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Climate change, crop-weed balance and the future of weed management

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ABSTRACT

Ever increasing global population, rapid industrialization, increased fossil fuel consumption, deforestation *etc*. lead to the increased concentration of greenhouse gases in the atmosphere. IPCC reports provide strong evidence that rising CO_2 and other trace gases could lead to a 3±12°C increase in global surface temperatures with subsequent effects on climate. Relationship between climate change and agriculture is of particular importance as the world population and world food production showing imbalance under pressure. As mean temperature increases, weeds expand their range into new areas. Climate change is likely to trigger differential growth in crops and weeds and may have more implications on weed management in crops and cropping systems. Growth at elevated CO_2 and elevated temperatures would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness. Climate change has an indirect influence on the occurrence of weeds via crop management and land use. There is a possibility that agricultural weed populations will evolve new traits in response to emerging climate and non-climate selection pressures. Reducing the impacts of weeds and preventing new weeds are essential to increasing the resilience of ecosystems and giving native species the best chance to deal with the adverse impacts of climate change.

Key words: Climate change, Elevated CO_2, Weeds, Weed invasion, Weed management

Global climate change is no doubt a severe problem that the world is facing today. Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and, which is in addition to natural climate variability observed over comparable time period (UNFCC 1994). Climate change is the change in statistical distribution of weather pattern that lasts for an extended period of time. Since the industrial revolution began around 1750, human activities have contributed substantially to climate change by adding CO_2 and other heat-trapping gases to the atmosphere. These gas emissions have increased the greenhouse effect and caused earth's surface temperature to rise. Projections suggest 2.4–6.4^{0}C increase of global average temperature by the end of 21st century (IPCC 2007). Studies indicate that significant warming is inevitable regardless of future emission reductions. Climate change will modify rainfall, evaporation, runoff and soil moisture storage. If these forecasts come into reality, crops and cropping systems are likely to experience significant changes. A relationship between climate changes and agriculture is of a particular importance as the world population and world food production showing imbalance under pressure.

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Increased CO_2 concentrations could have a direct effect on the growth rates of individual crop plants and weeds and also cause vegetation communities to change. Increased CO_2 concentration and temperature will alter the plant's ability to grow and compete with other individuals within a given environment. Increased CO_2 would enable many plants to tolerate environmental stresses, such as drought and temperature fluctuations (IPCC 1996, Parry 1998, Bunce 2001). Weeds affect agricultural production and biodiversity as they out-compete crops and native species and contribute to land degradation. Increased tolerance to stress is likely to modify the competitiveness of weeds and their distribution. Weeds with high reproduction and efficient seed dispersal mechanisms may better be able to take advantage of the expected calamities like cyclones and floods.

Crop-weed balance under climate change

Climate change is likely to trigger differential growth in crops and weeds and may have more implications on weed management in crops and cropping systems. The effects of climate change on crop-weed interactions are likely to vary by region and crop type. As the crop-weed interactions are balanced by various environmental factors, local changes in these factors may alter the balance towards either crop or weed. Changes in temperature and carbon dioxide are likely to have significant direct (CO_2 stimulated growth) and indirect (climatic variability) effects on weeds and that would affect crop-weed balance or lead to weed invasion.

Direct effects

Effect of elevated CO_2: The United Nations Inter-governmental Panel on Climate Change (UN-IPCC) predicts that atmospheric CO_2 concentration could exceed 700 ppm by the end of 21st century (Houghton *et al*. 1996). While the extent of temperature increases remains speculative, there is acknowledged consensus on the direct physiological impact of increasing CO_2 concentration on plant photosynthesis and metabolism (Stitt 1991, Bowes 1996). Increasing CO_2 concentration has been shown to stimulate growth and development significantly in hundreds of plant species (Kimball 1983, Kimball *et al*. 1993, Poorter 1993, Sage 1995). Plants vary in their response to CO_2 because of differential photosynthetic pathways *i.e.* C_3 and C_4.

