Journal of Crop and Weed, 5(2): 95-105 (2009)

How will weed management change under climate change? Some perspectives

N. CHANDRASENA

Ecowise Environmental Pty Ltd
24 Lemko Place, Penrith, NSW 2750, Australia

ABSTRACT

Human activities, including expanded fossil fuel use and deforestation, have caused atmospheric CO_2 to increase significantly from a pre-industrial concentration of about 280 $\mu L\ L^{-1}$ to a current estimate of about 370 $\mu L\ L^{-1}$. Even if CO_2 emissions are immediately scaled back, levels are expected to double sometime during this century. An increase in CO_2 and other greenhouse gases is likely to cause an increase in global surface temperature. Rainfall patters are likely to change across many areas of the globe and extreme events, like drought and cyclones, are predicted to be more prevalent and intense. The resultant major climate changes will affect the growth of plants, through modification of their photosynthetic performance and other physiological changes.

As CO_2 rises, C_3 plants are likely to benefit more, and respond with increased net photosynthesis, growth, and yield, compared to C_4 plants. Therefore, higher atmospheric CO_2 is predicted to stimulate the yields of most of the world's major crops, which are C_3 plants. An important question being asked is: Given that many of the most troublesome agricultural weeds are C_4 plants, will the competitive ability of these weeds be reduced relative to C_3 crops as climate change occurs? As 'colonising plants', weeds have many biological traits, including wide ecological amplitudes, which give them advantages over other plants to exploit more successfully disturbed habitat and changed environmental conditions. Also, there are a large number of C_3 weeds in the world, which may become more aggressive in many situations, under elevated CO_2 and warmer conditions. Under such changed climatic conditions, the likely scenario is that both C_3 and C_4 weeds will become more competitive, with potentially negative consequences for the environment, as well as agricultural productivity across different regions of the globe, negating some of the otherwise beneficial effects of CO_2 'fertilization' of the C_3 world crops. It is also probable that many colonising plants will extend their bio-geographical ranges as global environmental changes occur, and weed management in the field will become more costly and difficult.

Humans have no option, but to adapt to effects of elevated CO_2 and warming of the planet, which they exacerbated. However, climate change is not the only factor that will be changing as the 21st century unfolds. Population growth and varying economic and technological changes will increasingly affect the environment no less than will climate change. Developed countries, due to technological advancements, will adapt more effectively to respond to climate change, including the likely increased impacts of weeds. On the other hand, burdened by population pressure and declining natural resource bases, many developing countries will not be so well placed to face climate change and its flow-on effects, such as water and food scarcity.

With regarding to managing weeds, our adaptive responses need to be based on better knowledge of how plant communities will respond to climate change. Rather than ad hoc responses, scientists will have to re-evaluate their approaches and more rigorously apply scientific and ecological knowledge to effectively manage ecosystems, one of which is the agricultural field. Tools available for ecological weed management include breeding allelopathic crops cultivars and drought and stress-resistant varieties; minimum-tillage or conservation farming; agro-forestry and the use of allelopathic crop residues. Sustainable weed management under climate change will have to be more holistic and better integrated with pest management, where possible. Re-vitalizing the above-mentioned ecological approaches is a must. A crucial element in this response strategy will have to be adequate public education about the threats posed by the changing climate. Early detection, preventative weed management, border protection and risk management approaches, will have critical roles in the containment of invasive species In many ways, weed scientists and weed managers have to 'do what they have been doing better', under future climate change scenarios.

Humans must also take drastic action to reduce the primary root cause of climate change - the high rate of CO_2 emissions, by a variety of approaches. This would involve burning less fossil fuel, stopping large-scale deforestation occurring in the tropics, preventing reclamation of large wilderness areas for agricultural use and protecting conservation areas from invasive species. Other actions to mitigate the inevitable CO_2 build up involve some combination of conserving energy, and the increased use of alternative energy sources (e.g. solar, wind and hydropower) as substitutes for fossil fuels.

***Key Words*: Climate change, C_3 and C_4 plants, ecological weed management and knowledge-based solutions**

The earth is warmed largely by short-wave radiation (0.15-4.0 µm) emanating from the sun, which has a high temperature (6000°C). This radiation includes visible light (0.3-0.7 µm) and ultra-violet radiation (0.2-0.4 µm). The earth intercepts only a part of this radiation and the warm earth's surface re-emits its own radiation. The latter, called 'terrestrial radiation', is at longer wavelengths in the infrared or thermal part of the spectrum (4-50 µm), and is invisible to the human eye (Rosenzweig and Hillel, 1998).

Atmospheric gases, particularly water vapour, CO_2 and other trace gases (Table 1), re-absorb terrestrial radiation leaving the earth at particular wavelengths, while being transparent to incoming solar radiation. The effect is to warm the earth's surface to an average of 15⁰C, which allowed life on earth to be first established. This is the '*natural greenhouse effect*' of the atmosphere, so called because it is similar to the effect produced by gases inside an actual greenhouse. In a greenhouse, the glass shielding is transparent to visible light, but partly opaque to IR radiation. Sunlight entering a greenhouse is absorbed by the gases, converted to heat, and then re-emitted as IR, which is partially blocked by the glass. The trapped radiation then warms up the greenhouse, until it reaches a

---

Email:nchandrasena@ecowise.com.au

temperature at which the intensity of the outgoing IR equals the incoming radiation.

