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Elevated CO_2 and Temperature Resetting the Expression of Resistance, Pest Incidence, Geographical Distribution and Physiology in Insect-pests of Grain Legumes: A Review

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ABSTRACT

The most important factor that affects the crop production in terms of nutritional content of foliar plants is the global climate change. Herbivore's growth, development, survival and geographical distribution all are determined by elevated CO_2 and temperature. The interactions between herbivores and plants have changed due to increasing level of CO_2 and temperature. The effect of high CO_2 and temperature on grain legume plant which change in to plant physiology (*e.g.*, nutritional content, foliage biomass) and how it change in herbivory metabolism rate and food consumption rate. Plant injury is determined by two factors *viz.* resistance and tolerance and both are influenced by greater CO_2 and temperature. Legumes are an important source of food and feed in the form of proteins and also improve the soil environment. The repercussions of the abiotic factors mentioned above needs discussion among the scientific community. We may able to limit the negative repercussions of stated factors in future breeding projects by harnessing the practical favourable impacts and by including such influences of elevated CO_2 and temperature on pulses productivity. The extensive research is necessary to overcome the negative effects of high CO_2 and temperature on insect-plant interaction.

Key words: Elevated CO_2, Host-plant interaction, Legumes, Resistance, Temperature.

CO_2 level in the atmosphere is currently about 406.94 parts per million (ppm) on a worldwide scale (Anonymous, 2017). In the last 250 years, atmospheric CO_2 concentration has risen from 280 to 390 ppm and by the end of 2050, it expected to rise at least 550 ppm (IPCC, 2007). As an abiotic element, it affects the expression of plant resistance (Lindroth, 2010; Robinson *et al*., 2012). Elevated level of CO_2 increases the C:N ratio, which lowers the nitrogen concentration in the tissues of most plant species, making them more sensitive and affecting the feeding habits of insect-pest species (Bezemer *et al*., 2000; Sun *et al*., 2010; Couture *et al*., 2010; Guo *et al*., 2014). To balance this ration, the phytophagous animals would consume more foliage and therefore, more damage to crop plants (Bezemer and Jones, 1998). Variations in climatic change have a significant impact on pest abundance and dispersion (McKenzie and Andrews, 2010; Sharma, 2014). Alteration in CO_2 concentration also results in biochemical and morphological changes (Robinson *et al*., 2012) and that plays vital role in plant defence mechanism of host plant resistance to insect pests (War *et al*., 2012, 2013). Generally the plant develops many strategies to defend itself against the negative impacts of foliar feeders (Strauss and Agrawal, 1999; Fornoni *et al*., 2003). Plants respond by producing repellents or defensive elements so to reduce the effect of pest species (Halitschke and Baldwin, 2004). Elevated CO_2 also alters the activity of plant oxidative enzymes such as peroxidase (POD), polyphenol oxidase (PPO), phenylalanine ammonia lyase (PAL), tyrosine ammonia lyase (TAL), superoxide dismutase and catalase in the host plant (Badiani *et al*., 1993; Polle *et al*., 1997). The photosynthetic rate, which is regulated by ambient CO_2 level, has a significant impact on the physiology and biochemical composition (C:N ratio) of plant foliage, as well as the allocation of these components of plant leaves (Long *et al*., 2004). When wild tomato plants are grown and fed under elevated CO_2, the activities of total protease, trypsin-like enzymes and weak and active alkaline trypsin-like enzymes increased in the midgut of the cotton bollworm, *Helicoverpa armigera* (Hubner) (Guo *et al*., 2012). The negative impact of elevated CO_2 level on insect physiology has been investigated (Akbar *et al*., 2016). The development and physiology of herbivorous insects are affected by the changes in food quality (Khadar *et al*., 2014). Sharma *et al*. (2016a) investigated the effect of increased CO_2 on plant defense response in chickpea against *Helicoverpa armigera* and found increase in total phenols and condensed tannins. Tannins in plant foliage can protect

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against foliage feeder by making the plant toxic or deterring the insects from feeding on it (Barbehenn and Constabel, 2011). Hydrogen peroxide, oxalic and malic acid level were higher in *H. armigera*-infested plants at 750 ppm than at 350 ppm CO_2 level (Sharma *et al*., 2016b). The primary goal of this review paper was to determine the impact of increased CO_2 concentration and temperature on resistance expression, pest damage and insect development in grain legumes.

Elevated CO_2 and temperature *vs* pest incidence and geographical distribution

According to the third IPCC study, global average surface temperature is expected to rise by 1.4°C to 5.8°C by 2100 and after it will rise even more fast (Houghton *et al*., 2001). During the last 1,000 years, the rise in temperature in the twentieth century has been the most serious problem of any century. As a result of global warming, pest outbreak have become more common and severe (Sharma, 2014). The pest population became unstable due to rising CO_2 level and resulted in severe outbreak of pest species (War *et al*., 2016). Regional distribution, abundance, seasonal incidence and intensity of few pests got shifted due to elevated CO_2 level (Menendez, 2007; IPCC, 2014; Sharma, 2014). Change in climate fastens the severe outbreak of *H. armigera* and *Maruca vitrata* in legume crops (Sharma, 2005; Sharma, 2010). Among all the abiotic climatic variations, the extreme range of temperature has a significant impact on phytophagous herbivore distribution (Boullis *et al*., 2015). More potential of new pests and pest niches arise when the average temperature rises. Pod infestation by *H. armigera* and *M. vitrata* in pigeonpea crops varies and it depends the temperature at different planting dates (Jat *et al*., 2021; Jat *et al*., 2018a) (Table 1). In the pigeonpea crop, higher temperature results in a greater larval population as well as a higher incidence of *H. armigera* and *M. vitrata*. The larval population of *H. armigera* was positively correlated with the higher temperature (Jat *et al*., 2017). Furthermore, the occurrence of insect pests in pigeonpea and chickpea crops also varied in different months (Sharma *et al*., 2016b). In September and January seeded pigeonpea and chickpea crops, the crop damage was appreciably high due to infestation by *H. armigera* and *Spodoptera exigua* (Hub.) (Sharma *et al*., 2016b).

Effect of elevated CO_2 and temperature on foliage consumption and insect development

Nitrogen is one of the most critical limiting factors for phytophagous herbivores (Mattson, 1980). Decrease in the foliar nitrogen content of the host plant may impair the development and survival rates of phytophagous insects. Variability in climatic variables weakens the plant's defence against herbivorous insects by virtue of the fact that nitrogen is the most abundant component of proteins (Khadar *et al*., 2014; Sharma, 2016) and a limiting element for insect-pest reproduction and performance (Lindroth *et al*., 1993; Shwetha *et al*., 2019). Therefore, decrease in leaf nitrogen content under elevated CO_2 concentration results in plant nitrogen deficit (Lindroth *et al*., 1993). Feeding such plants would enhance the leaf consumption and duration of development (Feng *et al*., 2010). For instance, the chickpea plant grown in high CO_2 concentration has decreased protein content in their tissues, making them nutritionally deficient (Khadar *et al*., 2014). *H. armigera* needs more protein for proper growth and development and it will strive to compensate by consuming as much as possible. Carbon dioxide also reduced the plant's ability to defend itself against phytophagous insects (Zavala *et al*., 2008). Coviella and Trumble (1999) and Sharma *et al*. (2016b) hypothesized that plants grown under higher CO_2 and temperature level are less nutritious and herbivores will increase their feeding time and foliage consumption.

