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Response of weeds under elevated CO_2 and temperature: A review

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Abstract
Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Under changing climate, high temperature and elevated CO_2 are predicted to increase in frequency, causing serious challenges to sustain global food security. Among the 86-plant species which supply most of the world's food, only five are C_4 species. Among 18 most troublesome weeds in the world, 14 are C_4 species. Most of troublesome weeds species are C_4, while most major crops areC_3photosynthetic pathway. Various studies revealed that both crops and weeds respond to changing climate scenario. Weeds comes under C_3 pathway may dominate under elevated CO_2 conditions, whereas in elevated temperature, C_4 weeds may dominate. The interactive effect of elevated CO_2 and temperature showed that C_4 weeds dominate over C_3 weeds. Crop-weed competition was low at elevated CO_2 whereas high under elevated temperature. The interactive effect of elevated CO_2 and temperature on crop-weed competition was high. Hence, weed management is considered as a major threat to future agriculture.

Keywords: Climate change, Elevated CO_2, Elevated temperature, Crop weed competition, Weed invasion

1. Introduction
Climatic changes and increasing climatic variability are likely to enhance the problem of future food security by exerting pressure on agriculture. For the past few decades, the gaseous composition of earth's atmosphere is undergoing a considerable change, mainly through increased emissions from energy, industry and agriculture sectors, widespread deforestation as well as fast changes in land use and land management practices. Weeds are usually known as plants that interfere in growth, yield and production of cropping systems. Weeds, due to their competition with crops for soil and water resources, cause reduction of yield, quality and land value. Weeds are the major pests that cause largest yield reductions (Dass *et al*., 2017) [9]. Weeds causes 37% of total losses in agricultural production against 29% losses caused by insects, 22% by diseases and 12% by other pests (Yaduraju, 2007) [30]. Furthermore, weeds could be act as a host for pest and diseases and increase their control complexities.
Climate change also influences weeds indirectly by enforcing adaptations of farming methods such as choice of crop, sowing time, harvesting date, and other agronomical practices to these alterations (Fleming and Vanclay, 2010) [11]. Climate change may bring changes in weed population and their phenology. Many weed species may expand their range and spread to new areas. One of the important agricultural aspects which influenced from CO_2 elevation is weed-crop competition. Most `troublesome' weedy species are C_4 plants, while most major crops are C_3 plants (Patterson, 1995) [24]. For example, among the 18 most troublesome weeds in the world (Holm *et al*., 1977) [13], 14 are C_4, whereas of the 86-plant species which supply most of the world's food, only five are C_4 species (Patterson, 1995) [24].Under changing climate, high temperature and elevated $CO_2$are expected to increase in frequency, causing serious challenges global food security. The effect of increased levels of CO_2 on plants has been intensively studied (Rogers *et al*., 2008) [26]. Fewer studies have been done on the effect of climate change on weeds in India. Hence, the aim of this review paper is to address the response of weeds under changing climatic scenario.

2. Major weed flora in India
Major weed species prevalent in India are *Phalaris minor*, *Avenafatua*, *Chenopodium album, Convolvulus arvensis, Cirsium arvense* and *Plantagolanceolata* having C_3 photosynthetic pathways. Weed species like, *Amaranthus viridis*, *Dactyloctenium aegyptium, Echinochioacrusgalli, Leptochloachinensis, Trianthemaportulacastrum, Cynodondactylon* and *Cyperus species* are under C_4 photosynthetic pathways and the list of major C_3 and C_4 weeds,

their common name, family and characteristics are presented in table 1 (Jinger *et al.*, 2017) [16].

3. Climate change scenario in global and India

Current global climate models predict a mean increase in global temperature is 1.0 - 3.7 °C at the end of the 21st century (Stocker *et al.*, 2013) [28]. Around 9 out of the 10 warmest years after 1880 have occurred during the last decade (2000 – 2010), negatively affected global food production (Mittler *et al.*, 2012) [19]. For the past 15 years, 13 years recorded as a warmest year (2002-2017).Annual mean temperature in India has increased by about 1.2 °C since the beginning of the 20th century. The highest annual mean temperature25.12 °C in India was registered during 2016. The winter of 2016-17, the mean temperature was 2.95 °C higher than the baseline-the warmest in recorded history. The CO_2 concentration increment was 2ppm/year during past three years (Nalli *et al.*, 2018) [22]. Steady increase in atmospheric CO_2 concentration is noted and predicted to reach 700 pp mat the end of the 21st century.

