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Climate Change Influence on Herbicide Efficacy and Weed Management

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18.1 Introduction

Climate change refers to a change in the climate system that persists for long periods of time, irrespective of the cause. Since the industrial revolution, climate change has been more often associated with a rise in the concentration of greenhouse gases such as carbon dioxide (CO_2), methane, nitrous oxide, and halocarbons. The concentration of atmospheric CO_2 is steadily rising and is expected to reach $\sim$1000 $\mu molmol^{-1}$ by the year 2100 with a simultaneous increase of 2–4°C in the earth's annual surface temperature (IPCC, 2013). Human activities such as the burning of fossil fuels and deforestation have contributed to a large extent to the emission of greenhouse gases (IPCC 2013, MacCracken et al., 1990). Continued emission of these gases may lead to unprecedented climate changes involving high global temperatures, erratic precipitation and wind patterns, and weather extremities such as droughts, floods, and severe storms (Tubiello et al., 2007; Robinson and Gross, 2010; Gillett et al., 2011; Coumou and Rahmstorf, 2012). Such extreme weather events and rapid climatic changes will have major impacts on the stability of ecosystems; consequently influencing plant life and agriculture (Dukes and Mooney, 1999). Crop production and agronomic practices involving weed management and pest control may be severely affected by these altered abiotic conditions primarily caused by changes in climate and climate variability (Dukes et al., 2009, Singer et al., 2013). Warmer and wetter climates not only affect weed growth but also change chemical properties of certain herbicides; thereby altering their performance on weeds and their control (Poorter and Navas, 2003; Dukes et al., 2009). Determining the response of weeds and herbicides to increased CO_2 levels and associated changes in other climate variables is critical to optimize weed management strategies in the context of climate change. This chapter provides an overview of the impacts of climate change factors on weed growth and herbicide efficacy, particularly focusing on the impacts of climate factors on the underlying physiological mechanisms that determine herbicide performance.

Food Security and Climate Change, First Edition.
Edited by Shyam S. Yadav, Robert John Redden, Jerry L. Hatfield, Andreas W. Ebert, and Danny Hunter.

18.2 Herbicides in Weed Management

Agricultural production strongly depends on crop protection measures. Insects, pathogens, weeds, and other pests can adversely affect agricultural yields, if left uncontrolled. Outbreaks of pests and diseases may be random and irregular but weeds are relatively constant and cause severe negative effects on agriculture and other natural resources (Kostov and Pacanoski, 2007). Weeds cause extensive damage to cropland and non-cropland areas, and to public health. Weed management has become the primary focus for farmers and weed scientists around the world. Weeds cause yield losses by competing with crops for essential resources such as light, water, nutrients, and space. Weeds also interfere with harvest operations and contaminate the seed, thereby lowering the value of harvested crops. Furthermore, weeds are known to produce harmful chemicals and serve as hosts for several insect pests and diseases (Swinton et al., 1994; Boydston et al., 2008). Hence, weed control is critical for profitable crop production.

Weeds can be controlled through cultural, mechanical, biological, and chemical methods. However, chemical weed management through the use of herbicides is widespread in developed countries such as the US, where labor is limited and expensive. Use of herbicides is also increasing in developing countries. Herbicides are routinely applied for weed control in more than 90% of US crop acreage (Gianessi and Sankula, 2003) because of their simplicity in use and greater efficacy (McErlich and Boydston, 2013). Furthermore, weed control through herbicides offers many advantages to farmers by enabling timely weeding, early planting, reducing tillage and soil erosion, and lowering control costs. Despite the concerns of environmental pollution and toxicity to living organisms, their regulated use is essential to sustain the quantity and quality of current agricultural yields.

Selective control of weeds through the use of herbicides in several cropping systems has tremendously improved crop yields and quality of the produce. Selective action of herbicides largely depends on interaction with the plant and the environment. Environmental conditions such as light, temperature, relative humidity, and wind velocity at the time of herbicide application determine herbicide's performance and effectiveness on weeds. Furthermore, climate change associated with increasing temperatures may alter physiology and growth characteristics of weeds, as well as the efficacy of herbicides that currently are fatal to these weeds. Given the importance of herbicide use in sustainable crop production, it is essential to understand if and how climate change influences the efficacy of herbicides to control weeds in current and future climates.

18.3 Climate Factors and Crop-Weed Competition

Agriculture has considerable impact on climate change and is accountable for about 30% of greenhouse gas emissions (Nitze et al., 2008). Some modern agricultural practices do contribute to the emission of greenhouse gases, such as CO_2, nitrous oxide, and methane. Examples include the use of farm machinery, fertilizer applications, and the practices necessary for livestock production. Deforestation and other agricultural processes, such as wetland rice cultivation, are also major sources of gases such as methane. Nonetheless, most of the negative impacts of agriculture on climate can be counteracted to a large extent through appropriate and timely measures by improving best management practices (BMPs). Examples of some BMPs that can be considered are using precision agriculture, efficient use of resources, diversification of farming systems, agricultural intensification on existing land, and other technological advancements (Tilman et al., 2011; Mueller et al., 2012; Johnson et al., 2014). On the other hand, since agriculture is highly dependent on specific climate conditions, it is very important to give attention to understanding the impact of climate change factors on farming practices and agricultural output. The effects of climate change on agriculture will be very complex. Besides directly influencing crop growth and productivity, climate change may also affect crop-weed-pest interactions, and livestock farming systems. Higher CO_2 concentrations and subsequent rise in temperatures will result in erratic weather patterns and extreme weather events such as droughts, floods, heat stress, and freeze events increasing climate variability, which will have considerable negative impacts on the productivity of agro-ecosystems. Conversely, anticipated climate changes, especially elevated CO_2 levels, will probably have positive effects on the yield and quality of some crops (C3 crops such as wheat, *Triticum aestivum*; rice, *Oryza sativa*; barley, *Hordeum vulgare*; and soybean, *Glycine max*). Higher CO_2 levels have been predicted to increase the yields of some of these crops by as much as 13% by 2050 (Jaggard et al., 2010). However, increasing CO_2 concentration also leads to partial closure of stomata leading to an increase in plant tissue temperature, which will negatively influence plant growth and productivity. In addition, other directly associated factors such as unpredictable rainfall patterns and high temperatures during the growing cycle may reduce yield and quality of crops (Hartfield et al., 2011; Mahajan et al., 2012; Singh et al., 2013; Kadam et al., 2014). For most food crops the positive impacts of elevated CO_2 on growth and yield are more than negated by negative impacts of associated increases in temperatures (Prasad et al., 2001, 2005). Furthermore, rapidly changing climate is a major concern for management of agricultural pests and weeds, as it may affect weed, pest, and disease infestations in uncertain ways (Field et al., 1999; Scherm, 2004).

