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Will climate change pose serious threat to crop pest management: A critical review?

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Abstract- Abiotically stressful environment in changing climate is predicted to impact negatively the diversity and abundance of insect-pests; and ultimately the extent of damage caused in economically important agricultural crops. This may affect perilously the agricultural production and the livelihood of farmers especially in tropical and subtropical countries where larger proportion of work force is directly depending on climate sensitive sectors such as agriculture. In this article, we enlighten through the extensive literature survey, the climate change induced challenges that the crop growers have to face in near future in managing harmful insect pests of their crops along with its socio-economic impacts on farming community. We feel it is timely and important that further studies pertaining to climate change driven changes in serious insect-pests of crops and planning and development of adaptive strategies needs to be undertaken to lessen the yield losses and safeguard the food security of nation.

Index Terms- Biodiversity, climate change, climate resilience, crop pests, food security

I. Introduction

In recent decades, climate change resultant global warming has become issue of serious concern worldwide for existence of life on the earth (Abrol et al. 1996; IPCC, 2007). Over past hundred years, the global temperature has increased by 0.8^0C and is expected to reach 1.1-5.4 ^{0}C by the end of next century. On the other hand, CO_2 concentration in the atmosphere has increased drastically from 280 ppm to 370 ppm and is likely to be doubled in 2100 (IPCC, 2007). This change is attributed mainly to the overexploitation and misuse of natural resources for various anthropogenic developmental activities such as increased urbanization, deforestation and industrialization resulting in aberrant weather events like changes in rainfall patterns, frequent droughts and floods, increased intensity and frequency of heat and cold waves, outbreaks of insect-pests and diseases, etc. affecting profoundly, many biological systems and ultimately the human beings (IPCC, 2007).

Agro-ecosystem environment is largely governed by interactions between abiotic (temperature, humidity, rainfall, soil factors, pollutants etc.) and biotic (crop-plants, weeds, insect-pests, pathogens, nematodes, etc.) components. The abiotic stress factors modulate the effects of biotic stresses and are most harmful when occur in combination (Mittler, 2006), greatly influencing crop growth and productivity to the extent of 80% (Oerke et al. 1994; Theilert, 2006). Climate change resultant abiotic environment especially changes in hydrological cycles (Rowntree, 1990) and temperature regimes may alter the composition of agro-ecosystems resulting in altitude wise shift in distribution and range of animals and plant species (Porter *et al.* 1991; Sutherst *et al.* 1991; NACCAP, 2008). Hence, in the context of global climate change, it is an utmost need of hour to address multiple stresses threatening sustainability of agricultural production systems.

Pest menace under the influence of climatic factors, at various stages of crop growth is one of the factors limiting agricultural productivity (Oerke *et al.* 1994). In India, pest damage varies considerably in different agro-climatic regions across the country mainly due to differential impacts of several abiotic factors such as temperature, humidity and rainfall (Reed and Pawar, 1982; Sharma *et al.* 2005, 2010). This has major implication for the intensification of yield losses due to potential changes in crop diversity and increased incidence of insect-pests in the context of impending climate change.

Insect-pests of crop plants are the real candidates most affected by global climate change. Complex physiological effects exerted by the increasing temperature and CO_2 may affect profoundly, the interactions between crop plants and insect-pests (Hare, 1992; Caulifield and Bunce, 1994; Roth and Lindroth, 1995). It has been reported that, global climate warming may lead to altitude wise expansion of the geographic range of insect-pests (Hill and Dymock, 1989; Parry and Carter, 1989; Elphinstone and Toth, 2008), increased abundance of tropical insect species (Cannon, 1998; Patterson *et al.* 1999; Bale *et al.* 2002; Diffenbaugh *et al.* 2008), decrease in the relative proportion of temperature sensitive insect population (Petzoldt and Seaman, 2010; Sharma et al., 2005; 2010), more incidence of insect transmitted plant diseases through range expansion and rapid multiplication of insect vectors (Petzoldt and Seaman, 2010). Thus, with changing climate it is expected that the growers of crops have to face new and intense pest problems in the years to come.

