EMERGING WEED PROBLEMS UNDER CHANGING CLIMATIC CONDITION : A REVIEW

Abstract

Climate is a major force in earth’s environmental system, and even minor changes in climate can have complex and serious effects on the environment. Atmospheric CO_2, temperature and precipitation are major important abiotic variables that directly affect weed physiology and growth. Weeds are more genetically diverse than crops, hence show enhanced growth and reproductive stability than crops. Among the C3 and C4 weeds in cropped field, C3 weeds have more response in photosynthesis to increased CO_2 level in atmosphere. The elevated CO_2 under sufficient soil moisture condition will leads the higher C3 weed competitiveness in C4 crops. So weed growth is favoured as CO_2 is increased. Temperature changes resulted in an expansion of weeds, and shifting of weeds. Based on the differences in temperature, the C4 *spp*. able to tolerate high temperature than C3 *spp*. Therefore, C4 weeds benefit more than the C3 crops from temperature increases that accompany elevated CO_2 levels. Due to global warming, weeds expand their range into new areas. Precipitation is also one of the important climate variable that influences the growth and distribution of weeds growth. Even though CO_2 concentration level and temperature rise in future are predictable, amount, distribution, and intensity of rainfall patterns remains much more uncertain. Moisture is a key factor required for weed seed germination, growth and development. Climate change can affect the frequency and intensity of rainfall and result in occurrences of extreme events such as floods and droughts; consequently, weeds adapted to these conditions will have a higher competitive advantage.

Key words: *Climate change, elevated CO_2, Temperature, Precipitation, C3 and C4 weeds*

Introduction

The difficult of climate change is increasingly more receiving attention from scientists, public peoples, and policy makers (Petit *et al*., 1999; Loss *et al*., 2011; Seddon *et al*., 2021). Climate change is now a broadly accepted term, Climate change refers to “long-term shifts in temperatures and weather patterns” (Robinson and Gross, 2010). The atmospheric CO2 concentration has risen from about 280 ppm (pre-industrial period) to today’s about 390 ppm and it is expected that by the end of 21st century, it will reach to the levels of 600-700 ppm, if current emission trends continue (Leegood, 2002; IPCC, 2022). The carbon dioxide concentration is expected to rise 1.1 to 6.4°C, causing the earth's surface temperature to rise 1.1 to 6.4°C. (Houghton, 2001, IPCC, 2022;). Through global warming, as well as its associated changes in climate such as altered precipitation patterns, wind patterns, sea level rise, and flood and drought more frequently, global CO_2 enrichment is thought to influence the drymatter of weeds and crop yields directly (Zhu *et al*., 2016; Clements &

DiTommaso, 2022). It has been reported that elevated CO_2 concentration cause an increases in photosynthesis (Kendall *et al.*, 1985; Ghannoum *et al.*, 2000; Dass *et al.*, 2017), decrease in photorespiration and respiration (Ziska, 2000), different crop and weed species differ in their response to elevated CO_2 concentration levels (Poorter, 1993).

The various responses of C3 and C4 plants (weeds & crops) to elevated CO_2 and air temperature have important implications on crop/weed competition as most of the weeds are C4. However, since most crops have C3 photosynthesis while most weeds have C4 photosynthesis, weeds are mature and decay as before, and therefore weeds are as ripe as earlier. (Ziska, 2003; Pautasso *et al.*, 2010; Singh *et al.*, 2011). Evidently, there are four major C4 crops of economic importance (Maize, Pearl millet, Sorghum, and Sugarcane), and many important C3 weeds (e.g. *Chenopodium album, Avena ludoviciana, Phalaris minor, Eclipta prostrate, Ammania baccifera* etc.). CO_2 enrichment generally benefits plants with C3 photosynthetic pathways more than those with C4 pathways, however this is reversed with increasing temperatures. (Jinger *et al.*, 2016).

As a result of climate change, weed populations and phenology may change (Patterson, 1995). Many weed species may expand their range and spread to new areas. Literature also suggests that invasive species may become more problematic in changing climate since they respond strongly to elevated CO_2 and climate change compared to other native species (Marambe, B. & Wijesundara, S. 2021).

As well as some weed species causing allergic reactions, skin irritations, or internal poisoning, some weed species have produced a greater amount of plant biomass, pollens, or poisonous compounds in response to the changing climate, particularly to elevated CO2 levels. (Dukes *et al.*, 2009; Singer *et al.*, 2013). A wider gene pool in weeds, compared to crops, may allow them to adapt to diverse environmental conditions due to their greater sensitivity to temperature increases (Treharne, 1989). Increasing temperature stimulates photosynthetic activity and growth in C3 and C4 plants, respectively (Morgan *et al.*, 2001).

Precipitation is another important climate variable that influences the growth and distribution of vegetation. (Lobell and Burke, 2008; Robinson and Gross, 2010). Although CO2 concentrations and temperature rise in future are predictable, distribution and variation in the intensity of precipitation patterns remains much more uncertain. In order for weed seeds to germinate and establish, moisture is crucial (Skov and Svenning 2004; Bergmann *et al.*, 2010). Floods and droughts can occur due to climate change, and therefore, weeds that are adapted to these conditions will have an advantage over weeds that are not adapted to these conditions (Rodenburg *et al*., 2011). Finally, the present reviews covered a weed emergence problem under changing climatic condition. Further investigations and research areas are needed in this concern.

Characteristics of weeds

In this globe totally 46 major crops are there but, over 410 "serious" weed species.

1. Weed plants produces larger number of seeds compare to crops
2. Most of the weed seeds are small in size and contribute enormously to the seed reserves.
3. Weed seeds germinate earlier and their seedlings grow faster than crop seeds.
4. The viability of seeds remains intact, even if they are buried deep in the soil.
5. Weed seeds do not lose their viability for years even under adverse conditions.
6. They flower earlier and mature ahead of the crop they infest.
7. The seeds germinate under varied conditions, but are typically season-bound. The peak period of germination always takes place in certain seasons year after year.
8. Weed seeds possess the phenomenon of dormancy
9. Most of the weeds possess C4 type of photosynthesis, which is an added advantage during moisture stress.
10. They possess extensive root system, which go deeper as well as of creeping type.
11. Quick response to available soil moisture and nutrients.
12. Tolerance to shading effects by the crops at the time of establishment
13. Mimicry: Resembles the crop plants, morphological characters are similar to the crop Plants.
14. There are no geographical boundaries to weed dispersal. Common agents of weed dispersal are wind, water, animals, birds, organic manures, agriculture implements and human beings.

Climate change on weeds

The main parameters for climate change impacts on weeds include increased atmospheric CO_2 levels, temperatures, changed rainfall, more extreme weather, more frequent frosts, changed phenology and changed land use (Patterson, 1995; Ziska, 2016). The rate of response of invasive plants and weeds is expected to be faster than for other plants, including native species and crops. Additionally, climate change is likely to lead to the emergence of new weed species (Dukes *et al*., 2009; Singer *et al*., 2013).

Changes in atmospheric CO_2, temperature, rainfall, and wind will impact the distribution, growth, and physiology of weed species, as well as their predominance in weed and crop communities. These changes will also disrupt the crop-weed balance and encourage weed invasion. (Patterson, 1995; Ramesh *et al*., 2017; Anwar *et al*., 2021).

Impact of climate change on weed biology (Ziska, 2000) & (Bradley *et al*., 2010)

- Weed shifts and spread of invasive species
- Elevated CO_2 and its effects on weeds
- Effect of increased temperature on weeds
- Effect of change in precipitation on weeds
- Other environmental stresses and weed competitiveness.

Table 1: Impact of climate change on risks of invasiveness (Bradley *et al*., 2010)

Climate change factor	**Risks of invasiveness**
Elevated CO_2	Increase
Rising temperature	Might increase or decrease
Changing precipitation regime	Might increase or decrease

Impacts (Reddy, *et al*., 2010)

1. Increased CO_2: Promotes Photosynthesis, Growth, Lowers evapotranspiration, and Increases water use efficiency
2. With considerable drops in the yields of rival crops, many C3 weeds have demonstrated noticeable growth.
3. Increasing CO_2 levels have a favourable impact on the spread and persistence of invasive species (*Bromus tectorum*).