Weeds tend to have higher genetic diversity and physiological plasticity than crops. For this reason weeds adapt quickly to resource changes and have a greater ability to survive and flourish in different environmental conditions. It is predicted that climate change could lead to higher competition from weeds, and without proper weed management it could result in greater yield losses (Miri et al., 2012; Valerio et al., 2013). Many weed species will be able to take advantage of increased CO_2 levels and warmer conditions and will grow faster and better than most crops (Hartfield et al., 2011). Higher CO_2 levels will directly affect photosynthesis in plants and influence the ability of crops to compete with weed species (Chandrasena, 2009). Previous research has demonstrated that C3 and C4 weeds show significant increases in plant growth as a result of increased CO_2 and higher temperatures. For example, at elevated CO_2 concentrations, a 65% increase in the biomass of a C3 weed, common lambsquarters (*Chenopodium album*) was observed which resulted in the seed yield reduction of soybean by 39% (Ziska, 2000). Similarly, a 3°C rise in temperature was found to increase the growth rate of itch grass (*Rottboelliacochin chinensis*), a highly competitive C4 weed in many cropping systems–including sugarcane, corn, cotton, soybean, grain sorghum, and rice systems–and is projected to invade further into the central Midwest and California (Patterson et al., 1999). Elevated CO_2 (800 μmolmol^{-1}) and high temperatures (26/18°C; daytime maximum/nighttime minimum; d/n) have been reported to intensify competition to tomato crops from both C3 (common lambsquarters) and C4 (redroot pigweed; *Amaranthus retroflexus*) weeds (Valerio et al., 2013).

In general, C3 and C4 plants have different abilities for temperature acclimation of photosynthesis. In C3 plants, carboxylation of ribulose biphosphate (RuBP; first acceptor of CO_2) is favored at higher CO_2 levels. But when temperatures rise above 25°C, oxygenation of RuBP is favored which increases photorespiration and inhibits CO_2 assimilation (Jorden and Ogren 1984). Conversely, in C4 plants, temperature effect is negligible as lower photorespiration rates are maintained at all times, because CO_2 pumps in mesophyll cells (Hatch 1987). As a result of these differences in the photosynthetic pathways, C3 plants typically have a greater ability to respond positively to rising CO_2 levels, whereas C4 plants are better adapted to heat stress and drought (due to higher water use efficiency) (Osmond et al., 1982; Long, 1999; Morgan et al., 2001). Since the majority of agricultural weeds have a C4 photosynthetic pathway, weeds will have an advantageous position over crops (mostly C3 plants) under higher temperatures and limited water availability. Furthermore, the differential impacts of climate change variables–such as moisture regimes, $CO_{2,}$ and temperature levels–on weeds and crops allows weeds to compete well and thrive even in unpredictable environments (Hartfield et al., 2011). Hence, there could be serious implications of increasing the temperature and CO_2 concentration on crop–weed interactions and therefore, needs greater attention.

Climate change factors such as elevated CO_2, increased temperature, and water stress may also affect the availability of nutrients for plant growth and development in future. Root growth and volume plays an important role in nutrient acquisition in most plants. Plants that are under nutrient stress generally increase their root biomass to enhance physiological capacity of roots for nutrient uptake from deeper layers of soil (Bassirirad et al., 2001). Besides increasing shoot growth and photosynthetic activity, elevated CO_2 can also stimulate root biomass in many plants (Adair et al., 2009; Anderson et al., 2010; Dijkstra et al., 2010). Fine roots and its associated mycorrhizas, which form the primary pathways for nutrient uptake, are stimulated to increase nutrient-use-efficiency (Bassirirad, 2000; Gifford et al., 2000). Root growth at elevated CO_2 was found to increase by 50% and 57% in an evergreen dwarf shrub (*Calluna vulgaris*) and perennial grass (*Deschampsia flexuosa*), respectively (Arndal et al., 2013). Studies on root growth and nutrient uptake responses to elevated CO_2 and other climate factors in plants are limited and have shown highly inconsistent patterns among different species (Beier, 2004; Bielenberg and Bassirirad, 2005; Gutschick and Pushnik, 2005). With increases in CO_2 levels, some plants showed a decline in the tissue concentrations of major nutrients like N and P; whereas in other cases, leaves and roots had negligible effects on their P concentrations (Gifford et al., 2000; Taub and Wang, 2008). Assimilation of N by roots may decrease under elevated CO_2 due to inhibition of photorespiration, resulting in decreased carbohydrate accumulation in roots compared to shoots, particularly in C3 plants (Reich et al., 2006; de Graaff et al., 2006; Rachmilevitch et al., 2004; Bloom, 2009). At higher temperatures nutrient uptake is expected to increase due to longer growing seasons that create a wider window of opportunity for mineralization processes that increase nutrient availability to plants (Beier, 2004; Schmidt et al., 2002). Under prolonged drought conditions, dehydration of roots and reduced soil nutrient mobility impede root activity and nutrient uptake (Hinsinger et al., 2009). In some cases, water scarcity may increase root length while decreasing the density (Staddon et al., 2003). Elevated CO_2 also influences nutrient dynamics between crops and weeds. In a rice-barnyard grass competition scenario, rice was able to increase uptake and tissue concentrations of C, N, P, and K nutrients compared to barnyard grass, resulting in enhanced tillering and greater biomass in rice (Zeng et al., 2011).

Climate change is also speculated to be one of the most important determinants for the distribution of many weed species including the invasive and noxious weeds (McDonald et al., 2009; Pautasso et al., 2010). Climate change directly affects the composition and habitable range of both annual and perennial weed species. Global warming will result in longer growing seasons in temperate regions which will increase weed infestations, creating more challenges for weed management (Hartfield et al., 2011; Hakala et al., 2011). For example, survival of some winter annual weeds could be greater in wetter and milder winters, whereas summer annuals may start showing up in regions further north due to warmer summers and longer growing seasons (Walck et al., 2011; Hanzlik and Gerowitt, 2012). The geographical range of some weed species typically found in southern regions (e.g. Palmer amaranth; *Amaranthus palmeri*) may expand to northern regions as early spring and warmer winters make higher latitudes more conducive to plant growth. Invasive weeds such as kudzu (*Pueraria lobata*) may also expand their habitat range to new areas and higher latitudes and are projected to cause greater losses to crop, rangeland, and forest productivity (Blaustein, 2001; Ziska and George, 2004). Over the last decade, invasive plants have been reported to cause significant negative impact on agroecosystems including agriculture, forestry, rangelands and other human activities such as transportation, public health, recreation, and tourism (Pimentel et al., 2000; EEA, 2012; Sheppard and Stanley, 2014). These changes in weed distribution can incur greater losses to the US economy both in the newly infested areas and in their current habitat, if conditions become more favorable. On the other hand, traditionally problematic weeds will probably become less challenging in certain regions as higher temperatures create more unfavorable growth conditions (McDonald et al., 2009).

