Weed Turf. Sci. 3(3):174~182
http://dx.doi.org/10.5660/WTS.2014.3.3.174 Print ISSN 2287-7924, Online ISSN 2288-3312

Mini-Review **Weed & Turfgrass Science**

Weed & Turfgrass Science was renamed from formerly both Korean Journal of Weed Science from Volume 32(3), 2012, Korean Journal of Turfgrass Science from Volume 25(1), 2011 and Asian Journal of Turfgrass Science from Volume 26(2), 2012 which were launched by The Korean Society of Weed Science and The Turfgrass Society of Korea found in 1981 and 1987, respectively.

Weed Population Dynamics under Climatic Change

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ABSTRACT. This paper provides some of the scientific background on how projected environmental conditions could affect weeds and weed management in crops. Elevated CO_2 levels may have positive effects on crop competitiveness with C_4 weeds, but these are generally outnumbered by C_3 species in weed populations. Moreover, higher temperatures and drought will favor C_4 over C_3 plants. The implementation of climate change adaptation technologies, such as drought-tolerant germplasm and water-saving irrigation regimes, will have consequences for crop–weed competition. Rainfed production systems are thought to be most vulnerable to the direct effects of climate change and are likely to face increased competition from C_4 and parasitic weeds. Biotic stress-tolerant crop cultivars to be developed for these systems should encompass weed competitiveness and parasitic-weed resistance. In irrigated systems, indirect effects will be more important and weed management strategies should be diversified to lessen dependency on herbicides and mechanical control, and be targeted to perennial rhizomatous (C_3) weeds. Water-saving production methods that replace a weed-suppressive floodwater layer by intermittent or continuous periods of aerobic conditions necessitate additional weed management strategies to address the inherent increases in weed competition. Thus, climatic conditions have a great effect on weed population dynamics all over the world.

***Key words*:** Climate change, Weed competition, Weed management

Received on September 01, 2014; Revised on September 10, 2014; Accepted on September 11, 2014
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Introduction

Global agricultural systems vary considerably in their sensitivity to climate and in their vulnerability to changes in the climatic regime. Intensive farming systems are generally considered to have low sensitivity to climate change because a given change in temperature or rainfall has a modest impact (Chloupek et al., 2004) and because the farmers have resources to adapt and compensate by changing management. These systems may therefore respond favorably to a modest climatic warming (Olesen and Bindi, 2002). On the other hand, some of the low input farming systems currently in marginal areas may be severely affected by climate change (Reilly and Schimmelpfennig, 1999; Darwin and Kennedy, 2000). In particular, an increase in extreme events of both temperature and rainfall will affect the vulnerability of agro-ecosystems to climatic conditions.

Climate change is expected to affect agriculture very differently in different parts of the world (Parry et al., 2004). The resulting effects depend on current climatic and soil conditions, the direction of change, and the availability of resources and infrastructure to cope with change. There is a large variation in climatic conditions, soils, land use, infrastructure, political and economic conditions (Bouma et al., 1998). These differences are also expected to influence the responsiveness to climatic change (Olesen and Bindi, 2002).

Changes in atmospheric CO_2 levels, rainfall, temperature and other growing conditions will affect weed species distribution and their competitiveness within a weed population and within a rice crop. This may necessitate adaptations in crop management practices, which in turn will affect weed growth or the proliferation of certain species. Environmental conditions also have a large impact on the effectiveness of weed management operations such as chemical and mechanical control. The magnitude of these effects will largely depend on the extent to which environmental conditions change locally and regionally. Major global changes will comprise further increases in atmospheric greenhouse gases and likely changes in temperature (> 0.2°C per decade), soil degradation, and competing claims for land and water (IPCC, 1996). Thus, an experiment will be conducted considering the following objectives: (a) to monitor the effect of temperature on weed population growth; (b) to evaluate the direct effects of CO_2 on weed competition, abundance, and distribution; (c) to measure the effect of rainfall and humidity on the differential response of weeds.