Over the last two centuries, coinciding with the industrialisation of human societies, a variety of human activities have contributed heavily to increases in atmospheric concentration of many 'greenhouse gases'. Human activities that have caused significant emissions include massive deforestation, large-scale land clearing for agriculture and the combustion of fossil energy sources, such as coal, oil and gas. The increased concentrations of greenhouse gasses have further blocked the escape of terrestrial radiation from the earth's surface, and have re-emitted this energy back to earth, leading to warming of the atmosphere near the surface and changes to hydrological regimes. The overall climatic consequences, called '*global warming'*, is an *enhanced greenhouse effect*. The effectiveness of a greenhouse gas in warming the atmosphere depends both on its concentration and on the amount of time it remains in the atmosphere (Table 1). Of these gases, CO_2 is the most significant, contributing to about 64% of the effect, followed by CH_4 (19%), CFCs (11%) and N_2O (6%).

Table 1: A summary of greenhouse gas concentrations[1]

Parameters	**CO_2**	**CH_4**	**N_2O**	**[2]CFC-12**	**[3]HCFC-22**
[4]Preindustrial concentrations	280 ppmv	700 ppbv	275 ppbv	0	0
Concentration in 1994	358 ppmv	1714 ppbv	311 ppbv	503 pptv	105 pptv
Rate of concentration change	1.5 ppmv/yr	13 ppmv/yr	0.75ppmv/yr	18-20 ppmv/yr	7-8 ppmv/yr
Atmospheric lifetime (years)	50-200	12-17	120	102	13

[1]Source: IPCC, 1996a, b; [2]Chlorofluorocarbons, CFCs including CFC-12 are synthetic gases used as refrigerants, propellant sprays and foaming agents substitute; [3]A CFC substitute; [4]period between 1750-1800

Concentrations of these greenhouse gases will continue to increase in the 21st century, because the human population is still growing. As a result, combustion of fossil fuels will continue to increase for many decades. Even if the emissions were reduced immediately, atmospheric concentrations would continue to rise for some time, because of the long residence times of these gases in the atmosphere and slow uptake by impact reducing agents like the great oceans.

In addition to CO_2 increases and global warming, human activities are also causing a decrease in stratospheric ozone (O_3) concentrations and an increase in trophospheric ozone. Furthermore, deposition of nitrogenous compounds from the atmosphere into ecosystems is also likely to increase. The cumulative impacts of such changes are likely to be significant in agricultural systems or on natural ecosystems.

Effects of climate change

Various influential reports, books and review articles (IPCC, 1996, 2001, Luo and Mooney, 1999, Parry, 1990, 1998, Patterson, 1995, Rosenzweig and Hillel, 1998, Bunce, 2001, Stern, 2006) have pointed out that enhanced greenhouse effect may affect the global climate in several ways. These are summarised in Figure 1. The direct and indirect effects of the global changes on agriculture and natural ecosystems can be summarised 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 and are reviewed in this essay. Some perspectives are provided as to how the changing climate of the world may affect the growth of crops and weeds and their interactions. 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.

Effects of CO_2 enrichment

CO_2 has risen 33% from a pre-industrial concentration of about 280 $\mu L\ L^{-1}$ to a current estimate of about 370 $\mu L\ L^{-1}$ 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.