The climate change lead changes in insect-pest status will perilously affect agricultural production and the livelihood of farmers in the country where larger portion of work force is directly dependent on climate sensitive sectors such as agriculture (Chahal *et al.* 2008; Deka *et al.* 2008). This envises an urgent need to modify crop protection measures with changed climate in order to attain the goal of food security of the nation. In this article, we emphasize that the 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 pest management.

II. CLIMATE CHANGE IMPOSED CHALLENGES FOR 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 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; IMD, 2006, Rao *et al.* 2009; Samra, 2003). By the end of next century (2100), the temperature in India is likely to increase by 1-5^{0}C (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 (Samra, 2003), 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.

III. IMPACTS ON INSECT-PESTS OF AGRICULTURAL IMPORTANCE

Insects being poikilotherms, temperature is probably the single most important environmental factor influencing their behaviour, distribution, development, survival, and reproduction (Yamamura and Kiritani 1998; Bale *et al.* 2002; Petzolet and Seaman, 2010). Therefore, it is highly expected that, the major drivers of climate change *i.e.* elevated CO_2, increased temperature and depleted soil moisture can impact population dynamics of insect-pests (Figure 1) and the extent of crop losses, significantly (Caulifield and Bunce, 1994; Petzoldt and Seaman, 2010). Impact of climate change on interactions between crop plants and insect-pests has been extensively reviewed (Yamamura and Kiritani 1998; Rao *et al.* 2006; Deka *et al.* 2008; Diffenbaugh *et al.* 2008; Petzoldt and Seaman, 2010). The major predictions about impacts of climate change on insect-pests are compiled and presented below:

Loss of ecological biodiversity

The biodiversity signifies the biological wealth of habitat by means of species richness in an ecosystem. For sustainable agriculture development in any given country, biodiversity is of paramount importance (UN-HABITAT, 2004; Murugan, 2006). South Asia in general and India in particular is blessed with ecologically rich natural and crop-related biodiversity due to its unique geographic location and diversified climatic conditions. India is one of the 12 mega-biodiversity centres with three out of 34 biodiversity hotspots in the world (Myers *et al.* 2000; UN-HABITAT, 2004; Murugan, 2006). Due to change in the climate pattern in recent decades owing to increasing industrialization and over-exploitation of natural resources for various anthropogenic developmental activities, many species of plants, animals and insects are decreasing at an alarming rate (Costanza *et al.* 1987; Murugan, 2006; Sachs, 2008). The loss of biological diversity is still accelerating which may reduce the ecosystem's resilience to the climatic changes (Roy and Roy, 2008; Venkatraman, 2008).

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, are excellent pollinators for many of the economically important crops (Ingram *et al.* 1996; Klein *et al.* 2007; Ricketts *et al.* 2008) and contribute directly to the human economies through valuable products like silk, lac, honey and wax (Myers *et al*, 2000; Murugan, 2006; Sidhu and Mehta, 2008). 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).

The negative effects of climate change are accelerating the rate of biodiversity loss, worldwide. According to the Millennium Ecosystem Assessment (2005), more than one-third of species in the world are at the risk of extinction and an estimated 60% of the Earth's ecosystems have been degraded in the last 50 years, with negative consequences for the ecosystem flow. Nearly 99.9% of all species that ever existed have become extinct. Up to 50% of the Asia's total biodiversity is at risk due to climate change. Many other species could also be extricated as a result of the climate change and habitat fragmentation (Ishigami *et al.* 2005). According to the estimates of IUCN (1994), around 22 species of invertebrates (insects, earthworms, nematodes, crustaceans, spiders, etc.) are at the risk of extinction (Figure 2). This species extinction is largely driven by human activities (Costanza *et al.* 1987; Sachs, 2008; Sidhu and Mehta,

