

IMPACT OF ELEVATED CO₂ AND TEMPERATURE ON APHIDS - A REVIEW

M. SRINIVASA RAO*¹, O. SHAILA¹, B. ABDUL KHADAR¹, D. MANI MANJARI¹, S. VENNILA², M. VANAJA¹ AND CH. SRINIVASA RAO¹

¹Central Research Institute for Dryland Agriculture, Hyderabad - 500 059, INDIA

²National Research Centre for Integrated Pest Management, New Delhi - 110 001, INDIA

e-mail: msrao909@gmail.com

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*Corresponding author

ABSTRACT

Climate change manifested as increase in atmospheric carbon dioxide and temperature has impact on agriculture including insect pests that reduce crop yields. Species of aphids are diverse and ubiquitous but their importance among crops differs. The present publication reviews 80 studies on impact of elevated CO₂ and temperature (eCO₂ and etemp) on several species of aphids of various crops. 25 out of 30 studies on variation of development time (DT), reported the reduction of DT with increased fecundity at eCO₂ and etemp. Significant variations of life table parameters viz., increase in intrinsic rate of increase (r_m), net reproductive rate (R₀) and finite rate of increase (λ) with reduced generation time (GT) under eCO₂ and etemp conditions indicate the significant role of host plants. The indirect and direct effects of eCO₂ and etemp on growth and development of aphids reveal complex effects of temperature and CO₂ on plant-aphid interactions which in turn indicate specificity associated with aphid species and host plants. Impact studies of climate change on tri-trophic interactions are meager, however evidences of positive and negative influences exist. Continuous vigilance is needed on the climate change effects on the viruses transmitted by the aphids than on their direct damage.

INTRODUCTION

Climatic models predict 1.7-4.9°C increase in mean global temperature from 1990 to 2100. The increase in temperature between the periods of 1850 -1990 and 2003 - 2012 is 0.78 (0.72 to 0.85) °C. The increase in the amount of atmospheric CO₂ will be about 40% compared with pre-industrial levels of 280 ppm (IPCC, 2013). Climatic variability together with increase in atmospheric carbon dioxide and temperature have lot of implications in agriculture sector. The impact of climate change on agriculture could result in problems of food and livelihood securities of much of the agrarian population. Climate change can affect crop yields (both positively and negatively) and alter the type of crops that can be grown in certain areas by impacting natural resources such as water for irrigation and amount of solar radiation that affect plant growth besides influencing the prevalence of pests on crops.

Elevated atmospheric CO₂ (eCO₂) concentration influences the crop growth by altering photosynthesis (Norby *et al.*, 1999; Stitt and Krapp 1999; Ainsworth and Long, 2005), shoot root ratio (Rogers *et al.*, 1996; Madhu and Hatfield, 2013), leaf area (Sun *et al.*, 2013), biomass (Prasad *et al.*, 2005; Gregory *et al.*, 2009), stomatal conductivity (Bunce, 2004), C:N ratio (Hughes and Bazzaz, 1997; Hunter, 2001; Gutierrez *et al.*, 2008), increased carbon (Gutierrez *et al.*, 2008) and decreased nitrogen (Dixon *et al.*, 1993). Changes in plant N concentration, and C: N ratio affects the quality and quantity of food available to insect herbivores (Chen *et al.*, 2007). The effect of eCO₂ is decrease in host plant quality, particularly through increases in C:N ratio (Bezemer and Jones, 1998;

Coviella and Trumble, 1999; Hunter, 2001) and such reductions in plant quality have been shown to increase insect feeding rates to compensate for nutritional deficiencies (Hughes and Bazzaz, 1997).

Elevated atmospheric CO₂ levels have negative impacts on the performance of insect herbivores, in general often termed as host mediated or indirect effects. Reduced food quality leads to an increase in crop damage when herbivore insects prefer to have compensatory feeding by consuming more quantity of plant tissues (Coll and Hughes, 2008). Individual insect species responses to eCO₂ vary: consumption rates of insect herbivores increase although this does not necessarily compensate fully for reduced leaf nitrogen. Majority of experimental findings under eCO₂ suggested that aphids can proliferate in a huge number and become more serious to cause significant damage in crop plants (Cannon, 1998). Aphid responses to eCO₂ tested frequently have been "species-specific" and are negative or positive or neutral (Bezemer and Jones, 1998 and Hughes and Bazzaz, 2001).

