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Impact of Climate and Carbon Dioxide Change on Weeds and their Management–A Review

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ABSTRACT

Climate change directly affects the geographic range of species, the timing of species life cycle (phenology), the population dynamics of species, the decline and extinction of some species and the invasion of other species. Plants with C_3 photosynthetic pathways are expected to benefit more than C_4 from CO_2 enrichment. However, rising global temperature may give competitive advantage to C_4 plants than C_3. This differential response of C_3 and C_4 plants will alter crop weed interaction because of the fact that majority of weeds are C_4 and most of the food grain crops are C_3. Higher levels of carbon dioxide could stimulate the growth of some weed species and greater production of rhizomes and tubers in perennial weeds making them difficult to control. Warmer temperatures will accelerate the rate at which day degrees accumulate, so the life cycles of some plant species may accelerate. As a result weeds are likely to mature and start to decay earlier.

Key words : Global warming, crop-weed competition, life cycle, weediness

INTRODUCTION

Weeds with efficient seed-dispersal systems (wind, water and birds) will invade more quickly than weeds that rely on vegetative dispersal. An increase in extreme events, such as cyclones, storms and associated floods, may increase the dispersal of weed species that rely on wind and water to move seeds or pollen. Climate change will provide the opportunity for environmental weeds to invade new ecosystems.

Climate change will also impact the effectiveness of herbicides. Weeds that are under moisture stress can respond by thickening their leaf cuticles, slowing down vegetative growth and flowering rapidly. Drought stressed weeds are more difficult to control with post-emergent herbicides than plants that are actively growing for example, systemic herbicides that are translocated within the weed need active plant growth stage to be effective. Pre-emergent herbicides or herbicides absorbed by plant roots need soil moisture and actively growing roots to reach their target sites. Occurrence of drought has the potential to reduce the effectiveness of pre-emergent herbicides.

Climate change may provide an opportunity to tackle new weeds before they become established. To maximize the opportunities presented by climate change weed management strategy must adapt with biology and ecology of the weeds and impacts of seasonal variability.

Weeds cause substantial crop losses particularly in less-developed agricultural production systems and most cultivation and tillage practices are for weed control. Climate is the principal determinant of vegetation distribution at regional to global levels. It is expected that climate change will bring about a shift in the floral composition of several ecosystems at higher latitudes and altitudes, as changes in temperature and humidity will be reflected on flowering, fruiting and seed dormancy. In general, any direct or indirect consequence of increasing CO_2 or climate change, which differentially affects the growth or fitness of weeds and crops, will alter crop weed competitive interactions (Patterson, 1995). The result may be favouring the weed in one case, or the crop may benefit in another situation.

Climate change in IPCC usage refers to a change in the state of climate that can be identified (e. g. using statistical test) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Frame Work Convention on Climate Change (UNFCCC) where climate change refers to change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (IPCC, 2007).

Consensus among the majority of climatic modelers seems to be that, an increase of 1.5 to 4.5 ^{O}C in the earth's mean annual surface temperature in the 21st century (MacCracken *et al.,* 1990; Houghton *et al.*, 1992), however, climatologists are reluctant to attribute this change to the green house effect, because of the other factors which may have contributed to the apparent global warming. The increase in earth's mean temperature has largely resulted from an increase in night than day temperature. The temperature increase is greater in winter than in summer and greater at higher latitudes than in the tropics. Analysis of weather records since the late ninetieth century indicates an increase of about 0.76°C in the mean annual surface temperature of the earth already has occurred (IPCC, 2007). This trend is consistent with an increase in green house gases during the same period.

The concentration of CO_2 in atmosphere is more dependent on human activities and is, therefore, more amenable to management and control. The major natural sources of CO_2 include respiration by living organisms, biomass decay and natural fires. Anthropogenic sources include burning of fossil fuels, deforestation and cement production. The concentration of CO_2 in the global atmosphere has increased from about 280 to 379 ppm in 2005 since the beginning of the Industrial Revolution and continues to increase at the rate of 0.4% per year (Ashmore, 1990; MacCracken *et al.*, 1990). The annual CO_2 concentration growth rate was larger during the last 10 years (1995-2005) (average 1.4 ppm per year), although there is year to year variability in growth rates.