Due to the ongoing increases in atmospheric CO_2 there would be stimulation in leaf photosynthesis in C_3 plants by increasing the CO_2 level in the leaf interior and by decreasing the loss of CO_2 by photorespiration. The C_4 plants, however, have internal biochemical pump for concentrating the CO_2 at carboxylation site that reduces the oxygenase component of the rubisco thereby eliminating the carbon loss by photorespiration. Because of this differential response of the plants to the CO_2, it has been postulated that with higher CO_2 levels in the atmosphere, there may be significant alterations in the competitive interactions and certain genotypes or species may become extinct after several generations of altered competition. This differential response by C_3 and C_4 plants to higher CO_2 is specifically relevant to crop-weed competition because, most of the crops are C_3 plants and most of the weeds are C_4 plants. Several observations on the response of growth of C_3 and C_4 species to elevated CO_2 support the general expectation that the C_3 species are more responsive than C_4 species. For a C_3 crop such as rice and wheat, elevated CO_2 may have positive effects on crop competitiveness with C_4 weeds (Yin and Struik 2008, Fuhrer 2003). But this is not always true. To date, for all crop–weed competition studies, where the photosynthetic pathway is the same, weed growth is favoured as CO_2 is increased. Therefore, C_3 weeds like *P. minor* and *A. ludoviciana* in wheat (C_3) would aggravate with the increase in CO_2 due to climate change.

Elevated CO_2 has been shown to increase growth and biomass accumulation of the C_4 weed *Amaranthus viridis* (Naidu 2007). As high temperatures would also create increased evaporative demand, with its high water use efficiency and CO_2 compensation point, C_4 photosynthesis is better adapted to high evaporative demand (Bunce 1983). Developing leaves of C_4 plants use C_3 photosynthetic pathway until 'kranz anatomy' is fully differentiated (Nelson and Langdale 1989). During this early period a large proportion of the leaf area of these plants use C_3 photosynthetic pathway and therefore, they get benefited from elevated CO_2 condition.

It is evident that an increased CO_2 concentration leads to partial closure of stomata that reduces transpiration per unit area thereby reduces the plants' water requirement while promoting photosynthesis. Reduced water requirement and enhanced photosynthesis improve water use efficiency (WUE). Kimbal and Idso (1983) reported improvement of WUE by 70-100% for both C_3 and C_4 plants. Under the condition of high CO_2 concentration, C_3 plants are likely to become more water-efficient, potentially allowing C_3 weeds to move into drier habitats (Kriticos *et al.* 2003). With high CO_2 fixation rates and with characters like shorter life cycle, vegetative reproduction or easily disseminated seeds, the weeds would become very competitive.

Effect of elevated temperature: Climate change projections suggest 2.4–6.4^{O}C increase of global average temperature by the end of 21st century (IPCC 2007). Studies indicate that significant warming is inevitable regardless of future emission reductions. If these forecasts are realized, crops and cropping systems are likely to experience significant changes and it is so for the associated weeds too. Changes in temperature generally affect the length of growing period in plants. Most significant effect of temperature increase in the regions where temperature is the main limiting factor would be an extension of plant growth period. As mean temperatures increases, weeds expand their range into new areas. As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds. Under high temperature, plants with C_4 photosynthesis pathway (mostly weeds) have a competitive advantage over crop plants possessing the more common C_3 pathway (Yin and Struik 2008). Most of the weeds in rice are of C_4 type in India. For instance, incidence of *Ischaemum rugosum*, which was a common weed of rice in tropical areas, but has become a common weed with significant presence in northern states (Singh *et al.* 1991). Similarly, the incidence of *Rumex spinosus* in wheat in north-west India has increased.

Introduced in 1877 from Central America as a drought tolerant species suitable for afforestation in arid and semi arid zones of India, *Prosopis juliflora* has invaded nearly 6.0 million hectares of land contributing for 1.8% of geographical area of the country (Kathiresan 2005). The most potential invasive feature of the species is typical that a greater portion of assimilates are partitioning towards root, leading to extraordinary enlargement in the root mass with rich food reserves, aiding rapid and robust regeneration after mechanical lopping or after revival of ecological stress conditions such as drought or inundation. The annual increase in root bio-mass is greater in areas where the mean annual temperature is higher than that in areas of lesser mean annual temperature. The increase in root biomass largely contributes for the weed's ability to tolerate climatic extremes such as a peak summer associated with high temperature and water scarcity and a peak monsoon winter with water inundation and flooding. This adaptation favors the weed to predominate over other native floras that are susceptible to any one of the two extremes.

