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Weeds in Soybean *vis-a-vis* other Crops under Climate Change-A Review

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ABSTRACT

Weeds possess wider genetic diversity than field crops. The changes within environment resources due to climate change, caused changes to the biology and competitive abilities of agricultural pests (weeds, insects and pathogen) relative to crops. Weeds with C_3 *and* C_4 *photosynthetic pathways may exhibit differential responses to higher* CO_2 *levels and temperatures, which can affect the dynamics of crop–weed competition. Weed competition can result in potential crop losses of 34 per cent globally. Weed population will change with climate change and risks of invasiveness may increase. Effectiveness of current management practices may be affected. Most of the research concentrated only on single factor either elevated* CO_2 *or temperature) therefore research is needed to assess the interactive effects of multiple climate change factors simultaneously to help prediction how weed problems may change in future with changing climate in order to develop flexible integrated weed management practices which are based on a foundation of knowledge of weed biology and ecology. Weeds have been winner and will be winner in future climate change conditions because of more adaptive power and more diversity. In this review, the most of the things illustrated very precisely.*

Key words: Climate change, carbon dioxide, temperature, weeds

The mega drivers of agricultural production are environmental (CO_2, temperature, precipitation, sunshine hours, *etc.*), edaphic (physical, chemical and biological properties, *etc.*), genetic potential of crop and agronomic management. Climate change will have significant and generally negative impacts on agriculture and growth prospects in the lower latitudes (Vermeulen *et al.*, 2012; Field *et al.*, 2012; Stocker *et al.*, 2013). As climate prediction models show increased occurrences of drought, flooding and high temperature spells during the crop growing periods (IPCC, 2008; Mittler and Blumwald, 2010). Drought, flooding, high temperature, cold, salinity, and nutrient availability are abiotic factors that have a huge impact on world agriculture and account for more than 50 per cent reduction in average potential yields for most major crops (Wang *et al.*, 2003). By 2050, climate-related increases in water stress are expected to affect land areas twice the size of those areas that will

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experience decreased water stress (Bates *et al*., 2010]. Increased climate variability in the coming decades will increase the frequency and severity of floods and droughts, and will increase production risks for both croppers and livestock keepers and reduce their coping ability (Thornton and Gerber, 2010].

The earth is warmed largely by short-wave radiation (0.15-4.0 µm) emanating from the Sun, which has a high temperature 6000^{0}C). The overall climatic consequences, called '*global warming*', is an enhanced greenhouse effect. Of these gases, CO_2 is the most significant, contributing to about 64 per cent of the effect, followed by CH_4 (19 %), CFCs (11 %) and N_2O (6 %).

Overall, changes to the biology and competitive abilities of agricultural pests (insects, pathogens, weeds) relative to potential crop yield losses have not been well quantified (Scherm, 2004; Gregory *et al*., 2009). This is an important omission as the role of pests on constraining crop production is significant and well recognized. For example, weed competition can result in potential crop losses of, 34 per cent globally, with insect pests and pathogens resulting in additional losses of, 18 and 16 per cent, respectively (Oerke, 2006). Such omissions may reflect the complex challenges in relating atmospheric CO_2 and climate variables to potential reductions in crop production related to increased pest pressures. For example, weed growth and fecundity can be directly affected by increasing atmospheric CO_2 as well as rising temperature; insects and pathogens can also be directly affected by temperature, but indirectly by CO_2 and/or climate induced changes to their weed hosts (Oerke, 2006; Ziska and Runion, 2007). Overall, while a number of pest studies have been conducted, empirical evidence has been eclectic, although it has been suggested that pest pressures will probably increase with climate change (Patterson *et al*., 1999).

Increase in CO_2 to 550 ppm increases yields of rice, wheat, legumes and oilseeds by 10-20 per cent. A 1^{0}C increase in temperature may reduce yields of wheat, soybean, mustard, groundnut, and potato by 3-7 per cent. Much higher losses could be at higher temperatures. Productivity of most crops to decrease only marginally by 2020 but by 10-40 per cent by 2100 due to increases in temperature, rainfall variability, and decreases in irrigation water. The major impacts of climate change will be on rainfed or un-irrigated crops, which **are** cultivated in nearly 60 per cent of crop land. A rise by 0.5^{0}C in winter temperature is projected to reduce rainfed wheat yield by 0.45 tonnes per ha in India (Lal *et al*., 1998). Possibly some improvement in yields of chickpea, *rabi* maize, sorghum and millets; and coconut in west coast. Less loss in potato, mustard and vegetables in north-western India due to reduced frost damage. Increased droughts and floods are likely to increase production variability.