WEED BIOGEOGRAPHY

Climatologists predict that continued global warming will be accompanied by changes in the frequency and distribution of precipitation and by changes in wind patterns, potential evapotranspiration, and other weather characteristics like increased probabilities of droughts, temperature extremes and floods, strong winds and severe convective storms, including tropical cyclones and hurricanes (Pittock, 1988).Variations in seasonal rainfall pattern during south-west monsoon during past four decades have also been observed at Varanasi (Table 1). It is clear from the table that the end of monsoon season during four decades had advanced by 7-17 days which resulted in shortening of monsoon season by 18 days in the last decade.This is an indicative of recent shift in seasonal pattern of rainfall.

Table 1. Rainfall pattern during south-west monsoon season (1971-2010)

Period	Start of SW monsoon		End of SW monsoon		Duration of monsoon		Seasonal rainfall		No. of rainy days	
	Mean (Julian days)	CV (%)	Mean (Julian days)	CV (%)	Mean (Julian days)	CV (%)	Mean (mm)	CV (%)	Mean (No.)	CV (%)
1971-1980	176	4.9	278	3.5	102	6.3	947.7	26.5	46	17.9
1981-1990	178	6.2	271	3.7	92	14.7	909.1	23.8	48	27.5
1991-2000	180	7.0	269	4.2	89	15.3	890.3	24.2	49	20.3
2001-2010	176	5.2	261	3.5	85	8.6	762.0	25.7	35	21.5

Source : All India Co-ordinated Research Project for Dryland Agriculture, Varanasi.

Parry and Carter (1985) showed that the frequency of such extremes was highly sensitive to small changes in mean values. For example, if mean annual precipitation decreases by one standard deviation, droughts of a severity formally experienced only once per 100 year could be expected every 11 year (Wigley, 1985).

A sensitivity analysis of the effects of inter annual climatic variation on wheat yields predicted by the CERES wheat model revealed that increases in variability of precipitation and temperature led to increased yield variation and consequent crop failure (Mearns *et al.*, 1984). When interfaced with the CERES model, increases in mean annual temperature predicted from a global climate model also led to projections of increased frequency of wheat failures. Broad scale changes in climatic factors probably would alter productivity of agroecosytems and influence the distribution of agricultural pests and selection of crop varieties (Rosenweig, 1985; Stinner *et al*., 1987; Goudriaan and Unsworth, 1990; Prestidge and Pottinger, 1990; Porter *et al*., 1991).

The impact of climate change on single species and ecosystems are likely to be complex. In the case of aggressive weed species of tropical and sub-tropical origins, which are currently restricted to Mediterranean environments, future climatic conditions may lead to an expansion of their potential range into temperate regions. However, in contrast to crops, weeds are troublesome invaders, ecological opportunists and resilient plants with far more genetic diversity. 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 geographical and seasonal distribution of pests likely will change as the climate changes. 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. Rising CO_2 may be a selection factor in weed species dominance (Fig. 1). Events such as cyclones, flooding, drought and fires will become more common and weeds will be the first to gain a stronghold after these events.

Climate change

Extreme events (Floods, storms and cyclones)	Seasonal changes	Elevated CO_2 and temperature	Weed management
↓		Selection factor in weed species dominance, increased invasiveness	
Efficient weed seed dispersal	Phenology of weeds	↓	Biological weed control-altered behaviour of bio-agent Decreased herbicide efficacy

Adoption of Integrated Weed Management
Rethink on future of herbicide resistant crops

Fig. 1. Climate change indicator affecting weed biology and management.