Increase in atmospheric temperature resulted in reduction in survival and increase in developmental rate, resulting in more generations and thus more crop damage per year. Fewer studies show that warmer areas would be favorable for growth in insect populations that insect species would undergo rapid population growth through higher reproduction rates due to higher metabolic rates. Most of the studies indicate insect pests becoming more abundant with elevated temperatures through a number of inter-related processes such as range extensions and phenological changes, as well as increased

rates of population development, growth, migration and overwintering (Forno and Bourne, 1986), but can also facilitate success by shifting the geographic ranges in which plants and insects experience suitable thermal minima and maxima (Lu *et al.*, 2013; Allen *et al.*, 2013). Temperature is the most important abiotic factor affecting development and reproduction of aphids although geographically separated populations of aphids may differ in their response to temperature (Campbell *et al.*, 1974). Temperature influences both aphid development and mortality rates (Summers *et al.*, 1984) and the knowledge of the effects of temperature on various parameters of aphids is essential to investigate aphid population dynamics.

Increase in temperature and elevated CO₂ (eCO₂) significantly influence the crop growth and in turn affect the insect herbivores both directly and indirectly. Knowledge of the insect response to changes in the environmental variables can provide valuable information for pest management and chemical applications. It is well known that deleterious effects on insect performance (oviposition rate, mortality, growth and developmental time) would be at reduced temperatures. Effects of temperature and CO₂ on insect performance can be direct by changing insects behavior or indirect by changing the host nutritional quality resulting in changes of feeding behavior (Stiling and Cornelissen, 2007). Though it is known that the increase in temperature will have a greater effect on insects than the rising CO₂ concentration (Harrington *et al.*, 2001), the interactive and combinational effect of both parameters is more evident. The complex effects of temperature and CO₂ on plant–aphid interactions based on modelling which predicts aphid populations will be most likely to respond positively to enhanced CO₂ if their N requirements are low and they are insensitive to crowding (Newman *et al.*, 2003). Greater understanding of these dynamics will be essential for understanding plant responses to future climate conditions. Two key variables, eCO₂ and etemp influence plant–insect interactions (Robinson *et al.*, 2012; Stiling and Cornelissen, 2007).

Impacts of eCO₂ and etemp

It is well known that the impact of eCO₂ on insect herbivore and host crop interactions is significant and mostly of host mediated in nature. The meta-analysis of published information (Srinivasa Rao *et al.*, 2012 & Robinson *et al.*, 2012) on impact studies including majority of insect parameters designated that influence was substantial (Coviella and Trumble, 1999) and indirect (Hunter, 2001). The eCO₂ influences homopteran insect pests differently (Williams *et al.*, 2003) than that of lepidopterans (Holopainen and Peltonen, 2002; Srinivasa Rao *et al.*, 2014). Earlier reviews by Newman *et al.*, 2003 showed that homopteran insect pests are positively influenced by eCO₂. The information on various aphid parameters *viz.*, development time, fecundity and total life cycle which are measured to understand the change in growth and development of aphids under eCO₂ and etemp conditions was examined and the summary of findings was reviewed and presented here under

Development time (DT)

In case of phloem-sucking insects *i.e.*, aphids development time is considered as time duration between small nymph to

late age nymph stage though different authors have used terms like nymphal period, nymphal duration and developmental duration.

Impact of eCO₂

Aphids have species-specific responses to eCO₂ and are the only feeding guild to respond positively to eCO₂. In majority of studies reduction or shortened development time of aphids under eCO₂ was mentioned. Aphids are able to overcome the disadvantages of the indirect effects of eCO₂ by reducing development times (DT) under eCO₂ conditions (Smith, 1996; Xing *et al.*, 2003; Sun and Ge, 2011 and Alireza *et al.*, 2012,) *viz.*, *A. gossypii* in cotton, (Gao *et al.*, 2008). The reduction of DT also varied among different instars of aphids. The eCO₂ reduced only the development time (DT) of *Rhopalosiphum maidis* on barley fourth-instar nymph (Xie *et al.*, 2014). A few studies also showed that increased development time or no effect on aphids (Awmack *et al.*, 1996; Zhang *et al.*, 2003) though these are species and age specific. The implication of reduction of DT indicates that increase in aphid performance could lead to larger populations of aphids in a future eCO₂ environment and same was reported (Awmack *et al.*, 1997). It is understood that major source of variation in development time of aphids is due to host plants used as food source and the impact of eCO₂ is indirect and mainly attributed to less N availability (Coviella and Trumble, 1999; Hunter, 2001).