4. Impact of climate change on weeds

The impacts of climate change on single species and ecosystems are likely to be complex. Weed populations include individuals with the ability to adapt and flourish in different types of habitats. Any factor which increases environmental stress on crops may make them more vulnerable to attack by insects and plant pathogens and less competitive with weeds. The physiological plasticity of weeds and their greater intra specific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment events such as cyclones, flooding, drought and fires (from high temperature) will become more common and weeds will be the first to gain a stronghold after these events (Singh *et al.*, 2011) [27].

Table 1: Major weed species under C_3 and C_4 photosynthetic pathway in India

Major weeds	Common name	Family	Characteristics
C_3 weeds			
Agropyronrepens	Quack grass	Poaceae	Perennial grass herb
Argemonemexicana	Mexican poppy	Papaveraceae	Annual broad-leaved herb
Ageratum conyzoides	Billgoatweed	Asteraceae	Annual broad-leaved herb
Avenafatua	Spring wild oat	Poaceae	Annual grass herb
Abutilon theophrasti	Velvet leaf	Malvaceae	Annual broad-leaved herb
Ammaniabaccifera	Red stem	Lythraceae	Annual broad-leaved herb
Commelinabenghalensis	Day flower	Commelinaceae	broad-leaved grass herb
Chenopodium album	Common lambsquaters	Chenopodiaceae	Annual broad-leaved herb
Cassia obtusifolia	Sicklepod	Fabaceae	Annual broad-leaved herb
Cirsium arvense	Canada thistle	Asteraceae	Perennial broad-leaved herb
Convolvulus arvensis	Field bind weed	Convolvulaceae	Perennial broad-leaved twining stem
Datura stramonium	Thorn apple	Solanaceae	Annual broad-leaved under-shrub
Ecliptaprostrata	False daisy	Asteraceae	Annual broad-leaved herb
Eichhorniacrassipes	Water hyacinth	Pontederiaceae	Aquatic broad-leaved grass herb
Loliumperene	Rye grass	Poaceae	Perennial grass herb
Plantagolanceolata	Buckhorn	Plantaginaceae	Annual broad-leaved grass herb
Phalaris minor	Little seed canary grass	Poaceae	Annual grass herb
Poaannua	Blue grass	Poaceae	Annual grass herb
Rumexacetosella	Red sorrel	Polygonaceae	Annual broad-leaved herb
Striga asiatica	Witch weed	Scrophulariaceae	Parasitic weed herb
Solanum nigrum	Black nightshade	Solanaceae	Annual broad-leaved herb
C_4 weeds			
Andropogonvirginicus	Broom sedge	Poaceae	Monocot grass weed
Amaranthus retroflexus	Redroot pig weed	Amaranthaceae	Annual broad-leaved herb
Atriplex spongiosa	Saltbush	Amaranthaceae	Annual herb/sub-shrub
Boerhaviadiffusa	Hogweed	Nyctaginaceae	Perennial broad-leaved herb
Cyperus rotundus	Purple nutsedge	Cyperaceae	Perennial herb
Cyperus iria	Flatsedge	Cyperaceae	Annual herb
Cynodondactylon	Bermuda grass	Poaceae	Perennial herb
Dactylocteniumaegyptium	Crowfoot grass	Poaceae	Annual herb, creeping/erect branches
Digitariaciliaris	Large crabgrass	Poaceae	Annual spreading grass herb
Eleusineindica	Goose grass	Poaceae	Annual erect tufted grass
Euphorbia hirta	Garden spurge	Euphorbiaceae	Annual herb, deep rooted
Echinochioacrusgalli	Barnyard grass	Poaceae	Annual grass herb
Imperatacylindrica	Congo grass	Poaceae	Perennial grass
Leptochloachinensis	Sprangletop	Poaceae	Annual grass herb
Monochoria vaginalis	Monochoria	Pontederiaceae	Annual aquatic broad-leaved grass
Portulaca oleracea	Common purslane	Portulacaceae	Annual herb
Rottboelliacochinchinensis	Itch grass	Poaceae	Annual grass herb
glauca Setaria	Yellow foxtail	Poaceae	Annual grass herb
Saccharum spontanium	Tiger grass	Poaceae	Perennial grass/under-shrub
Sorghum halepense	Jhonson grass	Poaceae	Perennial grass
Trianthemaportulacastrum	Horse purslane	Aizoaceae	Annual broad-leaved herb