INVASIVENESS

Interactions between climate change and other processes (such as changes to land use), may also turn some currently benign species (both native and non-native) into invasive species and may lead to 'sleeper' weeds becoming more actively weedy, and have the potential to spread widely and have a major impact on agriculture.(Irmaileh, 2011).

Climate change will provide the opportunity for environmental weeds to invade new ecosystems. There is evidence of strong response of invasive weeds with elevated CO_2 concentration. Rising CO_2 may also affect growth and combustibility of many invasive weeds changing fire ecology. Increased CO_2 may select for invasiveness within assemblage of plants. Singh and Singh (2010) reported extensive coverage of vacant cultivated land during summer season by *Parthenium hysterophorus*. It is also reported that maximum seed is being produced during summer season by *Parthenium hysterophorus* (Anonymous, 2000), which signifies that in case of increased temperature more number of seed will be produced further facilitating spread of *Parthenium* to new areas during extreme climatic events.

WEED BIOMASS

CO_2 is the sole source of carbon for

photosynthesis and at present 96% of all plant species lack optimal CO_2.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). Ziska *et al*. (1999) observed significant increase in photosynthesis and a decrease in stomatal conductance in C_3 weed (*Chenopodium album*) but no change in *Amaranthus retroflexus* (C_4 weed) at elevated CO_2 level.

Fourteen of the world's 18 worst weeds are C_4 (Holm *et al*., 1977), by contrast, of the 86 plant species commodities that contribute 90% of national per capita food supplies world wide, only five are C_4. The remaining 81 are C_3, with the sole exception of pineapple which is a CAM plant (Prescott-Allen and Prescott-Allen, 1990). Bunce and Ziska (2000) reported that the competitive relationship between crop and weed might differ between regions. For instance, in the US, nine out of 15 worst weeds in the most important crops are C_3, and a substantial fraction of crops is C_4 [maize, sorghum, millet (*Pennisetum* spp.) and sugarcane]. Thus, the generalized prediction that in a CO_2 rich atmosphere the world's major crops will compete more successfully with the worst agricultural weeds, which are mostly C_4 species (Dukes and Mooney, 1999), may not be accurate.

Common weeds species found in India (Tables 2 and 3) such as *Ageratum conyzoides, Digitaria ciliaris, Cyperus* spp., *Echinochloa colona, Paspalum orbiculare* and *Setaria glauca* and having C_4 photosynthetic pathway will show smaller response in photosynthesis to increased CO_2 level in atmosphere, whereas weed species with C_3 photosynthetic pathways like *Agropyron repens, Argemone mexicana*, *Chenopodium album*, *Phalaris minor*, *Poa annua* and *Rumex acetosella,* may show enhanced photosynthesis to increased CO_2 level in

Table 2. Major weed species (C_3 pathway) and their life form (Patterson, 1985; Mishra, 2003)

Species	English name	Life cycle
Ageratum conyzoides L.	Goat weed	Ephemeral/Broad-leaved
Argemone mexicana L.	Mexican poppy	A/Broad-leaved
Brachiaria spp.	Para grass	P/grass
Chenopodium album L.	Common lambsquaters	A/Broad-leaved
Commelina nudiflora L.	Day flower	A/ Broad-leaved
Echinochioa colona (L.) Link	Jungle rice	A/ Grass
Eichhornia crassipes (Martius Solms-Laubach)	Water hyacinth	Floating aquatic
Elytrigia repens (L.) Nevski (*Agropyron repens*)	Quack grass	P/Grass
Leptochloa chinensis L.	Chinese sprangle top	A/Grass
Phalaris minor Retz.	Little seed canary grass	A/Grass
Poa annua L.	Annual blue grass	A/Grass
Rumex acetosella L.	Red sorrel	A/Broad-leaved
Rottboellia cochinchinensis (Lour.)	Itch grass	A/Grass

Table 3. Major weed species (C_4 pathway) and their life form (Patterson , 1985; Mishra, 2003)