Variations in air temperature, CO_2, and precipitation directly affect soybean yield. Heinemann *et al*., (2006) observed an increase of soybean yield at an elevated temperature and CO_2;

however, the rate of increase in yield was reduced with increased air temperatures in Georgia. Similar results were found when CO_2 concentration was doubled, and soybean yield increased 50 per cent; nevertheless, the positive effect of the CO_2 increase was offset by the air temperature increase of 3°C, and the final combined effect between CO_2 increase and temperature resulted in 36 per cent increase of soybean yield (Lal *et al*., 1999). Mohanty *et al.* (2017) showed that increasing CO_2 concentrations alone resulted in increased soybean yield in India. Similarly, reduction in rainfall amount indicated negative impact on it. This effect further compounded with increase in temperature and thus, reduced soybean yield. Increasing the temperature with 10 per cent decrease in rainfall declined the soybean yield by 10 per cent. An increase in temperature along with increase in rainfall has also not favored soybean growth. Decreasing the temperature from the base by 1°C and increasing the rainfall by more than 10 per cent benefitted the soybean productivity, whereas increasing the temperature by 1°C with no change in rainfall resulted decline in soybean productivity by 10-15 per cent. Soybean yields in China are predicted to decrease by 5-10 per cent under the slowest warming scenario and by 8-22 per cent under the fastest warming scenario by the end of the century (Chen *et al*., 2013).

The direct and indirect effects of the global changes on agriculture and natural ecosystems can be summarized as below.

(1) 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;

(2) CO_2 induced climate changes may alter temperature, rainfall patterns and amounts of radiation received in different parts of the world; this will influence the productivity of natural ecosystems or agricultural landscapes with significant regional variations; and

(3) Sea level rises, also with regional differences, may lead to loss of productive land, and to increasing salinity of groundwater in coastal zones.

Of the above effects, only the first two are most relevant to weed management. A better understanding of potential changes in both crops and weeds is crucial to enable adapting to future climate changes, and sustain our ability to manage weed populations effectively.

Of the 15 crops, which supply 90 per cent of the world's calories, 12 have the C3 photosynthetic pathway. In contrast, 14 of the 18 'World's Worst Weeds' are C4 plants (Patterson, 1984). The general consensus of the above and other similar studies is that the greater majority of weeds in the world, which are C3 plants, will benefit from increased CO_2 levels under climate change, while most tropical grasses, which are C4 plants, are not likely to show greatly increased growth in higher CO_2. However, because C4 plants are generally more tolerant of heat and moisture stress, the simple notion that climate change will only benefit C3 plants may not be accurate.

A lot of research literature is available on climate change effect on crops, yet, just a few papers cover the effects of climate change on weeds in relation to specific crops (Patterson *et al*., 1984; Alberto *et al*., 1996; Tungate *et al*., 2007).

Principals of weed reaction

The effects of changing climatic conditions impact arable weeds in various ways. In order to persist in a local habitat, species have to respond to the changes of the environment (Woodward and Cramer, 1996). These responses lead to shifts, which act at distinctive scales. Generally, plant species have following three options to avoid extinction (Lavorel and Garnier, 2002; Pautasso *et al*., 2010).

1. Migration with a favorable climate, which leads to alterations of the distribution of weeds—a process called range shift. For migration, weeds need to possess appropriate propagule dispersion mechanisms. In arable ecosystems, this is often also provided by human actions (Kubisch *et al*., 2013). Range shifts act at the landscape scale (Jump and Peñuelas, 2005).
2. Acclimation to changes in climate conditions basically refers to the response of species within their phenotypic plasticity without evolutionary adjustments (Pearman *et al*., 2008). These responses can be divided into tolerance and avoidance of climatic changes that lead to performance beyond the species' ecological optimum (Grime and Hodgson, 1987; Lavorel and Garnier, 2002). As a consequence, the fitness and the competitive ability of the weeds are either reduced or enlarged (Barrett, 2000). Consequently, the realized niche is being altered, which leads to niche shifts. They act at the community scale and can be determined visually as composition shifts.
3. Adaptation to changes in climate conditions, which is often associated with the evolution of new properties or with the optimization of existing ones (Harlan and deWet, 1965; Carroll *et al*., 2007; Tungate *et al*., 2007). These individual biological adaptations of weeds, which are driven by natural selection, result in trait shifts. They become apparent at the population scale, but are brought about by morphological, physiological, and genetic processes at the individual plant scale.