Weeds response to increasing of CO_2 levels (Elevated atmospheric CO_2)

Weeds have greater genetic diversity than crops. Due to increased efficiency of plant growth, weeds will often show a greater growth response if one of the environment's resources (light, water, nutrients, or carbon dioxide) changes. (Ziska, 2008). The interplay between CO_2 and growth is greatly controlled by the photosynthetic mode of the plant, and some plants (C4 and CAM), including many grasses and succulents, capture more energy than others (C3). (Patterson, 1995; Batts *et al.*, 1997; Morison and Lawlor, 1999; (Chauhan *et al.*, 2017).

Many of the weed species have the C4 photosynthetic pathway. However, this argument does not consider the range of available C3 and C4 weeds present in any agronomic environment. Therefore, if a C4 weed species does not respond, it is likely that a C3 weed species will (Morison and Lawlor, 1999). Additionally, a lot of farmers are aware that the worst weeds for a particular crop have similar growth patterns or a similar photosynthetic pathway; in fact, they are frequently the same uncultivated or "wild" species, such as red rice and white rice, sorghum, and wild oats. Weed growth is favoured when CO_2 levels rise in all studies of weed/crop competition to date where the photosynthetic pathway is the same. (Carter and Peterson 1983; Ziska, 2003).

The direct physiological effects of elevated CO_2 on photosynthesis and plant growth are well documented. As opposed to plants with C4 photosynthetic pathways, it is projected that plants with C3 photosynthetic pathways will gain more from CO_2 enrichment. (Patterson and Flint, 1980). Since most weeds are C4 plants, crop/weed competition may be significantly impacted by the differences in how C3 and C4 plants respond to elevated CO_2. It can therefore be suggested that many weed species will react to rising CO2 less strongly than crops, which largely use the C3 photosynthetic pathway. (Zangerl and Bazzaz, 1984; Ziska, 2003; Rogers *et al.*, 2008). To create successful weed management strategies for new species in the context of a changing climate, it is crucial to analyse crop/weed competition in cropping systems.

CO_2 versus Weeds in India

Common weeds species found in India such as *Ageratum conyzoides*, *Digitaria ciliaris*, *Cyperus spp.*, *Echinochloa colona*, *Paspalum orbiculare* and *Setaria glauca* and having C4 photosynthetic pathway will show smaller response in photosynthesis to increased CO_2 level in atmosphere (Singh *et al.*, 2011).

While some weed species, such as *Agropyron repens, Argemone mexicana, Chenopodium album, Phalaris minor, Poa annua, and Rumex acetosella,* may exhibit enhanced photosynthesis in response to elevated CO_2 levels in the atmosphere, many of the worst weeds for a given crop share similar growth habits or photosynthetic pathways, such as oats and wild oats, wheat and little seed canary grass (Patterson, 1985; Patterson, 1995; Mishra, 2003; Tang *et al.* 2009; Chandrasena, 2009; Singh *et al*., 2011).

Table 2: Important C3 and C4 weed species of rice and wheat crops in India (Singh *et al*., 2011)

Crop	C3 weeds	C4 weeds
Rice	*Oryza sativa f. spontanea* *Scirpus spp,* *Monochoria,* *Eclipta prostrata,* *Ammania baccifera*	*Echinochloa spp,* *Cyperus spp.,* *Leptochloa chinensis,* *Bracharia*
Wheat	*Chenopodium album,* *Phalaris minor,* *Avena fatua,* *Convolvulus arvensis,* *Canada thistle*	*Cynadon dactylon*

Table 3: Response of C3 and C4 weeds to double atmospheric CO_2 levels (Chandrasena, 2009)

Sn.	C3	Range of response biomass	C4	Range of response biomass
1	*Abutilon theophratsii*	1.0-1.52	*Amaranthus retroflexus*	0.9-1.41
2	*Bromusmollis*	1.37	*Andropogon virginius*	0.8-1.17
3	*Bromustectorum*	1.54	*Cyperus rotundus*	1.02
4	*Cassia obtusifolia*	1.4-1.8	*Digitaria ciliaris*	1.06-1.6
5	*Chenopodium album*	1.0-1.6	*Echinochloa crusgalli*	0.95-1.6
6	*Datura stramonium*	1.7-2.27	*Eleusine indica*	1.02-1.8
7	*Phalaris aquatica*	1.48	*Sorghum halepens*	0.56-1.1

Table 4: Shift in weed flora in India (Tang *et al.* 2009)

Crop	Original weed flora	New weed flora
Wheat (first phase)	*Chenopdium spp.,* *Spergula arvensis,* *Anagallis arvensis*	*Phalaris minor,* *Avena fatua,* *Lolium temulentum*

Wheat (Second phase)	*Phalaris minor,* *Avena fatua*	*Lathyrus aphaca,* *Convolvulus arvensis,* *Medicago spp.,* *Cirsium arvense*
Rice	*Echinochloa spp.*	*Cyperus iria,* *Fimbistylis miliacea,* *Sphenoclea zeylanica*
Sugarcane	Broadleaved weeds	Grassy weeds

Rice, wheat, soybeans, and other C3 crops have better photosynthetic rates at raised CO2, which means they will react to rising CO_2 levels more favourably than C4 weeds like kochia (*K. scoparia*), water hemp (*Amaranthus rudis*), and palmer amaranth (*A. palmeri*). (Elmore and Paul, 1983). The C3 weeds, on the other hand, such as lambsquarters, velvetleaf (*Abutilon theophrasti*), common ragweed (*Ambrosia artemisiifolia*), and giant ragweed (*Ambrosia tricda*), will react more favourably to elevated CO2 levels and pose a more serious threat to C4 crops like Corn, Sorghum, Sugarcane, etc. (Tang *et al.* 2009)

C3 weeds in C4 crops

- Increased C3 weed aggressiveness in C4 crops will result from elevated CO_2 under adequate water conditions. At high CO_2 level, C3 weeds significantly decreased sorghum seed production or total aboveground biomass. (Ziska, 2003; Siddiqui *et al.*, 2022).
- C3 weed dandelion (*Taraxacum officinale*) produced more fertile seeds and larger seedlings under elevated CO_2 (McPeek and Wang, 2007).

CO_2 versus C4 weeds and C4 crops

Ziska and Bunce (1997) compared the effect of elevated CO_2 levels on the growth and biomass production of six C4 weeds (*Amaranthus retroflexus*, *Echinochloa crusgalli*, *Panicum dichotomiflorum* Michaux, *Setaria faberi* Herrm, *Setaria viridis*, *Sorghum halapense*) and four C4 crop species (*Amaranthus hypochondriacus*, *Saccharum officinarum*, *Sorghum bicolor*, and *Zea mays*). In these C4 species, they showed a significant increase in photosynthesis. The largest and smallest increases observed were for *A. retroflexus* (+30%) and Z. mays (+5%).

CO_2 versus Soybean and C3 weeds

Ziska (2000) evaluated the outcome of competition between 'Round-up Ready' Soybean (*Glycine max*.) and a C3 weed (lambsquarter, *Chenopodium album*) and a C4 weed

(Redroot pigweed, *Amaranthus retroflexus*), grown at ambient and enhanced CO_2 (ambient + 250 µL L^{-1}). In a weed-free environment, elevated CO_2 resulted in a significant increase in soybean growth and seed yield, compared to the ambient CO_2 condition. However, soybean growth and seed yield were significantly reduced by the presence of either weed species at either level of CO_2. With lambsquarter, at elevated CO_2, In the presence of lambsquarter, soybean seed yield was reduced by 28 to 39% at elevated CO_2; concomitantly, lambsquarter dry weight increased by 65%.

Conversely, for pigweed, soybean seed yield losses diminished with increasing CO_2 from 45 to 30%, with no change in the dry weight of the weed (Ziska, 2000). Climate change may alter yield losses caused by weed competition; weed control will be crucial to achieving any potential increase in soybean yields as a result of climate change. (Chandrasena, 2008).