Species	English name	Life cycle
Cynodon dactylon (L.) Pers.	Bermuda grass	P/ Grass
Cyperus iria L.	Rice field flat sedge	A/ Sedge
Cyperus rotundus L.	Purple nut sedge	P/Sedge
Dactyloctenium aegyptium (L.) Willd	Crow's foot	A/Grass
Digitaria ciliaris (Retz) Koel	Crab grass	A/Grass
Euphorbia spp.	Garden spurge	A/Broad-leaved
Imperata cylindrica (L.) Raeuschel	Cogon grass	P/Grass
Monchoria vaginalis (Burm. f.) Persl.	Monchoria	P/Aquatic
Paspalum orbicuiare Forst	Ditch millet	A/ Grass
Eleusine indica (L.) Link	Goose grass	A/ Grass
Saccharum officinarum (L.)	Tiger grass	P/Grass
Setaria glauca (L.) Beauv.	Fox tail	A/Grass

atmosphere, in addition, many of the worst weed for given crop are similar in growth habit or photosynthetic pathways for example, oat and wild oat, wheat and little seed canary grass, rice and wild rice, and hence weed growth is more favoured due to increased CO_2 level in the atmosphere (Patterson, 1995).

Kimball (1983) estimated that doubling ambient CO_2 levels stimulated biomass yield of C_3 plants by 40% and data for C_4 plants indicated a stimulation of 11%. Cure and Acock (1986) estimated stimulation of biomass accumulation from CO_2 doubling to be 31% in wheat, 30% in barley, 27% in rice, 39% in soybean, 57% in alfalfa and 84% in cotton. Increase in C_4 crops like corn and sorghum was estimated at only 9%. Poorter (1993) also reported large ranges of responses to CO_2 doubling of major crop species (Table 4). In C_3 weeds, leaf area generally responds less than biomass to CO_2 enrichment. However, in C_4 weeds, leaf area and biomass responses to CO_2 doubling are similar (Tables 5 and 6). Patterson and Flint (1990) reported biomass responses to CO_2 doubling for 27 herbaceous non-crop C_3 species ranging from 79 to 272% of growth in ambient CO_2. Responses of 11 C_4 species ranged from 56 to 250%. Cure and Acock (1986) concluded that doubling ambient CO_2 concentrations tended to increase the root/shoot ratio in six of 10 major crop plants, indicating increased allocation to the below ground sink. Other workers also have concluded that CO_2 enrichment increases the root/shoot ratio, and increases leaf density thickness or specific leaf weight (Acock and Allen, 1985; Oechel and Strain, 1985).

Table 4. Effects of doubling CO_2 concentration on vegetative biomass of major C_3 and C_4 crops (Poorter, 1993)

Species	Range of response (times growth at ambient CO_2)	No. of reports	Mean values
C_3 species			
Rice	1.42-1.51	2	1.47
Wheat	1.07-1.97	6	1.49
Soybean	1.23-4.95	13	1.71
Cotton	1.07-2.94	7	1.78
C_4 species			
Maize	0.98-1.24	6	1.09
Sorghum	1.26-1.82	2	1.52

WATER RELATIONS

The C_4 photosynthetic pathway provides its greatest advantage under hot, arid high light conditions. C_4 plants have higher water use efficiency than C_3 plants. Competition between C_3 and C_4 weeds has been examined in relation to soil moisture regime (Matsunaka, 1983), C_3 plants are dominant in submerged soils; C_4 plants are dominant in dry land soils. Submergence protects rice plants from severe competition with C_4 weeds. On the other hand, upland rice and rainfed lowland rice with limited precipitation face severe competition with C_4 weeds. Under imposed drought, Patterson (1986) found

Table 5. Effects of doubling CO_2 concentration on biomass and leaf area of C_3 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.	Common 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 6. Effects of doubling CO_2 concentration on biomass and leaf area of C_4 weeds (Patterson, 1995)

Scientific name	Common name	Range of response (% of growth at ambient) 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.	Nutsedge, purple	102	92	1
Digitaria ciliaris (Retz.) Koel.	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 (Lour.) W. Clayton	Itch grass	121	113	1
Setaria faberi Herm.	Foxtail, giant	93-135	101-140	3
Sorghum halepense (L.) Pers.	Johnson grass	56-110	99-103	3

that CO_2 enrichment reduced the effects of water stress and significantly increased leaf area and total dry weight of the three C_4 grasses : *Echinochloa crus-galli, Eleusine indica* and *Digitaria ciliaris*. He concluded that CO_2 enrichment can increase the growth of both C_3 and C_4 plants under water stress, but growth stimulation can be expected to be greater in C_3 plants.

