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IMPACT OF CLIMATE CHANGE ON INSECT PESTS, PATHOGENS AND THEIR NATURAL ENEMIES

Suseelendra Desai and M. Srinivasa Rao

Central Research Institute for Dryland Agriculture,
Santoshnagar, Hyderabad 500059, Andhra Pradesh, India

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Climate variability and climate change are exerting additional load on developing countries of tropics and subtropics which are already burdened with the increasing demand for food owing to increasing population pressure. Even a small rise in temperature in these areas will cause significant yield decline in major food grain crops. The changing climate not only influences the crop growth and development but is also expected to alter stages and rates of development of the pathogen, modify host resistance, and change in the physiology of host-pathogen interactions. It is expected that the range of many insects, diseases and weeds will expand or change, and new combinations of pests and diseases may emerge when natural ecosystems respond to altered temperature and precipitation profiles. Although, the research in establishing the climate change impacts on pathogens and their natural enemies is at its infancy, independent studies conducted across laboratories world wide could be used to draw inferences. Elevated CO_2 levels are known to increase foliar density which in turn will influence the microclimate of the pathogen, altered host morphology which affects host-pathogen interaction, enhanced sporulation of pathogen, and increased dry-root rot under moisture stress conditions. For instance, an increase in temperature may lead to increased host susceptibility, a new/rapid development of the pathogen, more rapid vector development leading to faster spread of the vector transmitted viral diseases, a variable overwintering/over-summering of the pathogen/vector and shift in spread pattern of the pathogens. Initial studies show an increased sporulation and altered bio-control traits in *Trichoderma*, a known bio-control agent. Efforts are underway at CRIDA and other research organizations to assess climate change impact on important pathogens and their natural enemies. The present paper reviews the interaction of weather variables with different insects, diseases and weeds and the probable threats to food grain production, availability and quality.

Keywords: Climate change, Climate variability, Insect-pests, Natural enemies, Plant pathogens.

INTRODUCTION

The increased temperature, precipitation and atmospheric concentration of greenhouse gases (GHG) such as carbon dioxide, methane *etc.* are the major drivers of climate change. During the past 100 years global average surface temperatures has increased by approximately 0.6 ^{0}C (Houghton *et al*. 2001). The third IPCC report predicts that the global average surface temperature will increase further by 1.4-5.8 ^{0}C by 2100 with increase in atmospheric carbon dioxide (CO_2) from 540 to 970 ppm over the same period. Atmospheric CO_2 concentration and tem-

Correspondence: Suseelendra Desai (Email: desai1959@yahoo.com)

perature have both been rising very significantly since three decades and the effects are being experienced across all sectors in agriculture. These changes affect the growth and development of crop plants.

Evaluation of Had CM3 model projections with measured mean monthly and annual rainfall data has been attempted here. The projection data of rainfall for the year 2020 was taken from the output of Had CM3 model projections at various grid points and assumed that the projections follow a linear trend from 1990 to 2020 and calculated the values of year 2005 using rain gauge stations located at or nearby grid points. The spatial distribution of probability of occurrence of mild, moderate and severe droughts at national level indicate that major part of the country may experience 3 to 4 drought years in every ten years. An increasing trend in maximum temperature was noticed in 9 out of 12 stations (75%) in south zone followed by central (67%), east (60%) and west zones (57%). Minimum temperature showed increasing trend in 88 per cent of stations in central and east zones followed by north zone (80%), south zone (75%) and the least in west zone (57%). Decreasing trend in minimum temperature was seen in 29 per cent of stations in the west zone followed by 20 per cent and 8 per cent in north and south zones, respectively. Mean annual temperature trends from 47 locations spread across the country indicated increasing trend in the central and southern parts and NE regions.