Enhanced greenhouse effects associated with rise in CO_2 concentration and temperature levels can lead to changes in precipitation patterns and water availability that will significantly impact plant growth and propagation (Rodenburget et al., 2011). Most weeds have prolific seed production and rapid seed dispersal mechanisms, which enable them to spread quickly and establish in new territories. Consequently, weeds may have greater advantage with variable precipitation patterns resulting in migrations to new territories and altering the composition and integrity of ecosystems. For example, under prolonged drought conditions, cheatgrass (*Bromus tectorum*) and yellow star thistle (*Centaurea solstitialis*) are known to outgrow other species leading to a shift in the vegetation (Vollmer and Vollmer, 2006, Hartfield et al., 2011). Robinson and Gross (2010) studied the impact of variable precipitation on common lambsquarters and giant foxtail (*Setaria faberi*) and found that common lambsquarters was more tolerant to dry soil conditions than giant foxtail.

Climate change will impose new limitations on essential resources required for plant growth and may change the dynamics of crop-weed competition in several cropping systems. Therefore, it becomes imperative to expand our knowledge on how weeds and crops respond to climate change factors on a case-by-case basis. Extensive research is needed to identify the weeds that may become problematic in future climates to devise specific management strategies that are efficient in managing these weeds under such contexts.

18.4 Climate Change Factors, Herbicide Efficacy and Weed Control

Herbicides are important tools for weed management and offer several benefits to growers by being cost-effective and more reliable than any other methods of weed control. But the chemical properties of herbicides are as much liable to climate change factors as plant growth and development. Weed resistance to herbicides will probably increase due to more aggressive growth of weeds in future climate conditions, which can cause a decline in the efficacy of routinely used herbicides. This may necessitate increased use of herbicide mixtures and integrated weed management strategies (Rosenzweig et al., 2001; Bailey, 2003). Environmental conditions at the time of herbicide application significantly impact herbicide efficacy on weeds. Herbicide efficacy in susceptible plants is determined by many factors including herbicide absorption and translocation, herbicide metabolism, and herbicide binding with the target site in the plants. Each one of these factors may be influenced by environmental conditions such as light, moisture, humidity, temperature, and wind velocities at the plant level (microclimate). Changes in climate factors such as increased CO_2 levels and high temperatures may alter the physicochemical properties of the herbicide, thereby affecting the penetration and translocation of herbicides in the plants. In addition, changes in growth and physiology of plants will determine the ability of herbicide to interact with the plant surface and also the target site, once it is translocated inside the plant (Steurbaut, 2009; Keikotlhaile, 2011). Climate change impacts on foliar- and soil-applied herbicides depend on the specific environmental conditions, and can also vary among the different herbicide chemistries. Climate change factors can impact the underlying physiological mechanisms through which herbicide is absorbed and translocated in the plant to reach the target site and cause the lethal effect on the plant. It is important to critically examine the effects of major climate change variables such as rising CO_2 levels, high temperatures, moisture availability, and solar radiation on potential mechanisms that alter herbicide efficacy.

18.4.1 Effects of Elevated CO_2 and High Temperatures

Optimum concentrations of CO_2 and temperature are important not only for plant growth and development, but also for sustaining the chemical properties of herbicides. An increase in CO_2 and temperature will cause substantial effects on photosynthetic activity and stimulate overall plant growth (Gutierrez et al., 2008). Increase in aboveground plant growth can dilute the amount of foliar-applied herbicides absorbed in plants, thereby decreasing the herbicide residue that binds to the target site and kills the plant (Holland and Sinclair, 2004). An increase in plant biomass and leaf area resulted in lowering the efficacy of glyphosate in invasive weeds such as Rhodes grass (*Chloris gayana*) and dallisgrass (*Paspalum dilatatum*) at elevated CO_2 levels (Manea et al., 2011). Similarly, roots are also stimulated to grow more and may reach deeper soil layers at elevated CO_2 levels. This prevents the uptake of soil-applied herbicides, which are generally present in the top layers. Ziska et al. (2004) reported high root:shoot ratio of field-grown Canada thistle (*Circium arvense*) under elevated CO_2 levels, which reduced the efficacy of glyphosate due to the dilution effect caused by large volume of roots. However, in some cases, high temperatures could enhance root uptake of herbicides due to a decrease in soil organic matter and high evaporation rates (Miraglia et al., 2009). Another prominent effect of elevated CO_2 is the reduction in stomatal conductance by 50% in some plants (Bunce, 1993), which can alter the transpirational flow and reduce the efficacy of both foliar- and soil-applied herbicides. Furthermore, due to leaf thickening, stomata may remain closed, thereby reducing the amount of foliar-applied herbicide that is directly absorbed by plants. This has shown to protect the weeds from damage by post-emergence herbicides (Ziska, 2008; Jackson et al., 2011). Quackgrass (*Elymus repens*) exposed to high CO_2 concentration (720 $\mu molmol^{-1}$) was found to be more tolerant to glyphosate compared to plants exposed to ambient CO_2 concentration of 380 $\mu molmol^{-1}$. It was suggested that a reduction in stomatal conductance or increase in leaf starch concentrations may have decreased glyphosate absorption in these plants (Ziska and Teasdale, 2000). On the other hand, high temperatures can change the amount of herbicide diffused by altering the viscosity of cuticle waxes and physicochemical properties of spray solutions (Price, 1983). Higher temperatures have been shown to lower the viscosity of cuticular lipids, thereby increasing the permeability and diffusion of herbicides through the cuticle (Fausey and Renner, 2001). Changes in other temperature-dependent processes such as phloem translocation, respiration, and protoplasmic streaming in plants exposed to high temperatures will also change herbicide performance. For instance, ^{14}C-glyphosate translocated more to meristematic tissues of roundup ready® soybean at 35°C than at 15°C, possibly suggesting higher glyphosate injury when there is an increase in temperature (Pline et al., 1999). In some cases, high temperatures were also found to induce rapid metabolism of parent herbicide molecules and increase the activity of some antioxidant enzymes that help in the detoxification of reactive oxygen molecules, thus reducing herbicide activity on target plants. In a recent study by our group (Godar et al., 2015), the efficacy of mesotrione (HPPD-inhibitor) significantly decreased when palmer amaranth plants were exposed to a high d/n temperatures of 40/30°C. At these temperatures, although absorption of mesotrione was higher, the amount of herbicide translocated to the growing tissues was significantly lower compared to plants grown at optimum (32.5/22.5°C; d/n) or low temperatures (25/15°C; d/n). Furthermore, Palmer amaranth plants under high temperatures rapidly metabolized mesotrione molecules and had increased expression of target (HPPD) gene, possibly diluting the mesotrione toxicity in the treated plants. This suggests that weeds such as Palmer amaranth could be less sensitive to mesotrione under increased temperatures via multiple mechanisms. Temperature also can influence germination and seedling growth of plants, which, in turn, determine the sensitivity of plants to herbicide application (Hull et al., 1975).