Carlson and Bazzaz (1980) reported that doubling the CO_2 concentration from 300 to 600 ppm increased WUE by 55% in sunflower, 54% in corn, 48% in soybean, 128% in common ragweed, 87% in velvetleaf, 84% in jimson weed and 76% in redroot pigweed. They speculated that the greater stimulation of WUE in the weeds than in the crops might convey a competitive advantage to the weeds.

The complex interacting plant responses to elevated CO_2 and the elevated air temperature also limit the anti-transpirant effects of CO_2 (Eamus, 1991). Higher air temperature would increase leaf air vapor pressure deficit (VPD) which is the driving force for transpiration. However, growth enhancing effects of CO_2 enrichment will increase with increasing temperature (Idso *et al*., 1987; Idso, 1990). This would tend to increase water use efficiency because of greater biomass gain. On the other hand, greater production of leaf area by plants in future higher CO_2 environment would increase the transpiration surface area, particularly if higher leaf area indexes were attained earlier in growth cycle. This could increase total water loss per unit land area. All of these considerations require caution if predicting substantial gains in plant water status as a result of increasing CO_2.

NUTRIENT RELATIONS

Climate change has shown to reduce plant available nitrogen through elevated CO_2 (Williams *et al*., 2001; Zhang *et al*., 2005). The carbon nitrogen ratio of leaves is usually increased under CO_2 enrichment. Availability of nutrients such as nitrogen and phosphorus appears to quickly become limiting, even when carbon availability is removed as a constraint, on plant growth when ambient CO_2 concentrations are sufficiently increased (Hall and Allen Jr., 1993). C_4 plants have higher nutrient use efficiencies than C_3 grasses, and reduced nitrogen availability has been shown to benefit C_4 plants over C_3 plants in tall grass prairie (Bleier and Jackson, 2007). Changes that increase the dominance of C_4 plant species would change the plant community structure and may change ecosystem function, such as nutrient cycling, energy flow and have specific consequences for wildlife habitat (nutritional quality of forage and habitat requirements).

CROP-WEED INTERACTIONS

Crop-weed interactions vary significantly in various climatic regions, depending on temperature, precipitation, soil, etc. Physiological basis for variation in the competing ability of crops and weeds is their C_3 and C_4 photosynthetic pathways. C_3 and C_4 crops may interact with C_3 and C_4 weeds differentially in summer as well as winter seasons. In a cropping situation, crops are generally infested with a variety of weed flora and in changing climatic conditions, the competition offered by weeds depends on the relative population of both C_3 and C_4 weeds. Primarily following conditions may be encountered in crop-weed interaction under field conditions :

A. C_3 crop competing with both C_3 and C_4 weeds where C_3 weeds are dominant, whereas in another situation C_4 weeds are dominant.

B. C_4 crop competing with both C_3 and C_4 weeds where C_3 weeds are dominant, whereas in another situation C_4 weeds are dominant.