The interactions among host plant, pathogen and congenial weather over a period of time results in plant diseases. The interactions are significant from epidemiology point of view as they will decide the fate of the farmers either in terms of bountiful harvests or total crop loss. Weather has almost one-third influence on disease development and at the same time it is not uniform across all agro-climatic locations. The agricultural production systems in the recent years is constantly threatened by sudden outbreak of disease epidemics. In the conventional agricultural system, crops, their pathogens and natural enemies have established a harmony and hence, equilibrium was established through a natural evolution process over decades. This equilibrium helped in stabilizing the crop losses and thus sustaining the production system. However, increasing pressure on agricultural commodities has demanded increased productivity and thereby disturbing the equilibrium.

Insect-pests are known to inflict huge crop loss. While lepidopteran pests are known to cause damage to plant parts by feeding on them, sucking pests cause not only physical damage to plants but also transmit viral diseases as vectors. Muralidharan and Pasalu (2006) reported that projected damage due to 1% dead heart caused by yellow stem borer *Scirpophaga incertulas* over rice ecosystems as 6.4% yield loss. Pod borer in pigeon pea caused yield loss of 14-100% (Nath *et al*. 1977). Among oil seed crops, it is estimated that capitulum borer *Helicoverpa armigera* in sunflower caused 30-60% damage (Dhaliwal and Arora, 1994) and in castor, *Achoea janata* caused damage upto 30-50% and that of *Spodoptera litura* was 25-40% (Rao *et al*. 2009). In vegetables (tomato and brinjal), fruit borers (*Helicoverpa armigera and Spodoptera litura)* put up a loss ranging from 15-46% (Singh, 1991; Kulkarni and Shekharappa, 2001). Babu and Azam (1989) reported that grape vine mealy bugs caused the damage resulting in 90% yield loss.

Trichoderma is one of the most-exploited bio-control agents and is widely distributed across most agro-ecological niches. The other bio-control agents that have been successfully commercialized include species of *Pseudomonas, Bacillus etc.* Among entomopathogens, *Bacillus thuringiensis, Nomuraea rileyi, Verticillium lecanii, Beauveria bassiana, Metarrhizium anisopliae* and *Paecilomyces fumosoroseus* are often reported across crop production systems. *Trichoderma* was frequently isolated from four soil types under different plant cover from Chambal ravines of Bhind in Madhya Pradesh and a significant positive correlation was noted between fungal population and carbon and nitrogen contents of soils, whereas clay content and exchangeable calcium in the soil exhibited a significant negative relationship (Joshi and Chauhan, 1982).

The ability of *Trichoderma* sp. to colonize pine or maple litter differed with temperatures (Widden and Hsu, 1987). Generally *T. polysporum* and *T. viride* competed most effectively at low temperatures (5-15 ^{0}C) whereas *T. hamatum,* and *T. koningii* competed best at higher temperatures (20-25 ^{0}C). Thirteen species of *Trichoderma* were isolated from paddy fallows and populations in 90% of the samples ranged from 0.5 to 8.5x10^3 CFU/g of soil (Nagamani and Mew, 1987). Seasonal variability in *T. harzianum* in soil profiles was significant with no regular pattern (Eastburn and Butler, 1988). However, it was positively associated with the presence of bacteria and selected fungal species. There was a vide variation in distribution of microfungi in Turkey, at different altitudes of which *Trichoderma* formed 9.6% of the population (Karaoglu and Ulker, 2000). Similar variation in distribution pattern of *Trichoderma* was reported across North (Hebei) and South-West (Yunnan) areas of China (Zhang *et al*. 2005). *Pseudomonas* and *Bacillus* can tolerate a wide range of physical conditions and were isolated from soil, marshes, coastal marine habitats, and from plant and animal tissues. Boehm *et al.* (1993) found that the organic matter decomposition significantly influenced the composition of bacterial species in the rhizosphere. *Pseudomonas* spp. capable of suppressing *Pythium* damping-off predominated in the suppressive mix while in conducive mix *Bacillus* spp. predominated. Although effective bacterial bio-control agents were isolated from both the suppressive and conducive mixes, majority were isolated from the less decomposed suppressive mixes. Arbuscular mycorrhizae (AM) fungi not only protect plants from biotic stresses but also establish in heavy metal contaminated soils and act as a biological barrier in transport of toxic metals to shoots (Gaur and Adholeya, 2004). AM inoculation in tobacco (*Nicotiana tobaccum*) significantly decreased cadmium concentrations of plants grown in acidic soils (Janouskova *et. al*, 2007). The tripartite symbiosis could help plants produce better biomass and root-shoot ratios under high concentrations of cadmium and zinc as compared to the control plants. Similarly, Rabie and Almadini (2005) reported enhanced salinity tolerance by *Vicia faba* inoculated with AM fungi. Eighty nine species of AM fungi from six genera were detected in the iron stressed soils of Bailadila iron ore project in Baster region of Chattisgarh and the AM dependence of the host species was related to the establishment of the vegetation under metallotoxic conditions (Sastry and Johri, 1999).