Due to their direct impacts on photosynthetic activity, elevated CO_2concentrations and high temperature could have pronounced effects on the efficacy of herbicide chemistries such as Photosystem II inhibitors (PSII) and pigment inhibitors that interfere with photosynthesis. Efficacy of linuron was reduced by 15% in wild buckwheat (*Polygonum convolvulus*) at double-ambient CO_2 levels (Archambault et al., 2001). In contrast, high air temperatures maximized the control of velvet leaf and common ragweed after atrazine application (Stewart et al., 2009). High soil temperatures primarily affect the efficacy of soil-applied herbicides by decreasing permeability and increasing volatility and microbial breakdown. At a high soil temperature (25°C), volatilization of herbicide, triallate was increased from 14 to 60% and 7 to 41% in sandy and loamy soils, respectively (Atienza et al., 2001). Herbicides that inhibit amino acid biosynthesis (e.g. ALS inhibitors) were effective in controlling cheat grass, wild oat, jointed goat grass (*Aegilops cylindrica*), when temperatures were 25/23°C (d/n) after application compared to 5/3°C (d/n) (Olson et al., 2000). High temperatures may also have variable effects on the efficacy of some other herbicides, such as synthetic auxins. While temperature increase had no effect on the efficacy of dicamba/diflufenzopyr providing >95% control of common ragweed, common lambs quarters, and redroot pigweed; however, control of velvetleaf was reduced by 7% to 15% at low temperature (Stewart et al., 2009). Ou and Jugulam (unpublished) observed increased translocation of Dicamba resulting in improved kochia control at 17.5/7.5°C; d/n or 25/15°C; d/n temperatures compared to 32.5/22.5°C. In case of PPO inhibitors such as Flumiclorac and Fluthiacet, which are contact herbicides, high temperature increased herbicide diffusion as a result of reduction in the viscosity of cuticular waxes on the plant leaf surface (Fausey and Renner, 2001). Overall, the outcome of these studies suggests that there may be a need for increased dose and/or number of applications of some herbicides in future climate conditions to sustain the current efficacy of these herbicides (Rosenzweig et al., 2001; Noyes et al., 2009).

18.4.2 Effects of Precipitation and Relative Humidity

Precipitation and relative humidity (RH) are the other important climate factors that mainly influence herbicide retention on the leaf surface, as well as absorption and translocation inside the plant. Precipitation also influences the availability of soil moisture for plant growth. Variable precipitation likely accompanied by warmer temperature will lead to weather extremities such as droughts and floods affecting overall plant growth and development (Clements et al., 2014). In such scenarios, weeds again tend to fare better showing greater survival and tolerance mechanisms and even sustaining herbicide applications. In addition, intense rainfall immediately after herbicide application could result in washing-off of spray droplets from the plant surfaces and/or diluting the herbicide concentration applied to the plants, thus reducing herbicide retention time and uptake. Conversely, lower precipitation amounts will enhance herbicide uptake by rewetting dried spray droplets on the leaf surface (Olesen and Kudsk, 1987). Water stress caused by low amounts of precipitation also significantly affects herbicide activity due to lower translocation and decreased transpiration within the plant (Zanatta, 2008; Keikotlhaile, 2011). Activity of Acetyl CoA Carboxylase (ACCase) inhibitors was significantly lower in plantain signal grass (*Urochloa plantaginea*) when plants were grown under water stress (Pereira, 2010). Furthermore, under limited water availability, solubility and movement of soil-applied herbicides were decreased resulting in lower root uptake (Dao and Lavy, 1978; Moyer, 1987). All pre--emergence herbicides require optimum soil moisture for movement within the soil and active absorption by plant roots (Olson et al., 2000). Jurisk et al. (2013) reported a decrease in the activity of pethoxamid (seedling growth inhibitor) applied as PRE-emergence under dry soil moisture conditions. While dry soil conditions increase herbicide adsorption to soil particles, heavy rainfall immediately after the application may result in herbicide loss due to leaching (Soukup et al., 2004). Plant modifications, such as upright or downward orientation of leaves, in dry conditions lower retention of foliar-applied herbicides (Levene and Owen, 1995). Leaves of velvetleaf plants tilt downwards during drought conditions, which decreases glyphosate uptake and lower its efficacy on the plants

(Zhou et al., 2007). These studies indicate that changes in precipitation patterns may benefit herbicide dissipation rather than persistence, and that herbicide efficacy varies with the timing and intensity of rainfall (Bailey, 2003; Stenrod et al., 2008). Drought conditions during autumn and intense precipitation in humid regions can hinder field operations such as weed scouting and herbicide application for early weed control (Chen and McCarl, 2001; Miraglia et al., 2009).

Precipitation and RH are interdependent climate variables. While precipitation largely influences soil moisture availability, RH is a measure of atmospheric moisture content. Optimum RH is required for the herbicide spray droplet to interact with leaf cuticle and gain entry into the plant system before it starts drying on the leaf surface, at which point it cannot be absorbed by the plant (Muzik, 1976; Price, 1983). Research has shown that RH could exert greater influence on the uptake of foliar-applied herbicides than temperature (Devine et al., 1993, Anderson et al., 1993). Optimum levels of RH at the time of spraying will increase herbicide uptake and subsequently may lead to greater translocation inside the plant. RH has higher impacts on water-soluble herbicides such as glyphosate, bentazon, paraquat, and nicosulfuron compared to lipophilic herbicides (such as pendimethelin, atrazine, fluazifop, and carfentrozone). At plant level, high RH stimulates stomata to remain open, thus allowing more herbicide to be absorbed into the leaf surface (Kudsk et al., 1990). Ramsey et al. (2002) studied the efficacy of glufosinate ammonium on wild oat plants grown at high (>95%) and low RH (40%). Uptake and efficacy of glufosinate ammonium increased significantly in plants exposed to high RH for 30 min prior to and after herbicide application compared to those left continuously at low RH. High air temperature accompanied with high RH is beneficial for weed control by some herbicides like amino acid inhibitors, which show improved efficacy under these conditions (Stopps et al., 2013).