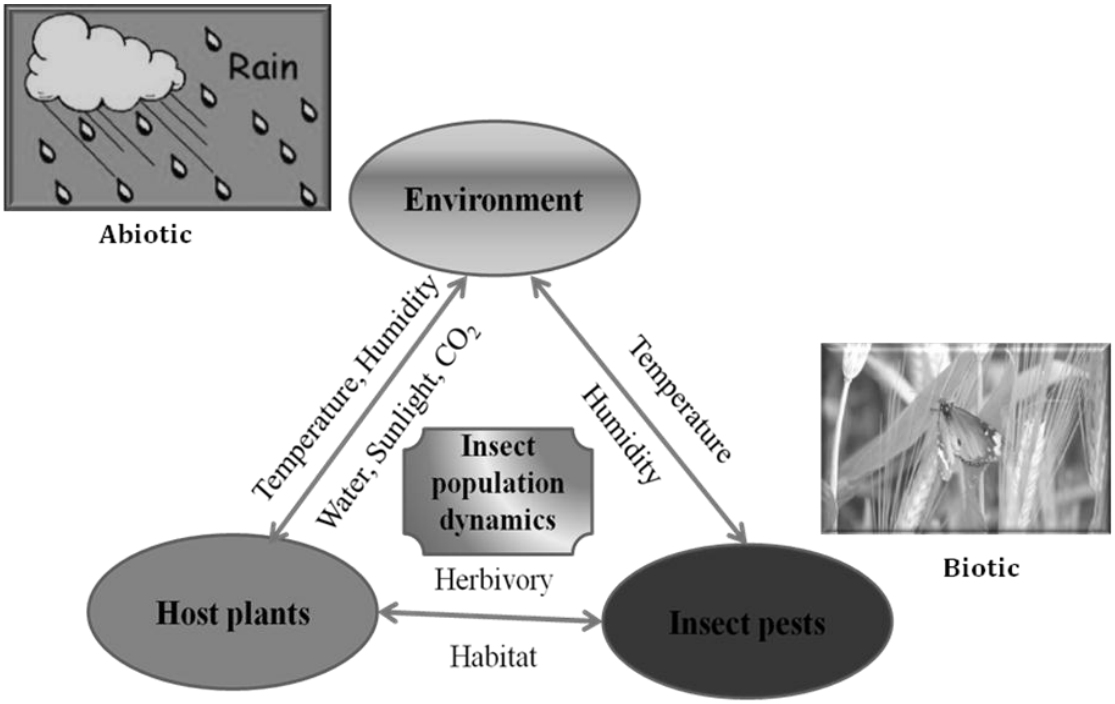

Figure 1. Crop - pest triangle showing interactions between abiotic and biotic factors

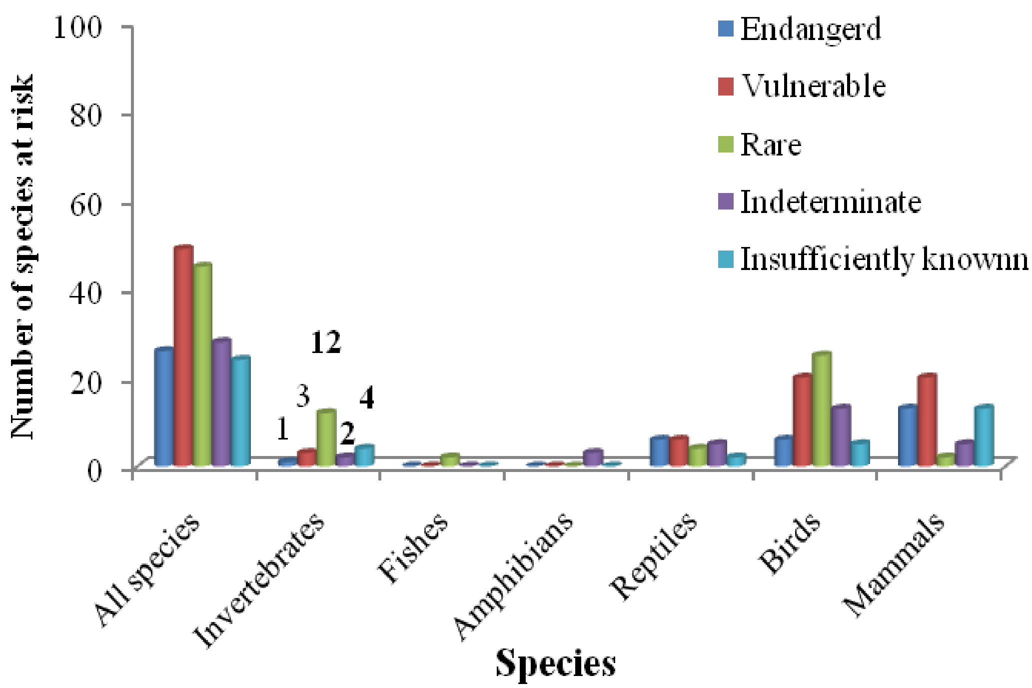

Figure 2. Number of threatened animal species per group (Source: IUCN threat categories, 1994)

2008). The loss of biodiversity may impact negatively the structure, composition and functioning of ecosystems and wildlife habitat leading to outbreaks of destructive insect-pests and diseases (Timoney, 2003; UN-HABITAT, 2004; IPCC, 2007).