Insect development and physiology directly influenced by temperature fluctuations, with equivalent impacts on the nutritional composition of host plants (Ayres and Scriber 1994). Hunter (2001) and Yadugiri (2010) investigated the direct and indirect effects of temperature and CO_2 on insect growth. In general, rising temperature leads to a higher survival rate and a shorter life cycle (Bale *et al*., 2002). Increasing in plant dry biomass and C:N ratio, longer main stem length, elongation of branches, individual leaf area

Table 1: Correlation coefficient between *H. armigera* and *M. vitrata* population and abiotic factors in different sowing dates.

Weather parameters	*H. armigera*				*M. vitrata*			
	D_1	D_2	D_3	D_4	D_1	D_2	D_3	D_4
Max T	0.626**	0.162	0.743*	-0.248	0.146	-0.200	0.704*	-0.340
Min T	0.537*	0.160	0.574	-0.067	-0.175	-0.653*	0.476	-0.179
AVP I	0.518*	0.087	0.500	0.019	-0.255	-0.688*	0.414	-0.104
AVP II	0.384	0.042	0.374	0.111	-0.405	-0.762**	0.312	-0.017
RH - I	-0.345	-0.038	-0.245	0.330	-0.139	0.274	-0.399	0.422
RH - II	0.118	-0.092	0.080	0.912**	-0.671**	-0.586*	-0.564	0.906*
WS (Km/h)	0.109	-0.189	0.389	-0.087	-0.533*	-0.829**	0.149	-0.160
BSS (Hrs)	0.476	-0.228	0.090	-0.278	0.163	0.091	0.496	-0.384
PAN (mm)	0.420	-0.136	0.414	-0.196	-0.164	-0.374	0.392	-0.289
Rainfall (mm)	-0.059	-0.377	0.829**	0.186	-0.552*	-0.454	0.282	0.219

D_1: 3rd week of June; D_2: 1st week of July; D_3: 2nd week of July; D_4: 3rd week of July.

per plant and reduced foliar nitrogen are the results of increased CO_2 sensitivity in C_3 plants (Chen *et al*., 2005a; Shwetha *et al*., 2019). Increased CO_2 (550ppm) results in significantly greater leaf area, root dry weight and total dry matter accumulation in French bean plants (Rao *et al*., 2015). Because of CO_2 fixation mechanisms, leguminous crops respond positively to elevated CO_2 level and results in increased biomass output among C_3 plants (Kimball *et al*., 2002). Some mungbean genotypes have a beneficial attributes with increased CO_2 concentrations (570-20 ppm) (Haque *et al*., 2005).

The drop in leaf N content caused by quicker growth of the foliage plants stimulated photosynthesis and growth in plants growing under elevated CO_2 circumstances (Stitt and Krapp, 1999). Under high CO_2, the leaf N content of legume crops reduced by an average of 7% (Cotrufo *et al*., 1998). Rao *et al*. (2012) found an 8% drop in leaf N content under increased CO_2 concentrations when compared to ambient CO_2. The foliar nitrogen concentration of the plant decreases as CO_2 level rises and results in 40% higher food consumption by herbivores (Sharma *et al*., 2016b; Chen *et al*., 2005b).

The nutritional composition of the plant became altered by increased CO_2 concentration and temperature, which might make the foliage plant unpleasant or nutritionally better for the insects (Sterner and Elser, 2002). Lower level of leaf nitrogen, higher carbon, higher relative proportions of carbon to nitrogen and higher polyphenols content have been recorded in groundnut plants cultivated under elevated eCO_2 (550 ppm and 700 ppm) level. When compared to ambient CO_2 level, leads to longer larval duration, greater larval weight and increase intake of groundnut plant leaf (Rao *et al*., 2012; 2014). Similarly, groundnut foliage grown in eCO_2 circumstances has reduced leaf nitrogen content, greater carbon and a higher C:N ratio (Shwetha *et al*., 2019).

Increased temperature causes a faster rate of development in arthropods and results in more generations per year and a wider geographical dispersion (Parmesan *et al*., 1999; Bale *et al*., 2002; Sharma, 2014). When *Helicoverpa armigera* larvae were reared under elevated CO_2, larval survival, larval weight, larval period, pupation and adult emergence were all negatively affected, whereas pupal weight, pupal period and adult fecundity were improved (Akbar *et al*., 2016). In brief, the growth and development, reproduction and survival of of *H. armigera*, were strongly influenced by rising temperature and precipitation (Sharma, 2014). Similarly, when the larvae of *Spodoptera litura* feed on groundnut plants with eCO_2 values (550 ppm and 700 ppm), showed a longer larval duration and larval weight (Rao *et al*., 2014). On the contrary, with elevated CO_2 concentrations (732.1±9.99 µl/liter), larval and pupal weights of *S. litura* were significantly reduced, but the duration of larval and pupa on soybean were significantly increased (Yifei *et al*., 2018).

Adati *et al*. (2004) investigated the effect of temperature on the development and survival of the legume pod borer, *Maruca vitrata*, under the *in vivo* condition. The developmental time for eggs, larvae and pupae reduced with increasing temperature from 14.4°C to 29.3°C. For development of egg, larval and pupal stages, the thermal constant and lower thermal threshold were 51.1, 234.7 and 116.5 degree-days and 10.5, 10.0 and 10.9°C, respectively.

The aphid population on soybean plants was considerably greater after 1 week under elevated CO_2 (550 L/L) concentrations, with populations twice the size of plants cultivated under ambient CO_2 level (O'Neill *et al*., 2011). Similarly, higher temperature has a detrimental impact on larval survival, larval duration, pupal weight and pupal period, but has a positive impact on larval growth. Increased metabolic rate may be responsible for increased larval growth (Bale *et al*., 2002; Jamieson *et al*., 2012). Increased food consumption and metabolism of *H. armigera* larvae were observed when CO_2 and temperature levels were enhanced (Akbar *et al*., 2016). This is due to increased activity of midgut protease, amylase and cellulose (carbohydrates) and mitochondrial enzymes. When larvae were reared under elevated CO_2 concentration compared to ambient CO_2 level, Khadar *et al*. (2014) found that food consumption rose by 81.67 percent. The food consumption of *S. litura* was maximum (3758.07 mg) during its whole life cycle when exposed to eCO_2 + eTemperature (550 ppm + 2°C) (Shwetha *et al*., 2019). In line, Wu *et al*. (2006) observed similar observations. Yifei *et al*. (2018) proposed that elevated CO_2 level promote an increase in the amount of feeding and excretion of soybean plants by *S. litura*.

Chickpea plants cultivated at high CO_2 level (550 ppm and 700 ppm) exhibited low nitrogen and high carbon content and that has led to increased food consumption by *H. armigera*, which in turn increased larval weight and increased the excreta (Khadar *et al*., 2014). More damage to chickpea plants is the result of no change in phenol content, more approximate digestibility and more relative consumption rate by the larva under elevated CO_2 as compared to ambient CO_2 level. The nutritional quality of mungbean leaves was reduced due to dilution of nitrogen content under elevated CO_2 level, resulting in increased feeding capacity of *S. litura* (Srivastava *et al*., 2002). As atmospheric CO_2 level goes up, it may decrease nitrogen concentration and high non-structural carbohydrate level. This climatic change may alter the plant-herbivore interaction, as well as *S. litura* feeding habits.