Effect of changes in rainfall: Weeds constrained by rainfall may also find new habitats under new climatic conditions. *Lantana camara*, for example, could expand if rainfall increased in some areas (McFadyen 2008). The meteorological data available at the Annamalai University showed that in the tail end of Cauvery river delta region of Tamil Nadu state, the average annual rainfall during the period of 1991 to 2000 has increased by 129 mm compared to the period during 1981 to 1990. The record also revealed that the annual evaporation has reduced by 255 mm from the period between 1981 to 1990 and 1991 to 2000. Further, wet years (years with excess average annual rainfall by more than ten per cent) are also more frequent during 1991 to 2000 than during 1980 to 1990. Phyto-sociological survey of floristic composition of weeds in this region reveals that rice fields were invaded by alien invasive weeds *Leptochloa chinensis* and *Marsilea quadrifolia*. These two weed species dominated over the native weeds such as *Echinochloa* spp. and others by virtue of their amphibious adaptation to alternating flooded and residual soil moisture conditions prevalent during this period in this region (Yaduraju and Kathiresan 2003, Kathiresan 2005).

Interaction effect of CO_2 and other factors: The interaction between increased CO_2 concentration and other environmental factors such as water, light intensity, nutrient availability and temperature may also result in differential response to increased CO_2 among weeds and crops (Bazzaz and Carlson 1984, Patterson and Flint 1982).

CO_2 and temperature: Plant response to the interaction effect of CO_2 and temperature may be complex (Bazzaz 1990). Some studies have shown that low or high temperatures reduce or eliminate the high CO_2 growth enhancement (Hofstra and Hesketh 1975, Idso 1990, Coleman and Bazzaz 1992) whereas, others have shown that CO_2 enrichment may increase the plant tolerance to temperature extremes (Sionit *et al.* 1981, Potvin 1985, Baker *et al.* 1989). Based on the differences in temperature optima for physiological processes, it is predicted that C_4 spp. will be able to tolerate high temperature than C_3 spp. Therefore, C_4 weeds may benefit more than the C_3 crops from any temperature increases that accompany elevated CO_2 levels. High CO_2 levels have been shown to ameliorate the effects of sub-optimal temperatures (Sionit *et al.* 1987) and other forms of stress (Bazzaz 1990) on plant growth. Tremmel and Patterson (1993) have shown that high CO_2 ameliorated the high temperature effects on quack grass (*Elytrigia repens*). Carter and Patterson (1983) obtained similar results. Data from the results of the experiments by Alberto *et al.* (1996) suggest that competitiveness could be enhanced in C_3 crop (rice) relative to a C_4 weed (*Echinochloa glabrescens*) with elevated CO_2 alone but simultaneous increases in CO_2 and temperature still favor C_4 spp. O'Donnell and Adkins (2001) reported that wild oat plants grown at high temperature 23/19 ^{0}C (day/night) completed their development faster than those grown at normal temperature 20/16^{0}C. If the maturation rate is faster relative to the crop, more seeds may be deposited in the soil seed bank with a consequent increase in the number of wild oat plants. The wild oat plants grown at 480 ppm CO_2 produced 44% more seed than those grown at 357 ppm.

CO_2, temperature and light intensity: It was reported that plants which are efficient in fixing CO_2 become relatively more competitive as light intensity increases. In addition, these species have high optimum temperature for photosynthesis and thus would become more competitive as temperature increases from 20^{0}C to 30^{0}C or 40^{0}C. At midday when light intensity and temperature both reach peak values weed species like redroot pigweed (*Amaranthus retroflexus*, C_4) and Johnson grass (*Sorghum halepense*, C_4) are expected to fix CO_2 at higher rate than the crops like soybean (C_3) and

Cotton (C_3). As high temperatures would also create increased evaporative demand with its high water use efficiency and CO_2 compensation point C_4 photosynthesis is better adapted to high evaporative demand (Bunce 1983).