5. Elevated CO_2 concentration

CO_2 is the sole source of carbon for photosynthesis of crop plants. The United Nations Intergovernmental Panel on Climate Change (UN-IPCC) predicts that atmospheric CO_2 concentration could exceed 700 ppm by the end of 21st century (Houghton *et al*., 1996) [14]. Due to the ongoing increases in atmospheric CO_2, there would be stimulation in leaf photosynthesis in C_3plants by increasing the CO_2 level in the leaf interior and by decreasing the loss of CO_2 by photorespiration. The C_4 plants, however, have internal biochemical pump for concentrating the CO_2 at carboxylation site that reduces the oxygenase component of the rubisco, thereby eliminating the carbon loss by photorespiration (Naidu, 2013) [20].

The current atmospheric CO_2 concentration is sub-optimal for photosynthesis in C_3 plants. However, plants with C_4 photosynthetic pathway have an internal mechanism for concentrating CO_2 at the site of fixation (Acock, 1990) [1]. Photorespiration is one reason why C_3 crops exhibit lower rates of net photosynthesis than C_4 crops, at ambient CO_2. However, due to the same reason, C_3 species will respond more favourably to elevated CO_2 levels, because CO_2 tends to suppress photorespiration. In C_4plants, the internal mesophyll cell arrangements are different to those of C_3 plants, making efficient transfer of CO_2 possible, and this minimizes photorespiration and favours photosynthesis (Drake *et al.*, 1997) [10]. Plants with C_3 photosynthetic pathways are expected to benefit more than C_4 from CO_2 enrichment (Patterson and Flint, 1980) [25]. Hence, many weeds species are under C_4photosynthetic pathway, they showed smaller response to elevated CO_2 relative to crops which are mostly C_3.

The crops come under C_3 pathway such as rice and wheat, response to elevated CO_2 may have positive effects on crop competitiveness with C_4 weeds (Yin and Struik, 2008; Fuhrer, 2003) [31, 12]. Elevated CO_2influences some physiological changes in plants like higher photosynthesis, increased leaf area and mass per unit area, increased tillering, high water use efficiency, advanced flowering, increase number of grains/ spiklets, grain weight, grain yield and harvest index(Jagadish *et al.*, 2011) [15]. It had been reported that doubling ambient CO_2 levels stimulated biomass yield of C_3 plants by 40% and C_4 plants by 11% (Kimball, 1983) [17]. The wild oat grown at 480 ppm CO_2 produced 44% more seed than those grown at 357 ppm (O'Donnell and Adkins, 2001) [23]. Ziska *et al*. (2010) [35] found that rice biomass increased with increase in CO_2 from 300 to 400 ppm but did not increase further with increase in CO_2 to 500 ppm. Elevated CO_2 has been shown to increase growth and biomass accumulation of the C_4 weed *Amaranthus viridis* (Naidu, 2013) [20]. Under present CO_2 levels, C_4 plants are more photosynthetically efficient than C_3 plants. It is also possible that in a CO_2 enriched atmosphere, important C_4 crops may become more vulnerable to increased competition from C_3weeds (Jinger *et al.*, 2017) [16].

6. Elevated temperature

Duration of plants in particular area is determined by prevailing temperature. Climate change projections suggested that 2.4-6.4ºC increase of global average temperature by the end of 21st century (Metz *et al.,* 2007) [18]. Changes in temperature generally affect the length of growing period in plants. Elevated temperature influences some physiological changes in plants like damage to photosynthetic apparatus, higher oxidative stress and membrane damage, shorter vegetative phase, reduced tillering, inadequate assimilate availability, decrease in duration and rate of spikelet production, reduced grain filling and grain weight (Jagadish *et al.,* 2011) [15].