Elevated CO_2 *vs* change in morphological and biochemical components

Hunter (2001) has clearly established the effect of increased CO_2 concentration on plant phytochemistry. Climate change, particularly changes in CO_2 and temperature regimes have a significant impact on host-plant resistance mechanisms (Sharma *et al*., 2016b) (Table 2 and 3). The photosynthetic route determines the growth and development as well as the biochemical contents of plants cultivated in high CO_2 environment. Groundnut and chickpea plants grown in CO_2 (550 ppm) had a considerable drop in leaf nitrogen and

protein, whereas the carbon C:N ratio, phenols and tannin content were much greater in CO_2 (550 ppm) and least in ambient concentration (Shwetha *et al*., 2019; Khadar *et al*., 2014). Elevated temperature seems to reduce the morphological and biochemical components of the pigeonpea resulting in increasing damage by pod borer (Jat *et al*., 2018a; Jat *et al*., 2021) (Table 4). In comparison to June sown pigeonpea genotypes to July or August sown genotypes, the phenol content and condensed tannins were found higher (Jat *et al*., 2018b) (Table 5 and 6). Such changes have led to the pod borer infestation in the pigeonpea. The mean phenol content of chickpea plants infested with *H. armigera* was substantially higher than that of uninfested plants (Sharma *et al*., 2016b). Under elevated CO_2 concentration (550 and 750 ppm), the activity of phenylalanine ammonia lyase (PAL), tyrosine ammonia lyase (TAL), total phenols and condensed tannins were increased in chickpea plants (Muzika, 1993; Sharma *et al*., 2016b). Increasing activity of these compounds affects the expression of plant resistance to foliage feeders. Several

Table 2: Amounts of phenols (mg TAE/g FW), tannins (mg CE/g FW) and chlorophyll (µg cm^{-2}) content of chickpea plants infested with *Helicoverpa armigera* under different CO_2 regimes.

CO_2 (ppm)	ICCL 86111		JG 11	
	Un-infested	Infested	Un-infested	Infested
Total phenols				
350 ppm	15.8±0.05^{a}	17.85±0.08^{a}	12.67±0.07^{a}	13.84±0.12^{a}
550 ppm	16.2±0.71^{a}	19.31±0.07^{a*}	14.47±0.10^{ab}	15.92±0.14^{ab}
750 ppm	16.9±0.27^{a}	19.70±0.08^{a*}	14.78±0.20^{ab}	16.03±0.14^{ab}
Ambient conditions	16.5±0.67^{a}	18.49±0.67^{a}	15.35±0.45^{b}	17.50±0.91^{b}
Mean	16.35	18.83	14.32	15.82
Tannins				
350 ppm	9.41±0.15^{a}	11.85±0.48^{a}	9.41±0.98^{a}	10.60±0.52^{a}
550 ppm	10.40±0.17^{a}	12.60±0.74^{a*}	10.40±0.30^{a}	11.82±0.74^{a*}
750 ppm	10.47±0.99^{a}	11.70±0.58^{a}	9.78±0.29^{a}	11.23±0.84^{a*}
Ambient conditions	9.90±0.97^{a}	12.11±0.92^{a*}	8.4±0.34^{a}	10.2±0.79^{a}
Mean	10.05	12.07	9.49	10.96
Chlorophyll				
350 ppm	28.6±1.15^{b}	28.15±2.41^{ab}	17.20±1.91^{ab}	30.22±2.55^{c}
550 ppm	27.83±1.70^{b}	23.30±1.97^{a*}	30.17±2.30^{c}	19.65±1.71^{a}
750 ppm	17.35±1.39^{a}	21.65±1.58^{a*}	14.95±1.20^{a}	17.78±1.08^{a}
Ambient conditions	29.53±2.09^{b}	29.53±2.09^{ab}	21.85±1.94^{b}	29.53±2.13^{b}
Mean	25.82	25.66	21.04	24.29

Values (means±SE) with the same letter within a column are not significantly different at $p \leq 0.05$.

*Values within a row across the infested and un-infested plants are significantly different at $p \leq 0.05$.

Table 3: Carbohydrate and protein content of chickpea plants infested with *Helicoverpa armigera* under different CO_2 regimes.

CO_2 (ppm)	ICCL 86111		JG 11	
	Un-infested	Infested	Un-infested	Infested
Chlorophyll content (mg/0.1 g leaf tissue)				
350 ppm	33.6±3.12^{a}	34.4±2.50^{b*}	33.6±1.45^{a}	35.2±1.56^{a*}
550 ppm	44.0±2.00^{b}	27.2±1.25^{ab*}	40.0±2.00^{b}	27.2±1.23*
750 ppm	48.0±1.50^{b}	24.0±2.20^{a*}	44.8±2.22^{bc}	24.8±1.56^{a*}
Ambient conditions	33.6±2.52^{a}	20.8±1.09^{a*}	26.8±1.20^{a}	19.6±1.72^{a*}
Mean	39.80	26.6	38.8	27.0
Protein (mg/g leaf tissue)				
350 ppm	49.5±1.48^{b}	33.0±1.50^{a*}	48.0±1.82^{c}	30.3±2.00^{a*}
550 ppm	45.0±1.80^{b}	39.0±2.97^{ab*}	42.0±1.24^{b}	32.0±2.12^{a*}
750 ppm	33.0±1.50^{a}	40.0±3.83^{b*}	33.0±1.50^{a}	36.0±2.12^{a}
Ambient conditions	46.0±2.56^{b}	42.1±2.56^{b}	40.0±2.70^{b}	42.0±2.10^{b}
Mean	43.38	38.53	40.75	35.0

Values (means±SE) with the same letter within a column are not significantly different at $p \leq 0.05$.

*Values within a row across the infested and un-infested plants are significantly different at $p \leq 0.05$.

studies have found that high temperature diminish the expression of genes influencing wheat resistance to several biotypes of the Hessian fly, *Mayetiola destructor* (Tyler and Hatchett, 1983). Certain environmental conditions, particularly temperature, have an impact on the success of transgenic crops in pest management (Sharma, 2014). This elevated condition changes the interaction between insect pests and their host plants.

Increased CO_2 concentration could reduce photorespiration in C_3 photosynthesis and makes photosynthesis more efficient. But the foliar nitrogen and protein concentrations dropped more than 12% (Ainsworth and Long, 2005). According to Dermody *et al*. (2008) higher CO_2 level alone and in combination with O_3 increased the abundance of western corn rootworm, *Diabrotica virgifera* adults (foliage chewer) and soybean aphids, *Aphis glycines* (phloem feeder), as well as the amount of leaf area damage in the soybean agroecosystem. At excessive CO_2 concentration (550), the Japanese beetle, *Popillia japonica*, significantly increased the foliage damage to soybean plants. Maximum consumption of leaf was observed among the beetle was observed when the temperature was raised to 37°C (Niziolek *et al*., 2013). The nutritional value of plants is greatly reduced due to loss of nitrogen and protein, influencing the growth and development of insect herbivores either directly or indirectly. On the other hand, plants using C_4 pathway of photosynthesis will have poor response to increased atmospheric CO_2 due to photosynthetic saturation (Leon and Vara, 2004).

Table 4: Per cent pod infestation by major pod borer complex in different pigeonpea varieties and different sowing dates.