Table 5: Effect of elevated CO_2 on crop weed interactions (Ziska, 2000)

Crop-weed interaction	**Ambient CO_2**	**Elevated CO_2**	**Percentage change**
Above ground biomass			
Soybean (C3)	340±13	448±14	+31.8
+C3 weed	261±18	297±29	+14.0
+C4 weed	204±17	329±27	+61.3
Seed yield			
Soybean (C3)	187±8	228±8	+21.9
+C3 weed	135±9	141±15	+4.4
+C4 weed	103±13	158±14	+53.4

(Total aboveground biomass and seed yield (±standard error) at maturity for soybean (g/m row) at ambient and elevated CO_2 (ambient +250 µl /l CO_2) when grown with or without the presence of a C3 weed (*Chenopodium album*) or a C4 weed (*Amaranthus retroflexus*).

CO_2 versus Redroot pigweed

The elevated CO_2 effect on Redroot pigweed (*Amaranthus retroflexus*) (C4 weed), no change in biomass and yield loss in soybean decreased from 30% to 45% in competition with this weed. Increasing atmospheric CO_2 levels favoured the growth of redroot pigweed in a sorghum field (Ziska *et al*., 2003; Zhao *et al*., 2022). *A. retroflexus* is established well under lack of soil moisture with good root system and may takes advantages of elevated CO_2 for increasing the drymatter production of Redroot pigweed (Weller *et al*., 2021). Redroot pigweed was grown with very well germination, growth, and CO_2 exchange rates at high temperatures, whereas the common lambsquarters grown well under low temperature (Chu, *et al*., 1978; Egley, 1989; Jabran *et al*., 2022).

CO_2 versus Weedy rice

Ziska *et al.*, (2010; 2013) found that in case of rice, 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, whereas rice yield did not respond to elevated CO_2. Red rice responded linearly in terms of biomass as well as seed production. The elevated CO_2 (700 ± 50 μmol mol^{-1}) had increased the weedy rice germination, growth and biomass (Balbinot *et al.*, 2022)

CO_2 versus Cocklebur

Ziska (2001) & Sreekanth *et al.*, (2023) reported the effects of elevated CO_2 on the growth of grain sorghum (C4) with and without common cocklebur (*X. strumarium*). C4 crops may become less productive in the presence of C3 weeds as future CO_2 levels increase, as biomass and leaf area were higher for the common cocklebur and lower for the sorghum in competitive mixtures. (Katoh and Esashi, 1975; Esashi *et al.*, 1988; Anwar *et al.*, 2021). The elevated CO_2 enhances the imbibed cocklebur seeds (Esashi and Katoh, 1975; Esashi *et al.*, 1978, Ishizawa *et al.*, 1988; Bailly *et al.*, 2023).

CO_2 versus Ragweed and Quack grass

Increased CO_2 stimulated ragweed (*Ambrosia artemisifolia) pollen production several* times more than that it stimulates overall growth (Singer *et al.*, 2005). Increasing CO_2 improved the effects of high temperature on quack grass (*Elytrigia repens*) and increased growth and reproduction, according to Tremmel and Patterson (1993). C3 weeds like lambsquarters or quackgrass are well grown in an elevated CO_2 environment (Tremmel and Patterson, 1994; Ziska *et al.*, 1999; Ziska and Teasdale 2000; Siddiqui *et al.*, 2022).

CO_2 versus Leaf area and Biomass

- In C3 weeds, leaf area generally responds less than biomass to CO_2 enrichment. (Patterson, 1995)
- However, in C4 weeds, leaf area and biomass more responses to CO_2 doubling (Fuhrer, 2003).
- C3 grass species - Increase in tillering and C4 grass species - Increase in leaf area. Increases in CO_2 and temperature could still favour a C4 species (Yin and Struik 2008).

Table 6: Effects of doubling CO_2 concentration on biomass and leaf area of C3 weeds (Patterson, 1995)

Range of response (% of growth at ambient)				
Scientific name	**Common name**	**Biomass**	**Leaf area**	**No. of reports**
Abutilon theophrasti Medicus	Velvet leaf	100-152	87-117	6
Cassia obtusifolia L.	Sicklepod	138-160	104-134	2
Chenopodium album L	lambsquarters	100-155	122	2
Cirsium arvense (L.) Scop	Canada thistle	121	92	1
Crotolaria spectabilis Roth	Showy crotaloria	167	154	1
Datura stramonium L.	Jimson weed	174-272	146	1
Elytrigia repens (L.) Neveski	Quack grass	164	130	1
Lolium perene L.	Perennial rye grass	134-143	-	2
Phalaris aquatica L.	Harding grass	143	131	1
Plantago lanceolata L.	Buckhorn plantain	100-133	133	2
Plantago major L.	Broad leaf plantain	155	-	1
Poa annua L.	Annual blue grass	100	-	1
Poa trivialis L.	Rough stalk blue grass	103	-	1
Rumex acetosella L.	Red sorrel	131	-	1
Rumex crispus L.	Curly dock	118	96	1

Table 7: Effects of doubling CO_2 concentration on biomass and leaf area of C4 weeds (Patterson, 1995)

Range of response (% of growth at ambient)				
Scientific name	**Common name**	**Biomass**	**Leaf area**	**No. of reports**
Amaranthus retroflexus L.	Pigweed, red rot	96-141	94-125	4
Andropogon virginicus L.	Broom sedge	81-117	88-129	2
Cyperus rotundus L.	Nut sedge, purple	102	92	1
Digitaria ciliaris (Retz.)	Crab grass	106-161	104-166	2
Echinochloa crusgalli (L.) *Beav.*	Barnyard grass	95-159	95-177	3
Eleusine indica (L.) *Gaertn.*	Goose grass	102-121	95-132	3
Rottboellia cochinchinensis	Itch grass	121	113	1
Setaria faberi	Foxtail, giant	93-135	101-140	3
Sorghum halepense (L.)	Johnson grass	56-110	99-103	3

CO_2 versus Crops and weeds

Increasing CO_2 levels can favour either the crop or the weed in the same field. Increasing atmospheric CO2 concentrations favored rice over barnyard grass in the rice-barnyard grass competition (Zeng *et al.*, 2011). Rice biomass growth was limited by nitrogen at elevated CO2 levels, while barnyard grass biomass growth was unaffected (Zhu *et al.*, 2008; Ziska, 2021).

CO_2 versus Rice and Wheat

The effect of CO_2 enrichment on weed species at the Directorate of Weed Science, Jabalpur revealed that a few weed species such as *Dactyloctenium aegyptium* and *E. colona responded to elevated* CO_2, but *Cyperus rotundus and Eleusine indica* did not respond to CO_2 enrichment (Manisankar & Ramesh, 2019). Compared to cultivated rice, wild rice (*Oryza sativa* L.) responded more strongly to rising CO_2 levels, suggesting that it could become a more problematic weed in the future. The growth and biomass accumulation was increased of the C4 weed (*Amaranthus viridis*) under elevated CO_2 (Naidu and Paroha, 2008; Kumar *et al.*, 2023).

Enhanced CO_2 levels may enhance C3 crop competitiveness against C4 weeds, such as rice. Climate change will exacerbate the problems caused by *P. minor* and *Artemisia ludoviciana* in wheat (Kumar *et al.*, 2021). Further, the problem could be aggravated with water scarcity. Due to CO_2 enrichment, the wheat plant could gain biomass against *P. minor*. With CO_2 enrichment, P. minor had an advantage over wheat under water stress (Fuhrer, 2003).