Impact of etemp

Majority of studies on impact of etemp on growth and development of insects including Homopterans showed that the direct effect of temperature is greater than that of eCO₂ (Finlay and Luck, 2011). Temperature and food quality are important factors which determine the DT of aphids. Aphids are physiologically sensitive to temperature and their development rate highly responsive to change in temperatures (Lange *et al.*, 2006). The shortened (Dean, 1974; Aalbersberg *et al.*, 1987; Van Steenis and Khawass, 1995; Ma *et al.*, 2004; Graf, 2006; Auad *et al.*, 2009; Mohammad, 2010; Aleosfoor and Fekrat, 2014; Xie *et al.*, 2014) and prolonged (Sheng and Hughes, 1987; Kieckhefer *et al.*, 1989; Islam and Chapman, 2001; Satar *et al.*, 2005; Mehrparvar and Hatami, 2007;) DT of aphids at increased temperature conditions was obvious. Some studies also mentioned the divergent response of aphids to etemp indicating the reduction of developmental rate and with extended DT and higher development rate with reduced DT (Hirano *et al.*, 1996). The development rates of *Drepanosiphum acerinum*, *D. platanoides* over a range of temperatures (6–20°C) were the same but in case of *Drepanosiphum acerinum* significantly higher growth rate was at high temperatures showing the species specificity (Wellings, 1981).

Interactive effects eCO₂ and etemp

Only a few studies are available on the impact of eCO₂ and etemp concurrently on aphid population. The interactive effect of these two factors is complex and confounding in nature and in some cases the temperature is found as dominant factor while in other cases the influence of eCO₂ is also found to be very significant and mostly species specific (Sun and Ge, 2011). The developmental duration varied with the stage of instars

and same was noted by Xie *et al.*, 2014 specifying that DT of fourth-instar nymph was reduced at etemp of 4°C and 700-750 l/liter of eCO₂ which in turn reduced the overall duration of nymphal stages of corn leaf aphid, *Rhopalosiphum maidis*. Shorter DT with rising temperatures of *Rhopalosiphum padi* and contradictory response to eCO₂ were observed by Finlay and Luck, 2011. A generalist aphid species, *Myzus persicae* responded directly to etemp with reduced DT where as Brassicae specialist, *Brevicoryne brassicae* was less affected (Himanen *et al.*, 2008).

Succinctly the information on interactive effect eCO₂ and etemp on DT of aphids specified the reduction or shortening of development time at both eCO₂ and etemp conditions though the effects are found to be species specific and host crop dependent. The reduction of DT indicates the shortening of nymphal duration of aphids and thus development of matured adults will be faster at eCO₂ and etemp conditions.

Fecundity

The published information on impact of eCO₂ on progeny production of sap sucking insects shows that aphids are the only insect herbivores that show positive responses to eCO₂ (Sudderth *et al.*, 2005). The reduction of DT with increased fecundity of aphids was opined by several authors under eCO₂ and etemp conditions designating the major apprehension of climate change scenarios that more abundant population will attack the crops (Awmack *et al.*, 1997).

Impact of eCO₂

Increased fecundity of aphids was noted though it is found to be species and host specific and in some cases the reduction of progeny production. It is more likely that phloem-sucking insects (aphids) are able to overcome the disadvantages of the indirect effects of eCO₂ by increasing fecundity under eCO₂ conditions (Sun and Ge, 2011). Awmack *et al.*, (1996 and 1997) proved that aphids (*Sitobion avenae*) started reproducing earlier and the fecundity was higher at eCO₂. The daily rate of production of nymphs (*Aulacorthum Solani*) was increased by 16% on beans while the rate of production was not affected on Tansy showing the host specificity. This increase in aphid performance could lead to larger populations of aphids in a future eCO₂ environment.