CO_2 and moisture stress: The CO_2 enrichment tends to reduce the deleterious effects of drought (Sionit and Patterson 1985). Due to CO_2 enrichment, the wheat plant could gain biomass against *P. minor.* Under water stress conditions, however, *P. minor* had advantage over wheat with CO_2 enrichment (Naidu and Varshney 2011).

Even under water limited conditions growth enhancement by CO_2 appears to be greater in C_3 crops than C_4 weeds if the temperature increase is not as dramatic as predicted (Patterson 1986). An increase in temperature with accompanying soil moisture stress will offset the growth benefits from CO_2 fertilization; the net effect depends on the level of moisture stress. Plants with C_4 photosynthetic metabolism sometimes increase photosynthesis and growth at elevated CO_2 concentration under dry conditions (Patterson 1986, Knap *et al.* 1993), when elevated level of CO_2 slows the development of stress.

CO_2 and nutrient availability: Number of studies showed that the rise in CO_2 concentration induces growth stimulation in crops as well as in weeds. If the availability of a resource changes within the environment, the weeds with greater genetic diversity and adaptability will show a better growth and reproductive response than that of crops. Nitrogen-fixing weeds may especially benefit because growth stimulated by CO_2 will not be constrained by low nitrogen levels (Poorter and Navas 2003). Under extreme nutrient deficiencies, there may be no response to elevated CO_2 in terms of biomass increase; under moderate limitations more relevant to agricultural situations, the increase in biomass may be reduced but the relative stimulation by elevated CO_2 is often similar (Wong 1979, Rogers *et al.* 1993). As in the case of water stress, reduction in growth caused by nutrient deficiency may reduce the impact of weeds on crop production (Patterson 1995b), since smaller plants interfere less among themselves.

Indirect effects

As weeds are closely associated with the cropping system (Pysek *et al.* 2005, Andreasen and Skovgaard 2009, Cimalova and Lososova 2009, Gunton *et al.* 2011), climate change has an indirect influence on the occurrence of weeds via crop management and land use. Irrigation water in North-West India is increasingly become scarce and many resource–conservation technologies have recommended to conserve irrigation water, for instance, zero tillage in wheat, bed planting in rice and wheat, and dry-seeded rice. This will have consequences on weed abundance and composition. Alternate wetting and drying in puddled as well as dry-seeded rice may encourage weeds such as *Leptochloa chinensis*, *Eleusine indica* and *Eclipta prostrata* (Mahajan *et al.* 2012).

Due to changing climate, timing of life-cycles are expected to changes and that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth (Boote *et al.* 2005). Flowering can be faster, slower or unchanged at elevated CO_2, depending on species. Reekie *et al.* (1994) reported that elevated CO_2 delayed flowering in four short day species and hastened it in four long day species. During the studies conducted in Open Top Chambers (OTCs) at the Directorate of Weed Research, Jabalpur, India, it was observed that CO_2 enrichment hastened the seed maturity in *Avena fatua* (wild oat), a common weed in wheat. The seeds matured 13 days in advance compared to the plants grown under ambient CO_2 conditions and may probably resulted into the enrichment of soil seed bank as the wild oat seeds shatter well before the harvest of the crop. Drought and dry soil conditions prolong the weed seed bank longevity.

Higher temperatures and other factors are likely to increase pollinators' (insects') breeding cycles and provide more weed pollination thereby increase the weed population. As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds. Climate change will render native species more vulnerable to weeds either directly or indirectly, for example by facilitating the spread of the serious plant diseases. Importing of fodder and grain into drought prone areas can bring new weed problems to the region.