Effects of elevated CO_2

CO_2 has risen 33 per cent from a pre-industrial concentration of about 280 µL per L to a current estimate of about 370 µL per L mostly due to population growth, burning of fossil fuels for energy and changes in land use practices, including deforestation (Parry, 1990, 1998; Bunce, 2001). Continuing increases in CO_2 and other trace gases could result in an increase in global surface temperature (IPCC, 1996) and alterations in the Earth's climate.

Consequences of increased atmospheric CO_2 are likely to be felt by plants mainly through direct effects on their physiological processes like photosynthesis and stomatal physiology, resulting in increased growth rates of many plants (Drake *et al.*, 1997). Other consequences are related to increased temperature, which can directly and indirectly affect plant growth and metabolism. Increased CO_2 concentration and temperature will alter a plant's ability to grow and compete with other individuals within a given environment. There is also evidence (IPCC, 1996; Parry, 1998; Bunce, 2001) that increased CO_2 would enable many plants to tolerate environmental stresses, such as drought and temperature fluctuations. Increased tolerance of environmental stress is likely to modify the distribution of weeds across the globe, and their competitiveness, in different habitats.

Photorespiration is one reason why C3 crops (rice, wheat, soybean, barley and sunflower) exhibit lower rates of net photosynthesis than do C4 crops (maize sorghum, sugarcane and millet), at ambient CO_2. However, due to the same reason, C3 species will respond more favourably to elevated CO_2 levels, because CO_2 tends to suppress photorespiration. In C4 plants, the internal mesophyll cell arrangements are different to those of C3 plants, making efficient transfer of CO_2 possible, and this minimizes photorespiration and favours photosynthesis (Drake *et al.*, 1997). Under present CO_2 levels, C4 plants are more photosynthetically efficient than C3 plants. Given that they are already efficient at harnessing CO_2, they are likely to be less affected by further CO_2 increases. It is also possible that in a CO_2 enriched atmosphere, important C4 crops of the world may become more vulnerable to increased competition from C4 weeds.

There is sufficient evidence that increased CO_2 concentration leads to partial closure of stomata through which CO_2 is absorbed and water vapour is released by transpiration. This lowers the water requirements of plants by reducing transpiration per unit leaf area, while promoting photosynthesis. The dual effect of promoting photosynthesis and reducing transpiration is to improve water use efficiency. Kimball and Idso (1983) reported improvement of water use efficiency by 70-100 per cent for both C3 and C4 species.

A doubling of CO_2 concentrations is predicted to cause a 30-40 per cent decrease in the stomatal aperture in both C3 and C4 plants, reducing transpiration losses by as much as 25-40 per cent. Savings in water can be expected, if elevated CO_2 stimulates increase in leaf area index more than it decreases stomatal conductance. In long-term field studies of whole plant responses to elevated CO_2, reviewed by Drake *et al.* (1997), leaf area index did not increase in any species, but evapo-transpiration was reduced compared with normal ambient in all of the species studied.

Differential response of weeds to elevated temperature

Patterson (1995) indicated

significant variations in response to CO_2 both within a species and between species, depending on experimental conditions. While the variability in plant responses is large, C3 weeds generally increased their biomass and leaf area under higher CO_2 concentrations compared with C4 weeds. In view of such results, it could be predicted that C3 weeds, like *Parthenium hysterophorus* L., and *Chromalaena odorata* L. will be much more competitive under raised CO_2 environment, independently of temperature and rainfall effects.