Climate change and plant pathogens

Climate change and climate variability are a concern for the present as well as future as it can potentially disrupt natural and social systems even as an accelerated trend in the climate change was observed for the last 30 years (Osborn and Briffa, 2006). Rising carbon dioxide concentration in the atmosphere will increase the carbon-to-nitrogen balance in plants, which in turn will affect insect feeding, concentrations of defensive chemicals in plants, compensation responses by plants to insect herbivory, and competition between pest species (Coviella and Trumble 1999). Changes in greenhouse gas concentrations are anticipated to impact agro-ecosystems, there by altering crop and their pest dynamics *per se*. These variations in turn will be affecting the crop pest interactions.

Environmental pollution has become an additional variable to be reckoned with which have impacts on all biological systems. The elevated CO_2 levels coupled with increasing temperatures do affect host-pathogen interactions. A few of the examples include the spread of coffee leaf rust throughout the world, soybean rust into Latin America and citrus tristeza virus in South and Central America and in the Mediterranean. Climate change will result in a higher unpredictability, therefore, is likely to cause additional crises in local agricultural production, in particular for small farmers and those dependent on subsistence agriculture (FAO, 2008).

a. Elevated CO_2 and host-pathogen interactions

Under elevated CO_2 levels, the morpho-physiology of the crop plants is significantly influenced. The available data clearly suggests that CO_2 enrichment asserts its greatest positive influence on infected plants compared to healthy ones. This influence in turn will modulate the balance of co-evolution between the host and the pathogen as well as pathogen and bio-control agent. Elevated carbon dioxide (ECO_2) and associated climate change have the potential to accelerate plant pathogen evolution, which may, in turn, affect virulence. Plant-pathogen interactions under increasing CO_2 concentrations have the potential to disrupt both agricultural and natural systems severely, but, lack of experimental data and future predictability act as a handicap. Furthermore, nothing is known about the mechanistic bases of increasing pathogen aggressiveness. Under ECO_2 conditions, mobilization of resources into host resistance through various mechanisms such as reduced stomatal density and conductance, (Hibberd *et al*., 1996a, 1996b); greater accumulation of carbohydrates in leaves; more waxes, extra layers of epidermal cells and increased fibre content (Owensby, 1994); production of papillae and accumulation of silicon at penetration sites (Hibberd *et al*., 1996a); greater number of mesophyll cells (Bowes, 1993); and increased biosynthesis of phenolics (Hartley *et al*., 2000), increased tannin content (Parsons *et al*., 2003) have been reported.

Malmstrom and Field (1997) reported that CO_2 enrichment in oats may reduce yield loss in drought affected plants and enable yellow dwarf diseased plants to compete better with healthy neighbors. On the contrary, in tomato, the yields were at par (Jwa and Walling, 2001). Tiedemann and Firsching (2000) reported yield enhancement in spring wheat infected with rust when incubated under ECO_2 and ozone conditions.