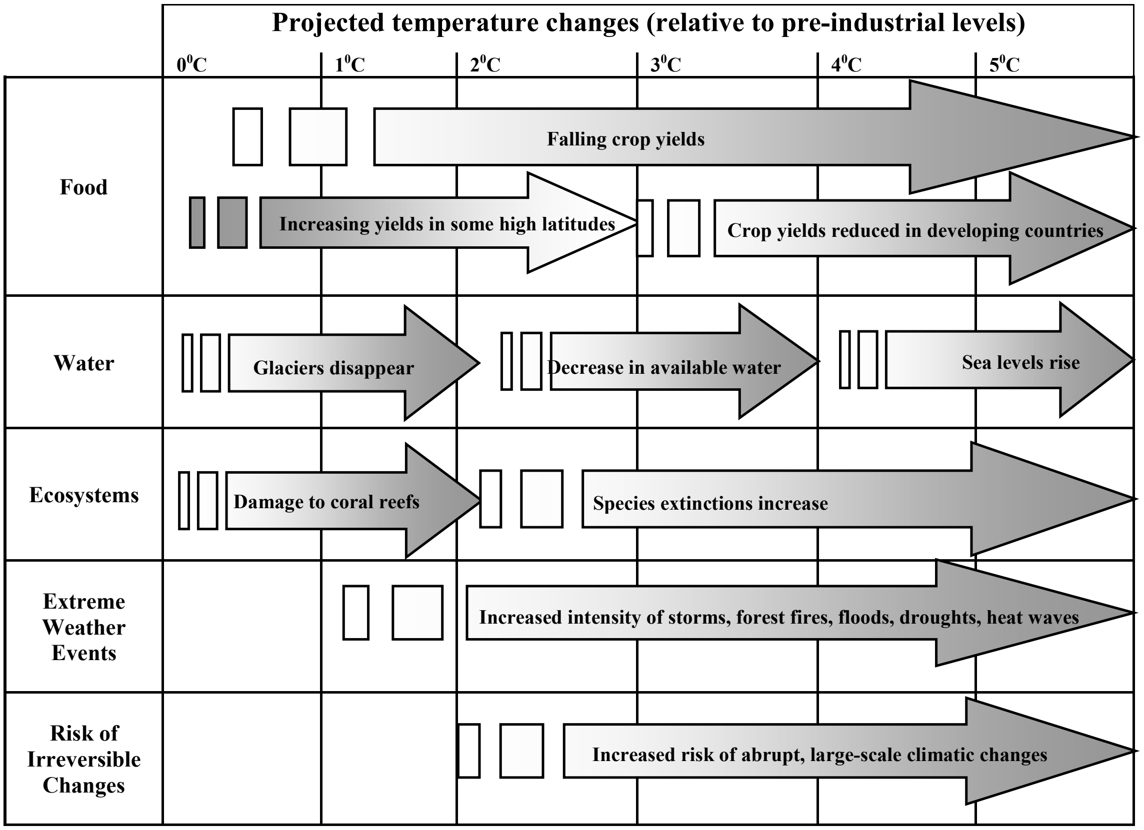

Fig. 1. Major Impacts of global climate change (Modified from the Stern 2006 Review on *Economics of Climate Change*)

Effects on photosynthesis and growth

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.

Plants vary in their response to CO_2 because of differing photosynthetic mechanisms, referred to as the C_3 and C_4 pathways. In C_3 photosynthesis, possessed by 95% of all known species, CO_2 is first captured by a sugar: ribulose bisphosphate, using the enzyme Ribulose-1, 5-bisphosphate carboxylase /oxygenase (RuBisCo). The first stable product of C_3 photosynthesis is phosphoglyceric acid, PGA (3-carbon acid). However, due to the dual carboxylase/oxygenase activity of RuBisCo, an amount of the substrate is oxidized rather than carboxylated, resulting in loss of substrate and consumption of energy. This process, known as 'photorespiration' and considered 'wasteful', is an adaptation to protect against damage that can be caused by too much sunlight (Kozaki and Takeba, 1996). In order to bypass the photorespiration pathway, C_4 plants have developed an alternative mechanism to efficiently deliver CO_2 to the RuBisCo enzyme. They utilize their specific leaf anatomy (known as Kranz anatomy) where chloroplasts exist not only in the mesophyll cells in the outer part of their leaves, but also in the bundle sheath cells as well. Instead of direct fixation by RuBisCo, CO_2 is first converted to a 4-carbon organic acid, which has the ability to regenerate CO_2 in the chloroplasts of the bundle sheath cells. The enzyme involved is phospho-enol pyruvate carboxylase (PEP Carboxylase), which has a higher affinity for CO_2 than RuBisCo. Bundle sheath cells can then fix this CO_2 to generate carbohydrates by the conventional C_3 pathway. The re-release of CO_2 creates a high CO_2 concentration in the bundle-sheath cells, promoting carboxylation over the oxygenation reaction by RuBisCo.

Photorespiration is one reason why C_3 crops (rice, wheat, soybean, barley and sunflower) exhibit lower rates of net photosynthesis than do C_4 crops (maize sorghum, sugarcane and millet), at ambient CO_2. However, due to the same reason, C_3 species will respond more favourably to elevated CO_2 levels, because CO_2 tends to suppress photorespiration. In C_4 plants, the internal mesophyll cell arrangements are different to those of C_3 plants, making efficient transfer of CO_2 possible, and this minimizes photorespiration and favours photosynthesis (Drake *et al*., 1997). Under present CO_2 levels, C_4 plants are more photosynthetically efficient than C_3 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 C_4 crops of the world may become more vulnerable to increased competition from C_3 weeds.

Effects on stomata and water use efficiency (WUE)

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 WUE (i.e. ratio of plant biomass, to the amount of water transpired). Kimball and Idso (1983) reported improvement of WUE by 70-100% for both C_3 and C_4 species.

A doubling of CO_2 concentrations is predicted to cause a 30-40% decrease in the stomatal aperture in both C_3 and C_4 plants, reducing transpiration losses by as much as 25-40%. How this effect will reduce evapotranspiration (ET) from plants depends on the effects of elevated CO_2 on leaf area index (LAI), as well as on stomatal conductance. Savings in water can be expected, if elevated CO_2 stimulates increase in LAI 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), LAI did not increase in any species, but ET was reduced compared with normal ambient in all of the species studied in a wetland, Kansas prairie and a Californian grassland. In the wetland, at ambient $CO_{2,}$ instantaneous values of ET averaged 5.5–6.5 mmol $H_2O\ m^{-2}s^{-1}$ for a C_3 community and 7.5–8.7 mmol $H_2O\ m^{-2}s^{-1}$ for a C_4 community. However, at elevated CO_2, ET was reduced 17–22% in the C_3 and 28–29% in the C_4 community. Such studies indicate a relatively greater effect of elevated CO_2 on stomatal conductance in C_4 species. An outcome of this effect will be that many species will grow well in environments where moisture availability is currently a limitation for sustaining populations. However, our knowledge about the differential responses C_3 and C_4 species to such environmental changes is still rudimentary.

Effects of increased temperatures

Models of global climate predict that mean surface air temperature of the Earth will rise by 1.5-4.5 ^{0}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 ET 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 50^0N) and mid-latitudes (above 45^0N). 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 temperate 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.