CO_2 versus Wild oat

The CO_2 enrichment/elevated CO_2 hastened the seed maturity in *Avena fatua* (*wild oat*) in wheat. The wild oat seeds shatter well before the crop is harvested; therefore the seeds were matured 13 days earlier compared to the plants cultivated under ambient CO_2 circumstances and enrichment of soil seed bank. At 480 ppm CO_2, wild oat plants produced 44% more seed than at 357 ppm. (O'Donnell and Adkins, 2001; Johannessen *et al.*, 2005; Granger *et al.*, 2012; Momtazi and Miri, 2015; Ziska, *et al.*, 2015; Oraki *et al.*, 2016; Ziska, 2017; Balbinot, 2020)

CO_2 versus Noxious or Invasive weeds

The noxious weeds' growth and development are accelerated by the higher CO_2. (Dukes, 2000; Polley *et al.*, 2003; Weltzin *et al.*, 2003; Salo, 2005). *Cynodon dactylon* in rice and *Convolvulus arvensis* in wheat. These weeds may show a strong response in growth with increase in atmospheric CO_2 (Ziska *et al.*, 2004). Parthenium hysterophorus in India had demonstrated tremendous growth in response to increased CO2. *Amaranthus viridis* (C4) and *Parthenium hysterophorus* (C3) both produced more flowers when the CO_2 level was higher. (Naidu, 2013; Waryszak *et al.*, 2018). Significant morphological and drymatter production alterations were seen in invasive *M. micrantha* and *W. trilobata* as a result of the higher CO_2 levels. (Song *et al.*, 2009). When grown singly or in monoculture, many invasive plants have been proven to respond well to high (CO_2). (Weltzin *et al.*, 2003). Examples of these are species that have invaded North America, such as cheatgrass (*Bromus tectorum),* kudzu (*Pueraria lobata) and Japanese* honeysuckle (*Lonicera japonica*, which has also invaded New Zealand and parts of Europe) (Ziska, 2003).

CO_2 versus Worst weed

Many farmers are aware of the comparable growth habits of the worst weeds for a certain crop. The 14 of the worst weeds in the world are classified as C4 plants. For instance: wild oats Little seed canary grass and wheat Wild rice growth is more favourable due to the rising atmospheric CO_2 level (Patterson, 1995; Ziska, 2022).

CO_2 with Temperature

The competitiveness could be enhanced in C3 crop (Rice) relative to a C4 weed (*Echinochloa glabrescens*) *with* elevated CO_2 alone but simultaneous increases in CO_2 and temperature still favour C4 weed *spp*. The competition outcomes between rice and a C4 weed - *Echinochloa glabrescens* L. were studied at two different CO_2 concentrations (393 and 594 $\mu L\ L^{-1}$) under day/night temperatures of 27/21°C and 37/29°C (Anwar *et al*., 2021). The average above ground biomass (+47%) and seed yield (+55%) of rice increased with increasing CO_2 concentrations at 27/21°C. A higher CO2 concentration had no significant effect on biomass or yield of the C4 weed.

When grown in mixture, the proportion of rice biomass increased significantly relative to that of the C4 weed in all mixtures at elevated CO_2 indicating increased 'competitiveness' of rice. Although rice competed better with weeds at elevated CO_2 levels on its own, rice's competitive ability was reduced at elevated CO_2 levels and temperatures, indicating that while rice competed better with weeds at elevated CO_2, it did not produce as much germination or reproductive activity as rice on lower CO_2 levels. (Alberto *et al.*, 1996; Manisankar & Ramesh, 2019).

Temperature versus Weed phenology

Weed phenology and population may vary as a result of climate change. More so than increasing CO_2, the increased temperature had an impact on plant phenological development. *C. album* and *S. viridis* emergence and flowering times were increased by 26 and 35 days, respectively, due to the temperature increase of 4°C. Higher temperatures had a substantial impact on the accumulation of biomass by annual grass species during their reproductive phase as opposed to the vegetative phase (Lee, 2011; March-Salas & Pertierra, 2020).

Weed response to increasing temperature

Temperature increases result from climate change. (Tubiello *et al.*, 2007). One of the main elements affecting the dispersion of weeds is temperature. Weeds move to higher latitudes or higher altitudes as temperatures rise. Plants with a C4 carbon fixation pathway mostly weeds have an advantage over crop plants in high temperatures. Higher temperatures that benefit C4 weeds over C3 crops are anticipated to be followed by increased atmospheric CO_2 levels (Ziska *et al.*, 2019). Under unpredictable rainfall brought on by climate change, a similar shift in weed species composition can also be anticipated. A crop may experience increased environmental stress as a result of a sudden change in the climate, making it more susceptible to insect and disease assault and less weed-competitive.

In addition to impacting crop weed competition, the weather anomalies also cause multiple flushes of weed seed germination, which poses major weed control challenges. In the wheat fields of northwest India, three *P. minor* flushes are not unusual, and they are not controlled by a single herbicide application. Weeds respond more strongly to rising temperatures than crops because they have a larger gene pool, which allows them to adapt to a variety of environmental situations. Normally, weeds will expand their distribution into new places as the mean temperature rises over a prolonged period. (Tubiello *et al.*, 2007).

Invasive plants will spread farther afield as a result of warmer seasonal temperatures and milder winters Ragweed and Kudzu (Garrett, 2012). C4 plants will have a competitive advantage over C3 plants when the temperature rises. Hanzlik and Gerowitt (2012) found that prickly sida (*Sida spinosa*) and sicklepod (*Senna obtusifolia*) were less negatively impacted by rising temperatures than soybean.

Temperature versus *Striga*

The distribution of weed species in a given geographic area is thought to be significantly influenced by the temperature of the atmosphere. There is a wide variety of Striga species. *Striga asiatica* is not particularly temperature-sensitive. Temperature changes may not have a direct impact on its dispersion as much as changes in the host crop's geographic range. (Mohamed *et al.*, 2007).

Temperature versus *Parthenium*

Summer time was when *Parthenium* seed germination was found to be more prevalent. According to Nguyen *et al.* (2010), warm temperatures produced the most *Parthenium* seeds, whereas chilly conditions produced the most unfilled seeds (60%) at a maximum rate. After only 50 days of growth in warm, dry conditions, reproduction is possible; in cool, wet conditions, it takes 75 days. Because of the abbreviated life cycle, higher temperatures promote the growth of *Parthenium*, increase canopy size and structure, and speed up population expansion (Singh 2011; Toh *et al.*, 2011).

INDIA

Sing *et al.* (1991) reported that most of the weeds in rice are of C4 type. *Ischaemum rugosum* are more in Tropical areas. *Rumex spinosus* in wheat of North West India has increased.

AUSTRALIA

The Buffel grass (*Cenchrus ciliaris*) is one of the few weeds in Australia to be extensively assessed for growth response to climate change (growth at 35°C versus 25°C). The warm temperature increases many C4 weeds, such as *Amaranthus retroflexus* L., *Setaria* sp., *Digitaria* sp., *Sorghum halepense* L., *Paspalum dichotomiflorum* (L.) are expected to expand further north side of Australia (Clements and DiTommaso, 2011). *Hieracium aurantiacum* L. (Brinkley and Bomford, 2002).

CALIFORNIA

Sleeper weeds can spread quickly depending on the temperature. In California's higher latitudes, there aren't as many of the extremely aggressive weeds that are currently found in the lower latitudes. With rising temperatures, the Itch grass has been tillering profusely (Bunce and Ziska 2000). With a 3°C warming trend, the robust grass weed might invade the central Midwest and California (Patterson, 1995).

EUROPEAN

The three significant Central European C4 weeds in maize, *Amaranthus retroflexus*, *Echinochloa crusgalli*, and *Setaria viridis*, have become more prevalent due to warmer weather. The majority of these weeds emerge from early summer to early autumn because they are late germinators (Walther *et al*., 2002). According to O'Donnell and Adkins (2001), wild oat plants developed more quickly at high temperature 23/19°C (day/night) than at normal temperature 20/16°C.

Weed response to Precipitation

Lantana camara, for example, could expand if rainfall increased in some areas (McFadyen 2008). The drought-tolerant C4 weeds, parasitic weeds that thrive in erratic and low rainfall environments (e.g. *Striga hermonthica*) or temporarily flooded conditions (e.g. *Rhamphicarpa fistulosa*) could benefit. *Striga spp*. problems are also associated with low soil fertility area (Kroschel, 2000). *A. philoxeroides*'s growth response and competitiveness in various plant communities to precipitation variability (Ren *et al*., 2023).