Ziska and Bunce (1997) compared the effect of elevated CO_2 levels on the growth and biomass production of six C4 weeds (*Amaranthus retroflexus* L., *Echinochloa crus-galli* (L.) P. Beauv., *Panicum dichotomiflorum* Michaux, *Setaria faberi* Herrm., *Setaria viridis* (L) P. Beauv., *Sorghum halapense* (L) Pers.) and four C4 crop species (*Amaranthus hypochondriacus* L., *Saccharum officinarum* L., *Sorghum bicolor* (L) Moench, and *Zea mays* L.). Eight of the ten C4 species showed a significant increase in photosynthesis. The largest and smallest increases observed were for *A. retroflexus* (+30%) and *Z. mays* (+5%), respectively. Weed species (+19 %) showed approximately twice the degree of photosynthetic stimulation as that of crop species (+10 %) at higher CO_2, which also resulted in significant increases in whole plant biomass for four C4 weeds (*A. retroflexus, E. crus- galli, P. dichotomiflorum, S. viridis*) relative to the ambient CO_2 condition. Leaf water potentials for three of the species (*A. retroflexus*, *A. hypochondriacus*, *Z. mays*) indicated that differences in photosynthetic stimulation were not solely due to improved leaf water status. This study confirmed that C4 plants may respond directly to increasing CO_2 in the atmosphere, and in the case of some C4 weeds (e.g. *A. retroflexus*), the photosynthetic increase could be similar to those published for C3 species.

C3 crop such as rice and wheat, elevated CO_2 may have positive effects on crop competitiveness with C4 weeds (Fuhrer, 2003; Yin and Struik, 2008). C3 weeds like *P. minor* and *A. ludoviciana* in wheat (C3) 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 C4 weed *Amaranthus viridis* (Naidu and Paroha, 2008). As high temperatures would also create increased evaporative demand, with its high water use efficiency and CO_2 compensation point, C4 photosynthesis is better adapted to high evaporative demand (Bunce, 1983).

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 (Patterson and Flint, 1982; Bazzaz and Carlson, 1984). 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 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 C4 species will be able to tolerate high temperature than C3 species. Therefore, C4 weeds may benefit more than the C3 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. Carter and Patterson (1983) and Tremmel and Patterson (1993) have shown that high CO_2 ameliorated the high temperature effects on quack grass (*Elytrigia repens*). Alberto *et al.,* (1996) suggest that 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 favor C4 species. 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 per cent more seed than those grown at 357 ppm. As high temperatures would also create increased evaporative demand with its high water use efficiency and CO_2 compensation point C4 photosynthesis is better adapted to high evaporative demand (Bunce, 1983).

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 C3 crops than C4 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 C4 photosynthetic metabolism sometimes increase photosynthesis and growth at elevated CO_2 concentration under dry conditions (Patterson, 1986; Knapp *et al*., 1993), when elevated level of CO_2 slows the development of stress.

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 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.

Crops show substantial differences in the composition and abundance of weed species (Schroeder *et al.*, 1993). The weed species composition is mainly affected by the grown crop besides edaphic factors, the season, altitude and climate (Pysek *et al.*, 2005; Andreasen and Skovgaard, 2009; Cimalova and Lososova 2009; Gunton *et al.*, 2011). 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). 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.

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).

The invasive weed *Parthenium hysterophorus* had shown tremendous growth response to elevated CO_2 (Naidu and Paroha 2008; Naidu, 2013)

Effects of elevated temperatures

Models of global climate predict that mean surface air temperature of the Earth will rise by 1.5- 4.5^{o}C in the 21st century, due to the doubling of CO_2 concentrations and the enhanced greenhouse effect (IPCC, 2001). Extreme high-temperature events are anticipated to increase in frequency. Plants, in many parts of the world, are thus likely to experience increasing high-temperature stress. However, the effect of increased temperature would be felt in different regions of the world differently. It could be argued that in sub-tropical and tropical regions, an increase of temperature by a few degrees could lead to an increase in evapo-transpiration rates to a point that the growth of some species would suffer, due to moisture deficiency. However, changes in rainfall patterns would offset such species responses, under a changing climate.

Temperature is the dominant factor that controls plant growth at high (above 50^{0}N) and mid- latitudes (above 45^{0}N). At high altitudes, this is due to the influence temperature has on the length of the growing season. Probably the most significant effect of a future increase in temperature in regions where it is the main limiting factor, would be to extend the growing season available for plants. However, the effects of such warming on the length of the growing period will again vary from region to region and from crop to crop.

Under high temperature, plants with C4 photosynthesis pathway (mostly weeds) have a competitive advantage over crop plants possessing the more common C3 pathway (Yin and Struik, 2008) Introduction in 1877 from Central America as a drought tolerant species suitable for afforestation in arid zones of India, *Prosopis juliflora* has invaded nearly 6 million hectares of land contributing for 1.8 per cent of geographical area of the country (Kathiresan, 2005).