18.4.3 Effects of Solar Radiation

Solar radiation or light is the most important determinant for photosynthesis in plants. Growth rate in plants is proportional to the amount of solar radiation intercepted, if all other conditions are favorable. Solar radiation affects herbicide activity primarily through changes in plant anatomy and growth. As light intensity increases, the rate of photosynthesis and phloem translocation increase which facilitates the movement of foliar-applied systemic herbicides within the plant and to the growing point/target sites for action. High light intensity also improves herbicide uptake as more stomata remain open. Herbicides such as Bentazon, Clethodim, and Talkoxydim showed higher efficacy on weeds as light intensity increased (McMullan, 1996, Hatterman-Valenti et al., 2011). In some cases, solar radiation may directly affect the chemical properties of herbicides through photo-degradation. For example, efficacy of CHD herbicides (ACCase inhibitors) decreased at low light intensity (UV light) due to photo-degradation (McMullen, 1996). For some herbicides such as cell membrane disrupters, which are contact herbicides, light is needed for activation to generate lethal symptoms in the affected plants (Wright et al., 1995). Paraquat is a contact herbicide belonging to this group which had decreased efficacy on velvetleaf and large crabgrass as UV radiation increased. The authors suggest a possible increase in the leaf wax content of these species at high UV radiation, resulting in lower absorption and efficacy (Wang et al., 2006).

18.5 Concluding Remarks and Future Direction

Several climate factors that can influence weed growth and herbicide efficacy have been presented. The projected increase in CO_2 levels and elevated temperatures will have a direct impact on weeds. Changes in future climate is expected to make some weeds more aggressive and tolerant to herbicide applications besides directly influencing herbicidal properties and its absorption and translocation within plants. In addition, climate change factors may lead to significant changes in the weed distribution patterns and cause shifts in the composition of weed species. Based on the information from existing studies, proactive steps are needed to restrict the potential spread of invasive weeds to new areas in the impending climate change conditions. Seasonal precipitation and temperature fluctuations will strongly influence the timing of herbicide applications and other weed management decisions. Overall, research suggests that higher volumes of different types of herbicides may need to be used at frequent intervals. However, such applications will have negative impacts on environment and will not be sustainable and benefit agricultural production. Further, under such situations, a greater number of weeds may evolve herbicide resistance at a faster rate, creating further challenges for weed management. This projected scenario is of major concern and will require extensive research to understand this delicate balance in using herbicides for weed control in future climates and environmental sustainability. High priority should be given for research on a critical case-by-case analysis of climate change impacts on different crop-weed competition at multiple locations with diversified cropping systems. Comprehensive research efforts that include ecological, physiological, and molecular analyses are needed to study the interactive effects of different climate variables on plant growth and herbicide performance rather than basing conclusions from single factor experiments. There is a strong need for research on development of integrated and more sustainable weed management practices in current and future climates for minimizing risk of weeds, safeguarding the environment, and finding sustainable practices.

Acknowledgments

We thank the Department of Agronomy for supporting the Weed Physiology program. This manuscript is approved for publication as Kansas Agricultural Experiment Station Contribution No. 16-188-B.

References

Adair, E.C., Reich, P.B., Hobbieand, S.E., and Knops, J.M. (2009) Interactive effects of time, CO(2), N, and diversity on total belowground carbon allocation and ecosystem carbon storage in a grassland community. *Ecosystems*, 12:1037–1052.

Anderson, D.M., Swanton, C.J., Hall, J.C., and Mersey, B.G. (1993) The influence of temperature and relative humidity on the efficacy of glufosinate-ammonium. *Weed Res.*, 33:139–147.

Anderson, L.J., Derner, J.D., Polley, H.D. et al. (2010) Root responses along a subambient to elevated CO_2 gradient in a C-3-C-4 grassland. *Global Change Biol.*, 16:454–468.

Archambault, D.J., Li, X., Robinson, D. et al. (2001) *The effects of elevated CO_2 and temperature on herbicide efficacy and weed/crop competition.* Report to the Prairie Adaptation Res. Coll. No. 29.

Arndal, M.F., Merrild, M.P., Michelsen, A. et al. (2013) Net root growth and nutrient acquisition in response to predicted climate change in two contrasting heathland species. *Plant and Soil*, 369:615–29.

Atienza, J., Tabernero, M.T., Álvarez-Benedı, J. and Sanz. M. (2001) Volatilisation of triallate as affected by soil texture and air velocity. *Chemosphere*, 42:257–261.

Bailey, S.W. (2003) Climate change and decreasing herbicide persistence. *Pest Manag. Sci.*, 60:158–162.

Bassirirad, H. (2000) Kinetics of nutrient uptake by roots: responses to global change. *New Phytol.*, 147:155–169.

Bassirirad, H., Gutschick, V.P., and Lussenhop, J. (2001) Root system adjustments: regulation of plant nutrient uptake and growth responses to elevated CO_2. *Oecologia*, 126:305–320.

Beier, C. (2004) Climate change and ecosystem function-full-scale manipulations of CO(2) and temperature. *New Phytol.*, 162:243–245.

Bielenberg, D.G. and Bassirirad, H. (2005) Nutrient acquisition of terrestrial plants in a changing climate. pp. 311–330. In: H. Bassirirad (ed.). *Nutrient Acquisition by Plants-An Ecological Perspective.* Springer, Berlin.

Blaustein, R.J. (2001) Kudzu's invasion into Southern United States life and culture. The Great Reshuffling: Human dimensions of invasive species. In: *The Great Reshuffling: Human Dimensions of Invasive Species,* (ed. J.A. McNeeley), 55–62. Switzerland and Cambridge, UK: IUCN, The World Conservation Union.

Bloom, A.J. (2009) As carbon dioxide rises, food quality will decline without careful nitrogen management. *Calif. Agr.*, 63:67–72.

Boydston, R.A., Mojtahedi, H., Crosslin, J.M. et al. (2008) Effect of hairy night shade (*Solanum sarrachoides*) presence on potato nematodes, diseases, and insect pests. *Weed Sci.*, 56:151–154.

Bunce, J.A. (1993) Growth, survival, competition, and canopy carbon dioxide and water vapor exchange of first year alfalfa at an elevated CO_2 concentration. *Photosynthetica*, 29:557–565.