In their responses to climate change, humans are likely to introduce more weeds and create more opportunities for invasion. Many crops proposed for biofuels, jatropha (*Jatropha curcas*) and giant reed (*Arundo donax*) for example are serious weeds (Low and Booth 2007). New hardier pasture and garden plants developed to withstand drier conditions expected under climate change are likely to have a high weed risk (Booth *et al.* 2009) Agricultural adaptations to climate change, including new products and shifts into new areas will also create more opportunities for weeds. More weeds will be one of the inevitable results of the proposed shift of more intensive agriculture.

Rise in CO_2 level increases the pollen production and thus the asthma by quadrupling in US since 1980 (AAAAI 2000). Increased CO_2 stimulated ragweed (*Ambrosia artemisifolia*) pollen production several times more than that it stimulates overall growth (Singer *et al.* 2005). Most of the weed species are associated with contact dermatitis, an immune-mediated skin inflammation. Chemical irritants can be present on all plant parts including leaves, flowers, and roots, or can appear on the plant surface when injury occurs. The amount and concentration of these chemicals vary with a range of factors, including maturity, weather, soil, and ecotype. These facts suggest plausible links among rising CO_2, plant biology, and increased contact dermatitis. Production of morphine in wild poppy (*Papaver setigerum*) showed significant increases with both recent and projected CO_2 concentrations (Ziska *et al.* 2008). Concurrent increases in temperature and CO_2 also affected the production and concentration of atropine and scopolamine in jimson weed (*Datura stromonium*) (Ziska *et al.* 2005).

Climate change and weed invasion

Climate change is expected to increase the risk of invasion by weeds from neighboring territories. With the competitive ability, weeds often find an opportunity to establish new populations when natural or desirable plant species decline. Climate change may also favour expansion of range of weeds that have already established but are currently restricted in range. The range expansion can be attributed to evolutionary adaptation (Clements and DiTommaso 2011, 2012). Weeds which have higher spread and establishment potential have the potential to invade new areas and increase their range.

Extreme weather events create conditions congenial for weeds to extend their range and invade new areas or out-compete native species in their existing range. Under drought, the competitiveness of native vegetation gets reduced and new weeds get the opportunity to invade. Flood assist in spreading weeds to weed free areas; provide opportunity for new weed invasion by washing away the vegetation and exposing the areas of disturbed soil. Warmer temperature will force some species to relocate, adapt or perish. Species that are active in summer will develop faster. Warmer climate restricts temperature sensitive species to high altitudes. In plains, this effect on distribution range is magnified because species without the ability to move to higher elevations must relocate further in the same altitude. Weeds with efficient dispersal mechanisms are better equipped to shift their range, while species with short life cycles are better equipped to evolve and increase their tolerance of warmer temperatures.

Weeds that are well-suited to adapt to the impacts of climate change may not only fill gaps left by more vulnerable native plants but, they may have an even greater effect by altering the composition of ecosystems and their integrity. In fact, climate change may favour certain native plants to such an extent that they then become weeds. Land management practices such as land clearing, habitat fragmentation and over grazing that clear native vegetation and degrade its condition adversely affect the biodiversity and favour weed invasion by providing opportunities for them to colonise new areas and by reducing the ability of native vegetation to compete with and suppress invading species.

Alien weeds are usually non-native, whose introduction results in wide-spread economic or environmental consequences (e.g. *Lantana camara*, *Parthenium hysterophorus*, *Eichhornia crassipes etc.* in India). These weeds have strong reproductive capability and are better dispersers and breeders. With these characteristics, they are benefitted from climate change. Studies indicate that these weeds may show a strong response to recent increases in atmospheric CO_2 (Ziska and George 2004). From the studies conducted at the Directorate of Weed Research, Jabalpur, India it was observed that the invasive weed *Parthenium hysterophorus* had shown tremendous growth response to elevated CO_2 (Naidu and Paroha 2008, Naidu 2013) suggesting the possibility that the recent increase in CO_2 during 20th century may have been a factor in the invasiveness of this species. Responses to climate change will be specific to individual species and will depend on a range of interacting factors.