Direct effects on weed competition, abundance, and distribution

The CO_2 concentration in the atmosphere will increase. This will affect weed species in different ways, depending on their photosynthetic pathways. Under drought and high temperatures, plants with the C_4 carbon fixation pathway have a competitive advantage over plants possessing the more common C_3 pathway. This competitive advantage of C_4 weeds diminishes or even reverses under conditions of high nitrogen or CO_2 concentrations (Bazzaz and Carlson, 1984). The C_4-type species are most dominant in upland ecosystems (52%) and occur least frequently in the lowlands (23%). For a C_3 crop like rice, elevated CO_2 levels may have positive effects on crop competitiveness with C_4 weeds (Fuhrer, 2003; Patterson et al., 1999), and tolerance to *Striga* infection (Watling and Press, 2000). Yet, empirical evidence also shows that higher CO_2 levels stimulate biomass production of both C_3 and C_4 grasses: C_3 grass species had a greater increase in tillering while C_4 grass species had a greater increase in leaf area under conditions of elevated CO_2 concentrations (Wand et al., 1999). Tillering and leaf canopy development are known important traits affecting inter-specific competition. Increased CO_2 levels are likely to be accompanied by higher temperatures favoring C_4 weeds over C_3 crops (Fuhrer, 2003). The same outcome can be expected under increased or prolonged drought conditions (Bjorkman, 1976). Although precise changes in rainfall are difficult to predict, precipitation will likely become more erratic with more frequent droughts and floods (Giannini et al., 2008). Consequently, weeds adapted to these conditions might have a comparative advantage in rainfed rice. Apart from drought-tolerant C_4 weeds, parasitic weeds that thrive in erratic and low rainfall environments (e.g., *Striga hermonthica*) or temporarily flooded conditions (e.g., *Rhamphicarpa fistulosa*) could benefit from future climate extremes.

Temperature changes will affect the geographic distribution of weeds (Patterson et al., 1999), with some species moving to higher latitudes (Patterson, 1995) and altitudes (Parmesan, 1996). For instance, *Striga* spp. might extend their geographical range because of climate change (Mohamed et al., 2006). Ecological niche modeling suggests that the highly diverse *Striga* species might expand into moderate climate zones (Mohamed et al., 2007). *Striga asiatica* is relatively insensitive to temperature (Patterson et al., 1982) and its distribution may be more affected by changes in the geographical range of the host crop than directly by temperature (Cochrane and Press, 1997). Phoenix and Press (2005) argue that this could be true for parasitic weeds in general.

Indirect effects on crop management adaptations and weed management effectiveness

Water is becoming a scarcer resource in many parts of agricultural land (Seckler et al., 1999) and rice varieties and cropping methods need to be adapted accordingly (Ingram et al., 2008). For upland rice, drought tolerance will be important not only just to reduce losses due to moisture stress but also to maintain or improve the crop's competitiveness against weeds (Asch et al., 2005). In lowland rice, approaches to conserve irrigation water, such as aerobic rice and alternate wetting and drying, may be adopted, but will have consequences for weed management (Krupnik et al., 2011), requiring more crop management skills and better access to production resources. Haden et al. (2007) observed a shift in weed populations, with an increased incidence of sedges under reduced flooding regimes. Where season-long flooding of lowland rice fields is replaced by only temporary flooding or aerobic conditions, increased weed infestations are observed (Krupnik et al., 2011). Hand-weeding requirements may increase by up to 35% with temporary, rather than permanent flooding in lowland systems (Latif et al., 2005). Maintaining a floodwater layer to suppress weeds is likely to become increasingly difficult in many areas as water becomes scarcer; consequently, farmers lacking the means for effective weeding are likely to suffer severe yield losses (Barrett et al., 2004).