Patterson (1993) indicated that the relative increase in plant biomass in weeds and crops at doubling of CO_2 concentration might reach over 2.4 times in C_3 compared to 1.5 times in C_4, with weeds gaining more growth than crops in both the categories. When cultivated together with either of *C. album* L. (C_3 weed) or *A. retroflexus* L. (C_4 weed), soybean seed yield was reduced at both ambient and elevated CO_2 relative to the weed-free control (Ziska and Teasdale, 2000). The decrease in yield was associated with a 65% increase in dry weight of the C_3 weed at elevated CO_2, whereas in the combination with the C_4 weed, the yield loss was reduced less at elevated, as compared to ambient CO_2. It was concluded in the study that the presence of weeds reduced the ability of soybean to respond positively to elevated CO_2, particularly in the combination with the C_3 weed (Table 7). However, Ziska and George (2004) reported that for all weed-crop competition studies where the photosynthetic pathway is the same, weed growth is favoured as CO_2 is increased over crop plants.

Increase in CO_2 alone favours C_3 crops and weeds, but any simultaneous increase in temperature will benefit C_4 crops and weeds (Rajkumara, 2007). Rice and *Echinochloa glabrescens* were assessed at two different CO_2 (ambient and ambient+200 ppm) and two different temperatures (day/night of 27/21 and 37/29^{O}C) at 27/21^{O}C, increased CO_2 favoured the crop (C_3 spp.), however, at higher temperature and CO_2 favoured the C_4 weed (Alberto *et al.*, 1996). *C. album* grew much taller and produced more pollen under warmer and higher CO_2 concentrations (Ziska, 2001; Ziska and George, 2004).

Table 7. Effect of elevated CO_2 on crop-weed interactions

Crop-weed interaction	Ambient CO_2	Elevated CO_2	Percentage change
Above ground biomass			
Soybean (C_3)	340±13	448±14	+31.8
+C_3 weed	261±18	297±29	+14
+C_4 weed	204±17	329±27	+61.3
Seed yield			
Soybean (C_3)	187±8	228±8	+21.9
+C_3 weed	135±9	141±15	+4.4
+C_4 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 C_3 weed (*Chenopodium album* L.) or a C4 weed (*Amaranthus retroflexus* L.) (Ziska, 2000).

WEED MANAGEMENT

Herbicides are essentially major tools for weed control in intensive agriculture that produces more food per unit area of available land. Environmental factors such as temperature, precipitation, wind and relative humidity influence the efficacy of herbicides (Muzik, 1976; Hatzios and Penner, 1982). Elevated temperature and metabolic activity tend to increase uptake, translocation and efficacy of many herbicides (Patterson *et al.*, 1999), while moisture deficit, especially when severely depressing growth, tends to decrease efficacy of post-emergence herbicides, which generally perform best when plants are actively growing. Post-emergence herbicides can be dramatically affected by drought. Drought can result in thicker cuticle development or increased leaf pubescence, with subsequent reductions in herbicide entry into the leaf. High concentrations of starch in leaves which commonly occur in C_3 plants grown under CO_2 enrichment (Wong, 1990), might interfere with herbicide activity (Patterson *et al.*, 1999).

Due to moisture stress, higher rates of application may be necessary or certain surfactants may have to be added to enhance the efficacy of weed control.

Pre-emergence herbicides are highly dependent on available water for movement into the zone of weed seed germination. Sunlight degrades some pre-emergence herbicides on the soil surface, and if optimum moisture does not become available within a week after application, poor weed control often results. Even for highly persistent herbicides, failure to move the compound into the soil due to the lack of moisture allows weeds to germinate just after planting. Soil microorganisms play a significant role in degradation of many herbicides. Activity of many microbes is favoured by warm, moist conditions. Under dry conditions, microbial degradation slows and herbicide persistence in the soil is extended. For long-residual products which have specific restrictions relating to carryover, persistence is greater for incorporated rather than surface applications (Brown, 2008). The same variables can also interfere with crop growth and recovery following herbicide application. On the other hand if conditions become more humid and warmer, herbicide persistence will be shortened (Bailey, 2004).