Effects on crop growth and yield

It is generally accepted that higher atmospheric CO_2 is likely to stimulate the growth of crops, and C_3 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% yield increase in C_3 crops like rice, wheat and soybean (Kimball, 1983, Poorter, 1993), the corresponding yield increase expected in C_4 crops, such as maize, sorghum and sugar cane, is 0-10%.

However, much will depend on prevailing growing conditions and limitations imposed by availability of water and nutrients. Moya *et al*. (1998) confirmed that elevated CO_2 alone increased the biomass and seed yield of rice. However, higher temperature (ambient + 4^0C) alone consistently decreased the seed yield of several rice cultivars, including a standard semi-dwarf (IR 72) and a heat and drought tolerant cultivar from India (N-22) with little change in plant biomass. For all cultivars, the combination of increased CO_2 and elevated air temperature resulted in reduced grain yields, compared to increased CO_2 alone. Hence, simultaneous exposure to rising temperatures may negate the increased grain yield response to elevated CO_2.

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

Weeds are opportunistic '*colonising 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.

A set of common biological characteristics (Baker, 1965) allows weeds to colonise disturbed habitats, to form extensive populations and, sometimes, to dominate, disturbed landscapes. However, a species may become an invader of landscapes only if a chance combination of circumstances makes its attributes particularly advantageous to its growth and survival. 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). In terms of evolutionary success *i.e.* continuation of a genetic line over time, most weeds are highly successful, because of their high reproductive capacity and the range of habitat they can occupy. 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). Weeds are likely to possess many pre-adaptations at the molecular, biochemical or whole plant level to respond more positively to climatic change, including elevated CO_2 and increased temperature, than other plants, as discussed below.

Differential response of weeds to elevated CO_2

Over the past three decades, many experiments have tested the effects of higher atmospheric CO_2 on weeds with C_3 and C_4 photosynthetic pathways. Some examples from an early review by Patterson (1995) indicate significant variations in response to CO_2 both within a species and between species, depending on experimental conditions, such as temperature, light, availability of water and nutrients (Table 2). While the variability in plant responses is large, C_3 weeds generally increased their biomass and leaf area under higher CO_2 concentrations compared with C_4 weeds. In view of such results, it could be predicted that C_3 weeds, like Parthenium (*Parthenium hysterophorus* L.) and Chromalaena [*Chromalaena odorata* (L.) R. M. King & H. E. Robinson] will be much more competitive under raised CO_2 environment, independently of temperature and rainfall effects.

Table 2. Response of some C_3 and C_4 weeds to doubled atmospheric CO_2 levels[1]

C_3 species	Range of response (x growth at ambient)		C_4 species	Range of response (x growth at ambient)	
	Biomass	Leaf area		Biomass	Leaf area
Abutilon theophratsii	1.0-1.52	0.87-1.17	*Amaranthus retroflexus*	0.9-1.41	0.94-1.25
Bromus mollis	1.37	1.04	*Andropogon virginicus*	0.8-1.17	0.88-1.29
Bromus tectorum	1.54	1.46	*Cyperus rotundus*	1.02	0.92
Cassia obtusifolia	1.4-1.6	1.1-1.34	*Digitaria ciliaris*	1.06-1.6	1.04-1.66
Chenopodium album	1.0-1.6	1.22	*Echinochloa crus-galli*	0.95-1.6	0.95-1.77
Datura stramonium	1.7-2.72	1.46	*Eleusine indica*	1.02-1.2	0.95-1.32
Elytrigia repens	1.64	1.3	*Paspalum plicatum*	1.08	1.02
Phalaris aquatica	1.43	1.31	*Rottboellia cochinchinensis*	1.21	1.13
Plantago lanceolata	1.0-1.33	1.33	*Setaria faberii*	0.93-1.35	1.0-1.4
Rumex crispus	1.18	0.96	*Sorghum halepense*	0.56-1.1	0.99-1.3

[1] Source: Patterson, 1985

Ziska and Bunce (1997) compared the effect of elevated CO_2 levels on the growth and biomass production of six C_4 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 C_4 crop species (*Amaranthus hypochondriacus* L., *Saccharum officinarum* L., *Sorghum bicolor* (L) Moench, and *Zea mays* L.). Eight of the ten C_4 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 C_4 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 due solely to improved leaf water status. This study confirmed that C_4 plants may respond directly to increasing CO_2 in the atmosphere, and in the case of some C_4 weeds (e.g. *A. retroflexus*), the photosynthetic increase could be similar to those published for C_3 species.

Of the 15 crops, which supply 90% of the world's calories, 12 have the C_3 photosynthetic pathway. In contrast, 14 of the 18 'World's Worst Weeds' are C_4 plants (Patterson, 1985). The general consensus of the above and other similar studies is that the greater majority of weeds in the world, which are C_3 plants, will benefit from increased CO_2 levels under climate change, while most tropical grasses, which are C_4 plants, are not likely to show greatly increased growth in higher CO_2. However, because C_4 plants are generally more tolerant of heat and moisture stress, the simple notion that climate change will only benefit C_3 plants may not be accurate.

