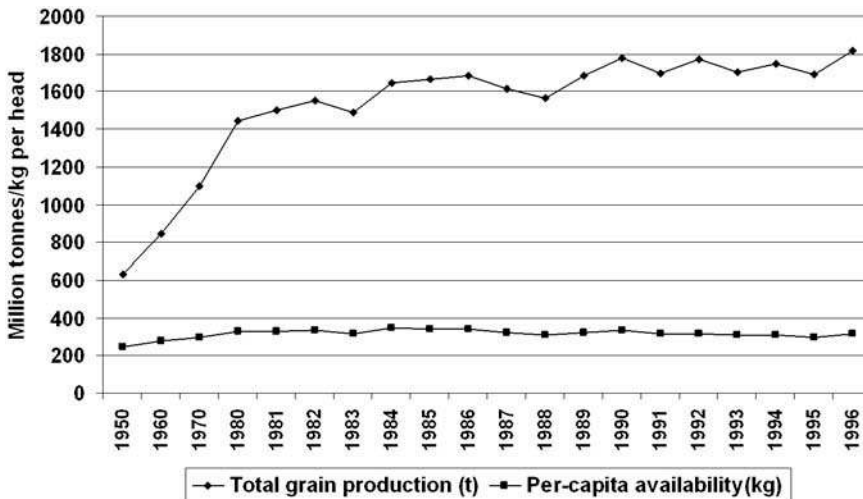


FIGURE 2 Food production and per capita availability of food over the past 50 years.

has been a remarkable increase in total grain production between 1950 and 1980, but only a marginal increase in grain production was realized after the 1990s (Myers 1999) (Figure 2). Much of the increase in grain production resulted from an increase in area under cultivation, irrigation, better agronomic practices, pest management, and improved cultivars. Yields of several crops have already reached a plateau in developed countries, and therefore much of the productivity gains in the future will have to be achieved through crop improvement, better use of natural resources, pest management, and improved productivity in developing countries. Productivity gains are essential for long-term economic growth; but in the short term, these are even more important for maintaining adequate food supplies for the growing

population. Reduction in damage by insect pests is one of the potential areas for increasing food production, and it is in this context that we should focus our attention on the likely effects of global warming and climate change on the activity and abundance of insect pests and their implications for crop protection and food security.

INSECT RESPONSE TO CLIMATE CHANGE

Insects are likely to be most affected by climate change because environmental factors have a strong influence on the development, reproduction, and survival of insect pests and their natural enemies (Bale et al. 2002). Insects have short generation times and high reproductive rates, and hence they are more likely to respond quickly to climate change than plants and vertebrates. Potential responses will include changes in phenological patterns, habitat selection and expansion, and/or contraction of geographic distribution. Species responses are expected to be idiosyncratic, depending on the flexibility of life history characteristics, and different growth rates and diapause requirements may influence species distribution and population increase (Bale et al. 2002). Fast-growing, nondiapausing species or those not dependent on low temperatures to induce diapause will respond to warming by expanding their distributions, whereas slow-growing species, which need low temperatures to induce diapause, will suffer range contractions.

Global warming will lead to faster development of immature stages, and adults will emerge much earlier than before. Observed responses include early adult emergence and an increase in the length of the flight period. Changes in butterfly phenology have been reported in Europe (Roy and Sparks 2000; Stefanescu et al. 2003), and species have advanced their flight periods by 2–10 days for every 1°C increase in temperature. In Spain, butterflies appeared earlier by 1 and 7 weeks during the past 15 years, and by 8 days per decade in California (Forister and Shapiro 2003). Several species of microlepidoptera have also shown temporal shifts in their phenology in Europe (Ellis et al. 1997). Early adult emergence and early arrival of migratory aphids have been observed in the United Kingdom (Zhou et al. 1995). A common phenological response has been observed in four unrelated species of insects (a butterfly, a bee, a fly, and a beetle) (Gordo and Sanz 2005). In most cases, earlier appearance was correlated with an increase in spring temperatures. Global warming and changes in climate will influence:

- Activity, diversity, and abundance of insect pests
- Geographical distribution of insect pests
- Overwintering; development and population dynamics
- Expression of host-plant resistance to insects
- Pest outbreaks and pest invasion
- Synchrony between plants and insect pollinators

- Effectiveness of crop protection technologies

As a result of global warming, insects may find suitable alternative habitats at greater latitudes and higher altitudes. Genetic variation and multifactor inheritance of innate recognition of environmental signals may mean that many insect species will have to adapt readily to such disruption. Many species may also have their diapause strategies disrupted as the linkages between temperature, moisture regimes, and day lengths will be altered. Climate change will also result in increased problems with insect-transmitted diseases. These changes will have major implications for food security, particularly in 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 a biological response to climate change. In addition, it is also desirable to keep ahead of undesirable pest adaptations, and it is important to consider global warming and climate change for planning research and development efforts for pest management and ensuring food security.

INSECTS AS INDICATORS OF CLIMATE CHANGE

Arthropods can be used as good bioindicators of human-driven changes in the environment, such as pollution, habitat loss, and fragmentation (McGeoch 1998), and monitoring of terrestrial arthropods can provide early warnings of ecological effects attributable to climate change. Insects can also be used as examples of how biodiversity and community structure are affected by climate change. However, we still have a long way to go in understanding the detrimental and beneficial effects of human-induced climate change on biological systems. Arthropods can serve as good indicators of environmental change more easily than vertebrates and plants (Scherm et al. 2000; Gregory et al. 2009). For monitoring purposes, indicator assemblages should exhibit varying sensitivities to environmental changes and show diversity in life history and ecological interactions. Realistic information on arthropod diversity must be integrated into policy planning and management practices if ecosystems are to be managed for use by future generations. Ecosystem baselines that document arthropod species assemblages that are comparable in space and time are important for the interpretation and implementation of strategies designed to mitigate the effects of global warming and climate change.

CLIMATE CHANGE AND ARTHROPOD DIVERSITY

Large-scale changes in rainfall caused by global warming will also have a major bearing on the abundance and diversity of arthropods. Extreme

TABLE 1 Species diversity among different groups of organisms.