Borer complex	Sowing	Varieties						Mean
		Paras	Manak	AL-201	Pusa-992	AL-881	H03-41	
H. armigera	D_1	3.92 (11.41)	3.40 (10.62)	2.62 (9.31)	4.34 (12.02)	3.46 (10.71)	3.65 (11.00)	3.56 (10.85)
	D_2	5.64 (13.71)	3.60 (10.87)	3.41 (10.59)	4.45 (12.17)	5.58 (13.63)	4.56 (12.25)	4.54 (12.20)
	D_3	2.00 (8.12)	5.51 (13.33)	2.42 (8.90)	4.07 (11.41)	3.27 (10.10)	1.84 (7.70)	3.18 (9.93)
	D_4	1.39 (6.75)	2.32 (8.75)	1.33 (6.63)	2.02 (8.02)	2.06 (8.24)	1.07 (5.73)	1.70 (7.35)
Mean		3.24 (10.00)	3.71 (10.89)	2.45 (8.86)	3.72 (10.90)	3.59 (10.67)	2.77 (9.17)	
S.Em.±	Factor A		(Dates of sowing)				0.34	
	Factor B		(Varieties)				0.42	
	Factor A × B		(Dates of sowing × varieties)				0.84	
CD	Factor A		(Dates of sowing)				0.97	
P= (*0.05*)	Factor B		(Varieties)				1.19	
	Factor A × B		(Dates of sowing × varieties)				2.37	
M. vitrata	D_1	3.23 (10.35)	3.35 (10.51)	1.58 (7.19)	3.69 (11.07)	3.52 (10.80)	2.19 (8.45)	2.93 (9.73)
	D_2	14.86 (22.66)	13.44 (21.49)	9.29 (17.74)	15.62 (23.27)	13.92 (21.90)	11.37 (19.70)	13.08 (21.12)
	D_3	3.81 (11.25)	6.25 (14.46)	2.79 (9.61)	10.73 (19.11)	2.58 (9.24)	3.17 (10.19)	4.89 (12.31)
	D_4	2.00 (8.10)	1.97 (8.00)	3.53 (10.82)	1.57 (7.18)	3.59 (10.89)	1.18 (6.19)	2.30 (8.53)
Mean		5.97 (13.09)	6.25 (13.61)	4.30 (11.34)	7.90 (15.16)	5.91 (13.21)	4.48 (11.13)	
S.Em.±	Factor A		(Dates of sowing)				0.19	
	Factor B		(Varieties)				0.23	
	Factor A × B		(Dates of sowing × varieties)				0.47	
CD	Factor A		(Dates of sowing)				0.55	
P= (*0.05*)	Factor B		(Varieties)				0.66	
	Factor A × B		(Dates of sowing × varieties)				1.33	
M. obtusa	D_1	1.87 (7.87)	3.21 (10.29)	1.36 (6.67)	1.96 (8.05)	1.80 (7.67)	1.97 (8.05)	2.03 (8.10)
	D_2	3.26 (10.39)	2.22 (8.55)	2.08 (8.29)	2.99 (9.95)	2.24 (8.60)	2.69 (9.44)	2.58 (9.20)
	D_3	2.46 (9.02)	2.65 (9.34)	1.24 (6.39)	2.72 (9.49)	2.75 (9.54)	1.72 (7.52)	2.26 (8.55)
	D_4	2.29 (8.64)	2.79 (9.59)	1.74 (7.58)	1.50 (6.94)	3.77 (11.11)	0.63 (4.48)	2.12 (8.06)
Mean		2.47 (8.98)	2.72 (9.44)	1.61 (7.23)	2.29 (8.61)	2.64 (9.23)	1.75 (7.37)	
S.Em.±	Factor A		(Dates of sowing)				0.18	
	Factor B		(Varieties)				0.22	
	Factor A × B		(Dates of sowing × varieties)				0.44	
CD	Factor A		(Dates of sowing)				0.51	
P= (*0.05*)	Factor B		(Varieties)				0.62	
	Factor A × B		(Dates of sowing × varieties)				1.24	

D_1= 3rd week of June; D_2= 1st week of July; D_3= 2nd week of July; D_4= 3rd week of July.

Table 5: Morphological traits of various pigeonpea varieties in different sowing dates.

Genotype/Variety	Trichomes on pods (/mm^{-2})									Pod length (mm)	Pod wall thickness (mm)	Seed size (mm)		No. of seeds / pod
	Top			Middle			Lower					Seed length	Seed width	
	A	B	C	A	B	C	A	B	C					
							D_1							
Paras	108.34	5.76	9.17	65.24	4.33	4.2	62.29	0	0.06	52.09	0.83	6.92	4.65	3.3
Manak	110.8	4.82	6.01	75.42	4.14	3.8	81	0.01	0.02	53.24	0.97	6.88	4.42	3.5
AL-201	152.3	8.06	1.68	135.24	6.92	1.87	71.94	0.03	0.02	47.63	2.19	6.72	4.01	2.7
Pusa-992	80.64	2	6	85.84	0.04	5.07	82.31	0.02	0.05	54.12	0.67	7.22	4.56	3.4
PAU-881	105.7	5.78	8.55	97.46	7.98	4	64.38	0	2	49.57	1.67	7.00	4.57	2.9
H03-41	151.46	3.88	8.07	96	6.34	3.8	121.04	1.03	2.93	54.41	1.06	7.26	4.48	4
							D_2							
Paras	107.42	4.18	9.27	55.44	4.39	3.87	59.33	0.07	0.5	49.15	0.71	7.76	4.66	3.68
Manak	116.28	5.34	6.53	86.22	4.04	4	83	0	1.02	40.31	1.39	6.21	4.12	3.31
AL-201	146.78	8.49	1	119.14	7.66	2	83.44	0.8	1	35.62	2.28	6.74	4.58	3.41
Pusa-992	95.12	4.72	6.27	78.31	1.1	5.17	83	0.04	0.5	50.47	1.15	8.22	4.40	3.81
PAU-881	66.32	5.00	8.13	82.66	7.89	6.14	61	0.6	1.87	51.00	1.45	7.56	4.61	4
H03-41	140.33	5.22	7.66	88	6.51	3.78	95.66	0.9	2	50.33	1.44	8.04	4.33	4.06
							D_3							
Paras	113	7.67	8	80.8	4.29	4	60.44	2	1.55	47.44	1.28	7.06	4.55	3.56
Manak	110.06	2.33	6.71	93.07	0.5	4.12	78.34	0.82	0.80	43.17	1.18	6.58	4.39	3.66
AL-201	155.03	6.88	0.88	125.87	6.88	2	80.56	0.61	2.22	37.58	1.88	5.92	4.41	3.3
Pusa-992	78.08	0	7	79.73	1	4.91	67	1.19	0.51	57.29	1.02	8.33	4.68	3.86
PAU-881	79.15	5.778	8.46	88.26	7.69	3.14	70.39	0.07	1.77	44.08	1.76	7.25	4.06	3.51
H03-41	153.73	3.88	7.16	96	6	3.19	109.47	1.46	2.91	45.61	1.83	7.02	4.12	3.79
							D_4							
Paras	110.33	9.22	9.27	78	4	4	62.13	0.1	0	43.00	1.42	5.56	4.44	3.00
Manak	114.8	2.66	6.53	92	1.18	4.36	82.67	0	0.1	48.67	1.28	6.14	4.25	3.26
AL-201	142.1	8.58	1	121.02	9.49	2	84.53	0.09	3	52.42	1.55	7.00	4.76	3.36
Pusa-992	86.91	0.9	6.27	66.44	1.58	4	70.93	1	0	47.35	1.39	6.48	4.45	3.31
PAU-881	67.2	4.46	8.13	85.17	5	4.19	66.66	0.02	0.06	52.71	1.45	7.36	4.86	3.53
H03-41	151.46	6.27	7.64	94	6.59	1.08	118.66	2	3	49.45	1.88	6.76	3.92	2.88

D_1= 3rd week of June; D_2= 1st week of July; D_3= 2nd week of July; D_4= 3rd week of July.