Weed/crop competition will be altered by climate change

The differential responses of C_3 and C_4 plants to increasing CO_2 are especially relevant to weed-crop competition in agroecosystems. However, studies on competition outcomes between C_3 crops and C_4 weeds, or vice versa, are limited in the literature. In general, elevated CO_2 levels would stimulate the growth of major C_3 crops of the world; the same effect is likely to also increase the growth of both C_3 and C_4 weeds. In all probability, this would lead to increased weed-crop competition, negating some of the otherwise beneficial effects of CO_2 'fertilization' of the C_3 crops and their yields. Some examples of relevant crop/weed competition studies are discussed below:

Carter and Peterson (1983) found that *Festuca elatior* L., a C_3, grass, out-competed *Sorghum halepense* (L.) Pers., a C_4 grass, in mixed cultures, under both ambient CO_2 levels and elevated CO_2, even under temperature unfavourable to C_3 photosynthesis (between 25 and 40^0C). The authors predicted that global CO_2 enrichment would alter the competitive balance between C_3 and C_4 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 C_3 weed (Common Lambsquarter, *Chenopodium album* L.) and a C_4 weed (Redroot Pigweed, *Amaranthus retroflexus*), grown at ambient and enhanced CO_2 (ambient + 250 $\mu L\ L^{-1}$). 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 lambsquarter, at elevated CO_2, the reduction in soybean seed yield relative to the weed-free control increased from 28 to 39%. Concomitantly, the dry weight of lambsquarter increased by 65%. Conversely, for pigweed, soybean seed yield losses diminished with increasing CO_2 from 45 to 30%, with no change in weed dry weight. This study suggests 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), studied competition outcomes between rice and *Echinochloa glabrescens* L., which is a C_4 weed, using replacement series mixtures at two different CO_2 concentrations (393 and 594 $\mu L\ L^{-1}$) under day/night temperatures of 27/21°C and 37/29°C. Increasing the CO_2 concentration, at 27/21°C, resulted in a significant increase in above ground biomass (+47%) and seed yield (+55%) of rice, averaged over all mixtures. For the C_4 weed*,* higher CO_2 concentration did not produce a significant effect on biomass or yield. When grown in mixture, the proportion of rice biomass increased significantly relative to that of the C_4 weed in all mixtures 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 C_3 crop like rice may compete better against a C_4 weed at elevated CO_2 alone, simultaneous increases in CO_2 and temperature could still favour a C_4 species.

Climate change may cause range shifts in weed distribution and abundance

A body of research is emerging (see reviews in Rosenzweig and Hillel, 1998; Luo and Mooney, 1999; Bunce 2000), which indicates 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. Most 'colonising' species have wide ecological amplitudes *i.e.* the capacity of a species to establish in various habitats along an environmental gradient, and are already adapted to a broad range of conditions under which they can thrive and perpetuate. This innate ability to tolerate varying and extreme conditions will enable weeds to benefit under climate change, at the expense of less 'weedy' species. 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. The distribution of some tropical and sub-tropical C_4 species could shift northwards. This would expose temperate zone agriculture to previously not-known, aggressive tropical colonisers (Parry, 1998), particularly C_4 grasses.

Similar range shifts are predicted in the southern hemisphere, due to climate change. For instance, in Australia, climate predictions for the next 30+ years are for a general increase in mean temperatures with a larger increase in mean minimum temperatures, as well as a reduction in frost days (CRC, 2008). In the tropical north of Australia, an increase in rainfall is expected especially in the north-west. Reduced rainfall is predicted for south-west Western Australia, and generally, across eastern and south-eastern Australia. In all areas, an increase in extreme events, including droughts, floods, severe storms and extended wet seasons is expected. With such climate predictions, models indicate a southward range shift of major invasive plants, with tropical and sub-tropical species moving south, and temperate species being displaced southward. An example is a modelling study on current and projected distribution of Prickly Acacia (*Acacia nilotica* (L.) Willd. ex Delile), a woody legume, previously introduced for landscape improvement, now spreading in Australia. The modelling by Kriticos *et al*. (2003b) indicated the potential for significant (a) southward shift of Prickly Acacia, favoured by increasing temperature; and (b) spread further inland, favoured by increased WUE, under elevated CO_2.

These and other studies (Kriticos *et al*., 2003a, b; 2005; 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; CRC, 2008). However, the actual spread of weeds may lag behind the predicted spread, depending on factors, such as the dispersal potential of individual species and any management efforts that are taken to slow their spread.

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. For example, mass germination and spread of Prickly Acacia occurred in the past after a series of very wet years (Kriticos *et al*., 2003b). 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.

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 C_3 or C_4 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 [(*N*-phosphonomethyl) glycine] tolerance at elevated CO_2 shown by different perennial species. In one study, Ziska *et al*. (1999) determined tolerance by following the growth of *Amaranthus retroflexus* (Redroot Pigweed), a C_4 species, and *Chenopodium album*. (Common Lambsquarters), a C_3 species, grown at CO_2 levels near ambient (360 $\mu L\ L^{-1}$) and twice ambient (720 $\mu L\ L^{-1}$) for 14 d following glyphosate application at rates 0.112 kg a.i. ha^{-1} (0.1 of commercial rate), and 1.12 a.i. ha^{-1} (commercial rate) in four separate trials. Irrespective of CO_2, growth of the C_4 species, *A. retroflexus,* was significantly reduced and the weed was eliminated altogether by glyphosate at both rates. However, the C_3 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 $C0_2$. Although glyphosate tolerance does increase with plant size at the time of application, differences in tolerance between the two levels of $C0_2$ in C. *album* could not be explained by size alone. These data indicate that rising atmospheric CO_2 could increase glyphosate tolerance in C_3 weeds and this could limit the efficacy of some herbicides.