Organisms	Number of Species
Protoctists (algae, protozoa, etc.)	80,000
Bacteria	4,000
Fungi	72,000
Plants	270,000
Invertebrates (arthropods: insects, spiders, mites, etc.)	1,272,000
Vertebrates	52,000
Total number of described species	1,750,000
Possible unknown species	14,000,000

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climatic events, such as drought, are likely to decrease multitrophic diversity and change the composition of arthropod communities, which, in turn, may affect other associated taxa. Arthropods (insects, spiders, and mites) are the most abundant and diverse group of organisms (Kannan and James 2009; Gregory et al. 2009) (Table 1). Insect pests are an important component of terrestrial and aquatic ecosystems and occupy a wide variety of functional niches and microhabitats (Kremen et al. 1993). Responses of arthropods to pollution depend on both temperature and precipitation; ecosystem-wide effects are likely to increase under predicted climate change (Zvereva and Kozlov 2010). Consequences of temperature increases of 1°C to 2°C will be comparable in magnitude to the currently seen climate change in the Antarctic region, for example, after two seasons of experimental warming, the total abundance of Collembola decreased in the lichen community as a result of the population decline of the isotomid, *Cryptopygus antarcticus* Willem. There was also a significant decline of mesostigmatid predatory mite, *Gamasellus racovitzai* (Trouessart), and a significant increase in the total number of Prostigmata (Bokhorst et al. 2008). The main effects of climate change and pollution on arthropod communities will be a decreased abundance of decomposers and natural enemies and increased herbivory, which may have negative consequences for the structure and services of entire ecosystems. For example, an increase in the amount of rainfall in the pampas region of Argentina has been shown to affect species with poor dispersal capabilities (Xannepuccia et al. 2009). At higher trophic levels, an indirect effect related to habitat loss and a reduction in prey availability has also been observed. In forest ecosystems, chronic stress significantly altered community composition, and the trees growing under high stress supported one-tenth the number of arthropods compared with trees growing under more favorable conditions (Talbot Trotter et al. 2008). Increased levels of tree stress are associated with an 8- to 10-fold decline in arthropod species richness and abundance. Arthropod richness and abundance on individual trees were positively correlated with a tree's radial growth during drought, suggesting that tree ring analysis could be used as a predictor of arthropod diversity (Stone et al. 2010).

CLIMATE CHANGE AND SPECIES EXTINCTION

Climate change will become a major factor for the extinction of arthropod species (Thomas et al. 1996 2004; Butchart et al. 2005). Mountain species and those restricted to high latitudes are most likely to become extinct as a result of climate change. The species adapted to cold conditions will be forced to move uphill to higher latitudes as a result of global warming. Some of the species may eventually run out of habitable areas and inevitably become extinct. Species decline is difficult to detect and takes place across several hundreds of years. There has been a considerable change in British butterfly species richness between 1970 and 1999 (Menéndez et al. 2006). Four butterfly species have disappeared from lower latitudes during the past 25 years in the United Kingdom, with climate change being responsible for at least half of the population extinctions (Franco et al. 2006). In Spain, lower elevation limits of 16 mountain butterflies have increased in altitude by around 212 m as a result of global warming (Wilson et al. 2005). Speciation takes between 100 and 1,000,000 years, resulting in 10–10,000 new species per annum. Nearly 99.9% of all species that ever existed have become extinct. We are now living through the sixth extinction spasm, which is largely driven by human activities. The relative abundance of different insect species may change rapidly because of climate change, and the species unable to withstand the stresses may be lost in the near future (Thomas et al. 2004; Jump and Penuelas 2005). The current extinction rates are 100–1000 times greater than what they were earlier, and nearly 45–275 species are becoming extinct every day. It is difficult to attribute extinctions solely to climate change because of the potential of other drivers of extinction, such as habitat loss and invasive species.

EFFECT OF CLIMATE CHANGE ON SPECIES INTERACTIONS

Climate-driven range expansion has created new interactions with potentially devastating consequences for crop production and food security. Changes in phenological patterns and distribution of individual species will result in altered species interactions within communities. The magnitude of response will differ between species, and there is considerable potential for the disruption of existing interactions among species (Visser et al. 2004). Interactions that involve two or more trophic groups, such as plant–herbivore, plant–pollinator, and insect–host–natural enemy interaction are likely to undergo a major change (Harrington et al. 1999). Some plant species may be unable to cope with climate change, resulting in the extinction of species that are specific to particular host plants (Thomas et al. 2004). Distributional changes are also expected to bring about changes in species interactions because some species are likely to expand their distribution to different areas, for example, the pine processionary moth, *Thaumetopoea pityocampa* (Denis &

Schiff.), has moved to higher elevations during the last 20 years as a result of increasing temperature and has encountered a new host, Scots pine (*Pinus sylvestris* [L.] var. *nevadensis* H. Christ.). In warmer years, the defoliation by this insect has increased from 5%–25% above 1700 m (Hódar and Zamora 2004). Many insect species have also advanced their phenology faster than their resources (budburst and flowering) (Visser and Both 2005). An increase of 3°C in mean daily temperature would cause the carrot fly, *Delia radicum* (L.), to become active a month earlier than at present (Collier et al. 1991) and temperature increases of 5°C–10°C would result in the completion of four generations each year compared with two to three generations presently (Biron et al. 2000), necessitating the adoption of new pest control strategies. Global warming will lead to earlier infestation by insect pests, such as *Helicoverpa zea* (Boddie) in North America (EPA 1989) and *Helicoverpa armigera* (Hub.) in north India (Sharma 2010), resulting in increased crop losses. Rising temperatures are likely to result in the availability of new niches for insect pests. The emergence of some insect pests from diapause now occurs much earlier than that of their natural enemies, resulting in a mismatch between the interacting species.