Table 6: Biochemical constituents of pigeonpea varieties in different sowing dates (dry weight basis).

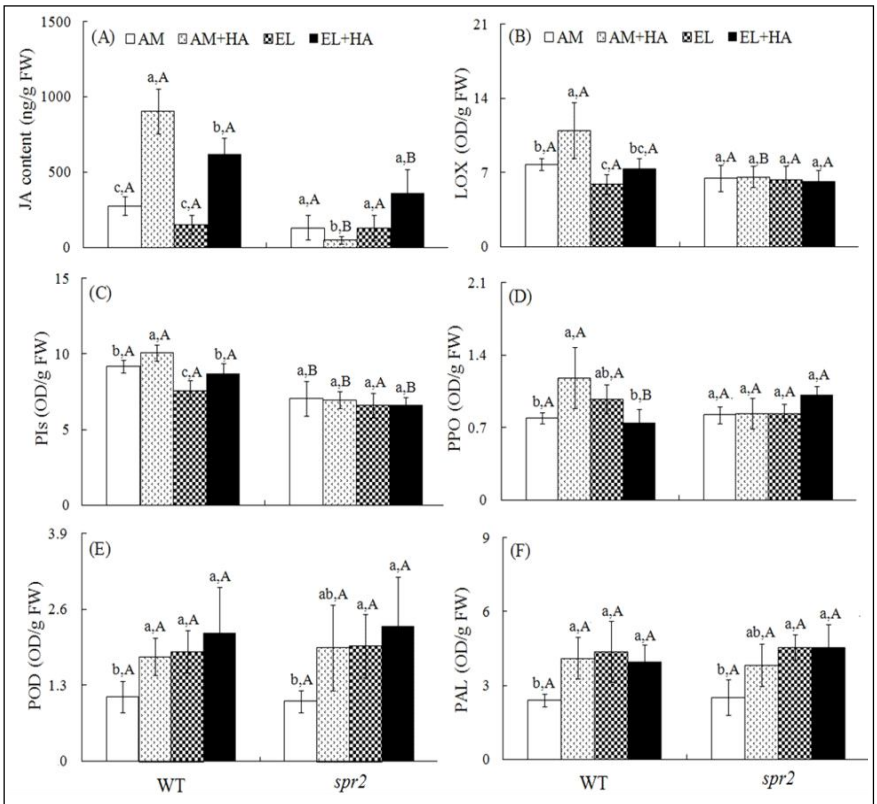
Genotype/ Variety	Pod wall composition on dry weight basis							Green seed composition on dry weight basis						
	TSS (%)	Protein (%)	Phenol (mg g^{-1})	Chlorophyll (mg g^{-1})	Moisture (%)	Fat (%)	Tannins (µg g^{-1})	TSS (%)	Protein (%)	Phenol (mg g^{-1})	Chlorophyll (mg g^{-1})	Moisture (%)	Fat (%)	Tannins (µg g^{-1})
							D_1							
Paras	2.68	12.25	0.65	2.41	73.2	2.6	59.80	5.00	23.46	0.75	1.58	73.4	3.3	73.94
Manak	2.69	11.91	0.78	2.26	72.8	2.4	50.54	4.45	24.51	0.42	1.54	71.4	3.3	61.22
AL-201	1.92	10.51	1.92	1.96	69.8	2.9	97.34	2.88	22.76	1.24	1.55	65	4.7	118.87
Pusa-992	2.38	12.25	0.45	2.04	71.6	2.3	34.63	3.04	21.36	0.34	1.43	67	4.0	67.39
PAU-881	2.24	9.46	1.74	1.68	71.2	2	58.03	4.35	21.01	0.68	1.39	67.6	4.2	85.17
H03-41	2.29	11.91	1.99	1.80	69.4	5.2	51.48	4.37	22.10	0.89	1.72	68.2	3.4	94.53
							D_2							
Paras	2.01	10.54	1.52	1.59	70.8	2.90	38.71	6.01	21.01	1.35	0.63	64.6	4.8	42.12
Manak	3.26	10.16	1.94	0.98	69.2	1.90	27.16	3.85	21.71	1.14	0.47	62.4	3.5	72.08
AL-201	1.88	10.18	2.97	1.54	70.00	2.00	55.22	5.93	20.31	2.12	0.53	63.2	5.2	81.43
Pusa-992	2.65	10.51	1.21	1.56	69.6	3.00	30.88	4.21	23.46	1.11	0.66	62.2	3.1	29.87
PAU-881	2.50	8.400	2.24	1.47	68.8	3.20	37.44	5.03	19.96	1.63	0.63	68	5.9	53.35
H03-41	2.06	10.86	1.92	1.51	69.2	2.70	33.69	4.54	23.11	1.59	0.29	64.6	4.6	52.41
							D_3							
Paras	2.59	11.56	1.68	1.25	68.2	3.2	59.90	4.03	23.41	0.52	0.57	68.6	3.6	37.88
Manak	4.68	10.51	0.69	1.26	69.8	3.3	46.80	5.58	25.56	0.48	0.58	69.2	3.9	45.89
AL-201	1.66	9.11	1.77	0.95	70.4	3.8	117.00	3.35	24.16	0.76	0.71	68	4.6	116.34
Pusa-992	4.10	11.21	0.89	1.03	69	2.5	75.81	4.17	23.46	0.53	0.74	62.2	3.4	90.79
PAU-881	2.37	10.16	1.07	1.03	69	2.9	104.83	4.84	19.96	0.66	0.54	68.6	4.1	121.68
H03-41	3.71	9.81	2.36	1.14	68.6	3.2	63.64	5.87	22.14	0.49	0.74	66.4	3.8	116.06
							D_4							
Paras	3.80	12.61	1.59	1.04	72	2.1	34.66	2.74	23.11	1.18	0.95	73.4	3.4	98.28
Manak	6.56	9.11	1.33	1.06	73.4	2.6	73.95	3.96	21.71	0.33	0.93	74	3.6	78.65
AL-201	3.19	9.81	2.69	1.26	70.4	4.3	232.12	2.53	20.31	1.19	0.7	68.6	5.5	239.61
Pusa-992	3.65	12.96	1.46	1.02	70.4	3.3	87.04	1.60	24.16	1.12	0.46	67.4	5.4	136.65
PAU-881	3.43	11.23	1.74	0.81	69.6	4.6	184.39	2.28	25.56	0.98	0.61	68	5.5	120.74
H03-41	2.66	11.68	2.41	1.25	70.4	3.7	82.36	4.08	23.21	0.42	0.58	70.4	4.9	131.97

D_1= 3rd week of June; D_2= 1st week of July; D_3= 2nd week of July; D_4= 3rd week of July.

Effect of elevated CO_2 and temperature on resistance resetting

Many studies have observed association between herbivore tolerance and resistance (Bailey and Schweitzer, 2010), but little is known about how abiotic factors like global CO_2 and temperature affect the relationship between tolerance and resistance. According to Guo *et al*. (2012) elevated CO_2 reduces tomato plant resistance to *H. armigera* by suppressing the critical defensive signal molecule JA and JA-pathway-related defensive enzymes. Tomato plants grown in elevated CO_2 are also less tolerant to *H. armigera* than plants grown in ambient CO_2. Raised CO_2 concentration produce higher leaf glucose concentration and lowered nitrogen content when combined with increased temperature (DeLucia *et al*., 2012). Both alterations in plant foliage reduce the plant's nutritional value, causing certain herbivores to consume more leaves to meet their nutritional requirement. Srivastava *et al*. (2002) observed the effect of long-term CO_2 enrichment on mungbean leaf chemistry. According to the above said researchers, under enriched CO_2 (600±50 µl l^{-1}) condition, foliage protein and non-protein nitrogen level decrease whereas, starch and total soluble sugar level of the leaves increase, resulting in more damage by *Spodoptera litura* damage. The change in herbivore feeding behavior caused by enhanced CO_2 has led to considerable ecological disruption. Moreover, high CO_2 level lowers the titre of plant defense hormone jasmonic acid (JA) and promote the production of salicylic acid (SA), these changes in plant hormones could potentially increase sensitivity to chewing insects (DeLucia *et al*., 2012).