Climate change and weed management

Cultural, manual, and mechanical weed management: A standard means of controlling weed populations, and the one most widely used in developing countries is mechanical removal. Tillage, either by animal or by mechanical means is regarded as a global method of weed control in agronomic systems. Elevated CO_2 commonly stimulate the growth of roots and rhizomes more than that of shoots. Increased below ground growth in such species may make manual removal a difficult task as

CO_2 rises. Consequently, mechanical tillage may lead to additional plant propagation in a higher CO_2 environment, with increased asexual reproduction from below ground structures and will have negative effects on weed control (Rogers *et al.* 1994, Ziska and Goins 2006). Cultural practices like manual weeding and intercropping may also be affected by altered growing seasons induced by climate change. Climate extremes *i.e.* precipitation or drought could also limit the opportunity for field operations. Changes in rice cultivation from transplanting to direct seeding under limited water availability necessitates emphasis on post emergence weed management in order to keep the yields high.

Chemical weed management: Under increased temperature and unpredictable precipitation scenarios, current recommendations of herbicides may not be effective. Increased temperature and drought can reduce herbicide uptake, increase volatility, structural degradation and reduce its effectiveness. Growth at elevated CO_2 would result in anatomical, morphological and physiological changes that could influence herbicidal uptake rates, besides translocation and overall effectiveness.

Stimulation of below ground growth under elevated CO_2 may lead to abundance of perennial weeds. Manea *et al.* (2011) showed that three of four C_4 grass species displayed increased tolerance to glyphosate under elevated CO_2. Similar results were also reported by Ziska and Goins (2006). The reasons for the reduced efficacy of the herbicides might be that increasing CO_2 can increase leaf thickness and reduce stomatal number and conductance possibly limiting the uptake of foliar applied herbicides. Greater increases in biomass could result in dilution of applied herbicide and thereby reducing its efficacy (Patterson 1995a).

High concentrations of starch in leaves which commonly occurs in C_3 plants grown under CO_2 enrichment (Wong 1990) might interfere with herbicide activity (Patterson *et al.* 1999). In general, protein content per gram tissue can be reduced with increasing CO_2 (Bowes 1996), which could result in less demand for aromatic amino acids thereby reducing the efficacy of glyphosate, a non-selective herbicide which inhibits the aromatic amino acid production through shikimic acid pathway. Decreasing stomatal conductance with increasing CO_2 could also reduce the transpiration and thereby the uptake of soil applied herbicides. If the growth of the weeds is stimulated by the future levels of atmospheric CO_2, the efficacy of the post-emergence herbicides would be reduced because the time spent by the weeds in seedling stage *i.e.* the stage of greatest herbicide sensitivity would be shortened (Ziska *et al.* 1999). In this situation, further applications or additional concentrations of the herbicides may be needed to control such weeds but add to the cost of control.

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 to be effective. Pre-emergent herbicides or herbicides absorbed by plant roots need soil moisture and actively growing roots to reach their target species.

Biological weed management: Introduction of biocontrol agent for weed management is a low cost technology and permanent strategy, because an effective and successful biocontrol agent is self-sustaining. Natural and manipulated biological control of weeds and other potential pests could be affected by increasing atmospheric CO_2 and climate change. Climate changes could alter the efficacy of the biocontrol agent by changing the growth, development and reproduction of the selected weedy target. Elevated CO_2 and temperature directly alter morphology and reproduction of weeds. Change in C:N ratio may alter the feeding habits and growth rate of herbivores. Direct effects of CO_2 on increasing starch concentration in leaves and lowering nitrogen contents could also affect the biocontrol by altering the behavior and growth rate of herbivores.

Conclusion

Almost all the studies indicate that both crops and weeds respond to climate change, but the balance will tilt towards weeds since they are naturally evolved with better adaptation strategies. The physiological plasticity of weeds and their greater intraspecific genetic variation compared with most crops could provide weeds with a competitive advantage in a changing environment. Controlling weeds is likely to be more difficult and expensive under climate change. Prediction of future damage by weeds is very important for sustainable weed management. In order to get the assured yields in light of predicted future climatic conditions and extreme weather events, adoption of intensive management practices is inevitable. However, climate is not the only factor that will be changing in future. Other factors like population growth, socio-economic and technological changes will have effect no less than climate change.

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