Increased tolerance of glyphosate was also reported in a perennial C_3 weed, quackgrass (*Elytrigia repens* (L.) Nevski) by Ziska and Teasedale (2000). Compared to ambient levels of CO_2 (380 μL L^{-1}), elevated CO_2 levels (720 μL L^{-1}) stimulated the growth of cohorts of the perennial grass at different life stages *i.e.* young, intermediate and old over. In the case of the old cohort, stimulation of leaf photosynthesis and vegetative plant growth under elevated CO_2 was consistent and high over a long (231 day) period of exposure. In contrast, the stimulation of biomass the intermediate-age and young cohorts was time-dependent. Higher CO_2 levels and acclimation had no effect on glyphosate control of the young cohort of quackgrass. However, in this work, glyphosate at 2.24 kg a.i. ha^{-1}, reduced the growth of, but did not eliminate the intermediate and old cohorts grown at elevated CO_2. Plant size at the time of glyphosate application could not explain the differences in response. The authors 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. The evidence is that sustained growth enhancement of perennial weeds could occur in a future, elevated CO_2 environment, and that control of quackgrass using herbicides like glyphosate could be altered as a result, especially for established plants. Obviously, quackgrass control could still be achieved if treatments are given to younger plants, early in the growth cycle, or if additional applications of glyphosate were used; but this could, potentially, alter the economic or environmental costs.

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 colonising species, because of their superior adaptations and wide ecological amplitudes (i.e. the limits of environmental conditions within which an organism can live and function). Although it is not possible to be specific, under climate change, weed management will become more important in the future at every scale, from farmlands to regional landscapes. As colonising species become abundant, and possibly more aggressive in many regions, humans will have to adapt to manage weed populations more effectively, in order to maintain productive landscapes and achieve food security.

Control of weeds, pests and diseases are all likely to be more difficult and more expensive under climate change, and there will have to be more emphasis on regional cooperation for preventing the spread of certain weeds, pests and diseases (as in the case of control of diseases, such as HIV Aids). Given that some well known invasive species are likely increase their bio-geographical ranges, and other, relatively mild species may become aggressive invaders, all countries need to be able to conduct risk assessments, at the appropriate level, for national planning to reduce the new threats posed by weeds. Global and regional co-operation is essential to establish new networks and the capacity to implement early detection and rapid response systems. Increased gathering of information, through local and regional surveys of distribution and abundance of potential invaders, sharing of such information and increased border protection of countries through quarantine, are likely to be of greater importance in the future. More effective integration of on-ground control methods (manual, mechanical, chemical and biological control) with broader pest control at farm level will be part of the future solution. What this means is that natural resource managers need to co-operate more with each other, and weed managers and researchers need to be even more effective than before. A new paradigm in weed management might include the view: '*…do what you have been always doing better…*' because the stakes are much higher now.

Projected changes in climate and crop yields in the latter part of the 21st century suggest that there will be yield increases in mid and high latitudes (Canada, Japan, European Union and New Zealand). These regions are recognised as having sufficient technology-based 'adaptive capacity' to face the changing global climate. In contrast, yield decreases are predicted for tropical and sub-tropical regions of lower latitudes, mainly developing countries, including the Indian sub-continent, Middle East and South-east Asia, with important regional differences (Parry, 1998). In the latter regions, presently characterized by persistent poverty and food insecurity, temperature maxima are already near the optimum under the current climatic conditions. Modelling indicates that warming may lead to decreased yield and production with an increase in risk of hunger (IPCC, 1996).

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. Under this scenario, in Africa, predictions are that by 2080, cereal production will decrease by 10% and the consequent risk of hunger will increase by 20%, although such effects can be partly offset by various farmer adaptations, technological changes and CO_2 fertilization effects (Parry, 1990; Rosenzweig and Hillel, 1998). Nevertheless, it is also predicted that the aggregate agricultural production in developing countries may not change much, as climate change occurs. Despite this prediction, there are specific regions within some countries that would be disproportionately affected by climate change, leading to increased poverty. Most experts agree that the future of global agriculture will be shaped by the: (a) Dynamics of change and developments in Science and Technology; (b) Sharing of knowledge and transfer of technology to developing countries; (c) Expected production gains in developed countries (mainly Europe); and (d) Impacts of trade liberalization.

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. The view that we may be approaching the ceiling for all three sources is not supported at the global level, although severe problems exist in specific countries and even whole regions (Parry, 1990). There will be major changes of land use, probably involving changes in farming locations. For instance, in tropical and sub-tropical countries, flood-prone areas will be less attractive to cropping, because of increased rainfall and flooding frequency. On the other hand, areas previously not farmed, due to varying degrees of aridity, salinity or low productive potential, may become important, also due to modified rainfall patterns. In temperate countries, global warming will reduce climatic constraints on agriculture, which is likely to expand and extend into uplands. In Europe, a 1^0C warming may raise climatic limits to cultivation by approximately 150 m (IPCC, 1996; 2001).