As mean temperatures increase, weeds expand their range into new areas. Under high temperature, plants with C_4 photosynthesis pathway (mostly weeds) have a competitive advantage over crop plants possessingC_3 pathway (Yin and Struik, 2008) [31]. Based on the differences in temperature, C_4 species will be able to tolerate high temperature than C_3 species. Therefore, C_4 crops may benefit more than the C_3 crops from any temperature increase (Ziska and Bunce, 1997) [33]. Wild oat grown at high temperature 23/19 ºC (day/night) completed their development faster than those grown at normal temperature 20/16ºC. If the maturation rate is faster relative to the crop, more seeds may be deposited in the soil with a consequent increase in seed bank of wild oat plants (O'Donnell and Adkins, 2001) [23]. Tunget *et al.,* (2007) [29] studied the effect of temperature on soybean, *Sida spinosa* (prickly sida) and *Cassia obustutifolia* (sicklepod) and reported that there was an increasing trend in root: shoot ratio in all species with increasing temperatures, however, the weeds consistently had higher root: shoot ratios. At temperatures where maximum growth occurred, the root: shoot growth ratio of soybean (at 32/27ºC) was 0.8, and it was 1.3 and 1.6 for *Sida spinosa* (at 36/31 ºC), and *Cassia obustutifolia* (at 36/31ºC), respectively.

7. Elevated CO_2 and temperature

Atmospheric CO_2 and air temperature raising together, studied in these effects are very limited. Most studies have focused mainly on the response of plant species to elevated CO_2. The outcome can be totally different when both factors are taken together compared to when consider only one factor**.** Plant response to the interaction effect of CO_2 and temperature may be complex (Bazzaz, 1990) [4]. Plants with C_3 photosynthetic pathways are expected to benefit more than C_4 from CO_2 enrichment (Patterson and Flint, 1980) [25]. Under high temperature, plants with C_4 photosynthesis pathway (mostly weeds) have a competitive advantage over crop plants of C_3 pathway (Yin and Struik, 2008) [31]. Based on the differences in temperature optima for physiological processes, it is predicted that C_4 species will be able to tolerate high temperature than C_3 species. Therefore, C_4 weeds may benefit more than the C_3 crops from any temperature. The plant comes underC_4 photosynthesis is usually not affected by atmospheric CO_2 enhancement (Carter and Peterson, 1983) [7]. At the same time elevated temperatures can override the stimulating effects of CO_2 on photosynthesis of C_3 plants (Batts *et al*., 1997) [3]. Hence, the interactive effect of elevated CO_2 and temperature increases the competitive ability of C_4 weeds than C_3 weeds.

8. Crop weed competition under elevated CO_2 and temperature

The impact of climate change on crop-weed interactions are likely to vary by region and crop type. As the crop-weed interactions are balanced by various environmental factors, local changes in these factors may alter the balance towards either crop or weed. Changes in temperature and carbon dioxide are likely to have significant direct (CO_2 stimulated growth) and indirect (climatic variability) effects on weeds and that would affect crop-weed balance or lead to weed invasion. This differential response of C_3 and C_4 plants to elevated CO_2 and temperature can have important implications on crop-weed competition. For a C_3 crop, such as rice and wheat, elevated CO_2 may have positive effects on crop competitiveness with C_4 weeds (Yin and Struik, 2008; Fuhrer, 2003) [31, 12]. Alberto *et al.,* (1996) [2] suggest that competitiveness could be enhanced in C_3 crop (rice) relative to a C_4 weed (*Echinochloaglabrescens*) with elevated CO_2 alone but simultaneous increases in CO_2 and temperature still favour C_4 species. Plants with C_3 photosynthetic pathways are expected to benefit more than C_4 from CO_2 enrichment (Patterson and Flint, 1980) [25].