It is generally accepted that higher atmospheric CO_2 is likely to stimulate the growth of crops, and C3 plants are the most likely to benefit. The consensus of three decades of research is that a doubling of CO_2 concentrations may cause a 10-50 per cent yield increase in C3 crops like rice, wheat and soybean (Kimball, 1983; Poorter, 1993), the corresponding yield increase expected in C4 crops, such as maize, sorghum and sugar cane, is 0-10 per cent.

Rising minimum temperatures associated with anthropogenic climate change could extend the potential geographic range of pest species and/or alter their demographics, although long-term changes in species diversity are unclear (Bradley *et al*., 2010; McDonald *et al*., 2009). Increases in minimum temperature result in a relatively greater increase in herbicide applied. Once temperature has reached a critical thermal threshold, it is a significant driver of shifts in insect and pathogen demography (Ziska and Runion, 2007; Fuhrer, 2003).

Effect of precipitation

Weeds constrained by rainfall may also find new habitats under new climatic conditions. Annual plant communities are likely to be strongly responsive to altered precipitation regimes because species composition and abundance are driven by germination dynamics that often depend on water availability (Baskin and Baskin, 1998; Lundholm and Larson, 2004). Events early in the growing season can have long-lasting impacts in annual communities (Ross and Harper, 1972; Levine *et al*., 2008). Variation in water availability throughout the growing season may also directly affect plant growth (Novoplansky and Goldberg, 2001; Sher *et al*., 2004). Weeds in row crop agriculture provide a widespread and economically important system dominated by annual plants (Davis *et al*., 2005) to examine the impacts of precipitation variability. In addition, knowledge of how annual weed communities respond to precipitation variability may have important consequences for agricultural management practices.

Lantana camara, for example, could expand if rainfall increased in some areas (McFadyen, 2008). 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* species 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).

How will 'colonizing species' (weeds) react to changing climate?

Weeds are opportunistic 'colonizing species' or 'pioneers of secondary succession' that are well adapted to grow in locations where disturbances, caused either by humans or by natural causes, have opened up space. Species can become weeds, because they are competitive, adaptable, highly fecund, and are able to tolerate a wide range of environmental conditions, including those in agricultural fields, or disturbed habitats.

In many cases, this opportunity arises because of lack of specific parasites or herbivores *i.e.* 'natural enemies', which gives them an advantage over crops or native flora (Naylor and Lutman, 2002). Thus, in terms of the Darwinian concept of 'struggle for existence', weeds, as a class, are the most successful plants that have evolved on our planet (Auld, 2004).

Weed/crop competition will be altered by climate change

In general, elevated CO_2 levels would stimulate the growth of major C3 crops of the world; the same effect is likely to also increase the growth of both C3 and C4 weeds. Carter and Peterson (1983) found that *Festuca elatior* L., a C3, grass, out-competed *Sorghum halepense* (L.) Pers., a C4, grass, in mixed cultures, under both ambient CO_2 levels and elevated CO_2, even under temperature unfavourable to C3 photosynthesis (between 25 - 40^{0}C). The authors predicted that global CO_2 enrichment would alter the competitive balance between C3 and C4 plants and this may affect seasonal niche separation, species distribution patterns, and net primary production within mixed communities.

Ziska (2000) evaluated the outcome of competition between 'Round-up Ready' soybean (*Glycine max* L.) and a C3 weed (*Chenopodium album L.*) and a C4 weed (*Amaranthus retroflexus*), grown at ambient and enhanced CO_2 (ambient + 250 µL/L). In a weed-free environment, elevated CO_2 resulted in increased soybean growth and yield, compared to the ambient CO_2 condition. However, soybean growth and yield were significantly reduced by both weed species at both levels of CO_2. With *Chenopodium album*, at elevated CO_2, the reduction in soybean seed yield relative to the weed-free control increased from 28 to 39 per cent. Concomitantly, the dry weight of *Chenopodium album* was increased by 65 per cent. Conversely, for *Amaranthus retroflexus*, soybean seed yield losses diminished with increasing CO_2 from 45 to 30 per cent, with no change in weed dry weight. This study suggested that rising CO_2 could alter yield losses due to competition from weeds, and that weed control will be crucial in realizing any potential increase in the yield of crops, such as soybean, as climate change occurs.