Not all plant species respond identically to elevated concentrations of CO_2 (Lindroth *et al*., 1993). For example, elevated CO_2 results in reduced in foliar nitrogen levels and increased condensed tannin levels in paper birch and but not in white pine (Roth and Lindroth, 1994). Chickpea plants reduce nitrogen-based defensive chemicals (*e.g*., alkaloids) when CO_2 level rose (Sharma *et al*., 2016b). Reduced resistance in wild tomato plants when grown under high CO_2 condition. When wild type tomato plants were infested with *H. armigera* larvae, the levels of jasmonic acid and the activities of lipoxygenase, proteinase inhibitors and polyphenol oxidase were found to be less (Guo *et al*., 2012) (Fig 1). The expression of resistance and tolerance to the test bug were highest in wild type plants under ambient CO_2 level. Increase in susceptibility of soybean plant to Japanese beetle, *Popillia japonica*, by lowering the expression of genes related to the defense hormones (jasmonic acid and ethylene). It decreases the gene expression and activity of cysteine proteinase inhibitors



(A) JA content and the activity of (B) lipoxygenase (LOX), (C) proteinase inhibitors (PIs), (D) polyphenol oxidase (PPO), (E) peroxidase (POD) and (F) phenylalanine ammonia lyase (PAL).

Fig 1: Chemical defensive components in two tomato genotypes grown under ambient (AM) and elevated CO_2 (EL) without and with *H. armigera* (+HA).

(CystPIs), which are the main anti-herbivore defense in plants (Zavala *et al*., 2010). Jasmonic acid lowered the efficiency of soybean plants when CO_2 level were high (Zavala *et al*., 2008). Similarly, increase of CO_2 levels affects the amounts of malic and oxalic acid in chickpea plants, thereby reduce the plant resistance mechanisms against herbivores (Selvaraj *et al*., 2013; Sharma *et al*., 2016b). Plants that grow under elevated levels of CO_2 are more sensitive to the Japanese beetle, *P. japonica* and the western corn rootworm, *D. virgifera* (Zavala *et al*., 2008). The synthesis of cysteine proteinase inhibitors (CystPIs) was reduced due to the down regulation of defense signaling genes (lipoxygenase 7 (lox7), lipoxygenase 8 (lox8) and 1-amino cyclopropane-1-carboxylate synthase (acc-s). These are the principal coleopteran herbivore deterrent chemicals in soybean. On the contrary, when the plants were infested by *P. japonica*, ethylene synthesis in healthy plants increased due to higher CO_2 level but reduced the expression of genes in the ethylene-signaling pathway (Casteel *et al*., 2008).

Pigeonpea plants with the shortest incubation period of 18 hours suffered the most *Phytophthora cajani* infection when grown under 30°C and 85% RH (Jadesha *et al*., 2019). Similarly, Pande and Sharma (2010) found a higher incidence of phytophthora blight disease when temperature was 28-30°C and relative humidity was between 75 and 96% inferring that. High temperature seems to reduce plant disease resistance, immunity (Dropkin, 1969) and defensive response, making the plant more susceptible to pathogens (Zhu *et al*., 2010).

CONCLUSION

Phytophagous herbivores' interactions with host plants are unquestionably influenced by changing environmental conditions. In general, increased level of CO_2 concentration and temperature interfere with pest-plant interactions. Pest distribution and severity, foliage composition (which determines pest damage) and the physiology and development of foliar feeder herbivores are determined by these parameters. Elevated CO_2 alters C and N-based molecules, phenolic components and tannins present in the plants, reducing their resistance mechanisms. The net result is such that the plants become susceptible to pest on one hand and the insect multiplies beyond the economic threshold level and bring down the legume yield drastically.

Conflict of interest

All authors declare that they have no conflict of interest at all.

REFERENCES

Adati, T., Nakamura, S., Tamo, M. and Kawazu, K. (2004). Effect of temperature on development and survival of the legume pod borer, *Maruca vitrata* (Fabricius) (Lepidoptera: Pyralidae) reared on a semi-synthetic diet. Applied Entomology and Zoology. 39(1): 139-145.

Ainsworth, E.A. and Long, S.P. (2005). What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy. New Phytologist. 165: 351-371.

Akbar, S.M.D., Pavani, T., Nagaraja, T. and Sharma, H.C. (2016). Influence of CO_2 and temperature on metabolism and development of *Helicoverpa armigera* (Noctuidae: Lepidoptera). Environmental Entomology. 45(1): 229-236.

Anonymous, (2017). https://climate.nasa.gov/vital-signs/carbon-dioxide/.

Ayres, M.P. and Scriber, J.M. (1994). Local adaptation to regional climates in *Papilio canadensis* (Lepidoptera: Papilionidae). Ecological Monographs. 64: 465-482.

Badiani, M.D., Annibale, A., Paolacci, A.R., Miglietta, F. and Rashchi, A. (1993). The antioxidant status of soybean (*Glycine max*) leaves grown under nature CO_2 enrichment in the field. Australian Journal of Plant Physiology. 20: 275-284.

Bailey, J.K. and Schweitzer, J.A. (2010). The role of plant resistance and tolerance to herbivory in mediating the effects of introduced herbivores. Biological Invasions. 12: 337-351.

Bale, J.S., Masters, G.J. *et al*. (2002). Herbivory in global climate change research: direct effects of rising temperature on insect herbivory. Global Change Biology. 8: 1-6.

Barbehenn, R.V. and Constabel, C.P. (2011). Tannins in plant-herbivore interactions. Phytochemistry. 72: 1551-1565.

Bezemer, T.M. and Jones, T.H. (1998). Plant-insect herbivore interactions in elevated atmospheric CO_2: Quantitative analyses and guild effects. Oikos. 82: 212-222.

Bezemer, T.M., Jones, T.H. and Newington, J.E. (2000). Effects of carbon dioxide and nitrogen fertilization on phenolic content in *Poa annua* L. Biochemical Systematics and Ecology. 28: 839-846.

Boullis, A., Francis, F. and Verheggen, F.J. (2015). Climate change and tritrophic interactions: Will modifications to greenhouse gas emissions increase the vulnerability of herbivorous insects to natural enemies? Environmental Entomology. 44: 277-286.

Casteel, C.L., O'Neill, B.F. *et al*. (2008). Transcriptional profiling reveals elevated CO_2 and elevated O_3 alter resistance of soybean (*Glycine max*) to Japanese beetles (*Popillia japonica*). Plant, Cell and Environment. 31: 419-434.

Chen, F.J., Gang, W., Jun, L. and Feng, G. (2005). Effects of elevated CO_2 on the foraging behavior of cotton bollworm, *Helicoverpa armigera*. Insect Science. 12: 359-365.

Chen, F.J., Ge, F. and Parajulee, M.N. (2005). Impact of elevated CO_2 on tri-trophic interaction of *Gossypium hirsutum*, *Aphis gossypii* and *Leis axyridis*. Environmental Entomology. 34: 37-46.