IMPACT OF CLIMATE CHANGE ON GEOGRAPHIC DISTRIBUTION OF INSECT PESTS

Climate change will have a major effect on geographic distribution of insect pests, and low temperatures are often more important than high temperatures in determining the distribution (Hill 1987; Thomas et al. 2001). A common approach in predicting developmental dynamics and migration of insects in relation to weather conditions involves the use of degree-day models (Bryant et al. 1998; Roltsch et al. 1999). However, temperature does not act in isolation to influence pest status, and therefore it is important to consider interactions with other variables, such as rainfall, humidity, radiation, and CO₂ concentrations (Harrington et al. 2001). Increasing temperatures may impart greater ability to insect species limited by low temperatures at higher latitudes to overwinter, extending their geographical range (EPA 1989; Hill and Dymock 1989; Elphinstone and Toth 2008). Sudden outbreaks of insect pests can wipe out certain crop species and also encourage invasions by exotic species (Kannan and James 2009). Spatial shifts in the distribution of crops under changing climatic conditions will also influence the distribution of insect pests in a geographical region (Parry and Carter 1989). However, whether or not an insect pest would move with a crop into a new habitat will depend on other environmental conditions, such as the presence of overwintering sites, soil type, and moisture.

Numerous cases of recent distributional shifts have been recorded for a variety of taxa around the world (Wilson et al. 2005, 2007). Changes in

species distribution ranges have been documented in butterflies in North America and Europe, where species have shifted their ranges northward and to higher elevations as a result of global warming (Parmesan 1996; Konvicka et al. 2003; Wilson et al. 2005). Many beetles, butterflies, dragonflies, grasshoppers, and aquatic bugs have moved northward and to higher elevations in the United Kingdom (Hickling et al. 2006). Populations of corn earworm, *H. zea*, in North America might move to higher latitudes/altitudes, leading to greater damage to maize and other crops (EPA 1989). The legume pod borers *H. armigera* and *Maruca vitrata* (Geyer) (Figure 3), presently confined to tropical climates in Asia, Africa, and Latin America, are most likely to move to northern Europe and North America over the next 50 years as a result of global warming and climate change (Sharma 2010). Increases of 1°C and 3°C in temperature would cause northward shifts in the potential distribution of the European corn borer, *Ostrinia nubilalis* (Hub.), up to 1220 km, with an additional generation in nearly all regions where it is currently known to occur (Porter et al. 1991). Although long-term distributional data are not available for lower latitudes and from tropical areas, movements of tropical species into temperate regions have also been reported (Paulson 2001). Range expansions have been recorded more often than range contractions. However, this pattern can be attributed partially to our

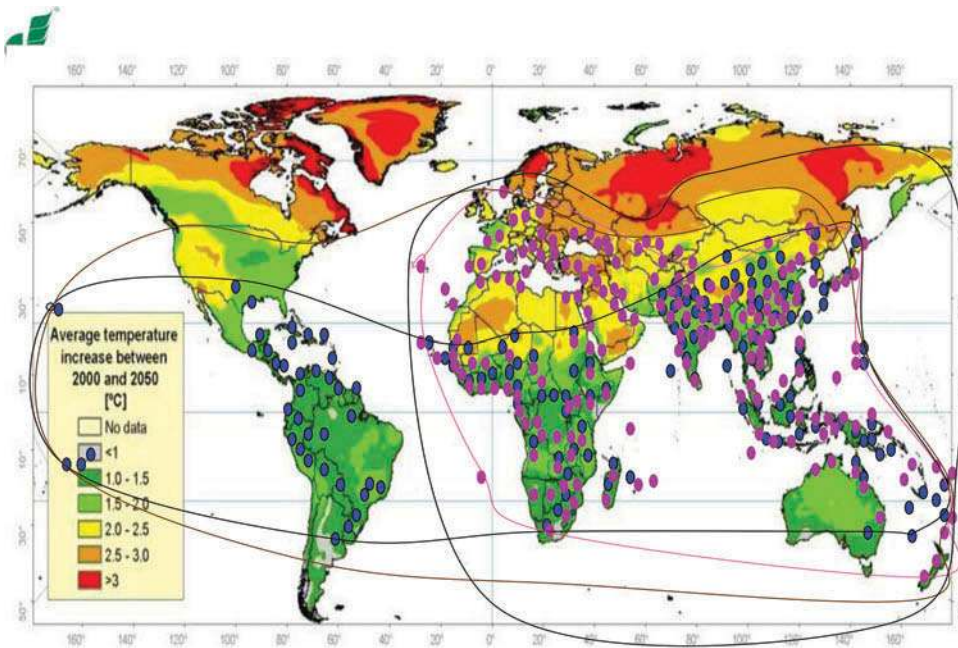


FIGURE 3 Likely changes in geographical distribution of *Helicoverpa armigera* (red line current, and black line likely distribution in future), and *Maruca vitrata* (blue line current and brown line future distribution).

failure to detect species declines (Thomas et al. 2006). When distributions are recorded at a broader scale, only one population needs to be established in a region to detect expansions. However, the extinction of all populations from a region is needed to detect species declines.

EVOLUTIONARY CHANGES AND EMERGING PEST PROBLEMS

Global warming may change the flowering times of plants, leading to ecological consequences, such as the introduction of new insect pests and the attainment of pest status by minor insect pests (Fitter and Fitter 2002; Parmesan and Yohe 2003; Willis et al. 2008). Climate change will alter selection pressures within populations because most populations are adapted to their local environments. Traits that confer fitness in an environment might not be as successful under new climatic conditions, and therefore it is imperative that evolutionary responses take place. The potential of evolutionary changes is quite high among insects as they grow fast, have short generation times, and have high reproductive rates. Insects will adjust rapidly to new environmental conditions because of faster generation turnover than other animals. Therefore, it is not surprising that most empirical evidence of evolutionary changes has come from insect species (Parmesan 2006). Adaptation to climate change has also been observed in species with high frequencies of preexisting high-temperature-tolerant genotypes. Chromosomal inversion polymorphism in *Drosophila* species changes with latitude and is related to climatic factors. Under warm climatic conditions, the frequency of high-temperature-adapted genotypes increases considerably within existing populations (Rodríguez-Trelles and Rodríguez 1998; Levitan 2003; Umina et al. 2005; Balanyá et al. 2006). However, true evolutionary responses have also been reported in the timing of life cycles. Mosquito larvae of pitcher-plant mosquito, *Wyeomyia smithii* (Coq.), enter overwintering state at an earlier date in the northern latitudes than in the south, and overwintering is genetically heritable within populations. The delay in the life cycle has been attributed to evolutionary response to increased length of the growing season (Bradshaw and Holzapfel 2001).