Chakraborty and Datta (2003) reported loss of aggressiveness of *Colletotrichum gloeosporioides* on *Stylosanthes scabra* over 25 infection cycles under ECO_2 conditions. On the contrary, pathogen fecundity increased due to altered canopy environment. McElrone *et al*. (2005) found that growth rates of *Phyllosticta minima* were 17% greater under ECO_2. In the host *Acer rubrum*, the infection process was hampered due to reduction in stomatal conductance by 21-36% and thereby leading to smaller openings for infecting germ tubes and altered leaf chemistry. Reduced incidence of potato virus Y on tobacco (Matros *et al*. 2006), enhanced glyocellin accumulation (phytoalexins) after elicitation with ß-glucan in soybeans against stem canker (Braga *et al*., 2006) and reduced leafspot in stiff goldenrod due to reduced leaf nitrogen content that imparted resistance (Strengbom and Reich, 2006) have been reported. Lake and Wade (2009) have shown that *Erysiphe cichoracearum* aggressiveness increased under elevated CO_2, together with changes in the leaf epidermal characteristics of the model plant *Arabidopsis thaliana*. Stomatal density, guard cell length, and trichome numbers on leaves developing post-infection increased under ECO_2 in direct contrast to non-infected responses. As many plant pathogens utilize epidermal features for successful infection, these responses provide a positive feedback mechanism facilitating an enhanced susceptibility of newly developed leaves to further pathogen attack. Furthermore, screening of resistant and susceptible ecotypes suggests inherent differences in epidermal responses to elevated CO_2. Gamper *et al*. (2004) noted that colonization levels of arbuscular mycorrhizae tended to be high on *Lolium perenne* and *Trifolium repens* grown under ECO_2 which may help in increased protection against stresses.

b. Impacts of changes in temperature and rainfall intensity

Under low moisture and high temperatures, organisms such as *Macrophomina phaseolina* that cause dry root rot may cause severe yield loss. Under low temperature and high humidity conditions, *Pythium* and *Phytophthora* could be of serious concern for many field crops (Boehm *et al*., 1993). In pigeon pea, it was observed that during high rainfall years, intensity of *Phytophthora* blight was very severe (Garrot *et al*., 2006). In sugar beet, humid conditions favoured *Cercospora* and *Ramularia* significantly. Low temperature and high humidity may also promote wilt pathogens. Excessive irrigation, which can be compared to frequent and high intensity rainfall effects, led to increased intensity of sugar beet leaf and crown wart. It is also presumed that *Rhizomania* virus, a major concern for sugar beet crop in the Europe, has spread due to irrigation, which can be equated with excess moisture conditions, because *Polymyxa betae* (a soil borne fungus), which is the vector for the beet necrotic yellow vein mosaic virus, prefers wet conditions. On the other hand, *Pleospora betae* causing blackleg was highest under drought conditions. Differential response of wheat leaf rust resistance genes was noticed at different temperatures (Tiedemann and Firsching, 2000). Minor or unknown pathogens may also become more aggressive such as Alternaria blight of pigeon pea. Meaningful scenarios could be arrived at through a holistic analysis of response of host-pathogen-bio-control system to the changing climate scenarios. Increasing temperature coupled with increasing moisture will favour the proliferation of *Ralstonia*, the causal agent of bacterial wilt across different crop species. The pathogen which is already playing havoc in South East Asia could be a threat to groundnut in India, where it is hitherto unknown.

Alternaria spp. and powdery mildew could be a major concern for various crops. Fungal species causing powdery mildews prefer dry and cool weather. In recent years, extended cloudy weather often prevails during crop season and these conditions are congenial for powdery mildew (Lake and wade, 2009). It has been observed that *Alternaria*, hitherto known as a minor pathogen in pigeon pea, could become a major disease in the years to come. Similarly, *Alternaria alternata* that causes leaf spot in many crops like groundnut, potato, cotton and castor becomes severe during long and hot dry spells. The fungus has been reported to sporulate three times more on plants cultivated under elevated CO_2 conditions. This increased spore density is not only harmful to the crops, but directly affects human being as an allergen also. In recent years, increased occurrence of Alternaria leaf spot has been observed in groundnut. Rice plants grown in an elevated CO_2 concentration were more susceptible to leaf blast than those in ambient CO_2 as indicated by the increased number of leaf blast lesions. Higher number of tillers observed under elevated CO_2 concentrations might increase the chance for sclerotia of *Rhizoctonia solani* to adhere to the leaf sheath at the water surface. Consequently, the potential risks for infection of leaf blast and epidemics of sheath blight would increase in rice grown under elevated CO_2 concentration.