Cotrufo, M.F., Ineson, P. and Scott, A. (1998). Elevated CO_2 reduces the nitrogen concentration of plant tissues. Global Change Biology. 4: 43-54.

Couture, J.J., Servi, J.S. and Lindroth, R.L. (2010). Increased nitrogen availability influences predator-prey interactions by altering host-plant quality. Chemoecology. 20: 277-284.

Coviella, C.E. and Trumble, J.T. (1999). Effects of elevated atmospheric carbon dioxide on insect-plant interactions. Conservation Biology. 13: 700-712.

DeLucia, E.H., Nabity, P.D., Zavala, J.A. and Berenbaum, M.R. (2012). Climate change: Resetting Plant-Insect Interactions. Plant Physiology. 160: 1677-1685.

Dermody, O., O'Neill, B.F., Zangerl, A.R., Berenbaum, M.R. and DeLucia, E.H. (2008). Effects of elevated CO_2 and O_3 on leaf damage and insect abundance in soybean agroecosystem. Arthropod-Plant Interactions. 2: 125-135.

Dropkin, V. (1969). The necrotic reaction of tomatoes and other hosts resistance to *Meloidogyne*: Reversal by temperature. Phytopathology. 59: 1632-1637.

Feng, Ge., Gang, Wu. and Chen, F. (2010). Elevated CO_2 lessens predation of *Chrysopa sinica* on *Aphis gossypii*. Entomologia Experimentalis et Applicata. 135: 140.

Fornoni, J., Valverde, P.L. and Nunez-Farfan, J. (2003). Quantitative genetics of plant tolerance and resistance against natural enemies of two natural populations of *Datura stramonium*. Evolution Ecology Research. 5: 1049-1065.

Guo, H., Sun, Y., *et al.* (2012). Elevated CO_2 reduces the resistance and tolerance of tomato plants to *Helicoverpa armigera* by suppressing the JA Signaling Pathway. PLoS ONE. 7: e41426. https://doi.org/10.1371/journal.pone.0041426

Guo, H., Sun, Y., Li, Y., Liu, X., Zhang, W. and Ge, F. (2014). Elevated CO_2 decreases the response of the ethylene signaling pathway in *Medicago truncatula* and increases the abundance of the pea aphid. New Phytologist. 201: 279-291.

Halitschke, R. and Baldwin, I.T. (2004). Jasmonates and related compounds in plant insect interactions. Journal of Plant Growth Regulation. 23: 238-245.

Haque, M.D., Shaidul, K.M.D. *et al.* (2005). Effect of elevated CO_2 concentration on growth, chlorophyll content and yield of mung bean genotypes. Journal of Tropical Agriculture. 49: 189-196.

Houghton, J.T., Ding, Y., Griggs, D.J., Noquer, M., Linden, P.J. and Xiaosu, D. (2001). Climate Change: The Scientific Basis. Cambridge University Press, Cambridge, United Kingdom, pp. 944.

Hunter, M.D. (2001). Effects of elevated atmospheric carbon dioxide on insect plant interactions. Agriculture and Forest Entomology. 3: 153-159.

Intergovernmental Panel on Climate Change (2007). Climate Change 2007; The Physical Science Basis. Summary for Policy Makers. Report of Working Group I of the IPCC. http://www.ipcc.ch/pub/spm18-02.pdf.

Intergovernmental Panel on Climate Change (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the IPCC [Pachauri, R.K., Meyer, LA. (eds.)]. Geneva, Switzerland. pp. 151.

Jadesha, G., Sharma, M. and Reddy, N. (2019). Phenotyping techniques for the selection of disease resistance in pigeonpea against *Phytophthora cajani*. Legume Research. 44: 661-666. doi: 10.18805/LR-4139.

Jamieson, M.A., Trowbridge, A.M., Raffa, K.F. and Lindroth, R.L. (2012). Consequences of climate warming and altered precipitation patterns for plant-insect and multi-trophic interactions. Plant Physiology. 160: 1719-1727.

Jat, B.L., Dahiya, K.K., Kumar, H. and Mandhania, S. (2018a). Morphological and chemical traits associated with resistance against spotted pod borer, *Maruca vitrata* in pigeonpea. Indian Journal of Plant Protection. 46: 39-50.

Jat, B.L., Dahiya, K.K., Kumar, H. and Mandhania, S. (2018b). Study of biophysical and structural mechanisms of resistance in pigeonpea against pod borer complex. The Bioscan. 13: 521-528.

Jat, B.L., Dahiya, K.K., Lal, R. and Niwas, R. (2017). Effect of weather parameters on seasonal incidence of pod borer complex in pigeonpea. Journal of Agrometeorology. 19: 255-258.

Jat, B.L., Dahiya, K.K., Yadav, S.S. and Mandhania, S. (2021). Morpho physicochemical components of resistance to pod borer, *Helicoverpa armigera* (Hübner) in pigeonpea [*Cajanus cajan* (L.) Millspaugh], Legume Research. 44: 967-976. doi: 10.18805/LR-4182.

Khadar, A.B., Prabhuraj, A., Rao, S.M., Sreenivas, A.G. and Naganagoud, A. (2014). Influence of elevated CO_2 associated with chickpea on growth performance of gram caterpillar, *Helicoverpa armigera* (Hüb.). Applied Ecology and Environmental Research. 12: 345-353.

Kimball, B.A., Kobayashi, K. and Bindi, M. (2002). Response of agricultural crops to free air CO_2 enrichment. Advances in Agronomy. 77: 293-368.

Leon, H. and Vara, P. (2004). Crop response to elevated carbon dioxide. Encyclopedia of Plant and Crop Science. doi: 10.1081/E-EPCS 120005566.

Lindroth, R.L. (2010). Impacts of elevated atmospheric CO_2 and O_3 on forests: Phytochemistry, trophic interactions and ecosystem dynamics. Journal of Chemical Ecology. 36: 2-21.

Lindroth, R.L., Kinney, K.K. and Cynthia, L.P. (1993). Response of deciduous trees to elevated atmospheric CO_2: Productivity, photosynthesis and insect performance. Ecology. 74: 763-777.

Long, S.P., Ainswoth, E.A., Rogers, A. and Ort, D.R. (2004). Rising atmospheric carbon dioxide: Plants face the future. Annual Review of Plant Biology. 55: 591-628.

Mattson, W.J. (1980). Herbivory in relation to plant nitrogen content. Annual Reviews of Ecological System. 11: 119-161.

McKenzie, B.A. and Andrews, M.S. (2010). Modelling Climate Change Effects on Cool Season Grain Legume Crop Production. LENMOD, A Case Study. In: Climate Change and Management of Cool Season Grain Legume Crops. [Yadav, S.S., McNeil, D.L., Redden R. (eds.)], Springer, Heidelberg/New York, pp. 11-22.

Menendez, R. (2007). How are insects responding to global warming? Tijd voor Entomology. 150: 355-365.

Muzika, R.M. (1993). Terpenes and phenolics in response to nitrogen fertilization: A test of the carbon/nutrient balance hypothesis. Chemoecology. 4: 3-7.

Niziolek, O.K., Berenbaum, M.R. and DeLucia, E.H. (2013). Impact of elevated CO_2 and increased temperature on Japanese beetle. Insect Science. 20: 513-523.

O'Neill, B.F., Zangerl, A.R. *et al.* (2011). Leaf temperature of soybean grown under elevated CO_2 increases *Aphis glycines* population growth. Insect Science. 18: 419-425.