IMPACT OF CLIMATE CHANGE ON THE BIOLOGY AND POPULATION DYNAMICS OF INSECT PESTS

Higher temperatures below the species' upper threshold limit will result in rapid development and increases in pest populations as the time to reproductive maturity will be reduced considerably. In addition to the direct effects of temperature changes on development rates, improvement in food quality because of abiotic stresses may result in dramatic increases in the growth rates of some insect species (White 1984), whereas the growth of certain

insect pests may be affected adversely (Maffei et al. 2007). Overwintering of insect pests will increase as a result of climate change, producing larger spring populations as a base for a buildup in numbers in the following season. These may be vulnerable to parasitoids and predators if the latter also overwinter more readily. The diamond back moth, *Plutella xylostella* L., was able to overwinter in Alberta, Canada, in 1994 (Doddall 1994), and if overwintering becomes common the status of this insect as a pest in North America will increase dramatically. Some insect species, such as cicadas and Arctic moths, take several years to complete one life cycle, and these insects will react to temperature variations during the course of their life history. With a 2°C increase in temperature, these insects might have one to five additional life cycles per season (Yamamura and Kiritani 1998). Temperature has a strong influence on the viability and incubation period of *H. armigera* eggs, which can be predicted on the basis of degree-days required for egg hatching (Dhillon and Sharma 2007).

Insect populations vary across seasons and locations. Both the onset of insect infestation and population buildup are influenced by the weather conditions during the crop growing season and/or during the preceding period. Because no two seasons have similar weather conditions, the insect population dynamics also varies across seasons and locations, for example, there is a large variation in the peak population of Oriental armyworm, *Mythimna separata* (Walk.), at ICRISAT-Patancheru, Andhra Pradesh, India, across seasons (Figure 4). Maximum moth catches in light traps were recorded during the 31st standard week in 1980 and the 40th standard week during 1976. Adults of *M. separata* are generally caught in light traps 15–20 days after the initiation of the monsoon rains in the first week of June, and they reach a peak in September, nearly 1 month after the peak in larval density

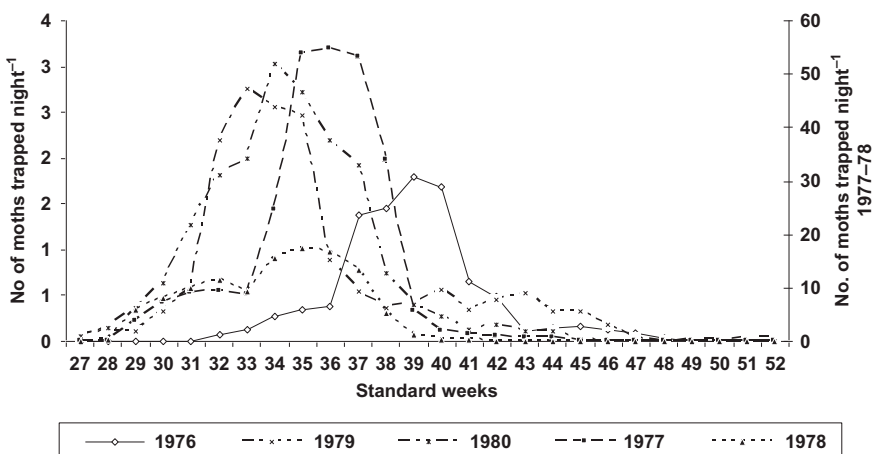


FIGURE 4 Population dynamics of the Oriental armyworm, *Mythimna separata*, from 1976 to 1980.

(Sharma et al. 2002b). Rain and maximum and minimum relative humidity are positively associated with moth catches in the light traps, whereas maximum temperature, open pan evaporation, solar radiation, sunshine hours, and wind velocity have a negative correlation with moth abundance. The population density (PY) of sorghum head bug, *Calocoris angustatus* Leth., is influenced by rainfall (R), maximum (T_{\max}) and minimum (T_{\min}) temperatures, and maximum (RH_{\max}) and minimum (RH_{\min}) relative humidity prevailing during the previous 2 weeks (SW2): $(PY = 220 + 0.6R + 44.3T_{\max} - 113.1T_{\min} + 15.6RH_{\max} - 5.7RH_{\min})$ (Sharma and Lopez 1994). The population and incidence of cotton bollworm/legume pod borer, *H. armigera*, in southern India is influenced by the amount of rainfall during the rainy and the post-rainy seasons (high incidence = $+A+B$, moderate incidence = $-A+B$, and low incidence = $-A-B$, where A = June–September rainfall and B = October–November rainfall) (Das et al. 2001). The onset of insect infestation and population dynamics will become more variable under global warming and climate change, thus making it more difficult to plan and undertake measures to control the damage by insect pests.

An increase of 2°C in temperature will reduce the generation turnover of the bird cherry aphid, *Rhopalosiphum padi* (L.), by varying levels, depending on the changes in mean temperature (Morgan 1996). There may also be increased dispersal of airborne insect species in response to atmospheric disturbances. Many insects such as *H. armigera*, *M. separata*, and *Spodoptera litura* (F.), which are migratory, may be well able to exploit new opportunities by moving rapidly into new areas as a result of climate change (Sharma et al. 2002b; Sharma 2005, 2010). Pest outbreaks are more likely to occur with stressed plants as a result of weakening of the plants' defensive system, thus increasing their level of susceptibility to insect pests (Rhoades 1985). However, many plant species in tropical regions have the capability to withstand the phenological changes that are a result of climate change (Corlett and LaFrankie 1998).