Hannukkala *et al.* (2007) reported increased and early occurrence of late blight of potato epidemic in Finland due to climate change and lack of crop rotation. One of the direct consequences of climate change in the host-pathogen relationship is the genetic resistance of plants to diseases. ECO_2 conditions are known to alter host physiology and biochemistry which will have an impact on the host-pathogen interactions (McElrone *et al.*, 2005). It is possible that the genes imparting resistance in host may respond differentially. Though ECO_2 effects on host may give beneficial effects, the impacts on pathogen cycles in terms of increased spore production capacity and faster multiplication rates may nullify these positive effects. Though there will be a delay in initial infection and reduction in host penetration, post-establishment fast growth of pathogen in the host may result in increased disease intensity. Under drought stress, the disease symptoms may be reduced but at the same time the resistance of the host can also be modified leading to higher disease incidence. Drought affected disease resistant plant types showed loss of resistance. Some pathogens could also enhance their ability to exhibit variability with which their fitness to the changed environment is enabled.

Limited studies have been conducted on effects of climate change on natural enemies. Warwick (2001) demonstrated that the rainfall regime and time of application of *Acremonium vittelinum* and *A. persicinum* for the control of the tar spot of coconut caused by *Catacauma torrendiella* and *C. palmicola* are crucial. Studies in this area will be important for understanding the interactions between host-pathogen-bio-control interactions. The outcomes of such studies will be helpful to draw meaningful conclusions in a holistic system approach. Such studies will also help in appropriate deployment of bio-control agents either by encouraging natural populations to develop or through introduction of better strains.

Effect of climate change on plant disease biological control is a complex issue and is currently based on indirect observations. Nevertheless, the vulnerability of bio-control agents will surely be higher with climate change, since this is one of the problems when applying antagonists (Garrett *et al*., 2006). Ghini and Bettiol (2008) reported that, in general, climate change may benefit natural as well as introduced biological control agents as more emphasis is being laid on development of eco-friendly disease management strategies compared to development of new fungicide molecules to reduce environmental pollution. The energy requirement for production of a unit of bio-control agents is far less than that is required for production of one unit formulated chemical molecule. Rezácová *et al*. (2005) observed that under free air carbondioxide enrichment (FACE) conditions, *Chlonostachys rosea*, a biological control agent of *Botrytis*, and *Metarrhizium anisopliae*, an important entomopathogen, were strongly associated with the cover crop in a high CO_2 concentration environment. The abundance of these fungi has been attributed to increased soil suppressiveness to phytopathogenic fungi.

Climate change and insect pests

Insects are cold-blooded organisms *i.e.* their body temperature is almost the same as that of the environment. Therefore, temperature is probably the single most important environmental factor influencing insect behaviour, distribution, development, survival and reproduction.

a. Increased temperature and insect pests

Increased temperatures can potentially affect insect survival, development, geographic range and population size. Temperature can impact insect physiology and development directly or indirectly through the physiology or existence of hosts. Depending on the development "strategy" of an insect species, temperature can exert different effects (Bale *et al*., 2002). Increased temperatures will accelerate the development of these types of insects –(cabbage maggot, onion maggot, European corn borer, Colorado potato beetle etc.) – possibly resulting in more generations (and crop damage) per year. In addition to the above observations some more predictions and generalizations were made by several researchers (Bale *et al*., 2002; Rao *et al*., 2008a). Increased temperature influenced the larval development and fecundity of *Operophtera brumata* and long term exposure to increased temperature shortened the insect development. Temperature enhancement increased the relative growth rate of chrysomelid beetles. Increased temperatures can potentially affect insect survival, development and population size. Insects proliferate more readily in warmer climate, as conditions for growth and multiplication is more favorable. Warmer winter temperatures may allow larvae to survive the winter whern they are limited by the cold. Thus, incidence of insect pests will be more in areas with increased temperature conditions.