The effectiveness of weed management is also hypothesized to change along with environmental conditions. Extreme weather may increase the risk of herbicides either causing crop damage or not being effective (Patterson et al., 1999). Increased temperatures affect herbicide persistence in the soil and the 'windows' for herbicide effectiveness (Bailey, 2004), while herbicides may be diluted and cease to be effective if rainfall becomes more frequent or intense (Kanampiu et al., 2003). Herbicide use is expected to increase soon and with it, more resistant weed ecotypes are likely to emerge. Environmental changes can accelerate this. Raised CO_2 levels, for instance, have been shown to increase the tolerance of weeds to herbicides (Ziska et al., 1999).

High CO_2 environments may also stimulate belowground root growth relative to aboveground shoot growth (Ziska, 2003) and favor rhizome and tuber growth of (in particular, C_3) perennial weeds (Oechel and Strain, 1985) rendering their control more difficult (Patterson, 1995; Patterson et al., 1999). Increased tillage, for instance, could then lead to a multiplication of vegetative propagation material (Ziska, 2008). For rice production in Africa, this could mean increasing problems with perennial lowland weeds like *Oryza longistaminata*, *Leersia hexandra*, *Bolboschoenus maritimus*, *Sacciolepis africana,* and *Cyperus halpan*. Other perennial weeds with difficult-to-control belowground structures (e.g., *Imperata cylindrica* and *Cynodon dactylon* in the uplands and *Cyperus esculentus* and *C. rotundus* on upland and hydromorphic soils) are all C_4 types.

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. 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 in an increased CO_2 environment, independently of temperature and rainfall effects.

Ziska and Bunce (1997) compared the effect of elevated CO_2 levels on the growth and biomass production of six 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. crusgalli, P. dichotomiflorum, S. viridis*) relative to the ambient CO_2 conditions. Leaf water potentials for three of the species (*A. retroflexus*, *A. hypochondriacu*s, *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 is 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 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 conditions 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.

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

Weeds are opportunistic colonizing species or pioneers of secondary succession that are well adapted to grow in locations where disturbances, caused either by humans or by natural causes, have opened up space. Species can become weeds, because they are competitive, adaptable, highly fecund, and are able to tolerate a wide range of environmental conditions, including those in agricultural fields, or disturbed habitats. A set of common biological characteristics (Baker, 1965) allows weeds to colonize 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 a 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.

Weed-crop competition under climatic 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 also likely to 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 temperatures unfavorable to C_3 photosynthesis (between 25 and 40°C). 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 (lambsquarters, *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 conditions. However, soybean growth and yield were significantly reduced by both weed species at both levels of CO_2. With lambsquarters, 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 lambsquarters 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 the increased competitiveness of rice. However, under elevated CO_2 levels 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 favor a C_4 species.

Weed distribution and abundance in the range under climatic change

Bunce (2000) 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 colonizing 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 for low temperatures under elevated CO_2 for several chilling-sensitive plants of tropical or sub-tropical origin. The 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 unknown, aggressive tropical colonizers (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 northwest. Reduced rainfall is predicted for southwestern Western Australia, and generally, across eastern and southeastern 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, favored by increasing temperature; and (b) spread further inland, favored by increased water use efficiency (WUE), under elevated CO_2.

These and other studies (Kriticos et al., 2003a, b; 2006) have indicated significant and increased risks of spread and invasion of new areas by well-known aggressive colonizers. 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 rubber vine (*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 that are currently limited to higher rainfall zones. Reduced rainfall will also reduce the growth of pastures and crops, increasing bare ground and reducing canopy cover, which favors 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 open up gaps for weed invasion in areas of pristine native vegetation, especially in the wet tropics.

Adapting mechanisms to climatic change

It is clear that both crops and weeds will respond to climate change, but the overall winners of their competition in the field will be the colonizing species, because of their superior adaptations and wide ecological amplitudes (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 colonizing species become abundant, and possibly more aggressive in many regions, humans will have to adapt to manage weed populations more effectively, 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). 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 the farm level will be part of the solutions. What this means is that natural resource managers need to cooperate 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 recognized 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 Southeast 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 labor 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 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 10°C 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, to 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 shortages 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 a new irrigation infrastructure will have to be installed, to substitute for moisture losses due to increased transpiration.