Chandrasena, N. (2009) How will weed management change under climate change? Some perspectives. *J. Crop and Weed*, 5:95–105.

Chen, C.C. and McCarl, B.A. (2001) An investigation of the relationship between pesticide usage and climate change. *Clim. Change*, 50:475–87.

Clements, D.R., DiTommaso, A., and Hyvönen, T. (2014) Ecology and management of weeds in a changing climate. pp. 13–37. In: B.S. Chauhan and G. Mahajan (eds.). *Recent Advances in Weed Management*. Springer, New York.

Coumou, D. and Rahmstorf, S. (2012) A decade of weather extremes. *Nat.Clim. Change*, 2:491–496.

Dao, T.H. and Lavy, T.L. (1978) Extraction of soil solution using a simple centrifugation method for pesticide adsorption-desorption studies. *Soil Sci. Soc. Am. J.*, 42:375–377.

de Graaff, M.A., van Groenigen, K.J., Six, J. et al. (2006) Interactions between plant growth and soil nutrient cycling under elevated CO2: a meta-analysis. *Global Change Biol.*, 12:2077–2091.

Devine, M.D., Duke, S.O., and Fedtke, C. (1993) *Foliar Absorption of Herbicides*. Prentice-Hall, Englewood Cliffs, New Jersey.

Dijkstra, F.A., Blumenthal, D., Morgan, J.A. et al. (2010) Contrasting effects of elevated CO_2 and warming on nitrogen cycling in a semiarid grassland. *New Phytol.*, 187:426–437.

Dukes, J.S. and Mooney, H.A. (1999) Does global change increase the success of biological invaders? *Trends Ecol. Evol.*, 14:135–139.

Dukes, J.S., Pontius, J., Orwig, D. et al. (2009) Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: what can be predicted? *Can. J. For. Res.*, 39:231–248.

[EEA] European Environmental Agency (2012) Climate change, impacts, and vulnerability in Europe 2012. EEA report No. 12/2012. Copenhagen, Denmark. 300 pp.

Fausey, J.C. and Renner, K.A. (2001) Environmental effects on cga-248757 and flumiclorac efficacy/soybean tolerance. *Weed Sci.*, 9:668–674.

Field, C.B., Daily, G.C., Davis, F.W. et al. (1999) Confronting climate change in California: ecological impacts on the Golden State. Report of the Union of Concerned Scientists and the Ecological Society of America. Cambridge, MA and Washington D.C.

Gianessi, L.P. and Sankula, S. (2003) *The Value of Herbicides in U.S. Crop Production*. Natl. Centre for Food and Agric Policy.

Gifford, R.M., Barrett, D.J., and Lutze, J.L. (2000) The effects of elevated [CO2] on the C: N and C: P mass ratios of plant tissues. *Plant and Soil*, 224:1–4.

Gillett, N.P., Arora, V.K., Zickfeld, K. et al. (2011) Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geosci.*, 4:83–7.

Godar, A.S., Varanasi, V.K., Nakka, S. et al. (2015) Physiological and molecular mechanisms of differential sensitivity of palmer amaranth (*Amaranthuspalmeri*) to mesotrione at varying growth temperatures. *PLoS ONE*, 10:e0126731–e0126731.

Gutierrez, A.P., Ponti, L., d'Oultremont, T., and Ellis, C.K. (2008) Climate change effects on poikilothermtritrophic interactions. *Clim. Change*, 87:167–92.

Gutschick, V.P. and Pushnik, J.C. (2005) Internal regulation of nutrient uptake by relative growth rate and nutrient-use efficiency. pp. 63–88. In: H. Bassirirad (ed.). *Nutrient Acquisition by Plants-An Ecological Perspective*. Springer, Berlin.

Hakala, K., Hannukkala, A., Huusela-Veistola, E. et al. (2011) Pests and diseases in a changing climate a major challenge for Finnish crop production. *Agric. Food Sci.*, (Finland) 20:3–14.

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

Hartfield, J.L., Boote, J.K., Kimball, B.A. et al. (2011) Climate impacts on agriculture: Implications for crop production. *Agron. J.*, 103:351–370.

Hatch, M.D. (1987) C_4 photosynthesis: A unique blend of modified biochemistry, anatomy and ultrastructure. *Biochem. Biophys. Acta*, 895:81–106.

Hatterman-Valenti, H., Pitty, A., and Owen, M. (2011) Environmental effects on velvetleaf (*Abutilon theophrasti*) epicuticular wax deposition and herbicide absorption. *Weed Sci.*, 59:14–21.

Hinsinger, P., Bengough, A.G., Vetterlein, D., and Young, I.M. (2009) Rhizosphere: biophysics, biogeochemistry and ecological relevance. *Plant Soil*, 321:117–152.

Holland, J. and Sinclair, P. (2004) Environmental fate of pesticides and the consequences for residues in food and drinking water. pp. 27–62. In: D. Hamilton and S. Crossley (eds.). *Pesticide Residues in Food and Drinking Water: Human Exposure and Risks*. John Wiley and Sons.

Hull, H.H., Morton, H.L., and Wharrie, J.R. (1975) Environmental influences on cuticle development and resultant foliar penetration. *The Botanical Review*, 41:421–52.

[IPCC] Intergovernmental Panel on Climate Change (2013) Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis, Summary for Policymakers. www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

Jackson, L., Wheeler, S., Hollander, A. et al. (2011) Case study on potential agricultural responses to climate change in a California landscape. *Clim. Change*, 109:407–427.

Jaggard, K.W., Qi, A., and Ober, E.S. (2010) Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365:2835–51.

Johnson, J.A., Runge, C.F., Senauer, B., Foley, J., and Polasky, S. (2014) Global agriculture and carbon trade-offs. *Proc. Natl. Acad. Sci. USA*, 111:12342–12347.

Jordan, D.B. and Ogren, W.L. (1984) The CO2/O2 specificity of ribulose 1, 5-bisphosphate carboxylase/oxygenase. *Planta*, 161:308–313.

Jursík, M., Kočárek, M., Hamouzová, K. et al. (2013) Effect of precipitation on the dissipation, efficacy and selectivity of three chloroacetamide herbicides in sunflower. *Plant Soil Env.*, 59:175–182.

Kadam, N.N., Xiao, G., Melgar, R.J. et al. (2014) Agronomic and physiological response to high temperature, drought, and elevated CO2 interaction in cereals. *Adv. Agron.*, 127:111–156.