EFFECT OF CLIMATE CHANGE ON THE ACTIVITY AND ABUNDANCE OF INSECT POLLINATORS

Anthropogenically induced temperature increases have the potential to affect the phenology of both plants and pollinators. Many plants have reacted to increasing temperatures by earlier flowering (Fitter and Fitter 2002; Menzel et al. 2006; Miller-Rushing et al. 2007). Insect-pollinated plants generally react more strongly to increased warming than wind-pollinated plants and species flowering early in the season appear to be the most sensitive (Fitter and Fitter 2002; Miller-Rushing et al. 2007). The onset of flowering is correlated with mean temperature in the month of flowering or in the months prior to flowering (Sparks et al. 2000; Menzel et al. 2006). Photoperiod, precipitation, soil

humidity, and snow melting also have a bearing on flowering and pollination (Inouye et al. 2003). If climate change disrupts the relationships among the environmental cues that plants use to initiate flowering, past combinations of cues might reappear at novel times in the season (Price and Waser 1998), resulting in “bizarre” flowering times. Such future responses not only depend on a plant species’ direct response to temperature or other cues but may also be modified ecologically or through evolutionary interactions with pollinators. In general, global warming will result in:

- Altered phenology of plants
- Altered composition of pollinators
- Extinction and/or emergence of new pollinators
- Asynchrony in pollinator activity and plant phenology
- Landscape changes caused by changes in plant communities and pollinators

Global warming will affect both the phenology of plants and the abundance of insect pollinators. There is limited information on how the elevated temperatures affect plant–pollinator mutualism. The onset of flowering in plants and the first appearance of pollinators advance linearly in response to increased temperatures (Hegland et al. 2009). Phenological responses to climate change may occur at the same time in the plants and the pollinators, although there may be considerable variation in responses across species. Despite the overall similarities in responses, a few studies have indicated that climate warming may generate temporal mismatches between the pollinators and the plants. Studies on multispecies plant–pollinator assemblages have indicated that the overall structure of pollination networks is quite robust against the disturbances caused by climate change.

Food availability is one of the important factors governing the activity and population density of pollinators (Hegland and Boeke 2006; Steffan-Dewenter and Schiele 2008). Different cues or combinations of cues may have a disproportionate influence on phenological events across species, ecosystems, and geographical regions. For example, bumblebee queen emergence in the Rocky Mountains is tied to snowmelt, as is the case for the plants they pollinate (Inouye 2008). Tropical insects are most likely to experience the deleterious effects of global warming because of their narrow thermal tolerance, despite a lower temperature increase in tropical regions than in temperate regions (Deutsch et al. 2008). Identification of such fitness curves of thermal tolerance for plants and their pollinators will enable simulations of potential future mismatches among the plants and the insect pollinators. The population dynamics of pollinators is also controlled by resource availability, for example, floral resources and nesting sites in a geographical region. Because many plants and pollinators are generalists (Waser

et al. 1996), an understanding of the outcome of a single interaction between two mutualistic species may be quite unrealistic. Manipulation of resource availability and subsequent assessment of population dynamics of pollinators will be important for estimating potential consequences of climate change (Steffan-Dewenter and Schiele 2008).

EFFECT OF CLIMATE CHANGE ON PEST MANAGEMENT AND FOOD SECURITY

Host plant resistance, biopesticides, natural enemies, and synthetic chemicals are some of the potential options for pest management. However, the relative efficacy of many of these pest control measures is likely to undergo change as a result of global warming. Changes in precipitation are of greater importance for agriculture than temperature changes, especially in regions where the lack of rainfall may be a limiting factor for crop production (Parry 1990). Global mean annual precipitation may increase as a result of the intensification of the hydrological cycle (Rowntree 1990), which will cause disruption of agriculture as the cropping systems and the composition of fauna and flora undergo a gradual change (Porter et al. 1991; Sutherst 1991). High mobility and rapid population growth will increase the extent of losses caused by insect pests. As a result of global warming, insect pests confined to tropical and subtropical regions may move to temperate regions along with a shift in the areas of production of their host plants. Global warming will:

- Change the expression of host plant resistance to insects
- Affect the efficacy of insect-resistant transgenic crops
- Affect the activity and abundance of natural enemies
- Reduce the effectiveness of bio-pesticides and synthetic pesticides for pest management

Expression of Host Plant Resistance to Insect Pests

Host plant resistance to insects is one of the most environment-friendly components of pest management. However, climate change may alter the interactions between insect pests and their host plants (Bale et al. 2002; Sharma et al. 2005, 2010). There will be increased impact on insect pests that benefit from weakened host defenses as a result of the stress caused by the lack of adaptation to suboptimal climatic conditions. The chemical composition of some plant species changes in direct response to biotic and abiotic stresses, which renders the host plant less suitable for the growth and survival of insect pests (Sharma 2002). Problems with new insect pests will

occur if climatic changes favor the introduction of insect-susceptible cultivars or crops into new areas as one of the adaptive methods to mitigate the effects of climate change (Parry and Carter 1989).

Climate change will affect the availability of water and, thus, indirectly affect plant growth and insect–host plant interactions. Populations of *Aphis fabae* Scop. have lower rates of reproduction on water-stressed plants (McMutry 1962). High levels of water stress also reduce the damage by the sorghum shoot fly, *Atherigona soccata* (Rond.) (Soman et al. 1994). However, water-stressed plants of sorghum suffer greater damage by the spotted stem borer, *C. partellus*, and the sugarcane aphid, *Melanaphis sacchari* (Zehnt.), than the plants grown under irrigated conditions. Thus, moisture stress can alter plant reaction to insect damage, leading to either an increase or a decrease in insect damage. Atmospheric humidity also interferes with insect–plant interactions (Sharma et al. 1999). High humidity increases the ease of detection of odors and, thus, may influence host finding by insect pests. Unusually severe drought increases the damage by insect species, such as spotted stem borer, *C. partellus*, in sorghum (Sharma et al. 2005). Sorghum genotypes with moderate levels of resistance to *C. partellus* exhibit a susceptible reaction under drought stress (Figure 5). Sorghum varieties exhibiting resistance to sorghum midge, *Stenodiplosis sorghicola* (Coq.), in India become susceptible to this pest under high humidity and moderate temperatures near the equator in Kenya (Sharma et al. 1999, 2003). Minimum temperature (<18°C) and maximum relative humidity (<60%) had a negative effect on midge damage in the midge-resistant cultivars ICSV 197 and AF 28 but not in the susceptible cultivar CSH 5 (Figure 6). The increase in head bug, *C. angustatus*, population and grain damage across panicle sizes