Expansion of geographic 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. Altered temperature and rainfall regimes with the predictable changes in climate will determine the future distribution, survival and reproduction of the species (NACCAP, 2008). The differential rates of range adjustments between annual and perennial plant species along with local extinctions will definitely affect distribution and survival of insect fauna associated with them(Thomas *et al.* 2004). Earlier researches have shown that altitude wise shifts in insect distributions along with their host plants in response to changing climate are already in progress (Table 1).

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 (Figure 3) (Hill and Dymock 1989; Parry and Carter 1989; Kuchlein et al., 1997; Rosenzweig *et al.* 2001; 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.

Global warming resultant altitudes 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 (Timoney, 2003; UN-HABITAT, 2004; IPCC, 2007).

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). The temperature in India is expected to increase by 1-5^{0}C within next 100 years (De and Mukhopadhyay, 1998; Lal, 2003; IPCC, 2007; 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 (Figure 4). This gives an important implication that increase in temperature in the range of 1^{0}C to 5^{0}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). Very few studies have concentrated on the direct effects of higher winter temperatures on rates of development and reproduction in insects (Coulson *et al.* 2000; Konestabo *et al.* 2007; Bale and Hayward, 2010).

Increase in number of generations

As stated earlier the temperature being the single most important regulating factor for insects (Yamamura and Kiritani 1998; Bale *et al.* 2002; Petzolet and Seaman, 2010), 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 and ultimately it will result in more crop damage (Yamamura and Kiritani 1998; Petzoldt and Seaman, 2010). The impacts of climate change on seasonability of insects have been studied by many workers (Porter *et al.* 1991; Bale *et al.* 2002; Walther *et al.* 2002).

Risk of introducing invasive alien species

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.