Under drought conditions, *Abutilon theophrasti* and *Anoda cristata* (L.) became more competitive with cotton (Patterson and Highsmith, 1989). In contrast to water-stressed soybeans, a yield loss caused by *Xanthium strumarium* L. was more pronounced in well-watered soybeans (Mortensen and Coble, 1989). Increased rainfall made *Cirsium arvense* more of a threat to wheat yield and growth (Donald and Khan, 1992).Under water stress, *Amaranthus spinosus* and *Leptochloa chinensis* (L) flourished and generated a sizable number of tillers and branches.

Annual weeds that may withstand drought conditions include cheat grass and Yellow star thistle (*Centaurea solstitialis*) (Vollmer and Vollmer, 2006). While yellow star thistle competes with native plants by growing deeper roots, cheat grass completes its life cycle based on the amount of moisture that is available (Hatfield *et al*., 2011). Dry soil and drought conditions increase the lifetime of the weed seed bank.

Weed response to flooding

The rice plants are shielded against C4 weeds by submersion. On the other hand, C4 weeds pose a serious threat to highland rice and rainfed lowland rice with little precipitation. In both puddled and dry seeded rice, alternating wetting and drying may promote the growth of weeds like *Livistona chinensis, Eleusine indica, and Eleusine prostrata*. According to Rodenburg *et al*. (2010), flooding occurrences boost (increase growth) *Rhamphicarpa fistulosa*, Willows (*Salix* spp.), Tamarisk (*Tamarix aphylla*), and Tamarisk (*Tamarix aphylla*).

Weed response to wind

The increasing CO_2 levels may increases the dispersal of weed seeds by wind either increasing the height of the weed plant or by increasing the plant size. Wind dispersed invasive weed species are *Cirsium arvense*, *Sonchus arvensis* L., *Sonchus oleraceus* L., and *Carduus nutans* L (Ziska and Dukes 2011).

Weed response to Fire

Under severe weather, *Andropogon gayanus*, or *Gamba grass*, can catch fire. Extreme weather frequently affects the incidence and severity of fires, which are frequent extreme events in Australia.

Climate change: Crop-weed interactions

Depending on factors like soil, temperature, precipitation, and others, interactions between crops and weeds vary greatly among different climate zones.

A. C3 crop competing with both C3 and C4 weeds where C3 weeds are dominant, whereas in another situation C4 weeds are dominant (Bunce and Ziska, 2000).
B. C4 crop competing with both C3 and C4 weeds where C3 weeds are dominant, whereas in another situation C4 weeds are dominant.

Table 8: Crop/weed competition outcome at elevated CO_2 conditions (Bunce and Ziska 2000)

Weed species	Crop	Favoured under elevated CO_2	References
Amaranthus retroflexus (C4)	Soybean (C3)	Crop	(Ziska, 2000)
Amaranthus retroflexus (C4)	Sorghum (C4)	Weed	(Ziska, 2003)

Chenopodium album (C3)	Soybean (C3)	Weed	(Ziska, 2000)
Taraxacum officinale (C3)	Lucern (C3)	Weed	(Bunce, 1995)
Albutilon theophrasti (C3)	Sorghum (C4)	Weed	(Ziska, 2003)
Taraxacum and Plantago (C3)	Grasses (C3)	Weed	(Potvin and Vasseur, 1997)
Red rice (C3)	Rice (C3)	Weed	(Ziska *et al.*, 2010)
Echinochloa glabrescens (C4)	Rice (C3)	Weed	(Alberto *et al.* 1996)

Weed management under climate change

- Continue current control options
- Integrated Weed Management (IWM)
- Use weed control methods are suitable for current extreme events.
- Develop new weed control methods adapted for climate change.

Climate change on weed management

Herbicide Efficacy

I. Carbon Dioxide and Temperature

Both foliar and soil applied herbicides can have their effectiveness affected by decreased stomatal conductance. Changes in temperature and CO2 levels may modify transpiration, the quantity of leaf stomata, or the thickness of the leaf, which may impact how well herbicides are absorbed and transported.

II. Relative Humidity

Relative humidity may influence the efficacy of foliar-applied herbicides through interactions between the herbicide droplet, leaf cuticle, and availability of water (Devine *et al.*, 1993).

III. Wind

Wind might not have as much of an impact on how well a pesticide works. However, windy conditions can hinder surface application and cause spray drift, which decreases the effectiveness of spray application. Wind dispersed invasive weed that lives in agricultural fields and uncivilised areas (Bastida *et al.*, 2021).

IV. Rainfall

Increased rainfall intensity and frequency will have a negative impact on the uptake, retention, and action of herbicides applied to the soil.

Conclusion

Global climate change factors have serious implications for not only crop and weed growth and also herbicide performance and the effectiveness of chemical weed management. Because of their increased inter-specific genetic variety and physiological adaptability, weeds often exhibit stronger survival strategies under changing climatic conditions. Weed biology is anticipated to be significantly impacted by changes in temperature and carbon dioxide, both directly (CO_2 stimulation of weed growth) and indirectly (climatic variability). Despite the significance of weed biology for agriculture and the environment, little is understood about how these climate changes affect invasive or agronomic weeds reproductive success and the potential repercussions for their management. Under changing climatic conditions, it has been demonstrated in several research that weeds and crops both react to climate change scenarios. Under conditions of elevated CO_2, weeds tend to follow the C3 pathway (C3 weeds), whereas under conditions of increased temperature, they may follow the C4 pathway (C4 weeds). As a result, managing and controlling weeds in agriculture will be a significant issue in future. Therefore, more research on weeds and weed management is required.

References

Alberto, A.M.P., L.H. Ziska, C.R. Cervancia, and P.A. Manalo. (1996). The Influence of Increasing Carbon Dioxide and Temperature on Competitive Interactions Between a C3 Crop, Rice *(Oryza sativa)* and a C4 Weed *(Echinochloa glabrescens)*. *Australian Journal of Plant Physiology*, 23, 795-802.

Anwar, M. P., Islam, A. M., Yeasmin, S., Rashid, M. H., Juraimi, A. S., Ahmed, S., & Shrestha, A. (2021). Weeds and Their Responses to Management Efforts in A Changing Climate. *Agronomy*, 11(10), 19-21.

Bailly, C., Jurdak, R., & Corbineau, F. (2023). Ethylene in the regulation of seed dormancy and germination: Molecular mechanisms. *The Plant Hormone Ethylene*, 41-60.

Balbinot, A. (2020). *Effect of enhanced CO2 atmospheric concentration on rice and weedy rice* (Master's thesis, Universidade Federal de Pelotas).

Balbinot, A., da Rosa Feijó, A., Fipke, M. V., Gehrke, V. R., Agostinetto, D., Kruse, N. D., and de Avila, L.A. (2022). Rising atmospheric CO2 concentration affect weedy rice growth, seed shattering and seedbank longevity. *Weed Research*. 62(4), 277-286

Bastida, F., Menéndez, J., Camacho, D., & González-Andújar, J. L. (2021). Season-long seed dispersal patterns of the invasive weed *Erigeron bonariensis* in south-western Spain. Crop Protection, 148, 105720.

Batts, G.R, Morison, J.I.L and Ellis, R.H. (1997) Effects of CO2 and temperature on growth and yield of crops of winter wheat over four seasons. *European Journal of Agronomy*, 7, 43-52.

Bergmann J, Pompe S, Ohlemüller R (2010) The Iberian Peninsula as a potential source for the plant species pool in Germany under projected climate change. *Plant Ecology,* 207, 191-201.

Bradley, B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska. 2010. Predicting plant invasions in an era of global change. *Trends in Ecology and Evolution*., 25, 310-318.

Brinkley, T. R., and M. Bomford. 2002. Agricultural Sleeper Weeds: What is the Potential Threat? Kingston, ACT: *Bureau of Rural Sciences.*

Bunce, J. A., and L.H. Ziska, 2000. “Crop ecosystem responses to climatic change: crop/weed interactions,” in Climate Change and Global Crop Productivity, eds K. R. Reddy and H. F. Hodges (New York, NY: CABI), 333-348.

Carter DR, Peterson KM (1983) Effects of a CO2-enriched atmosphere on the growth and competitive interaction of a C3 and a C4 grass. *Oecologia*, 58, 188-193.