The fecundity of *Rhopalosiphum padi* under eCO₂ was far larger than the one under aCO₂ (David and Mark, 2002; Zhang *et al.*, 2003). Similar response of increased fecundity was noticed in case of *R. padi* on rice (Zhang *et al.*, 2003), *A. gossypii*, on cotton (Chen *et al.*, 2005), *M. persicae* on wheat and rapeseed (Oehme *et al.*, 2011) and *A. craccivora* on cowpea (Srinivasa Rao *et al.*, 2013). Elevated future CO₂ concentrations will enhance aphid population outbreaks (Alireza *et al.*, 2012) as a consequence of increased fecundity (Awmack *et al.*, 1996) longer settling times (Smith, 1996). The direct effect of CO₂ on aphid population parameters was negligible, although adult fecundity tended to increase (Alireza *et al.*, 2012). Consistency was not noticed with respect to the reduction of fecundity of aphids under eCO₂ conditions. Docherty *et al.* (1997) reported reduced fecundity of *Phyllaphis fagi* on beech and sycamore saplings, and possibly other plants as well.

Divergent trends were not uncommon between two aphids

viz., *Brevicoryne brassicae* reared on cabbage produced significantly reduced offspring at eCO₂, whereas increased trend for *M. persicae* on the same host and no response on *Senecio vulgaris* (Bezemer *et al.*, 1999). Similar different responses were noticed by Awmack *et al.*, 2004 with *Ceppegillettea betulaefoliae* and Awmack *et al.*, 1997 with potato aphid, *Aulacorthum solani*.

Impact of etemp

The direct effect of etemp on insects by altering their development, survival, range, and abundance was well known (Bale *et al.*, 2002). The association of progeny production of aphids with increase in temperature follows the non-linear trend and after certain level of temperature the reduction of progeny is noticed. The fecundity of corn leaf aphid was significantly increased under the etemp (Xie *et al.*, 2014). While the fecundity increased from 11.38 to 28.88 with increase in temperature from 15°C to 22°C and later decreased to 8.38 as the temperature increased from 22°C to 25°C (Mehrpour and Hatami, 2007). Similarly, there was a reduction in fecundity above 25/30°C (Lange *et al.*, 2006). In general the optimal range of temperature was found to be 25 to 30°C for the population growth of *B. brassicae* on white cabbage (Satar *et al.*, 2005), *Aphis gossypii* in cotton (VanSteenis and Khawass, 1995), *A. nerri* (Aleosfoor and Fekrat, 2014). In some cases, low temperatures (10–15°C) caused aphids to produce alate forms (*Brevicoryne brassicae*), while suppression of same was noted at high temperatures (25–30°C) (Lamb and White, 1966).

Differential responses with lower and higher temperatures were reported by various authors referring the species specificity of host and insect pests. Different authors mentioned increased/decreased fecundity at different temperatures. All the nymphs of cereal aphids *viz.*, *Metopolophium dirhodum*, *Rhopalosiphum padi* and *Macrosiphum avenae* died at 30°C *R. padi* had a 4-16 times increase in fecundity above 15°C than the other two species (Dean, 1974) and increase in fecundity of *Aphis glycines* (Soybean aphid) at 22°C (Hirano *et al.*, 1996). The mean daily fecundity (m_x) of corn leaf aphids *Metopolophium dirhodum* (rose grain aphid) was found to be high at high temperatures in warm regions, while at 35°C average adult fecundity decreased (Ma *et al.*, 2004). Generally alate forms of aphids have lower fecundity than apteral forms (Sheng and Hughes, 1987) and that the fecundity of sowthistle aphid, *Hyperomyzus lactucae* increased between 12.5–24 °C and decreased with an increase in temperature.

Interactive effects eCO₂ and etemp

The fecundity of corn leaf aphid *Rhopalosiphum maidis* was significantly high under the etemp and eCO₂. Additionally the combined effects of both etemp and eCO₂ increased the number of alates that may enhance the aphid migration/dispersal, the spread of plant viruses and also aphid biology aggravated damage on barley under the climate change (Xie *et al.*, 2014).

Majority of the studies referred that the increased fecundity or production of offspring was more under eCO₂ and etemp conditions meaning that proliferation or multiplication will be higher during future climate change scenarios. This might be due to the variations of biochemical constituents of the crop plants under eCO₂ and etemp conditions implying that crop

plants may experience severe infestation by aphid population.