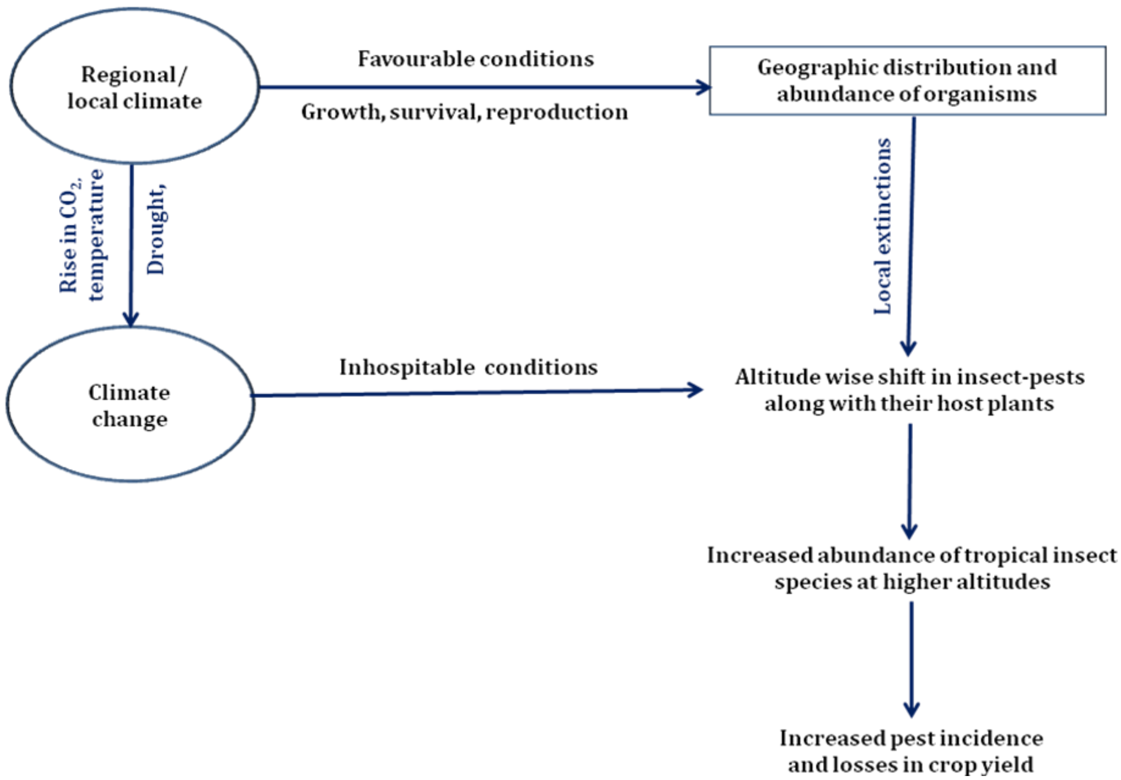

Figure 3. Thematic presentation of range expansion of insect-pests due to climate change

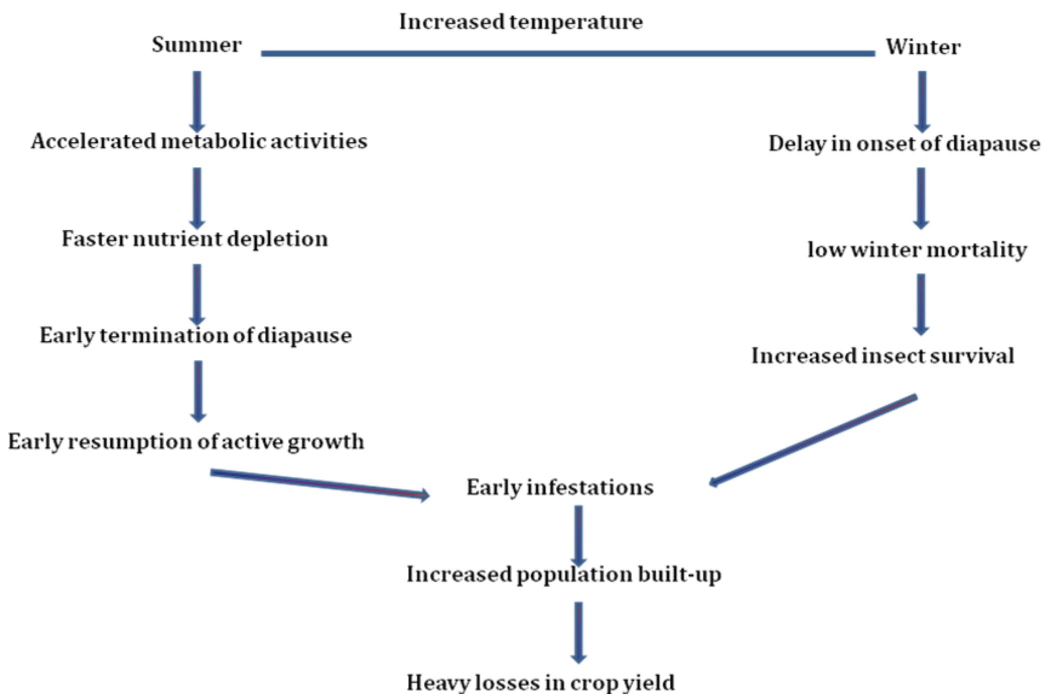

Figure 4. Thematic presentation of impact of climate change on insect survival and population built-up

Table 1. Published reports of empirical studies on impact of climate change on future geographic range and distribution of insect pests