Perennial weeds may become more difficult to control, if increased photosynthesis stimulates greater production of rhizomes and other storage organs. Patterson and Flint (1990) noted that chemical control could be difficult if additional CO_2 will result in higher root, rhizome, or tuber growth. The role of CO_2 in enhancing underground growth of weeds and its subsequent effect on efficacy of herbicides is still not well documented. Canada thistle (*Cirsium arvense*) and quack grass (*Elytrigia repens*) become more resistant to herbicides when grown in higher concentrations of CO_2, making them harder to control. It was hypothesized that this may be a result of faster growth as the weeds mature more rapidly, leaving behind more quickly the seedling stage during which they are most vulnerable (Ziska *et al.,* 1999; Ziska and Teasdale, 2000). Ziska *et al.* (2004) reported that glyphosate efficacy was reduced under CO_2 enriched environment, suggesting that the tolerance in weed might be due to dilution effect and increased root biomass of Canada thistle (*Cirsium arvense*) (Table 8).

Potential changes in the weed biogeography of agricultural systems pose a challenge to management, but also an opportunity. If weed species can be identified as favoured due to emergent climate conditions in a given region, nascent populations can be targeted for control before they become well established.

Besides changes in climate, agronomic practices for particular crops are not static in time and space; new classes of herbicides, cultivars, tillage system, irrigation techniques and seed sowing practices can all influence the geographic distribution and crop damage caused by weeds. Ecosystems with high levels of disturbance are more vulnerable to colonization by newly introduced plant species and are likely to reach a comparatively rapid equilibrium with emergent climate factors (Hobbs and Huenneke, 1992; Milchunas and Lauenroth, 1995).

Many genetically modified crops specific for a given herbicide are available in market; consequently, it is likely that the use of these herbicides would persist in coming decades. Raising herbicide resistant crops can significantly change weed community composition.

Table 8. Canada thistle shoot and root dry weight (±SE) 43 and 42 d after glyphosate application for plants grown at ambient and elevated CO_2 concentrations (Ziska *et al*., 2004)

	Year	(CO_2) (µmol mol^{-1})	Sprayed	Unsprayed
Shoots (g m^{-2})	2000	421	24.4±7.2	60.3±16.7[a]
		771	58.7±3.0[b]	64.5±7.1
	2003	417	18.1±6.7	79.1±11.1[a]
		753	85.7±7.2[b]	116.5±17.3[b]
Roots (g 2.43 L soil)	2000	421	0.08±0.03	0.43±0.04[a]
		771	0.45±0.03[b]	0.70±0.10 [a,b]
	2003	417	0.09±0.04	0.74±0.26[a]
		753	0.69±0.25[b]	1.46±0.30 [a,b]

[a]A significant difference between sprayed and unsprayed plants at a given (CO_2).
[b]A significant difference as a function of (CO_2) for either sprayed or unsprayed plants. Significance was determined at $P< 0.05$ (t test assuming unequal variances).

Decreased efficacy of herbicides due to climate change may also affect weed management strategies in herbicide resistance crops.

Climatic changes and increased CO_2 could also disrupt natural and classical biological control of weeds. The efficiency of bio-control agents will be altered by CO_2-induced changes in morphology, phenology and reproduction of weeds. Overall synchrony between biology of bio control agents and their selected target weeds will change in periods of rapid climatic change.

Tactical weed control will become more important because some traditional weeds will need fewer years to set seed. However, weeds by their very nature are highly adaptive; so monitoring for population increases and incursions of new species remain critical. To compensate for any loss of herbicide effectiveness under warmer and drier conditions growers may need to review the reliance on herbicide use in any integrated weed management approach.

CONCLUSIONS

Estimates of yield stimulation by elevated CO_2 may be too high if effects from competition with weeds are ignored, unless weed management adapts flexibly. It is clear that the agricultural, environmental and health costs of not visualizing the impact of climate change on weed may be substantial. Therefore, scientific database is required to fully understand CO_2- induced changes in weed dynamics to formulate sustainable weed management strategies, including herbicide use in various agro-ecological conditions. Further, interaction effect of climate change and edaphic factors on crop production system is very complex, experiments with different crop weed systems under a range of atmospheric and edaphic conditions are needed to allow for more accurate predictions.

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