Keikotlhaile, B.M. (2011) *Influence of the processing factors on pesticide residues in fruits and vegetables and its application in consumer risk assessment*. PhD Dissertation, Ghent University, Ghent.

Kostov, T. and Pacanoski, Z. (2007) Weeds with major impact on agriculture in Republic of Macedonia. *Pak. J. Weed Sci. Res.*, 13:227–239.

Kudsk, P., Olesen, T., and Thonke, K.E. (1990) The influence of temperature, humidity and simulated rain on the performance of thiameturon-methyl. *Weed Res.*, 30:261–269.

Levene, B.C. and Owen, M.D.K. (1995) Effect of moisture stress and leaf age on bentazon absorption in common cocklebur (*Xanthium strumarium*) and velvetleaf (*Abutilon theophrasti*). *Weed Sci.*, 47:7–12.

Long, S.P. (1999) Environmental responses. pp. 215–249. In: R.F. Sage and R.K. Monson (eds.). The Biology of C_4Photosynthesis. Academic Press, San Diego, California.

MacCracken, M.C., Budyko, M.I., Hecht, A.D., and Izrael, Y.A. (1990) *Prospects for future climate*. Lewis Publ. Inc. Chelsea, Michigan.

Mahajan, G., Singh, S., and Chauhan, B.S. (2012) Impact of climate change on weeds in the rice–wheat cropping system. *Curr. Sci. India*, 102:1254–1255.

Manea, A., Leishman, M.R., and Downey, P.O. (2011) Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Sci.*, 59:28–36.

McDonald, A., Riha, S., DiTommaso, A., and Degaetano, A. (2009) Climate change and geography of weed damage: analysis of US maize systems suggests the potential for significant range transformation. *Agric. Ecosyst. Environ.*, 130:131–140.

McErlich, A.F. and Boydston, R.A. (2013) Current state of weed management in organic and conventional cropping systems. Publications from USDA-ARS/UNL Faculty. Paper 1387.

McMullan, P.M.(1996) Grass herbicide efficacy as influenced by adjuvant, spray solution pH, and ultraviolet light. *Weed Technol.*, 10:72–77.

Miraglia, M., Marvin, H.J.P., Kleter, G.A., et al. (2009) Climate change and food safety: An emerging issue with special focus on Europe. *Food and Chem. Toxicol.*, 47:1009–1021.

Miri, H.R., Rastegar, A., and Bagheri, A.R. (2012) The impact of elevated CO_2 on growth and competitiveness of C_3 and C_4 crops and weeds. *European J. Exp. Biol.*, 2:1144–1150.

Morgan, J.A., LeCain, D.R., Mosier, A.R., and Milchunas, D.G. (2001) Elevated CO2 enhances water relations and productivity and affects gas exchange in C3 and C4 grasses of the Colorado shortgrass steppe. *Global Change Biol.*, 7:451–466.

Moyer, J.R. (1987) Effects of soil moisture on the efficacy and selectivity of soil-applied herbicides. *Rev. Weed Sci.*, 3:19–34.

Mueller, N.D., Gerber, J.S., Johnston, M. (2012) Closing yield gaps through nutrient and water management. *Nature*, 490:254–257.

Muzik, T.J. (1976) Influence of environmental factors on toxicity to plants. pp. 204—247. In: L.J. Audus (ed.). *Herbicides: Physiology, Biochemistry, Ecology*, 2e. Academic Press, New York.

Nitze, W.A., Topping, J.C., Goldberg, M. et al. (2008) Reducing our food's impact on climate change. *Clim. Alert*, 18:6.

Noyes, P.D., McElwee, M.K., Miller, D. et al. (2009) The toxicology of climate change: Environmental contaminants in a warming world. *Env. Int.*, 35:971–986.

Olesen, T. and Kudsk, P. (1987) The influence of rain on the effect of chlorsulfuron, fluazifop-butyl and glyphosate. pp. 256—266. In: *Proceedings 4th Danish Plant Protection Conference on Weeds.*

Olson, B.L., Al-Khatib, K., Stahlman, P., and Isakson, P.J. (2000) Efficacy and metabolism of MON 37500 in *Triticumaestivum* and weedy grass species as affected by temperature and soil moisture. *Weed Sci.*, 48:541–548.

Osmond, C.B., Winter, K., and Ziegler, H. (1982) Functional significance of different pathways of CO2 fixation in photosynthesis. In: *Physiological Plant Ecology II* (ed. O.L. Lange, P.S. Nobel, C.B. Osmond, and H. Ziegler), 479—547. Springer, Berlin, Heidelberg.

Patterson, D.T., Westbrook, J.K., Joyce, R.J.C. et al. (1999) Weeds, insects and diseases. *Clim. Change*, 47:711–727.

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

Pereira, M.R.R. (2010) Efeito de herbicidas sobre plantas de *Brachiaria plantaginea* submetidas a estresse hídrico. *Planta Daninha*, 28:1047–1058.

Pimentel, D., Lach, L., Ziniga, R., and Morrison, D. (2000) Environmental and economic costs associated with non-indigenous species in the United States. *BioScience*, 50:53–65.

Pline, W.A., Wu, J., and Hatzios, K.K. (1999) Effects of temperature and chemical additives on the response of transgenic herbicide-resistant soybeans to glufosinate and glyphosate applications. *Pesticide Biochem. Physiol.*, 65:119–131.

Poorter, H. and Navas, M.L. (2003) Plant growth and competition at elevatedCO_2: on winners, losers and functional groups. *New Phytol.*, 157: 175–198.

Prasad, P.V.V., Craufurd, P.Q., Kakani, V.G., and Boote, K.J. (2001) Influence of high temperature during pre- and post-anthesis stages of floral development on fruit-set and pollen germination in peanut. *Aust. J. Plant Physiol.*, 28: 233—240.

Prasad, P.V., Allen, L.H., and Boote, K.J. (2005) Crop responses to elevated carbon dioxide and interaction with temperature: grain legumes. *J. Crop Improv.*,13:113.

Price, C.E. (1983) The effect of environment on foliage uptake and translocation of herbicides. pp. 157–169. In: *Aspects of Applied Biology 4: Influence of Environmental Factors on Herbicide Performance and Crop and Weed Biology*, vol. 4. (ed. A.O.A. Biologists). Warwick: The Association of Applied Biologists.

Rachmilevitch, S., Cousins, A.B., and Bloom, A.J. (2004) Nitrate assimilation in plant shoots depends on photorespiration. *Proc. Natl. Acad. Sci. USA*, 101:11506–11510.