Insect pest	Order/ Family	Host plant/ s	Impact on insects/ behavioural response	Reference
Corn earworms *Heliothis zea* (Boddie) and *Helicoverpa armigera* (Hubner)	Lepidoptera: Noctuidae	Maize	• Altitudes wise range expansion and increased overwintering survival in USA	Diffenbaugh et al., 2008
European corn borer *Ostrinia nubilalis*		Maize	• Northward shifts in the potential distribution up to 1220 km are estimated to occur • An additional generation per season	Porter et al, 1991
104 common microlepidoptera species inhabitant in Netherlands	Lepidoptera	Many crops of agricultural importance	• Changing patterns in phenology and distribution of microlepidoptera in theNetherlands • Advancement of flight peak dates almost by 12 days since 1975-1194 • Changes in the species composition of the local fauna	Kuchlein and Ellis, 1997
Old world Bollworm *Helicoverpa armigera* (Hubner)			• Phenomenal increase in the United Kingdom from 1969-2004 and outbreaks at the northern edge of its range in Europe	Cannon, 1998
Cottony cushion scale *Icerya purchasi*			• Populations appear to be spreading northwards	Cannon, 1998
Oak processionary moth *Thaumetopoea processionea*			• Northward range extension from central and southern Europe into Belgium, Netherlands and Denmark	Cannon, 1998
Cottony camellia scale *Chloropulvinaria floccifera*			• More abundant in the United Kingdom, • Extending its range northwards in England and increasing its host range in the last decade	Cannon, 1998
35 species of non migratory European butterflies	Papilionidae, Lycaenidae, Nymphalidae, Satyrinae		• Pole ward shift of the geographic range and distribution	Parmesan and Yohe, 2003
Cotton bollworm/ Pulse pod borer *Helicoverpa armigera* (Hubner)	Lepidoptera: Noctuidae	Cotton, Pulses, vegetables	• Expansion of geographic range in Northern India • Adult flights/ migratory behaviour	Sharma et al., 2005; 2010

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).

Impact on pest population dynamics and outbreaks

Climate change resultant abiotic environment (increased temperature, elevated CO_2 and depleted soil moisture) will affect significantly the diversity and abundance of insect-pests through geographic range expansion, increased overwintering survival and more number of generations per year, thereby increasing the extent of crop losses. 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 (Table 2). 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.

Breakdown of host plant resistance

Host plant resistance is one of the ecofriendly options 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). However, expression of the host plant resistance is greatly influenced by environmental factors like temperature, sunlight, soil moisture, air pollution, etc. 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). Thermal and drought stress associated breakdown of plant resistance have been widely reported (Table 3) (Rhoades 1985; Sharma *et al.* 2005; Volney and Fleming, 2000; Logan *et al.* 2003). 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). Development of insect resistant transgenics opened new avenues for exploiting host plant resistance in integrated pest management. A gene encoding delta-endotoxin proteins from entomopathogenic soil bacterium *Bacillus thuringiensis* is deployed in transgenic plants (Kranti *et al.* 2005). However, expression of *Bt* toxins in transgenic plants is greatly influenced by environmental factors like temperature, soil moisture and plant age (Dhaliwal and Dilavari, 1993; Sachs *et al*. 1998; Kranti *et al.* 2005). The environmental factors like high temperature have been found affecting transgene expression in *Bt* cotton resulting in reduced production of Bt toxins. This lead to enhanced susceptibility of the crops to insect-pests like bollworms *viz., Heliothis virescens* (F.) (Kaiser, 1996), *Helicoverpa armigera* (Hubner) and *Helicoverpa punctigera* (Wallen) (Hilder and Boulter, 1999).

Impact on crop-pest interactions

The increasing temperature and CO_2 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 (Table 3) (Hare, 1992; Caulifield and Bunce, 1994; Roth and Lindroth, 1995; Coviella and Trumble, 1999; Gutierrez, 2008). The CO_2 enriched environment reduces the nitrogen content of the plant tissue due to widening of Carbon: Nitrogen (C: N) ratio, thus cause a slight decrease in nitrogen-based defenses like alkaloids and in turn may increase in carbon-based defenses such as tannins (Hare, 1992; Caulifield and Bunce, 1994; Roth and Lindroth, 1995; Coviella and Trumble, 1999; Gutierrez, 2008). This enhances the feeding by insect herbivores in order to obtain sufficient nitrogen for their metabolism (Lincoln, 1993; Coviella and Trumble 1999). Ultimately, it slows down the insect development and increases the length of life stages resulting in more foliage feeding than the normal (Lincoln *et al.* 1984; Coviella and Trumble, 1999; Gregory *et al.* 2009).