Changes in the types of crops grown are also likely in regions where there are substantial increases in the temperature of the growing seasons, and in areas where agricultural productivity is currently limited by temperature. In many situations, tropical and sub-tropical crops with higher thermal requirements would become more attractive. In all areas of the world, there will be a need to have stress-tolerant and hardy crop cultivars, including more drought-tolerant cultivars, in order to effectively face the uncertainties of climate change.

As rainfall patterns change and areas become prone to drought, irrigation will be crucial to maintain world food supplies and its role is expected to increase under climate change. One in five developing countries will face water shortage and water availability is already critical in West Asia and North Africa and will be so also in South Asia in 2030 (IPCC, 1996, 2001). Greater efficiency in water use needs to be achieved, and new irrigation infrastructure will have to be installed, in order to substitute for moisture losses due to increased transpiration. Maintaining soil fertility would be challenging, because in some areas, increased rainfall will cause increased leaching, while in other areas, warming may increase productive potential, so that yields can be maintained without much additional fertilizer. Adopting farming methods that reduce the costs of production and minimise environmental damage while maintaining or even increasing production will be crucial. In this regard, no-till or conservation agriculture, which can raise crop yields by 20-50%, will have a major role under climate change.

Experts agree that 80% 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. However, regions other than tropical Latin America and Sub-Saharan Africa face a shortage of suitable land, and in these regions intensification through improved management and technologies will be the main source of production growth.

The development and dissemination of new Science and Technology-based solutions will be much sought after for more holistic and integrated pest and weed management. Taking '*no regrets*' actions, i.e. undertaking those strategies that make sense for reasons other than climate change, is seen as important. Two such approaches are breeding more allelopathic crops and modification of crops by introducing genes that will confer more competitiveness, allied with yield components, and increased resistance to pests.

In the past, environmental policies for agriculture have traditionally focused largely on practices of soil conservation, reducing land and water quality and reducing the impacts of excessive use of herbicides and pesticides in farming landscapes. More recently, agriculture has turned attention to conserving biological diversity on rural landscapes. Given that agriculture is a major contributor of the greenhouse gases methane and nitrous oxide, it seems prudent to expand these policies to limit emissions of CO_2, CH_4 and N_2O from agricultural practices. It is also necessary to encourage agriculture to more aggressively adopt and expand on agroforestry opportunities for carbon sequestration benefits. On a farm level, this will require revitalizing well established conservation farming practices, including avenue cropping, minimum tillage, allelopathic crop residues and similar ecological approaches to holistic management of populations of weeds, pests and pathogens.

Humans must take action to reduce the primary root cause: the high rate of CO_2 emissions, by a variety of approaches, such as decreased burning of fossil fuels, eradicating large-scale deforestation and reclamation of large wilderness areas for agricultural or other human uses. Among the most feasible actions to mitigate the CO_2 build up involve some combination of conserving energy, substituting alternative energy sources (e.g. solar, wind and hydropower) for fossil fuels, and reducing the deforestation occurring in the tropics.

The trend of increasing concentrations of greenhouse gases and enhanced greenhouse effect is likely to continue in the coming decades presenting serious threats to both agricultural systems and natural ecosystems. Climate change is therefore the biggest challenge faced by humanity. The response of crops, weeds, or natural vegetation communities, is inexorably linked to the climate modifications that humans have exacerbated. This essay has provided an overview of some key issues and the complex and multiple-driver nature of global change.

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.

Global Change is a somewhat deceptive expression for what is actually an exceedingly complex array of dynamic processes and specific interactions and manifestations in different regions (Rosenzweig and Hillel, 1998). Climate change, sea level rises, increases in CO_2 concentrations, UV radiation and tropospheric ozone are but a few of the potentially fateful factors involved. In dealing with an issue as complex as climate change, there are many significant uncertainties, including the disordered behaviour of the physical climate and our inadequate understanding of that system, especially in regard to the interactions of oceans, clouds and ice. Still other uncertainties are the fast pace and unknown directions of future social, political and technological changes. Such uncertainties and unpredictable developments will impact on how the Earth's ecosystems and our agricultural landscapes respond to climate change, and ultimately, how humans will respond.

However, climate is not the only factor that will be changing as the 21st century unfolds. Population growth and varying economic and technological changes are likely to affect the environment no less than will climate change *per se*. Furthermore, the socio-economic and technological conditions will seriously interact with agriculture as well, and our ability to sustain effective production, whilst ensuring sustainable land use. To define how and what we may realistically achieve is a problem in itself, but taking no action is not an option.

ACKNOWLEDGEMENT

I thank Professor R. K. Ghosh for the invitation to write this review article. Dilsiri Chandrasena is acknowledged for assisting with the review of literature.

REFERENCES

Alberto, A. M. P., Ziska, L. H., Cervancia, C. R. and P. A. Manalo. 1996. The influence of increasing carbon dioxide and temperature on competitive interactions between a C_3 crop, rice *(Oryza sativa)* and a C_4 weed *(Echinochloa glabrescens). Aust.J.Pl. Physiol.* **23**: 795-802.

Auld, B. A. 2004. The persistence of weeds and their social impact. *Int. J. Social Eco*., 31 : 879-86.

Baker, H. G. 1965. Characteristics and modes of origin of weeds. *In*: H. G. Baker and G. L. Stebbins (Eds.), *The Genetics Colonizing Species*. pp. 147– 72, Academic Press, New York.