Ziska (2000) [32] reported soybean biomass (32%) and yield (23%) increased at elevated CO2 (ambient + 250 ppm) when grown in mono-culture. But when soybean was grown in competition with *Chenopodium album* (C3 weed), soybean biomass and yield reduction increased from 23% and 28% at ambient CO_2 to 34 and 39% at elevated CO_2, respectively due to 65% increase in *C. album* dry weight. Conversely, soybean yield diminished from 45% to 30% at elevated CO_2 compared to ambient CO_2 when grown in competition with *A. retroflexus*. These results suggest that under elevated CO_2, *C. album* would be benefited more than soybean and could become more dominating weed. In contrast, *A. retroflexus* would be less benefitted with rising CO_2 and soybean will likely have competitive edge when grown in competition with this species. In various crop-weed competition studies, where the photosynthetic pathway is the same, weed growth is favoured as CO_2 is increased. Therefore, C_3 weeds like *P. minor* and *A. ludoviciana* in wheat (C_3) would aggravate with the increase in CO_2 due to climate change (Naidu, 2013) [20]. Red rice responded linearly in terms of biomass as well as seed production. These results suggest that under elevated CO_2 concentrations, red rice will be more competitive than rice and will produce more seeds than at current CO_2 concentration

Weed competition will consequently decrease with increasing atmospheric CO_2in C_3plants. At the same time raising temperature override the stimulating effect of CO_2 in C_3plants. Weed competition increases with increasing atmospheric CO_2 and temperature. In general, under elevated CO_2, when weed is C_4 and crop is C_3, crop is likely benefitted, whereas in all other cases weeds will get competitive advantage over crop. The crop-weed competition of different crops and weeds under elevated CO_2 is presented in (table 2) (Bunce and Ziska, 2000) [6].

Table 2: Crop-weed competition under elevated CO_2 conditions

Weed species	Crop	Favored under elevated CO2
Amaranthus retroflexus(C_4)	Soybean (C_3)	Crop
Amaranthus retroflexus(C_4)	Sorghum (C_4)	Weed
Chenopodium album (C_3)	Soybean(C_3)	Weed
Taraxacumofficinale(C_3)	Lucern (C_3)	Weed
Albutilontheophrasti(C_3)	Sorghum (C_4)	Weed
Taraxacum and Plantago(C_3)	Grasses (C_3)	Weed
Red rice (C_3)	Rice (C_3)	Weed
Echinochloaglabrescens(C_4)	Rice (C_3)	Weed

9. Climate change and weed invasion

Climate change is expected to increase the risk of invasion by weeds from neighbouring territories. With the competitive ability, weeds often find an opportunity to establish new populations when natural or desirable plant species decline. Climate change may also favour expansion of weeds that have already established, but are currently restricted in range. The range expansion can be attributed to evolutionary adaptation (Clements and Ditommaso, 2012) [8]. Warmer temperature will force some species to relocate, adapt or perish. Species which are active in summer will develop faster. Warmer climate restricts temperature sensitive species to high altitudes. In plains, this effect on distribution range is magnified because species without the ability to move to higher elevations must relocate further in the same altitude (Naidu, 2015) [21].

In fact, climate change may favour certain native plants to such an extent that they then become weeds. Alien weeds are usually non-native, whose introduction results in wide-spread economic or environmental consequences (e.g. *Lantana camara, Parthenium hysterophorus*, *Eichhorniacrassipes* etc. in India). These weeds have strong reproductive capability and are better dispersers and breeders. With these characteristics, they are benefitted from climate change. Studies indicated that these weeds showed a strong response to increases in atmospheric CO_2 (Ziska *et al.*, 2004) [34]. From the studies conducted at the Directorate of Weed Research, Jabalpur, India it was observed that the invasive weed *Parthenium hysterophorus* had shown tremendous growth response to elevated CO_2 (Naidu, 2013) [20]. Hence, the possibility that the recent increase in CO_2 during 20th century may have been a factor in the invasiveness of this species. (Bradley *et al.*, 2010) [5] Reported that the risk of invasiveness was higher under elevated CO_2 whereas elevated temperature it might be increase or decrease.

10. Conclusion

In conclusion, increasing temperature and elevated CO_2 are the important issues of changing climate with pronounced impacts on agriculture ecosystems in general and weed species specifically. In various studies, it is confirmed that both crops and weeds respond to changing climate scenario. Weeds comes under C_3pathway dominates under elevated CO_2 conditions, whereas C_4 weed may dominate under elevated temperature. The interactive effect of elevated CO_2 and temperature showed that C_4 weeds dominate over C_3weeds. Crop weed competition was below at elevated CO_2 where as high under elevated temperature alone as well as the interactive effect of elevated CO_2 and temperature. Hence, weed management will be a serious issue in future agriculture.

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