Life table parameters

Life table parameters are important indicators for understanding the population dynamics of insect pests and explain the impact on growth, survival and reproduction of insect population. The variation of life table parameters of lepidopterans (Guang *et al.*, 2000; Hardev *et al.*, 2013; Srinivasa Rao *et al.*, 2014) and homopterans (Alireza *et al.*, 2012) with temperature and CO₂ is significant and well documented (Iranipour *et al.*, 2010; Xie *et al.*, 2014). Among these parameters the intrinsic rate of increase (r_m) is the most important one which explains the rate of progeny production per female per day, Net reproductive rate (R_0) indicates the number of times that the population would multiply by the end of each generation, Finite rate of increase (λ) is the number of individuals added to the population per head per unit time or number of births per female per day whereas, generation time (GT) is the time required to complete a generation.

Impact of eCO₂

The r_m of *Rhopalosiphum padi* and *Myzus persicae* was only slightly and non-significantly increased under eCO₂ conditions (Oehme *et al.*, 2011) whereas that of *Brevicoryne brassicae* was the highest at eCO₂ (1050 ppm) because of their faster development, high daily rate of progeny production and higher survivorship (Alireza *et al.*, 2012). Earlier it was noted (Awmack *et al.*, 1996) that r_m was not affected by eCO₂ in case of *Sitobion avenae* signifying the effect of eCO₂ varies with species of aphids. The finite rate of increase (λ) of *A. glycines* was increased (Hirano *et al.*, 1996).

Impact of etemp

The impact of temperature on r_m of aphid species was significant. The intrinsic rate of increase (r_m) was positively correlated with temperature but was inversely related to temperature when measured on a physiological time scale of *Hyperomyzus lactucae* (Sheng and Hughes, 1987). Better adaptation of corn leaf aphids in population growth to a wider range of high temperatures (35°C) was with higher r_m in warm regions (Ma *et al.*, 2004). The highest per capita growth rate of aphids was at 25°C and lowest at 30°C implying the non-linear trend while the average reproduction rate per female (R_0) was greater (47.1 aphids/aphid) at 25°C, as temperatures increases it was found to be decreased (30°C) (Satar *et al.*, 2005).

The r_m of *M. rosae* was shortest at 22°C and 15°C, among four temperatures tested and the longest and shortest generation time (GT) was at 15°C and 22°C (Mehrpour and Hatami, 2007). The negative impact on biology and life table parameters of *Rhopalosiphum padi* at 32°C and the time interval between each generation (GT) and the population doubling time (DT) diminished, as temperature increased yet with highest r_m , λ and R_0 at 24°C and 28°C (Auad *et al.*, 2009). The development, survivorship and reproduction of melon or cotton aphid (*Aphis gossypii*) were strongly influenced by temperature and quality of food and r_m increased with increase in temperature. The mean generation time decreased with increasing temperature from 16–30°C (Mohammad, 2010) and the varied values of r_m with highest R_0 of *A. nerri* (Aleosfoor and Fekrat, 2014).

Interactive effect of eCO₂ and etemp

The combined effects of both etemp and eCO₂ on aphid biology may exacerbate aphid damage on barley under the climate change (Xie *et al.*, 2014). Corn leaf aphid had the highest intrinsic rate of increase (r_m) under the elevated temperature and CO₂ combinations in the second generation. Significant variation of life table parameters under eCO₂ and etemp conditions particularly with increase in r_m , R_0 and λ with reduced GT indicate the vital role of host plant and temperature. The increased r_m and R_0 shows that the intrinsic rate of female aphid will increase under eCO₂ and etemp conditions leading to higher reproducing capacity. The reduction of GT may lead to possibility of occurrence of more generations through reduction of life cycle of aphids under future climate change scenarios. The summarized information indicates that the proliferation of aphid population would be more in climate change conditions resulting in higher population build up.

Population size/abundance

The population size or abundance indicates the absolute population developed after natural key mortality factors during hatching period. Generally the survival rates of an individual are also taken into account while estimating the population size. Abundance is determined by the combined effects of all the factors and all the processes that impinge on a population are the dependent or independent of the density.