Chandrasena, N. (2008). Weeds and weed management under a changing climate. In *Conference: Biennial Conference of Indian Weed Science Society.*

Chandrasena, N. (2009). How will weed management change under climate change? Some perspectives. *Journal of Crop and Weed*, *5*(2), 95-105.

Chauhan, B. S., Matloob, A., Mahajan, G., Aslam, F., Florentine, S. K., & Jha, P. (2017). Emerging challenges and opportunities for education and research in weed science. *Frontiers in plant science*, 8, 1537.

Chu, C.C., Ludford, P.M., Ozbun, J.L., & Sweet, R.D. (1978). Effects of Temperature and Competition on the Establishment and Growth of Redroot Pigweed and Common Lambsquarters 1. *Crop Science*, *18*(2), 308-310.

Clements, D. and A. Ditommaso. 2011. Climate change and weed adaptation: Can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Res.,* 51, 227-240.

Clements, D. R., & DiTommaso, A. (2022). Climate Change and the Persistence of Weeds. *Persistence Strategies of Weeds*, 219-243.

Dass, A., Shekhawat, K., Choudhary, A.K., Sepat, S., Rathore, S.S., Mahajan, G. and Chouhan, B.S. 2017. Weed management in rice using crop competition- a review. Crop Protection, 95, 45-52.

Devine, M.D., S.O. Duke, and C. Fedtke. 1993. Foliar Absorption of Herbicides. Prentice-Hall, Englewood Cliffs, NJ. 29-52.

Donald, W.W., and M. Khan, 1992. Yield loss assessment for spring wheat (*Triticum aestivum*) infested with Canada thistle (*Cirsium arvense*). *Weed Sci*., 40, 590-598.

Dukes JS, Pontius J, Orwig D (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of north eastern North America: what can we predict? Can J For Res., 39, 231-248.

Dukes, J.S., 2000. Will the increasing atmospheric CO$_2$ concentration affect the success of invasive species? In: Mooney, H.A., Hobbs, R.J. (Eds.), Invasive Species in a Changing World. Island Press, Washington.

Dukes, J.S., J. Pontius, D. Orwig. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can we predict? *Can J For Res*., 39, 231-248.

Egley, G. H. (1989). Some effects of nitrate-treated soil upon the sensitivity of buried redroot pigweed (Amaranthus retroflexus L.) seeds to ethylene, temperature, light and carbon dioxide. *Plant, Cell & Environment*, *12*(5), 581-588.

Elmore, C.D., & Paul, R.N. (1983). Composite list of C4 weeds. *Weed Science*, *31*(5), 686-692.

Esashi, Y., & Katoh, H. (1975). Dormancy and impotency of cocklebur seeds III. CO$_2$ and C2H4-dependent growth of the embryonic axis and cotyledon segments. *Plant and cell physiology*, *16*(4), 707-718.

Esashi, Y., Kawabe, K., Isuzugawa, K., & Ishizawa, K. (1988). Interrelations between carbon dioxide and ethylene on the stimulation of cocklebur seed germination. *Plant Physiology*, *86*(1), 39-43.

Esashi, Y., Okazaki, M., Yanai, N., & Hishinuma, K. (1978). Control of the germination of secondary dormant cocklebur seeds by various germination stimulants. *Plant and Cell Physiology*, *19*(8), 1497-1506.

Fuhrer, J. 2003. Agro-ecosystem responses to combination of elevated CO$_2$, ozone and global climate change. *Agric. Ecosys. Environ*., 97, 1-20.

Garrett, K. (2012). *Climate Change Impacts on Insect Pests, Weeds, and Disease (PowerPoint)* (No. 1456-2016-120261).

Ghannoum O, von Caemmerer S, Ziska LH, Conroy JP (2000). The growth response of C4 plants to rising atmospheric CO2 partial pressure: a reassessment. Plant, Cell and Environment, in press.

Granger, K. L. (2012). *Mitigation of drought-induced reductions in wild oat seed quality by elevated carbon dioxide*. The Pennsylvania State University.

Hanzlik, K., and B. Gerowitt. 2012. Occurrence and distribution of important weed species in German winter oilseed rape fields. *J. Plant Dis. Prot.*, 119, 107-120.

Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe. 2011. Climate impacts on agriculture: implications for crop production. *Agron. J.*, 103, 351-370.

Houghton, J. (2001). The science of global warming. Interdiscip. Sci. Rev. 26, 247-257.

IPCC, (2022). The Intergovernmental Panel on Climate Change. http://www.ipcc.ch/

Ishizawa, K., Hoshina, M., Kawabe, K., & Esashi, Y. (1988). Effects of 2, 5-norbornadiene on cocklebur seed germination and rice coleoptile elongation in response to CO2 and C2H4. *Journal of Plant Growth Regulation*, *7*(1), 45-58.

Jabran, K., Chandrasena, N. R., Ahmad, T., & Ijaz, A. (2022). How may Climate Change affect the activity of Glyphosate on Weeds? Some reflections. Weeds-Journal of the Asian-Pacific Weed Science Society, 4(2), 21-38.

Jinger, D., Dass, A., Kumar, V., Kaur, R., & Kumari, K. (2016). Weed Management Strategies eed Management Strategies Weed Management Strategies weed Management Strategies. *Indian Farming, 66*(9), 09-13.

Johannessen, M. M., Mikkelsen, T. N., Nersting, L. G., Gullord, M., Von Bothmer, R., & Jörgensen, R. B. (2005). Effects of increased atmospheric CO_2 on varieties of oat. *Plant Breeding*, *124*(3), 253-256.

Katoh, H., & Esashi, Y. (1975). Dormancy and impotency of cocklebur seeds I. CO_2, C_2H_4 O_2 and high temperature. *Plant and Cell Physiology, 16*(4), 687-696.

Kendal, A.C., J.C. Turner, and S.M. Thomas.1985, "Effects of CO_2 enrichment at different irradiances on growth and yield of wheat", I. Effects of cultivar and duration of CO_2 enrichment. *Journal of Experimental Botany,* 36, 252-260.

Kroschel J. 2000. *Striga* - How will it affect African agriculture in the future? - An ecological perspective. 137-158.

Kumar, V., Kumar, S., Kamboj, N., Payum, T., Kumar, P., & Kumari, S. (Eds.). (2021). Biological Diversity: Current Status and Conservation Policies (Vol. 1). Agro Environ Media, Publication Cell of AESA, Agriculture and Environmental Science Academy.

Kumar, V., Kumari, A., Price, A. J., Bana, R. S., Singh, V., & Bamboriya, S. D. (2023). Impact of Futuristic Climate Variables on Weed Biology and Herbicidal Efficacy: A Review. *Agronomy*, 13(2), 559.

Lee, J. 2011. Combined effect of elevated CO_2 and temperature on the growth and phenology of two annual C3 and C4 weedy species. *Agric. Ecosys. Environ.*, 140, 484-491.

Leegood, R.C. (2002). C4 photosynthesis: principles of CO_2 concentration and prospects for its introduction into C3 plants. J. Exp. Bot. 53, 581-590

Lobell DB, Burke MB (2008) Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environ Res Lett., 3, 1-8.

Loss SR, Terwilliger LA, Peterson AC (2011) Assisted colonization: integrating conservation strategies in the face of climate change. Biol Conserv., 144, 92-100.

Mahajan, G., S.Singh and B.S. Chauhan. 2012. Impact of climate change on weeds in the rice–wheat cropping system. *Current Science,* 102, 1254-1255.

Manisankar, G., & Ramesh, T. (2019). Response of weeds under elevated CO2 and temperature: A review. *Journal of Pharmacognosy and Phytochemistry*, 8(2S), 427-431.

March□Salas, M., & Pertierra, L. R. (2020). Warmer and less variable temperatures favour an accelerated plant phenology of two invasive weeds across sub□Antarctic Macquarie Island. *Austral Ecology*, 45(5), 572-585.

McFadyen, R. 2008. *Invasive Plants and Climate Change. Weeds* CRC Briefing Notes. CRC for Australian Weed Management.