Maintaining soil fertility will 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 additional fertilizer. Adopting farming methods that reduce the costs of production and minimize 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, are 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 the 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 act 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 buildup 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 an 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 review 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 favor 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 favor their establishment.

More effective management solutions will therefore be required to reduce the threat posed by aggressive colonizers, which can make production of food and management of land and water resources much more difficult. Global change is a somewhat deceptively simple 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 increases, higher 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 uncertainties, including the disordered behavior 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 affect 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.

Conclusion

Although the uncertainties of future climate changes are large, we already know that changes will alter the balance between weed species, rice production systems, and ecosystems. Irrigated systems are likely to suffer mainly from the indirect effects of climate change. In these systems, herbicides are the dominant weed control method and they are likely to become less effective due to CO_2 increases and more frequently occurring weather extremes. Moreover, water-saving production methods in response to water-scarcity will be implemented in these systems and cause severe increases in weed competition. We hypothesize that in irrigated, temperate rice systems, temperature and rainfall variability increases will have less impact than CO_2 increases. Higher CO_2 concentrations will probably make rice and C_3 weed species (particularly rhizomatous perennials such as *Oryza longistaminata*, *Leersia hexandra*, *Bolboschoenus maritimus*, *Sacciolepis africana,* and *Cyperus halpan*) more competitive against C_4 weeds, while mechanical control will become more difficult due to the stimulating effect on belowground growth.

Rainfed production systems will be impacted by the direct effects of climate change as these systems harbor most of the C_4 and all the parasitic weed species. They are most vulnerable to rainfall irregularities and soil degradation. Here we suggest that the area infested with parasitic weeds *Striga asiatica*, *S. hermonthica*, *S. aspera* and *Rhamphicarpa fistulosa* could increase, particularly in places where soil degradation and erratic rainfall become prevalent. Furthermore, because of their likely higher drought and heat tolerance, C_4 species like the perennial grasses *Imperata cylindrica*, *Paspalum scrobiculatum,* and *Cynodon dactylon*, the annual grasses *Rottboellia cochinchinensis*, *Digitaria horizontalis*, *Eleusine indica*, *Dactyloctenium aegyptium*, *Pennisetum purpureum,* and *Echinochloa colona*, and the sedges *Fimbristylis littoralis* (annual), *Cyperus rotundus* and *C. esculentus* (perennial) are likely to become more competitive in rainfed rice. Drought- and heat-tolerant rice cultivars will gain popularity. Should these tolerance traits not be combined with a certain degree of weed competitiveness or resistance against parasitic weeds, adaptive and competitive (C_4 and hemiparasitic) weeds might prevail.

While atmospheric CO_2 levels are certain and temperatures are highly likely to increase, the spatial distribution of future rainfall remains much more uncertain (Giannini et al., 2008). This uncertainty about such a vital vegetative growth factor, combined with a lack of understanding about the interaction between different environmental factors that are likely to change, means that any predictions of future distribution of plant species must be evaluated carefully. The net effect of climate change on weeds will depend on the composition of local weed populations and the $CO_2 \times$ temperature $\times$ water availability interaction effects. These effects should be investigated for different species, ecosystems, and agro-ecological zones, in the context of subsistence agriculture and emerging social issues and resource scarcity. Weed management strategies should be diversified to lessen dependency on herbicides and mechanical control, and targeted to likely future problem species such as hemi-parasitic and perennial rhizomatous weeds. Moreover, future climate change adaptation strategies for rice-based production systems, such as new cropping system designs or improved stress-tolerant cultivars, should simultaneously address possible implications for weed competition.

Acknowledgements

This work was carried out with the support of "Cooperative

Research Program for Agriculture Science & Technology Development (Project title: Development of prediction system for management of rice weeds under climate change, Project No. PJ01052603)" Rural Development Administration, Republic of Korea.

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