In CO_2 enriched atmosphere water use efficiency of plants increases owing to the reduced water loss through less stomatal opening (Groninger *et al.* 1996). Increased water content in plants is beneficial for most of the herbivorous insects as it helps in nutrient assimilation and digestion especially nitrogen (Reitz *et al.* 1997). Increased water use efficiency enables the plants to extend their life spans providing longer periods of habitat suitability for transient insects. Contrary, under elevated temperature, the concentrations of certain allellochemicals like terpenes and phenolic compounds increases in plants that act as defensives against attacking insect-pests (Hare, 1992; Caulifield and Bunce, 1994; Roth and Lindroth, 1995; Coviella and Trumble, 1999; Gutierrez, 2008).

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).

Increased incidence of insect vectored plant diseases

Table 2. Recorded instances of recent insect pest outbreaks in relation to changing climate scenario in India

Insect pest	Order/ Family	Host plant/ s	Region/ location	Probable reason/ s	Impact of pest outbreak	Reference
sugarcane woolly aphid *Ceratovacuna lanigera* Zehntner	Hemiptera: Aphididae	Sugarcane	Sugarcane belt of Karnataka and Maharashtra States during 2002-03	• Recent abnormal weather patterns • Insecticide misuse	• 30% yield losses • Reduced cane recovery	Joshi, and Viraktamath, 2004; Srikanth, 2007
Rice plant hoppers *Nilparvata lugens* (Stal) and *Sogatella furcifera* (Horvath)	Hemiptera: Fulgoridae	Rice	North India	- do-	• Crop failure over more than 33,000 ha paddy area	IARI News, 2008 IRRI News, 2009
Mealybug, *Phenacoccus solenopsis* Tinsley	Hemiptera: Pseudococcidae	Cotton, Vegetables and ornamentals	Cotton growing belt of the country	• Recent abnormal weather patterns • Insecticide misuse • Changed cropping environment (introduction of Bt cotton)	• Heavy yield (30-40 %) loss to the cotton • Increased cost of crop protection due to overuse of pesticides	Dhawan et al., 2007
Papaya mealybug *Paracoccus marginatus*	Hemiptera: Pseudococcidae	Papaya	Tamil Nadu, Karnataka, Maharashtra	• Recent abnormal weather patterns • Insecticide misuse	• Significant yield loss to the papaya growers	Tanwar et al., 2010

Table 3. Published reports on empirical studies on crop-insect pest interactions in the context of climate change

Insect pest/ s	Order/ Family	Host plant/ s	Climatic factor/ s studied	Impact on host plant	Impact on insect pest	Reference
Many foliage feeding Lepidopterans	Lepidoptera: Lymantridae, Noctuidae, Pyralidae	Economically important agricultural and forest species	Increased CO_2	• Reduced nitrogen content of the plant tissue due to widening of Carbon: Nitrogen (C: N) ratio • Decrease in nitrogen-based plant defenses like alkaloids • Increase in carbon-based defenses such as tannins	• Enhanced feeding by insects in order to obtain sufficient nitrogen for their metabolism • Slower development • Increased length of life stages • More foliage feeding than the normal	Lincoln et al., 1993; Coviella and Trumble, 1999; Gregory et al., 2009
				• Less stomatal opening • Increased water use efficiency • Reduced water loss through stomata • Extension of plant life spans	• Ease in nutrient assimilation and digestion especially the nitrogen • Longer periods of habitat suitability for insects	Groninger et al., 1996; Reitz et al., 1997
Gypsy moth *Lymantria dispar* L.	Lepidoptera: Noctuidae	Red maple *Acer rubrum* L. Sugar maple *Acer saccharum* Margh.	Temperature x CO_2 combination (Ambient and elevated)	• Reduced leaf water content • Increased concentration of soluble sugars • Declined nutritional quality of foliage	• Reduced larval weight gain • Increased larval feeding • Prolonged development	Williams et al., 2000
Midge *Stenodiplosis sorghicola* (Coq.) and Spotted stem borer *Chilo partellus* Swinhoe	Diptera: Cecidomyidae Lepidoptera: Pyralidae	Jowar *Sorghum bicolor* L.	High temperature, Drought/ water stress	• Breakdown of resistance against target insect pests • Heavy loss in yield due to increased pest damage	-	Sharma et al., 2005; 2010
Bollworms *Heliothis virescens* (F.) *Helicoverpa armigera* (Hubner) and *Helicoverpa punctigera* (Wallen)	Lepidoptera: Noctuidae	Cotton	High temperature, Drought/ water stress, Photoperiod	• Negative impacts on transgene expression in Bt cotton • Reduced production of Bt toxins • Enhanced susceptibility of the crops to insect-pests	-	Kaiser, 1996 Hilder and Boulter, 1999

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).