Pande, S. and Sharma, M. (2010). Climate change: Potential impact on chickpea and pigeonpea disease in the rainfed semi-arid tropics (SAT). In: 5th International Food Legume Research Conference (IFLRC V) and 7th European Conference on Grain Legumes (AEP VII), Antalya, Turkey. 26-30.

Parmesan, C., Ryrhlm, N., Stefanescu, C. *et al*. (1999). Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nature. 399: 579-583.

Polle, A., Eiblmeier, M., Sbeppard, L. and Murray, M. (1997). Responses of antioxidative enzymes to elevated CO_2 in leaves of beech (*Fagus sylvatica* L.) seedlings grown under a range of nutrient regimes. Plant Cell and Environment. 20: 1317-1321.

Rao, M.S., Manimanjari, D. *et al*. (2012). Impact of elevated CO_2 on *Spodoptera litura* on peanut, *Arachis hypogea*. Journal of Insect Science. 12: 103.

Rao, M.S., Manimanjari, D. *et al*. (2014). Response of multiple generations of tobacco caterpillar, *Spodoptera litura* feeding on peanut to elevated CO_2. Applied Ecology and Environmental Research. 13: 373-386.

Rao, N.K.S., Hamatha, H. and Laxman, R.H. (2015). Effect of elevated CO_2 on growth and yield of French bean (*Phaseolus vulgaris* L.) genotypes. Legume Research. 38: 72-76. doi: 10.5958/0976-0571.2015.00012.0.

Robinson, E.A., Ryan, G.D. and Newman, J.A. (2012). A meta-analytical review of the effects of elevated CO_2 on plant-arthropod interactions highlights the importance of interacting environmental and biological variables. New Phytologist. 194: 321-336.

Roth, S.K. and Lindroth, R.L. (1994). Effects of CO_2-mediated changes in paper birch and white pine chemistry on gypsy moth performance. Oecologia. 98: 133-138.

Selvaraj, S., Ganeshamoorthi, P. and Pandiaraj, T. (2013). Potential impacts of recent climate change on biological control agents in agro-ecosystem: A review. International Journal of Biodiversity and Conservation. 5: 845-852.

Sharma, H.C. (2010). Effect of Climate Change on IPM in Grain Legumes. In: 5th International Food Legumes Research Conference (IFLRC V) and the 7th European Conference on Grain Legumes (AEP VII), 26-30th April, 2010, Anatalaya, Turkey.

Sharma, H.C. (2014). Climate change effects on insects: implications for crop protection and food security. Journal of Crop Improvement. 28: 229-259.

Sharma, H.C. (2016). Climate Change *vis-à-vis* Pest Management. Proceedings in Conference on National Priorities in Plant Health Management. February 4-5, 2016, Tirupathi, pp. 17-25.

Sharma, H.C. (Ed.) (2005). *Heliothis*/*Helicoverpa* Management: Emerging Trends and Strategies for Future Research. New Delhi, India: Oxford and IBH and Science Publishers, USA. pp. 469.

Sharma, H.C., Pathania, M., War, A.R., Pavani, T., Vashist, S. (2016a). Climate Change Effects on Pest Spectrum and Incidence in Grain Legumes. Pulses: Challenges and Opportunities under Challenging Climatic Scenario [Dixit, G.P., Singh, G., Singh, N.P. (Eds.)]. ICAR-IIPR, Kanpur. pp. 124-137.

Sharma, H.C., War, A.R., Pathania, M., Sharma, S.P., Akbar, S.M.D. and Munghate, R.S. (2016b). Elevated CO_2 influences host plant defense response in chickpea against *Helicoverpa armigera*. Arthropod Plant Interactions. 10: 171-181.

Shwetha, Sreenivas, A.G., Ashoka, J., Nadagoud, S. and Kuchnoor, P.H. (2019). Effect of elevated CO_2 and temperature on biochemistry of groundnut and its effect on development of leaf eating caterpillar, *Spodoptera litura* Fabricius. Legume Research. 42: 399-404. doi: 10.18805/LR-3867.

Srivastava, A.C., Tiwari, L.D., Pal, M. and Sengupta, U.K. (2002). CO_2-mediated changes in mungbean chemistry: Impact on plant-herbivore interactions. Current Science. 82: 1148-1151.

Sterner, R.W. and Elser, J.J. (2002). Ecological Stoichiometry: The Biology of Elements from the Molecules to the Biosphere. Princeton University Press, Princeton, USA. pp. 439.

Stitt, M. and Krapp, A. (1999). The interaction between elevated CO_2 and nitrogen nutrition: The physiological and molecular background. Plant, Cell and Environment. 22: 583-621.

Strauss, S.Y. and Agrawal, A.A. (1999). The ecology and evolution of plant tolerance to herbivory. Trends in Ecology and Evolution. 14: 179-185.

Sun, Y.C., Cao, H.F., Yin, J., Kang, L. and Ge, F. (2010). Elevated CO_2 changes the interactions between nematode and tomato genotypes differing in the JA pathway. Plant, Cell and Environment. 33: 729-739.

Tyler, J.M. and Hatchett, J.H. (1983). Temperature influence on expression of resistance to Hessian fly (Diptera: Cecidomyiidae) in wheat derived from *Triticum tauchii*. Journal of Economic Entomology. 76: 323-326.

War, A.R., Hussain, B. and Sharma, H.C. (2013). Induced resistance in groundnut by jasmonic acid and salicylic acid through alteration of trichome density and oviposition by *Helicoverpa armigera*. AoB Plants. 5. plt053; doi:10.1093/aobpla/plt053.

War, A.R., Paulraj, M.G., Tariq, A., Buhroo, A.A., Hussain, B., Ignacimuthu, S. and Sharma, H.C. (2012). Mechanisms of plant defense against insect herbivores. Plant Signal Behavior. 7: 1306-1320.

War, A.R., Taggar, G.K., War, M.Y. and Hussain, B. (2016). Impact of climate change on insect pests, plant chemical ecology, tritrophic interactions and food production. International Journal of Climate and Biological Sciences. 1: 16-29.

Wu, G., Chen, F.J. and Ge, F. (2006). Response of multiple generations of cotton bollworm, *Helicoverpa armigera* Hubner, feeding on spring wheat, to elevated CO_2. Journal of Applied Entomology. 130: 2-9.

Yadugiri, V.T. (2010). Climate change: The role of plant physiology. Current Science. 99: 423-425.

Yifei, Z., Yang, D., Guijun, W., Bin, L., Guangnan, X. and Fajun, C. (2018). Effect of elevated CO_2 on plant chemistry, growth, yield of resistant soybean and feeding of a target *Spodoptera litura*. Environmental Entomology. 47: 848-856.

Zavala, J.A., Casteel, C.L., DeLucia, E.H. and Berenbaum, M.R. (2008). Anthropogenic Increase in Carbon Dioxide Compromises Plant Defense against Invasive Insects. Proceedings of National Academy of Science USA, 105: 10631-10631.

Zavala, J.A., Casteel, C.L., Nabity, P.D., Berenbaum, M.R. and DeLucia, E.H. (2009). Role of cysteine proteinase inhibitors in preference of Japanese beetle (*Popillia japonicum*) for soybean (*Glycine max*) leaves of different ages and grown under elevated CO_2. Oecologia. 161: 35-41.

Zhu, Y., Qian, W. and Hua, J. (2010). Temperature modulates plant defense response through NB-LRR proteins. PLoS Pathogens. 6: 1-12.