Alberto *et al.* (1996) concluded that at elevated CO_2 indicating increased 'competitiveness' of rice. However, under elevated CO_2 level and the higher temperature regime, competitiveness and reproductive stimulation of rice was reduced compared to the lower growth temperature, suggesting that while a C3 crop like rice may compete better against a C4 weed (*Echinochloa glabrescens* L) at elevated CO_2 alone, simultaneous increases in CO_2 and temperature could still favour a C4 species.

Climate change may cause range shifts in weed distribution and abundance

A body of research is emerging (Rosenzweig and Hillel, 1998; Luo and Mooney, 1999; Bunce, 2000), which indicated that elevated CO_2 levels are likely to increase the ability of plants to tolerate both high and low temperatures. However, the responses are linked with moisture availability through modified rainfall patterns, and possibly other factors like nitrogen deposition. Boese *et al*. (1997) established the increased tolerance of low temperatures under elevated CO_2 for several chilling-sensitive plants of tropical or sub-tropical origin. Possible reasons were: improved plant water balance, less severe wilting and less leaf damage under elevated CO_2 compared with ambient levels.

Temperature is recognized as a primary factor influencing the distribution of weeds across the globe, particularly at higher latitudes. Increased temperature and precipitation in some parts of the earth may provide suitable conditions for stronger growth of some species, which are currently limited by low temperatures.

These and other studies (Kriticos *et al*., 2003a, b; 2004, 2006) are indicating significant and increased risks of spread and invasion of new areas by well-known aggressive 'colonisers'. In Australia, species currently restricted to the lowlands, such as Lantana (*Lantana camara* L.) are expected to move into higher altitude areas. Frost-intolerant species such as Rubbervine (*Cryptostegia grandiflora* R. Br.) and *Chromalaena odorata* could also shift their ranges significantly further south (Kriticos *et al*., 2003a and CRC, 2008).

Increased rainfall may also cause range shifts in the distribution of some weeds, which are currently limited to higher rainfall zones. Reduced rainfall will also reduce growth of pastures and crops, increasing bare ground and reducing canopy cover which favours weed invasion. Increased extremes, *e.g.*, long drought periods interspersed with occasional very wet years, will worsen weed invasion, because established vegetation, both native and crops, will be weakened, leaving areas for invasion. More severe cyclones will both disperse weed seeds through wind and floods, and also open up gaps for weed invasion in areas of pristine native vegetation, especially in the wet tropics.

Invasive weeds

There is already a burgeoning concern over our inability to manage the spread of invasive plants (Clements and Catling, 2007; Rew *et al*., 2007), and climate change threatens to make the task more difficult. In fact, the impact of invasive plant species is expected to increase with climate change (Thuiller *et al*., 2006; Vila *et al*., 2007), including increases in species distributions (Kriticos *et al*., 2003b). One example of this cross-border expansion in North America is *Datura stramonium* L., a weed of the solanaceae that causes interference in economically important crops in this region (Weaver and Warwick, 1984; Henry and Bauman, 1991). *Hypericum perforatum* L. exhibits larger leaves in more northern North American latitudes (Maron *et al*., 2004). This short-lived perennial infests areas such as grasslands, old fields or roadsides and has invaded numerous regions worldwide from its original range in Europe, North Africa and Asia (Maron *et al*., 2004). For many weed species, the damage niche (McDonald *et al*., 2009) is showing potential for shifting, whereby the weed species is already present in a region but is in sufficiently small enough populations that it does not have a negative economic impact. *Bromus tectorum* L. (cheat grass) already occurs in Canada, but Valliant *et al*. (2007) demonstrated its large potential to expand to other areas of Canada through the development of weedy genotypes de novo. Indeed, a review by Daehler (2003) demonstrated that invasive species exhibited more phenotypic plasticity than native species occurring in the same region. The role of plasticity versus genetic change continues to be one of the key issues in the study of invasive biology (Richardson and Pysek, 2006). Invasive plants are frequently viewed as harbingers of climate change owing to their potential to cause economic and ecological damage in the process of expanding their ranges. Models are being developed to help predict the range expansion of these plants, based on known tolerance ranges. Success of weeds has often been attributed to an all-purpose genotype, implying a high level of phenotypic plasticity. However, recent work has shown that many species are capable of relatively rapid genetic change as well, enhancing their ability to invade new areas in response to anthropogenic ecosystem modification (Clement and Ditommaso, 2011). Opportunistic weed species possess the ability to track climate change by means of sophisticated dispersal and superior adaptation capabilities (Chapin *et al*., 1996; Bergmann *et al*. 2010; Pautasso *et al*., 2010). For a variety of invasive plant species, the potential for range expansion has been identified but not yet realized.