Because of warm winter and spring, many aphid species started their spring migration much earlier than 'normal' and the peach-potato aphid (*Myzus persicae*), in particular, has been captured in unprecedented numbers in the traps.

The rate at which most pests develop is dependent on temperature and every species has a particular 'threshold temperature' above which development can occur, and below which development ceases. As temperature rises, some pest species may be able to complete more generations in a year. This effect may be most noticeable in insects with short life-cycles such as aphids and the diamond-back moth. On the other hand, the temporary exposure of populations to extremely high temperatures may delay the development of surviving individuals and thus delay the subsequent generation. Climate change may affect our ability to control pests. For example, high temperature is reported to reduce the effectiveness of some pesticides. If pests are able to complete more generations in a season then this may lead to greater pesticide use.

b. Elevated CO_2 levels and insects

Generally CO_2 impacts on insects are thought to be indirect from changes in the host crop. Studies have shown that rising CO_2 can potentially have important effects on insect pest problems. Recently, FACE and open top chamber (OTC) technologies were used to create an atmosphere with CO_2 concentrations similar to what climate change models predict for the middle of the 21st century. Researchers observed that insects sometimes feed more on ECO_2 grown with leaves lowered nitrogen content in order to obtain sufficient nitrogen for their metabolism (Coviella and Trumble, 1999; Hunter, 2001). Increased carbon to nitrogen ratios in plant tissue resulting from increased CO_2 levels may slow insect development and increase the length of life stages vulnerable to attack by parasitoids (Coviella and Trumble, 1999). Atmospheric CO_2 concentrations have increased by above 20% and elevated CO_2 affects the plant growth and range of physical and chemical characteristics of the plant/crop. These include reduction in the leaf nitrogen content, changes in the defense compounds, water and carbohydrates contents and leaf thickness. Indications are that exposure to elevated CO_2 levels will increase plant photosynthesis, growth, above ground biomass, leaf area, yield and C:N ratio. Information on effect of elevated CO_2 on insect pests has been compiled and presented by Rao *et al.* (2008a).

Interestingly, climate changes have important implications on transgenic insect-resistant plants like cotton and corn. The *Bacillus thuringiensis* (Bt) toxins are nitrogen-based defenses that have a major impact on several common insect pests. Chen *et al*. (2005) showed growing transgenic plants in elevated carbon dioxide resulted in a nearly 25% reduction in the expression of these proteins. This reduction allowed some lepidopteran larvae (*H. armigera*, *Spodoptera exigua*) to survive on these plants, which would likely lead to the rapid selection of pest populations resistant to these proteins. Again, growers can overcome this effect by adding additional nitrogen. Though, nitrogen supplementation could be a possible solution, it will once again add to environmental pollution. The toxic effect of *Bt* in cotton leaves was diluted when plants were grown under elevated CO_2 conditions as evidenced by increased larval survival of *Helicoverpa armigera* (Rao *et al*., 2008b).

Climate change impacts on pests and plant pathogens: Indian initiative

Under the Indian Council of Agricultural Research funded national network project entitled 'Impacts, Adaptation and Vulnerability of Indian Agriculture to Climate Change', research has been initiated to study impacts of climate change and climate variability on plant pathogens and beneficial microbes. Under this umbrella project, studies are being conducted to understand the impacts of elevated CO_2 and temperature on major soil-borne plant pathogens *viz. Sclerotium rolfsii*, *Macrophomina phaseolina*, *Fusarium oxysporum* f.sp. *ricini*, *Botrytis ricini* and *Rhizoctonia solani*. Similarly, impact studies are also being conducted on *Pseudomonas* and *Trichoderma* isolates which are commonly used as bio-control agents. The focus on pathogens is on variability in pathogencity and morho-physiological changes over generations. In bio-control agents, thrust is being laid on bio-control ability, plant growth promoting traits and morpho-physiological parameters such as growth, sporulation and enzyme production patterns. So far, it has been observed that after exposure for 30 generations, sporulation increased and chitinase production enhanced in *Trichoderma* considerably. The strains of *Pseudomonas* differed for their plant growth promoting traits. Studies are in progress regarding pathogenicity of the test organisms on their respective hosts.