Impact of eCO₂

It is well known that the insect herbivores exhibited increase in population size in response to eCO₂ and among these phloem feeders are the most important ones (Whittaker, 1999). The response of aphid populations to eCO₂ was species-specific and Dukes, (2000) found that increased aphid abundance was not significantly related to foliar nitrogen concentration. Aphid species that have lower nitrogen requirements and that are less sensitive to their own density will be more likely to have larger populations in eCO₂ compared to aCO₂ (Hughes and Bazzaz, 2001 and Newman *et al.*, 2003). Peak and mean population size increased with rising CO₂ and showed a positive response to CO₂ enrichment and these effects on mean population and growth rate were significant (Xing *et al.*, 2003). Increase in *Macrosiphum euphorbiae* population size was in response to eCO₂ or increased nitrogen availability on *Solanum dulcamara* grown under low N conditions. No population size responses were noticed for aphids infesting *Amaranthus viridis*, showing the significant role of host crop (Sudderth *et al.*, 2005). The aphid population under eCO₂ was far larger than that of aCO₂ (Xing *et al.*, 2003, Zhang *et al.*, 2003) and 32% and 50% more population of *Sitobion avenae* at 550 - ppm and 750-ppm CO₂ than ambient CO₂ (Chen *et al.*, 2004). It was implied that the faster development and higher survivorship of *Brevicoryne* species (Alireza *et al.*, 2012) and *Diuraphis noxia* (Jimoh *et al.*, 2013) at eCO₂ would allow aphid population to increase and in turn would lead to outbreaks.

According to Bezemer *et al.*, 1999 the direct effect of eCO₂ concentration on aphid population parameters was minor. There was a decline/no effect in aphid population under eCO₂ referring the significance of host and aphid specificity. No differences were in population sizes of *B. brassicae*, *M. persicae* (Bezemer *et al.*, 1999) and colonization of *R. padi* at eCO₂. In

fact, the plants grown in air of eCO₂ contained far fewer aphids than the plants grown in ambient air indicating the lower levels of aphid density under eCO₂ (Newman *et al.*, 1999). The prediction of incidence of aphids by using mathematical modeling indicated that an increasingly dramatic decline in cereal aphid abundance from the 1961 to 1990 baseline with increasing CO₂ emissions. The pest status of cereal aphids in Southern Britain would significantly decline by the end of this century (Newman, 2005). Year-wise variations in the abundance/population growth of aphid *Obtusicauda coweni* were common (Adler *et al.*, 2007) and further it was mentioned that warming reduced or did not affect aphid density in each of three years. In case of green pea aphid (Mondor *et al.*, 2010) and *Sipha flava* (O'Neill *et al.*, 2011) on different hosts the role of host specificity was highlighted on population abundance of aphids. Evidences are available that crop plant with A₁ resistant gene are more susceptible to aphids (*Amphorophora idaei*) at eCO₂ and population was doubled compared to the same plants grown at aCO₂, designating the impact of eCO₂ despite having the resistant gene (Martin and Johnson, 2011). Elevated CO₂ increased the susceptibility of the crop plant and thus allowed the aphid population to multiply in larger number.

Impact of etemp

According to Aleosfoor and Fekrat, 2014 the optimum temperature range for *A. nerri* population growth was 25-30 °C. Thus, an increase in temperature of only 2°C would allow the number of generations produced per year to increase from 18 to 23°C in UK with a potentially huge increase in population size (Harrington *et al.*, 1999).

Interactive effects of eCO₂ and etemp

Aphid abundance was enhanced by both the eCO₂ and etemp, which suggest that peach potato aphid, *M. persicae*, an important pest of many crops, might increase its abundance under conditions of climate change (Bezemer and Jones, 1998; Bezemer *et al.*, 1999). Aphid (*Myzus persicae*) abundance was enhanced by eCO₂ (Jones *et al.*, 1998). Although life history parameters reflect positive effects with increasing temperature and eCO₂, the fact that increased host susceptibility would have an interactive and determining role over periods. If the UK situation of decreasing cereal aphids with increasing CO₂ emissions predicted through models is to be a reality, pest managers can be relaxed with no expectations of aphid outbreaks.