Reduced effectiveness of biological control agents

Biological control of insect-pests is one of the important components of integrated pest management, safeguarding the ecosystem. Natural enemies of crop pests viz., predators, parasitoids and pathogens are prompt density responsive in their action subjected to the action of abiotic components. Being tiny and delicate, natural enemies of the insect-pests are more sensitive to the climatic extremes like heat, cold, wind and rains. Precipitation changes can also affect predators, parasites and pathogens of insect-pests resulting in a complex dynamics. With changing climate, incidence of entomopathogenic fungi might be favoured by prolonged humidity conditions and obstinately be reduced by drier conditions (Newton *et al.* 2011). Natural enemy and host insect populations may respond differently to changes in climate. Hosts may pass though vulnerable life stages more quickly at higher temperatures, reducing the window of opportunity for parasitism which may give great set back to the survival and multiplication of parasitoids (Gutierrez, 2000; Petzoldt and Seaman, 2010).

Disruption of plant-pollinator interactions

Insects play vital role in providing various ecosystem services, a foundation for human life on earth (Kremen *et al.* 1993; Kannan and James, 2009). One of the important ecosystem service provided by insects is pollination as they are excellent pollinators for many of the economically important crops (Myers et al., 2000; Murugan, 2006; Sidhu and Mehta, 2008). The majority of the flowering plants require insect pollinators like flies, butterflies, moths, beetles and especially bees for their reproduction and formation of fruits and seeds (Ingram et al., 1996; Ricketts et al., 2008). Honey bees are perhaps the best known pollinators because of their floral fidelity. Insect pollination, mostly by bees, is necessary for 75% of all crops that are used directly for human food worldwide. 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).

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; Ingram et al., 1996; 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.

IV. SOCIO-ECONOMIC IMPACTS OF CHANGING PEST SCENARIO

Climate change driven changes in populations of insect-pests and resultant crop losses will have serious environmental and socio-economic impacts on rural farmers whose livelihoods depend directly on the agriculture. How the climate mediated pest scenario will affect the farming community are discussed in the following paragraphs.

New and intense pest problems

The growers of crop have to face new and intense pest problems due to spread of insect-pests to new areas along with shift in cultivation areas of their host crops (Rosenzweig *et al.* 2001; Elphinstone and Toth 2008; Petzoldt and Seaman, 2010). Hence, insect management strategies need to be changed in accordance with the projected changes in pest incidence and extent of crop losses in view of the changing climate.

Reduced effectiveness of pest management strategies

Certain effective cultural pest management practices like crop rotation, early/ late planting, etc. will be less or no effective with changed climate because of shrinking of crop growing seasons, colonization of crops by early insect arrival and or increased winter survival (Harrington et al., 2001; Sharma et al., 2005; NACCAP, 2008; Petzoldt and Seaman, 2010). Disruption of synchrony between insect-pests and their natural enemies may upset the natural biological control (Petzoldt and Seaman, 2010). Certain pesticides like pyrethroids, organophosphates and especially the biopesticides being highly thermo-unstable degrade faster at higher temperatures. Altered temperature regimes may render many of these products to be less or no effective in pest control, necessitating frequent insecticide applications for effective control (Musser and Shelton 2005). This may intensify the pest problems due to the increased chances of resistance development in insects. Ultimately it will add to increased cost of crop protection to the farmers and in turn environmental cost. (Musser and Shelton 2005; NACCAP, 2008; Petzoldt and Seaman, 2010). The forewarning models for predicting insect arrival/ infestations based on earlier climate profiles need to be revised in accordance with location specific changes in climate in order to provide precise and accurate forecast of the pest incidence.

Implications for Food Security

The greatest challenge for humanity 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 (Patterson et al., 1999; Gutierrez, 2000; Parry et al., 2004; IPCC, 2007; Chahal et al., 2008). 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 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

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.

V. CHALLENGES 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.

VI. CONCLUSIONS

Climate change now a day is globally acknowledged fact. Considering the declining production efficiency of agro-ecosystems 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 challenging topic 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.

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