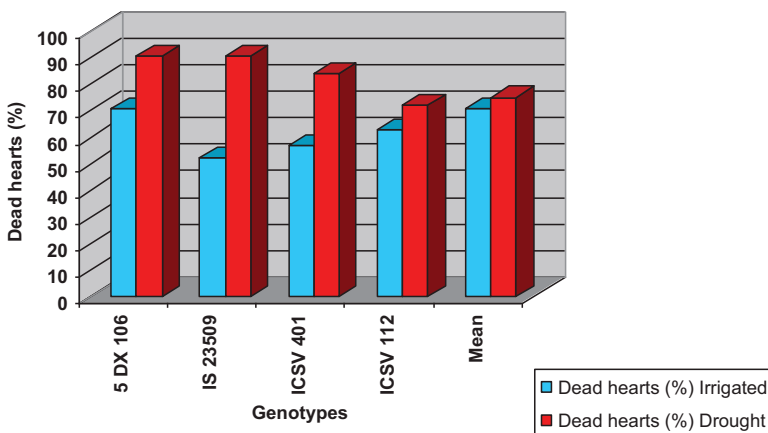


FIGURE 5 Effect of drought on expression of resistance to the stem borer, *Chilo-partellus*, in sorghum.

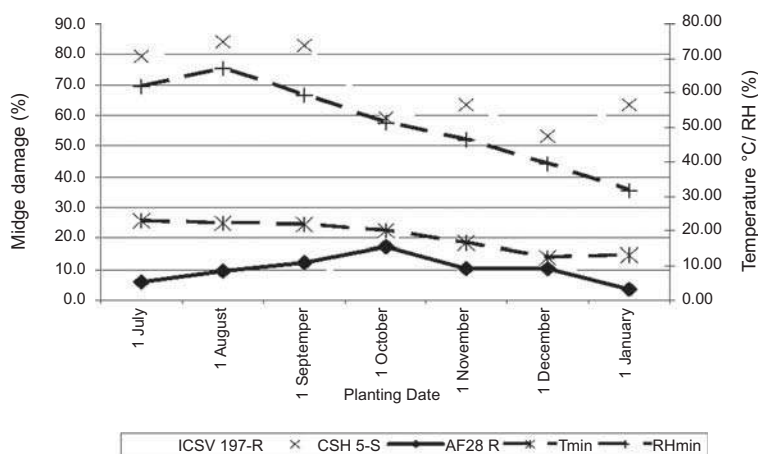


FIGURE 6 Influence of climatic conditions on midge, *Stenodiplosis sorghicola*, damage in sorghum.

or infestation levels were greater during the rainy season compared with the dry season (Sharma and Lopez 1994).

Insect–host plant interactions will also undergo a change in response to the effects of CO₂ on nutritional quality and secondary metabolites of the host plants. Increased levels of CO₂ will enhance plant growth, but they may also increase the damage caused by some phytophagous insects (Gregory et al. 2009). In the CO₂-enriched atmosphere, many species of herbivorous insects will confront less nutritious host plants that could induce both lengthened larval developmental times and greater mortality (Coviella and Trumble 1999). The effects of increased atmospheric CO₂ on herbivory will not only be species specific but also be specific to each insect–plant system. Although increased CO₂ levels tend to enhance plant growth rates, the larger effects of drought stress will probably result in slower plant growth (Coley and Markham 1998). In atmospheres experimentally enriched with CO₂, the nutritional quality of leaves declined substantially because of dilution of nitrogen by 10%–30% (Coley and Markham 1998). Increased CO₂ may also cause a slight decrease in nitrogen-based defenses (e.g., alkaloids) and a slight increase in carbon-based defenses (e.g., tannins). Acidification of water bodies by carbonic acid (because of high CO₂) will also affect floral and faunal diversity (Gore 2006). The lower foliar nitrogen content caused by CO₂ causes an increase in food consumption by herbivores up to 40%. Endophytes, which play an important role in conferring tolerance to both abiotic and biotic stresses in plants, may also undergo a change in response to the disturbance in soil caused by climate change (Newton et al. 2009). For forest insects, the performance of insect herbivores depends on the type of plant tissue available for consumption (Lindroth et al. 1993). The quality of foliage is better at the time of budburst, and therefore egg hatching long after budburst will be disadvantageous to the herbivores (Dewar and Watt 1992).

For a generalist herbivore, such as the gypsy moth, *Lymantria dispar* L., the loss of a single host can be catastrophic. This moth develops on red and black oaks, *Quercus rubra* L. and *Quercus velutina* Lam. and eggs hatched before budburst will lead to starvation, whereas eggs hatched too late after budburst (resulting in reduced foliage quality) will lead to reduced fecundity (Ward and Masters 2007).

Expression of Resistance to Insects in Transgenic Crops

Environmental factors, such as soil moisture, soil fertility, and temperature, have a strong influence on the expression of *Bacillus thuringiensis* (*Bt*) toxin proteins deployed in transgenic plants (Sachs et al. 1998). Possible causes for the failure of insect control in transgenic crops may be inadequate production of the toxin protein, effect of the environment on transgene expression, *Bt*-resistant insect populations, and development of resistance because of inadequate management (Sharma and Ortiz 2000; Sharma et al. 2004). Cotton bollworm, *Heliothis virescens* (F.), destroyed *Bt*-transgenic cottons because of high temperatures in Texas (Kaiser 1996). Similarly, *H. armigera* and *H. punctigera* (Wallen.) destroyed *Bt*-transgenic cotton in the second half of the growing season in Australia because of the reduced production of *Bt*-toxins (Hilder and Boulter 1999). The damage inflicted by bollworms on cotton, regardless of the presence or absence of insecticidal genes, is predicted to be more serious under elevated CO₂ (Chen et al. 2005). Genetically modified cottons with *Bt*-toxin genes have lower nitrogen, and higher carbon–nitrogen ratio, carbon defensive compounds, condensed tannin, and gossypol under elevated CO₂, which results in a significant decrease in the *Bt*-toxin expression and has a considerable influence on the effectiveness of transgenic crops for pest management (Coviella et al. 2002; Chen et al. 2005). The levels of *Bt*-toxin Cry1Ac in transgenic plants decrease with plant age (Figure 7), resulting in greater susceptibility of the crop to insect pests during the later stages of crop growth (Sachs et al. 1998; Greenplate et al. 2000; Adamczyk et al. 2001; Kranthi et al. 2005). A decrease in relative humidity from 90% to 70%, and increases in minimum and maximum temperatures from 9°C to 18°C and 25°C to 35°C, respectively, increases the efficacy of transgenic cotton against the larvae of the bollworm, *H. armigera* (Figure 8). However, there is a significant decrease in biological activity once the minimum and maximum temperatures are >22°C and >38°C, respectively. It is therefore important to understand the effects of climate change on the efficacy of transgenic plants for pest management.