McPeek, T.M., & Wang, X. (2007). Reproduction of dandelion (*Taraxacum officinale*) in a higher CO2 environment. *Weed Science*, *55*(4), 334-340.

Marambe, B., & Wijesundara, S. (2021). Effects of climate change on weeds and invasive alien plants in Sri Lankan agro-ecosystems: policy and management implications. Frontiers in Agronomy, 3, 641006.

Mishra, G. N. 2003. Weeds and their management in upland rice. Ind. Farming. 18-21.

Mohamed, K.I., J.F. Bolin, L.J. Musselman, and A. Townsend Peterson. 2007. Genetic diversity of *Striga* and implications for control and modelling future distributions. 71-84. *In:* Ejeta G and Gressel J eds. *Integrating New Technologies for Striga Control - Towards ending the witch-hunt*. World Scientific, Singapore.

Momtazi, F., & Miri, H. (2015). Growth and competitiveness of wheat against C3 and C4 plant in CO_2 enrichment and drought condition. *Journal of Plant Ecophysiology*, *7*(20), 112-127.

Morgan, J.A., D.R. LeCain, A.R. Mosier, and D.G. Milchunas. 2001. Elevated CO_2 enhances water relations and productivity and affects gas exchange in C3 and C4 grasses of the Colorado short grass steppe. *Global Change Biol.*, 7, 451-466.

Morison JIL and Lawlor DW (1999) Interactions between increasing CO_2 concentration and temperature on plant growth. Plant Cell Environ., 22, 659-682.

Mortensen, D.A., and H.D. Coble. 1989. The influence of soil water content on common cocklebur (*Xanthium strumarium*) interference in soybeans (*Glycine max*). *Weed Sci.*, 37, 76-83.

Naidu V.S. and S. Paroha. 2008. Growth and biomass partitioning in two weed species, *Parthenium hysterophorus* (C3) and *Amaranthus viridis* (C4) under elevated CO_2. *Ecology Environment and Conservation.* 14, 9-12.

Naidu, V.S.G.R., 2013. Invasive potential of C3-C4 intermediate *Parthenium hysterophorus* under elevated CO_2. *Indian Journal of Agricultural sciences.* 83, 176-179.

Nguyen, T.L.T., S.C. Navie, and S.W. Adkins. 2010. The reproductive capacity of *Parthenium* weed under different climatic conditions. In Proceedings 17th Australasian

Weeds Conference, Published by New Zealand Plant Protection Society (Ed. S. M. Zydenbos). 26-30th September. 124-127

O'Donnell, C.C. and S.W. Adkins. 2001. Wild oat and climate change: the effect of CO_2 concentration, temperature, and water deficit on the growth and development of wild oat in monoculture. *Weed Sci.,* 49, 694-702.

O'Donnell, C.C., & Adkins, S.W. (2001). Wild oat and climate change: The effect of CO_2 concentration, temperature, and water deficit on the growth and development of wild oat in monoculture. Weed Science, 49(5), 694-702.

Oraki, H., Modares-Sanavi, S. A. M., Zand, E., & Mokhtassi-Bidgoli, A. (2016). Effect of carbon dioxide enrichment on yield and yield components of wheat under weed competitive pressure of winter wild oat (Avena ludoviciana L.). *Iranian Journal of Field Crop Science*, *47*(2).

Patterson , D.T. 1985. Comparative ecophysiology of weeds. In : Weed Physiology : Reproduction and Ecophysiology, S.O. Duke (ed.). CRC Press, Inc. Boca Raton, Florida. 101-132.

Patterson, D.T. (1995). Effects of environmental stress on weed/crop interactions. *Weed Science*, *43*(3), 483-490.

Patterson, D.T. 1995. Weeds in a changing climate. *Weed Science,* 43, 685-701.

Patterson, D.T., and M.T. Highsmith. 1989. Competition of spurred anoda (*Anoda cristata*) and velvet leaf (*Albutilon theophrasti*) with cotton (*Gossypium hirsutum*) during simulated drought and recovery. *Weed Sci.*, 37, 658-664.

Pautasso M, Dehnen-Schmutz K, Holdenrieder O et al (2010) Plant health and global change—some implications for landscape management. Biol Rev 85:729-755.

Petit JR, Jouzel J, Raynaud D et al (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399:429-436.

Polley, H.W., Johnson, H.B., Tischler, C.R., 2003. Woody invasion of grasslands: evidence that CO2 enrichment indirectly promotes establishment of *Prosopis glandulosa*. Plant Ecol 164, 85-94

Poorter, H., 1993. "Interspecific variation in the growth response of plants to an elevated ambient CO_2 concentration", *Vegetation*, 104/105, 77-97.

Ramesh, K., Matloob, A., Aslam, F., Florentine, S. K., & Chauhan, B. S. (2017). Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. *Frontiers in plant science, 8*, 95.

Reddy, A.R., Rasineni, G.K., & Raghavendra, A.S. (2010). The impact of global elevated CO_2 concentration on photosynthesis and plant productivity. *Current Science*, 46-57.

Ren, G., Du, Y., Yang, B., Wang, J., Cui, M., Dai, Z., & Du, D. (2023). Influence of precipitation dynamics on plant invasions: response of alligator weed (*Alternanthera* *philoxeroides*) and co-occurring native species to varying water availability across plant communities. *Biological Invasions,* 25(2), 519-532.

Robinson, T.M.P, Gross, K.L. (2010). The impact of altered precipitation variability on annual weed species. Am J Bot., 97, 1625-1629.

Rodenburg, J., C.R. Riches, and J.M. Kayeke. 2010. Addressing current and future problems of parasitic weeds in rice. *Crop Prot.*, 29, 210-221.

Rodenburg, J., H. Meinke, and D.E. Johnson. 2011. Challenges for weed management in African rice systems in a changing climate. *J. Agric. Sci.*, 149, 427-435.

Rogers HH, Runion GB, Prior SA et al (2008) Effects of elevated atmospheric CO_2 on invasive plants: comparison of purple and yellow nutsedge (*Cyperus rotundus* L. and *C. esculentus* L.). J Environ Qual 37:395-400.

Salo, L.F., 2005. Red brome (Bromus rubens subsp. madritensis) in North America: possible modes for early introductions, subsequent spread. Biol. Invasions 7, 165-180.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C. & Turner, B. (2021). Getting the message right on nature□based solutions to climate change. *Global change biology*, 27(8), 1518-1546.

Singer, A., J.M.J. Travis, K. Johst. (2013). Interspecific interactions affect species and community responses to climate shifts. *Oikos,* 122, 358-366.

Singer, B.D., L.H. Ziska, D.A. Frenz, D.E. Gebhard, and J.G. Straka. 2005. Increasing Amb a1 content in common ragweed (*Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology,* 32, 667-670.

Singh T., J.S Kolar, and R.K. Bhatia. (1991). Emergence behaviours of *Ischaemum rugosum* (Wrinkle Grass) as affected by variable temperature, submergence period and depth of seed placement in the soil. *Indian Journal of Weed Science,* 23, 56-60

Singh, R.P., Singh, R.K., & Singh, M.K. (2011). Impact of climate and carbon dioxide change on weeds and their management-a review. *Indian Journal of Weed Science*, *43*(1&2), 1-11.

Siddiqui, A. O., Yazlık, A., & Jabran, K. (2022). Weed Management and Climate Change. Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective, 211-223.

Skov, F., & Svenning, J.C. (2004) Potential impact of climatic change on the distribution of forest herbs in Europe. Ecography (Cop) 27, 366-380.

Song, L., Wu, J., Li, C., Li, F., Peng, S., & Chen, B. (2009). Different responses of invasive and native species to elevated CO2 concentration. *Acta Oecologica*, *35*(1), 128-135.

Sreekanth, D., Pawar, D. V., Mishra, J. S., & Naidu, V. S. G. R. (2023). Climate change impacts on crop-weed interaction and herbicide efficacy. Current Science (00113891), 124(6).

Tang, J., Xu, L.,Chen, X. and Hu, S. 2009. Interaction between C4 barnyard grass and C3 upland rice under elevated CO_2: Impact of mycorrhizae. *Acta Oecologica*, 35, 227- 235.