Weights and RGR

The data on amount of ingestion or feeding (TC), excretion (faecal matter) and the weight gain of insect/aphid are considered as insect primary parameters which in turn used for estimating the indices of insect performance or feeding efficiency (Srinivasa Rao *et al.*, 2013). Most of the studies included weight gain and relative growth rate (RGR) of the insect for estimating the growth and development at a set condition.

Impact of eCO₂

The variation in weight gain of insects, feeding percentage and RGR of lepidopterans and homopterans under eCO₂ conditions has been well reviewed (Hunter, 2001). The divergent observations were made by several authors referring

the species selectivity among aphids. The higher weight of *Amphorophora idaei* on raspberry (Martin and Johnson, 2011), *Rhopalosiphum padi* on barley (Oheme *et al.*, 2011) at eCO₂ than ambient, in contrast to reduction of weights of *Myzus persicae* on cotton (Oheme *et al.*, 2011), *Brevicoryne brassicae* on cabbage (Klaiber *et al.*, 2013) was observed. There was a non-significant tendency for eCO₂ to reduce the individual weights and RGR of *Phyllaphi fagi* (Docherty *et al.*, 1997).

Impact of etemp

The adult weight of aphids, *Acyrtosiphon pisum* on peas (Lamb *et al.*, 1987), *Macrosiphum euphorbiae* on *Solanum dulcamara* (Flynn *et al.*, 2006) decreased with increase in temperatures. In case of *Myzus persicae* (Peach potato aphid) had a close linear correlation with temperature, decrease in body size at higher temperature. In *M. antirrhinii*, the temperature relations were reversed (Blackman and Spence, 1994). While the influence of etemp and eCO₂ can be different with respect to aphid species, the response of the host plants also play an important role through the altered nutritional and secondary allelochemicals.

Tritrophic interactions

Tritrophic often referred as multi-trophic interactions with respect to insects explain the impacts of three popular trophic levels on each other *viz.*, host plant, insect herbivore and its natural enemy. Global warming is expected to affect tritrophic interactions between plants, herbivores, and their natural enemies. Assessing the effect of climate change on each level of trophic interactions is important to gain a deeper understanding of the status of an ecological community in light of a changing climate (Sentis *et al.*, 2013).

Climate is critical in predicting population dynamics and therefore success of natural and biological control agents is climate dependent (Zalucki and van Klinken, 2006; Ramawatar and Singh, 2014). Climate change either facilitates or inhibits biological control depending on the responses of both the target pest species and their biological control agents (Hellman *et al.*, 2008). Warming which is primary indicator of climate change may alter the geographical distribution of insects and thus allowing the 'pest shifts' to the new geographical locations where plants and bio-control agents could experience either ideal or non-ideal temperatures (Lu *et al.*, 2013; Allen *et al.*, 2013).

Impact of eCO₂

It was reported that decreased DT of predator, *Lysiphlebia japonica* on *A. gossypii* at eCO₂ conditions without affecting the parasitism or emergence rates (Sun *et al.*, 2013) and similarly higher abundance of *Aphis gossypii* at eCO₂ without influencing the parasitism rates (Gao *et al.*, 2008). Increased stage-specific larval durations of the ladybird beetle when fed on aphids from eCO₂ (Jones *et al.*, 1998). The bio-control efficiency of *Aphidius picipes* against *S. avenae* can be enhanced in eCO₂ and these results signified that eCO₂ markedly changes the predation/parasitization preference (Chen *et al.*, 2007). While effects of CO₂ on biological control may vary, the general patterns of decreased plant quality and insect preference with eCO₂ may not augur well for biological control applications. Very few studies are available on impact of climate change on tritrophic interactions and the lack of

research on concurrent effects of etemp and eCO₂ on plant-insect interactions and biological control indicate the complex nature of the subject area (Zvereva and Kozlov, 2006; DeLucia *et al.*, 2012).

Impact of etemp

The etemp influenced coccinellid populations positively and caused the reduction in the number of aphids between 40-60% (Skirvin and Fenlon, 2003; Hemchandra *et al.*, 2010). The greatest effect of coccinellid to reduce both maximum and total aphid numbers was predicted to occur at relatively hot summers. It could be that the summer conditions are ideal for exhibition of higher predatory-prey relations over a longer period of time.

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