Marker-Assisted Selection and Climate Change

Marker-assisted selection (MAS) can be used to accelerate the pace of transferring insect-resistant genes into improved cultivars to overcome the effects

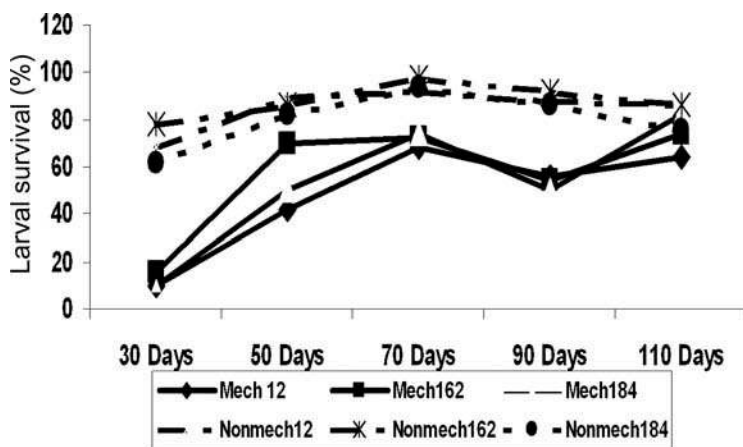


FIGURE 7 Expression of resistance to the bollworm, *Helicoverpa armigera*, in *Bacillus thuringiensis* transgenic cotton over the crop-growing season.

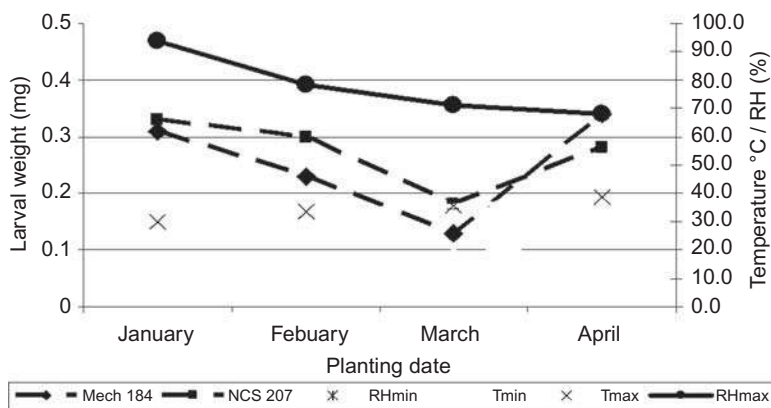


FIGURE 8 Effect of climatic factors on expression of resistance (larval weight) in *Bacillus thuringiensis* transgenic cotton to the bollworm, *Helicoverpa armigera*.

of climate change. Molecular markers, such as random-amplified polymorphic DNAs, restriction fragment-length polymorphisms, microsatellites and polymerase chain reaction (PCR)-based DNA markers, such as sequence characterized amplified regions, simple sequence repeats, sequence tagged sites, amplified fragment-length polymorphic DNAs, based on F_2 (segregating lines from a cross between two genotypes) and backcross populations, near isogenic lines, doubled haploids and recombinant inbred lines, can be used for MAS for insect resistance (Yencho et al. 2000; Sharma et al. 2002a). Molecular markers can help in improving the efficiency of plant breeding by carrying out selections based on markers linked to a trait (Smith 2005). Molecular markers are environment neutral and are detectable at all stages of

plant growth. The environment influences the expression of biochemical and morphological markers, and this makes them less reliable than the molecular markers. A number of methods have been used for mapping quantitative trait loci associated with insect resistance. Molecular markers linked with insect resistance have been identified in several crops, and the success of MAS depends on availability of techniques to screen large populations and high reproducibility of the phenotypic data (Sharma 2009). Potential benefits of this approach have been discussed widely, but at the moment there are very few examples of successful application of this approach to develop cultivars with broad-based resistance to insects. Once the markers linked closely to the resistance genes are identified, MAS can be practiced in early generations at early stages of plant development and can speed up the selection process (Yencho et al. 2000). Marker-assisted selection can also be used for gene pyramiding from diverse sources to overcome the effects of climate change.

Activity and Abundance of Natural Enemies

Quantifying the effect of climate change on the effectiveness of natural enemies will be a major concern in future pest management programs. Tritrophic interactions between plants, herbivores, and parasitoids are the result of a long coevolutionary process, which is specific to a particular environment. 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. The higher trophic levels are more likely to be affected by climate change because they depend on the capacity of the lower trophic levels for development and survival. Biodiversity plays an important role in the relative abundance of insect pests and their natural enemies, and there is a need to increase functional diversity in agroecosystems vulnerable to climate change to improve system resilience and decrease the extent of losses caused by insect pests (Newton et al. 2009). Changes in cropping patterns as a result of climate change will drastically affect the balance between insect pests and their natural enemies. Because climate change will lead to a shift in cultivation of crops in nontraditional areas, this may influence the prevalence and importance of specific insect pests and their natural enemies (Maiorano et al. 2008). System diversity can be exploited to enhance the resilience of agroecosystems, improve resource utilization, and stabilize yields to cope with the effects of global warming and climate change on food security (Alteiri 1994; Sharma and Waliyar 2003; Newton et al. 2009).

Changes in temperature will alter the pattern and timing of diurnal activity of different groups of insects (Young 1982; Heong and Domingo 1992), and changes in interspecific interactions could also alter the effectiveness of natural enemies for pest management (Hill and Dymock 1989). The majority of insects are innocuous to agroecosystems, and there is considerable evidence to suggest that this is because of population control through

interspecific interactions among the insect pests and their natural enemies—pathogens, parasites, and predators (Price 1987). Oriental armyworm, *M. separata*, populations increase during extended periods of drought, which is detrimental to its natural enemies, followed by heavy rainfall (which is favorable to the armyworm) (Sharma et al. 2002b). Increasing climatic variability has resulted in a reduced level of parasitism of caterpillars, which in turn may increase the frequency and intensity of herbivore outbreaks (Stireman et al. 2005).