Boese, S. R., Wolfe, D. W. and J. J. Mekonian. 1997. Elevated CO_2 mitigates chilling-induced water stress and photosynthetic reduction during chilling. *Pl., Cell Env.*, **20**: 625-32.

Bunce, J. A. 2000. Acclimation of photosynthesis to temperature in eight cool and warm climate herbaceous C_3 species: Temperature dependence of parameters of a biochemical photosynthesis model. *Photosynthetic Res.*, **63**: 59-67.

Bunce, J. A. 2001. Weeds in a changing climate. *BCPC Symp. Proc*. No. 77: The World's Worst Weeds, 109- 18.

Cater, D. R. and K. M. Peterson. 1983. Effects of a CO_2-enriched atmosphere on the growth and competitive interaction of a C_3 and a C_4 grass. *Oecologia*, **58**:188- 93.

CRC Australian Weed Management. 2008. *Briefing Notes. Invasive Pl. Climate Change.* http://www.weedscrc.org.au/documents/bn_climate_change_2007.pdf.

Drake, B. G., Gonzàlez-Meler, M. A. and S. P. Long. 1997. More efficient plants: A consequence of rising atmospheric CO_2? *Ann. Rev. Pl. Physiol. Pl. Molecular Biol.*, **48**: 609–39.

IPCC, 1996. Climate Change 1995: The Science of Climate Change. (Eds.) J. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell, *Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third *Assessment Report of the Intergovernmental Panel on Climate Change*, (Eds.) J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, C. A. Johnson, Cambridge University Press, Cambridge, pp.881

Kimball, B.A. 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. *Agron. J.,* **75**:779- 88.

Kimball, B. A. and S. B. Idso. 1983. Increasing atmospheric CO_2: Effects on crop yield, water use and climate. *Agricl. Water Management*, **7**: 55-72.

Kozaki, A. and G. Takeba. 1996. Photorespiration protects C_3 plants from photooxidation. *Nature*, **384**: 557-60.

Kriticos, D. J., Alexander, N. S. and S. M. Kolomeitz. 2006. Predicting the potential geographic distribution of weeds in 2080. In: *Proc. 15th Aust. Weeds Conf.* Weed Management Society of South Australia, Adelaide. pp. 27-34.

Kriticos, D. J., Sutherst, R. W., Brown, J. R., Adkins, S. W. and G. F. Maywald. 2003a. Climate change and biotic invasions: A case history of a tropical woody vine. *Biol. Invasions*, **5**:147- 65.

Kriticos, D. J., Sutherst, R. W., Brown, J. R., Adkins, S. W. and G. F. Maywald. 2003b. Climate change and the potential distribution of an invasive alien plant: *Acacia nilotica* ssp. *Indica. Aust. J. App. Eco.*, **40**:111- 24.

Luo, Y. and H. A. Mooney. 1999. *Carbon dioxide and Environmental Stress*. Academic Press, San Diego.

Moya, T. B., Ziska, L. H., Namuco, O. S. and D. Olszyk. 1998. Growth dynamics and genotypic variation in tropical field-grown paddy rice (*Oryza sativa* L.) in response to increasing carbon dioxide and temperature. *Global Change Biol.*, **4**: 645- 56.

Naylor, R. E. L. and P. J. Lutman. 2002. What is a Weed? *In:* Robert E. L. Naylor (Ed.), *Weed Management Handbook* 9^{ed} Edition, British Crop Protection Council. pp. 1-15. Blackwell Science, Oxford, U.K.

Parry, M. L. 1990. *Climate Change and World Agriculture.* Earthscan, London.

Parry, M. L. 1998. The impact of climate change on European agriculture. *In:* T. Lewis (Ed.), *The Bawden Memorial Lectures* 1973-1998, Silver Jubilee Edition, pp. 325-38, British Crop Protection Council, Surrey, U.K.

Patterson, D. T. 1985. Comparative eco-physiology of weeds and crops. *In:* S. O. Duke (Ed.), *Weed Physiology*, Vol 1, pp. 101-29, CRC Press, Boca Raton.

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

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

Rosenzweig, C. R. and D. Hillel. 1998. *Climate Change and Global Harvest*. Oxford University Press, Oxford.

Stern, N.. 2006. *Stern Review: The Economics of Climate Change.* London: Treasury Office of the Government of the United Kingdom and Northern Ireland.

Ziska, L. H. 2000. The impact of elevated CO_2 on yield loss from a C_3 and C_4 weed in field-grown soybean. *Global Change Biol.*, **6**: 899-905.

Ziska, L. H. and J. A. Bunce. 1997. Influence of increasing carbon dioxide concentration on the photosynthetic and growth stimulation of selected C_4 crops and weeds. *Photosynthesis Res.,* **54:** 199–208.

Ziska, L. H. and J. R. Teasdale. 2000. Sustained growth, photosynthesis and increased tolerance to glyphosate observed in a C_3 perennial weed, quackgrass (*Elytrigia repens* (L.) Neveski), grown at elevated carbon dioxide. *Aust. J. Pl. Physiol.*, **27**: 157- 64.

Ziska, L. H., Teasdale, J. R. and J. A. Bunce. 1999. Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Sci.*, **47**: 608-15.