Toh R, J. Hanan, K. Dhileepan, R.G. Shivas and S.W. Adkins. 2011. Stimulation of *Parthenium* weed canopy under changing climate using L - systems. 19th International Congress on Modelling &Stimulation, Perth, Australia. 12-16th December. 1009-1015

Treharne, K., 1989. The implications of the 'greenhouse effect' for fertilizers and agrochemicals. In: Benner, R.D. (Ed.), The Greenhouse Effect and UK Agriculture. Ministry of Agriculture, Fisheries and Food, London, pp. 67-78.

Tremmel, D.C., & Patterson, D.T. (1994). Effects of elevated CO2 and temperature on development in soybean and five weeds. *Canadian journal of plant science*, *74*(1), 43-50.

Tremmel, D.C., and D.T. Patterson. 1993. Responses of soybean and five weeds to CO_2 enrichment under two temperature regimes. *Can. J. Plant Sci.*, 73, 1249-1260.

Tubiello, F.N., J.F. Soussana, and S.M. Howden. 2007. Crop and pasture response to climate change. Proc. Natl. Acad. Sci. U.S.A. 104, 19686-19690.

Vollmer, J.L., J.G. Vollmer. 2006. Controlling cheat grass in winter range to restore habitat and endemic fire. In: Kitchen, S.G., Pendleton, R.L., Monaco, T.A., Vernon, J. (Comps.). Proc. Shrublands under fire: disturbance and recovery in a changing world, 6-8.

Walther, G.R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.M. Fromentin, O. Hoegh-guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature*. 416, 389-395.

Waryszak, P., Lenz, T. I., Leishman, M. R., & Downey, P. O. (2018). Herbicide effectiveness in controlling invasive plants under elevated CO2: sufficient evidence to rethink weeds management. *Journal of environmental management*, *226*, 400-407.

Weller, S., Florentine, S., Javaid, M. M., Welgama, A., Chadha, A., Chauhan, B. S., & Turville, C. (2021). Amaranthus retroflexus L.(Redroot Pigweed): Effects of elevated CO2 and soil moisture on growth and biomass and the effect of radiant heat on seed germination. *Agronomy*, *11*(4), 728.

Weltzin, J.F., Belote, R.T., & Sanders, N.J. (2003). Biological invaders in a greenhouse world: will elevated CO2 fuel plant invasions?. *Frontiers in Ecology and the Environment*, *1*(3), 146-153.

Weltzin, J.F., Belote, R.T., Sanders, N.J., 2003. Biological invaders in a greenhouse world: will elevated CO2 fuel plant invasions? Front. Ecol. Environ 1, 146-153.

Yin, X., and P.C. Struik. 2008. Applying modelling experiences from the past to shape crop. *New Phytologist*. 179: 629-642.

Zangerl, A.R, Bazzaz, F.A. (1984). The response of plants to elevated CO_2-II. Competitive interactions among annual plants under varying light and nutrients. *Oecologia*, 62, 412–417

Zeng, Q., B. Liu, B. Gilna, Y. Zhang, C. Zhu, H. Ma, J. Pang, G. Chen, and J. Zhu. 2011. Elevated CO_2 effects on nutrient competition between a C3 crop (*Oryza sativa* L.) and a C4 weed (*Echinochloa crusgalli* L.) nutrient cycling. *Agroecosystems.* 89, 93-104.

Zhao, C., Zhao, X., & Li, J. (2022). Elevated CO2 and Increased N Intensify Competition between Two Invasive Annual Plants in China. *Life*, 12(10), 1669.

Zhu, C., Q. Zeng, L.H. Ziska, J. Zhu, Z. Xie, and G. Liu. 2008. Effect of nitrogen supply on carbon dioxide-induced changes in competition between rice and barnyard grass (*Echinochloa crusgalli*). *Weed Sci.*, 56, 66-71.

Zhu, Z., Piao, S., Myneni, R. B., Huang, M., Zeng, Z., Canadell, J. G., & Zeng, N. (2016). Greening of the Earth and its drivers. *Nature climate change*, 6(8), 791-795.

Ziska LH, Teasdale JR (2000) Sustained growth, photosynthesis and increased tolerance to glyphosate observed in a C3 perennial weed, quackgrass, grown at elevated carbon dioxide. Australian Journal of Plant Physiology, 27, 157-164

Ziska LH, Teasdale JR, Bunce JA (1999) Future atmospheric carbon dioxide concentrations may increase tolerance to glyphosate [N-(phosphonomethyl) glycine] in weedy species. Weed Science, 47, 608-615.

Ziska, L. H. (2003). Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany, 54* (381), 395-404.

Ziska, L. H. and J.S. Dukes. 2011. *Weed Biology and Climate Change.* Ames, IA: Blackwell Publishing Ltd, 68-205.

Ziska, L. H., Gealy, D. R., Burgos, N., Caicedo, A. L., Gressel, J., Lawton-Rauh, A. L., & Merotto Jr, A. (2015). Weedy (red) rice: an emerging constraint to global rice production. *Advances in agronomy*, *129*, 181-228.

Ziska, L. H., Tomecek, M. B., & Gealy, D. R. (2013). Assessment of cultivated and wild, weedy rice lines to concurrent changes in CO2 concentration and air temperature: determining traits for enhanced seed yield with increasing atmospheric CO2. *Functional Plant Biology*, *41*(3), 236-243.

Ziska, L.H. (2008). Rising atmospheric carbon dioxide and plant biology: the overlooked paradigm. *DNA and Cell Biology*, *27*(4), 165-172.

Ziska, L.H. (2016). The role of climate change and increasing atmospheric carbon dioxide on weed management: herbicide efficacy. *Agriculture, Ecosystems & Environment*, *231*, 304-309.

Ziska, L.H. (2017). Could recent increases in atmospheric CO 2 have acted as a selection factor in *Avena fatua* populations? A case study of cultivated and wild oat competition. Weed Research, 57(6), 399-405.

Ziska, L.H. 2000. The impact of elevated CO_2 on yield loss from a C3 and C4 weed in field-grown soybean. *Global Change Biology*, 6, 899-905.

Ziska, L.H., D.E. Gebhard, D.A. Frenz, S. Faulkner, and B.D. Singer. 2003. Cities as harbingers of climate change: Common ragweed, urbanization, and public health. *Journal of Allergy and Clinical Immunology,* 111, 290-295.

Ziska, L.H., Faulkner, S., and Lydon, J. (2004). Changes in biomass and root: shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO2: implications for control with glyphosate. *Weed Science, 52*(4), 584-588.

Ziska, L.H., M.B. Tomecek, and D.R. Gealy. 2010, "Evaluation of competitive ability between cultivated and red weedy rice as a function of recent and projected increases in atmospheric CO_2", *Agronomy Journal,* 102,118-123

Ziska, L.W. and J. Bunce, 1993, "Inhibition of whole plant respiration by elevated CO_2 as modified by growth temperature", *Physiologia Plantarum,* 87, 459-466.

Ziska, L.W., 2000, "The impact of elevated CO_2 on yield loss from a C3 and C4 weed in field-grown soybean", *Global Change Biology,* 6, 899-905.

Ziska, L.W., 2001,"Changes in competitive ability between a C4 crop and a C3 weed with elevated carbon dioxide", *Weed Science,* 49, 622-627.

Ziska, L.W., 2003,"Evaluation of yield losss in field sorghum from a C3 and C4 weeds with increasing CO_2", *Weed Science,* 51, 914-918.

Ziska, L. H., Blumenthal, D. M., & Franks, S. J. (2019). Understanding the nexus of rising CO2, climate change, and evolution in weed biology. Invasive Plant Science and Management, 12(2), 79-88.

Ziska, L. H. (2021). Crop adaptation: weedy and crop wild relatives as an untapped resource to utilize recent increases in atmospheric CO2. *Plants*, 10(1), 88.

Ziska, L. H. (2022). Chapter Eight CO2 is plant food the bad. In Greenhouse Planet (pp. 71-93). Columbia University Press.