Feeding trials conducted at CRIDA indicated that growth of *H. armigera* fed on *Bt (Cry 1 A (c))* and Non *Bt* cotton under elevated CO_2 affected the larval parameters significantly. Larvae of *H. armigera* consumed more elevated CO_2 foliage of both *Bt* and non *Bt* plants than ambient CO_2 foliage. In both the conditions, larvae consumed more non *Bt* cotton foliage than the *Bt* cotton grown foliage. Studies were also done using OTCs to study the impact of elevated CO_2 levels on insects. An automatic CO_2 enrichment technology was developed using a software SCADA to accurately maintain the desired levels of CO_2 inside the OTCs. The concentration of CO_2 in the chambers was monitored by a non-dispersive infrared gas analyzer. Castor and groundnut plants were grown in these OTCs by maintaining CO_2 at 700±25 ppm and 550±25 ppm. Various experimental trials were conducted using the foliage from these crops to understand the insect-behaviour. The results are summarized below:

- Larval duration of *Spodoptera litura* and *Achaea janata* was increased by about two days when fed with foliage grown under elevated CO_2 conditions.
- *A. janata* consumed 62.6% more of foliage grown at 700 ppm CO_2 foliage than control. The rate of consumption was higher for larvae fed with elevated CO_2 foliage each day resulting in increased ingestion.
- Final larval weights were higher with elevated CO_2 foliage, but differences in larval weight were not as marked as found in the amount of leaf ingested.
- Larval growth rates were significantly lower with elevated CO_2 foliage in case of *A. janata*, while in case of *S. litura*, the differences were not significant (Rao *et al.*, 2009).
- While the conversion efficiency of ingested food into body mass was lower in *A. janata*, it was not significant in *S. litura*.

CONCLUSION

The tri-trophic interactions *i.e.* host-pest-natural enemy or host-pathogen-natural enemy are considerably influenced by climate variability and climate change. While each of these organisms are independently affected by changing weather parameters, the net result on crop production systems will be the interaction among these organisms which is a sum of positive and negative impacts. A process-based approach to quantify the impact on pathogen/disease cycle is the most useful in defining the impact of elevated CO_2 on plant diseases. The projections for the future depict that appropriate adaptation and mitigation strategies should be developed to meet worst possible scenarios. Suitable adaptation strategies need to be developed to reduce the negative impacts. The research efforts therefore must be focused on;

a. Understanding the tri-trophic interactions

b. Understand host-pest-pathogen dynamics

c. Disease epidemiology

d. Relationship of weather components on insectpests, pathogens and natural enemies through simulation modeling and real-time ground-truthing

e. Increasing awareness about climate change impacts among farmers

f. Practices adopted by farmers to overcome climate change impacts

g. Development of suitable policy framework to promote R&D and develop adaptation strategies.

For assessing the impacts of climate change on pest occurrence, simulation models used for pest forecasting can form the basis to simulate spatial and temporal distribution of pathogens using future climate scenarios as inputs. For vector-transmitted pathogens, the risk analysis will also include behaviour of the vector population as discussed by Harrington (2002) for the barley yellow dwarf disease. In view of these opposing changes in pathogen behavior at elevated levels of atmospheric CO_2, it is difficult to know the ultimate outcome of atmospheric CO_2 enrichment for this specific pathogen-host relationship. More research, especially under realistic field conditions, will be needed to clarify the situation. Similarly, the relationship between bio-control agents and the pathogens need to be studied in relation to enhanced CO_2 to assimilate the ultimate effects for different climatic conditions.

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