Implications for weed management

Given the physiological plasticity of many weeds and their greater genetic diversity relative to crops, it is possible that elevated CO_2 could provide an even greater competitive advantage to weeds, with concomitant negative effects on crop production. Therefore, in future decades, when climate change effects are more consistently felt, weed management requirements in agriculture and non-agricultural situations will change. Aggressive growth of C3 or C4 weeds will require more energy and labour intensive management. The abundance of perennial weeds may increase, since elevated CO_2 stimulates greater rhizome and tuber growth. Greater increases in biomass will result in dilution of herbicide applied, making weed control more difficult and costly (Patterson, 1995). Some direct evidence of this scenario comes from the increased glyphosate tolerance at elevated CO_2 shown by different perennial species. However, the C3 species, *C. album* showed significant tolerance of glyphosate at elevated CO_2. In contrast to the ambient CO_2 treatment, the lower glyphosate rate had no effect on *C. album*, and the higher rate only reduced, but did not eliminate the weed, in elevated CO_2. These data indicated that rising atmospheric CO_2 could increase glyphosate tolerance in C3 weeds and this could limit the efficacy of some herbicides.

Increased tolerance of glyphosate was also reported in a perennial C3 weed, quackgrass (*Elytrigia repens*) by Ziska and Teasedale (2000). They also concluded that sustained stimulation of photosynthesis and growth in perennial weeds could occur as atmospheric CO_2 increases, and such changes would reduce the effectiveness of chemical control.

As discussed by Patterson, (1995) growth at elevated CO_2 could result in anatomical, morphological and physiological changes, which alter herbicide uptake, translocation and overall effectiveness. Increasing CO_2 can increase leaf thickness, reduce stomatal number and decrease conductance, possibly limiting the uptake of foliar-applied herbicides. Ziska, (2014) stipulated that increases in pesticide application rates may be a means to maintain soybean production in response to rising minimum daily temperatures and potential increases in pest pressures.

Adapting to climate change

It is clear that both crops and weeds will respond to climate change, but the overall winners of their competition in the field will be the colonizing species, because of their superior adaptations and wide ecological amplitudes. Control of weeds, pests and diseases are all likely to be more difficult and more expensive under climate change.

The agricultural systems in many developing countries are more vulnerable to climate change, because they are dependent on declining natural resource bases, are labour intensive and less capital and technology dependent. The increasing population pressure on natural resources in developing countries is well known; it has already led to pronounced degradation of land and water resources and has increased the risk of hunger. Technically, adapting to climate change will require significant transformation of agriculture production across the globe, by tapping three main sources for growth: (a) Expanding the land area, (b) Increasing the land cropping intensity (mostly through irrigation), and (c) Boosting yields. Experts agree that 80 per cent of increased crop production in developing countries still has to come from intensification of agriculture, which involves: (a) Increased cultivable land; (b) Higher yield crops; (c) Increased crop diversification and multiple cropping; and (d) Shorter fallow periods.

Overall, climate change can be expected to favour invasive plants over established, and slow-growing, native vegetation, especially if accompanied by an increase in extreme conditions, such as droughts alternating with very wet years. Pioneering species with various physiological adaptations and wide ecological amplitudes are better equipped to adapt to new climatic conditions. Weeds generally have excellent propagule dispersal mechanisms, often by human activities or by birds, and are likely to spread rapidly into new areas, quickly exploiting changing climatic conditions that favour their establishment. More effective management solutions will therefore be required to reduce the threat posed by aggressive colonisers, which can make production of food and management of land and water resources much more difficult.

However, climate is not the only factor that will be changing as the 21st century unfolds. Weeds have been winner and will be winner in future climatic conditions because of more adaptive power and more diversity. Weed population will change with climate change and risks of invasiveness may increase. Effectiveness of current management practices may be affected. Most studies evaluated effect of single factor (elevated CO_2) and only few studies have evaluated the interaction of multiple factor of change. Research is needed to assess the interactive effects of multiple climate change factors simultaneously to help prediction how weed problems may change in future with changing climate in order to develop flexible integrated weed management practices which are based on a foundation of knowledge of weed biology and ecology.

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