Aphid abundance increases with an increase in CO₂ and temperature; however, parasitism rates remain unchanged under elevated CO₂. Temperature increases up to 25°C will enhance the control of aphids by coccinellids (Freier and Triltsch 1996). Parasitoids depend on their insect hosts to develop, and exposure of either the insects or the parasitoids to stressful temperatures will induce lethal and sublethal effects on the parasitoids. Temperature not only affects the rate of insect development but also has a profound effect on fecundity and sex ratio of the parasitoids (Dhillon and Sharma 2008, 2009). It also decreases longevity, mobility, ability to orient toward odors, and learning capacities. The endosymbiont bacteria associated with either parasitoids or their insect hosts are also suppressed by short exposures to high temperatures. Because climate change affects the insect hosts and their parasitoids differently, it may lead to a change in the distribution range of different species, resulting in rearrangements of insect communities, including the parasitoids (Hance et al. 2007). Climate change will also disturb the predator–prey and parasitoid–host interactions and even alter the balance between insect pests, natural enemies, and host plants because of alterations in their synchrony. A rise in temperature will generally favor insect development and survival in winter season (Evans et al. 2002). Therefore, 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 programs in the future.

Effectiveness of Biopesticides

Growing awareness about the hazardous effects of synthetic pesticides has led to increasing interest in the use of biopesticides in pest management. Natural plant products, entomopathogenic viruses, fungi, bacteria, and nematodes are highly sensitive to climate change. An increase in temperature and ultraviolet (UV) radiation and a decrease in relative humidity may render many of these control tactics less effective, and such an effect will be more pronounced on natural plant products and biopesticides (Isman 1997). However, changes in temperature, relative humidity, CO₂, and UV radiation have shown differential effects on biopesticides (Lathika and Jacob 1974; Verhaar et al. 1998; Coviella and Trumble 2000; Godoy et al. 2007;

Campos-Herrera et al. 2010). Temperature and humidity are the key factors for the activity of entomopathogenic fungi and nematodes, and very low and very high temperatures result in a significant loss of biological activity (Kung et al. 1991; Chen et al. 2003; Ganguly and Gavas 2004). Several studies have shown that the virulence of entomopathogenic bacteria on insect pests increases at high temperatures (van Frankenhuyzen 1994). In case of entomopathogenic fungi and viruses, high relative humidity is associated with high mortality in insect hosts, but the effects on insect hosts infected with bacteria are quite variable (Walstad et al. 1970; Thompson et al. 2006). UV light is known to affect the biological activity of biopesticides adversely (Krieg et al. 1980). Insect viruses are inactivated by extreme temperatures, sunlight, and UV radiation (Krieg et al. 1980; Thompson et al. 2006).

An increase in CO₂ concentration significantly reduces spore germination and growth rates but increases insect mortality because of disruptions in C/N balance and increases in food consumption. Similar effects have also been observed on biopesticides based on viruses and bacteria (Coviella and Trumble 2000). Fungal development is influenced by soil pH (Thompson et al. 2006). The quantity of insecticidal active constituents of plants is also affected by changes in climatic conditions (Ermel et al. 1986; Rengasamy and Parmar 1995; Kaushik et al. 2007). Environmental influences on insect-pathogen interactions operate through the biology of the pathogen, the immune response of the insect, and/or the rate of pathogen entry into the insect. Therefore, the effectiveness of pesticides will vary with environmental conditions. In situations where biopesticides are used as a component of pest management, environmental conditions should be considered carefully while selecting a product for use in pest management.

Efficacy of Synthetic Insecticides

There will be an increase in 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. Rapid dissipation of insecticide residues because of increases in temperature and precipitation will require more frequent application of insecticides. A hot and humid climate will increase crop protection costs through more frequent use of pesticides for crop protection (Chen and McCarl 2001). Changes in climatic factors, such as temperature, relative humidity, CO₂, pH, rainfall, and soil properties, have shown varying effects on the efficacy of synthetic pesticides. Temperature has shown a positive effect on organochlorines, organophosphates, and carbamates (although there are a few exceptions) but has shown a negative effect on synthetic pyrethroids (Lydy et al. 1999; Li et al. 2006; Uddin and Ara 2006; Wang and Shen 2007). Higher temperatures and lower humidity

reduce the fumigation period of phosphine against *Liposcelis bostrychophila* (Badinell) (Nayak and Collins 2008). Soil texture, moisture, organic matter content, and organic acids influence toxicity and, in turn, affect the efficacy of insecticides for pest management (Achik et al. 1989). Rainfall reduces insecticide toxicity; however, the effects vary with the intensity and amount of rainfall, formulation, and the adjuvants used. Carbon dioxide, pH, and sunlight have shown variable influences on insecticide toxicity (Warwick 1985; Taylor and Matthews 1986; Nayak and Collins 2008). Therefore, there is a need to take a critical look at the effectiveness of various insecticides under global warming and climate change for sustainable crop production and food security.

CONCLUSIONS

Current estimates of climate change indicate an increase in global mean annual temperature and CO₂ concentration and a decrease in annual precipitation, which might result in severe adverse effects on agroecosystems, resulting in changes in crop diversity and the availability of food. Global warming and climate change will trigger major changes in arthropod diversity, geographical distribution of insect pests, insect population dynamics, herbivore–plant interactions, activity and abundance of natural enemies, and efficacy of crop protection technologies for pest management. Distribution of insect pests and their natural enemies will also be influenced by changes in the cropping patterns triggered by climate change. Several insect species currently confined to tropical regions may move to temperate regions, resulting in greater damage to cereals, grain legumes, vegetables, fruit crops, and forest trees. Global warming will also reduce the effectiveness of host plant resistance, transgenic plants, natural enemies, biopesticides, and synthetic chemicals for pest management. As a result, economic relationships between the costs and benefits of pest control measures are expected to change. Therefore, there is a need to generate information on the likely effects of climate change on insect pests to develop robust technologies that will be effective and economical in the future under global warming and climate change.

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