Ramsey, R.J.L., Stephenson, G.R., and Hall, J.C. (2002) Effect of relative humidity on the uptake, translocation, and efficacy of glufosinate ammonium in wild oat (*Avenafatua*). *Pesticide Biochem. Physiol.*, 73:1–8.

Reich, P.B., Hobbie, S.E., Lee, T. et al. (2006) Nitrogen limitation constrains sustainability of ecosystem response to CO2. *Nature*, 440:922–925.

Robinson, T.M. and Gross, K.L. (2010) The impact of altered precipitation variability on annual weed species. *American J. Botany*, 97:1625–9.

Rodenburg, J., Meinke, H., and Johnson, D.E. (2011) Challenges for weed management in African rice systems in a changing climate. *The J. Agricultural Sci.*, 149:427–435.

Rosenzweig, C., Iglesias, A. Yang, X. et al. (2001) Climate change and extreme weather events; implications for food production, plant diseases, and pests. *Global Change and Human Health*, 2:90–104.

Scherm, H. (2004) Climate change: Can we predict the impacts on plant pathology and pest management? *Can. J. Plant Pathol.*, 26:267–273.

Schmidt, I.K., Jonasson, S., Shaver, G.R. et al. (2002) Mineralization and distribution of nutrients in plants and microbes in four arctic ecosystems: responses to warming. *Plant Soil*, 242:93–106.

Sheppard, C.S and Stanley, M.C. (2014) Does elevated temperature and doubled CO_2 increase growth of three potentially invasive plants? *Invasive Plant Sci. Manag.*, 7:237–246.

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

Singh, R.P., Prasad, P.V.V., and Reddy, K.R. (2013) Impacts of changing climate and climate variability of seed production and seed industry. *Adv.Agron.*, 118:49–110.

Soukup, J., Jursík, M., Hamouz, P. et al. (2004) Influence of soil pH, rainfall, dosage, and application timing of herbicide Merlin 750 WG (isoxaflutole) on phytotoxicity level in maize (*Zea mays* L.). *Plant Soil Env.*, 50:88–94.

Staddon, P.L., Thompson, K., Jakobsen, I. et al. (2003) Mycorrhizal fungal abundance is affected by long-term climatic manipulations in the field. *Global Change Biol.*, 9:186–194.

Stenrod, M., Puserceval, J., Benoit, P. et al. (2008) Cold climatic conditions: Effects on bioavailability and leaching of the mobile pesticide metribuzin in a silt loam soil in Norway. *Cold Regions Sci. Technol.*, 53:4–15.

Steurbaut, W. (2009) *Neveneffecten van pesticiden*. Fytofarmacie, Ghent University, Ghent.

Stewart, C.L., Nurse, R.E., and Sikkema, P.H. (2009) Time of day impacts postemergence weed control in corn. *Weed Technol.*, 23:346–355.

Stopps, G.J., Nurse, R.E., and Sikkema, P.H. (2013) The effect of time of day on the activity of postemergence soybean herbicides. *Weed Technol.*, 27:690–695.

Swinton, S.M., Buhler, D.D.,Forecella, F. et al. (1994) Estimation of crop yield loss due to interference by multiple weed species. *Weed Sci.*, 42:103–109.

Taub, D.R. and Wang, X.Z. (2008) Why are nitrogen concentrations in plant tissues lower under elevated CO_2? A critical examination of the hypotheses. *J. Integr. Plant Biol.*, 50:1365–1374.

Tilman, D., Balzer, C., Hill, J., and Befort, B.L. (2011) Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA*, 108:20260–20264.

Tubiello, F.N., Soussana, J.F., and Howden, S.M. (2007) Crop and pasture response to climate change. *Proc. Natl. Acad. Sci. USA*.,104:19686−90.

Valerio, M.,Tomecek, M., Lovelli, S., and Ziska, L. (2013) Assessing the impact of increasing carbon dioxide and temperature on crop-weed interactions for tomato and a C_3 and C_4 weed species. *European J. Agronomy*, 50:60–65.

Vollmer, J.L. and Vollmer, J.G. (2006) Controlling cheatgrass in winter range to restore habitat and endemic fire. pp. 57−60. In: *Proceedings-Shrublands under fire: disturbance and recovery in a changing world*. (ed. S.G. Kitchen, R.L. Pendleton, T.A. Monaco, and J. Vernon). Proc. RMRS-P-52. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Walck, J.L., Hidayati, S.N., and Dixon, K.N. (2011) Climate change and plant regeneration from seed. *Global Change Biol.*, 17:2145–2161.

Wang, S., Duan, L. Li, J. et al. (2006) UV-B radiation increases paraquat tolerance of two broad-leaved and two grass weeds in relation to changes in herbicide absorption and photosynthesis. *Weed Res.*, 47:122–128.

Wright, T.R., Fuerst, E.P., Ogg, A.G. Jr. et al. (1995) Herbicidal activity of UCC-C4243 and acifluorfen is due to inhibition of protoporphyrinogen oxidase. *Weed Sci.*, 43:47–54.

Zanatta, J.F. (2008) Teores de água no solo e eficácia do herbicidafomesafen no controle de *Amaranthushybridus*. *Planta Daninha*, 26:143–155.

Zeng, Q., Liu, B., Gilna, B. et al.(2011) Elevated CO_2 effects on nutrient competition between a C_3 crop (*Oryza sativa* L.) and a C_4 weed (*Echinochloacrusgalli* L.) *nutrient cycling*. *Agroecosystems*, 89:93–104.

Zhou, J., Tao, B. Messersmith, C.G., and Nalewaja, J.D. (2007) Glyphosate efficacy on velvetleaf (*Abutilon theophrasti*) is affected by stress. *Weed Sci.*, 55:240–244.

Ziska, L.H. (2000) The impact of elevated CO2 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 Teasdale, J.R. (2000) Sustained growth and increased tolerance to glyphosate observed in a C_3 perennial weed, quackgrass (*Elytrigiarepens*), grown at elevated carbon dioxide. *Functional Plant Biol.*, 27:159–166.

Ziska, L.H. and George, K. (2004) Rising carbon dioxide and invasive, noxious plants: potential threats and consequences. *World Resource Rev.*, 16:427–447.

Ziska, L.H., Faulkner, S.S., and Lydon, J. (2004) Changes in biomass and root: shoot ratio of field-grown Canadathistle (*Cirsiumarvense*), anoxious, invasive weed, with elevatedCO2: implications for control with glyphosate. *Weed Sci.*, 52:584–588.

Ziska, L.H. (2008) Rising atmospheric carbon dioxide and plant biology: The overlooked paradigm. *DNA Cell Biol.*, 27:165–172.