Journal of Agricultural Science (2011), **149**, 427–435. © *Cambridge University Press* 2011
doi:10.1017/S0021859611000207

CLIMATE CHANGE AND AGRICULTURE PAPER

Challenges for weed management in African rice systems in a changing climate

J. RODENBURG[1]*, H. MEINKE[2]† AND D. E. JOHNSON[3]

[1] *Africa Rice Center (AfricaRice), East and Southern Africa Rice Program (ESARP), P.O. Box 33581, Dar es Salaam, Tanzania*
[2] *Department of Plant Sciences, Centre for Crop Systems Analysis (CSA), Wageningen University, Wageningen, The Netherlands*
[3] *Crop and Environmental Sciences Division, International Rice Research Institute (IRRI), DAPO Box 7777, Metro Manila, Philippines*

(*Revised MS received 4 November 2010; Accepted 23 November 2010; First published online 25 February 2011*)

SUMMARY

Global changes including increases in temperature, atmospheric greenhouse gases, soil degradation and competition for land and water resources, will have multiple impacts on rice production systems in Africa. These changes will affect weed communities, and management approaches must be adapted to take this into account. Higher temperatures and limited water availability will generally advantage C_4 over C_3 plants (e.g. rice). Conversely, elevated carbon dioxide (CO_2) levels will improve the competitiveness of rice relative to C_4 weeds, which comprise many of the problem weeds of rice. Increased atmospheric CO_2 levels may also improve tolerance of rice against parasitic weeds, while prevalence of parasitic species may be amplified by soil degradation and more frequent droughts or floods. Elevated CO_2 levels tend to promote growth below-ground relative to above-ground, particularly in perennial (C_3) species. This may render mechanical control of weeds within a cropping season less effective or even counterproductive. Increased CO_2 levels, rainfall and temperature may also reduce the effectiveness of chemical control, while the implementation of adaptation technologies, such as water-saving irrigation regimes, will have negative consequences for rice–weed competition. Rain-fed production systems are prevalent throughout Africa and these are likely to be most vulnerable to direct effects of climate change (e.g. higher temperatures and changes in rainfall patterns). Effective weed management strategies in these environments could encompass off-season tillage, the use of well-adapted cultivars (i.e. those with drought and heat tolerance, high weed competitiveness and parasitic weed resistance or tolerance) and rotations, intercropping or short, off-season fallows with weed-suppressive legumes including those that suppress parasitic weeds. In irrigated, non-flooded rice systems, weeds are expected to become more serious. Specifically, perennial rhizomatous C_3 weeds and species adapted to hydromorphic conditions are expected to increase in prevalence. By implementing an integrated weed management strategy primarily targeted at weed prevention, dependency on flood water, herbicides and mechanical control can be lessened. Off-season deep tillage, stale seed bed techniques, use of clean seeds and irrigation water, competitive cultivars, timely transplanting at optimum spacing and judicious fertilizer timings are suitable candidate components for such a strategy. Integrated, novel approaches must be developed to assist farmers in coping with the challenges of weed control in the future.

* To whom all correspondence should be addressed. Email: j.rodenburg@cgiar.org
† Current address: Tasmanian Institute of Agricultural Research (TIAR), University of Tasmania, Hobart, Tasmania, Australia.

INTRODUCTION

Rice is an increasingly important commodity in Africa (Balasubramanian *et al.* 2007); in 2007, rice production reached 23·5 Mt (FAO 2009). Trends show production is rapidly increasing and African production now rivals that of Latin America (Meinke *et al.* 2009*a*). Five main rice agro-ecosystems are distinguished in sub-Saharan Africa (SSA) based on hydrology and topography: (1) rain-fed uplands and hydromorphic slopes (0·39 of total area under rice), (2) rain-fed lowlands in valley bottoms and floodplains (0·33), (3) irrigated lowlands (deltas and floodplains) and highlands (0·19), (4) deep-water basins along major rivers and (5) mangrove-swamps in lagoons and deltas (4 and 5 combined = 0·09) (Balasubramanian *et al.* 2007; FAO 2009).

A review of rice yield losses due to uncontrolled weed growth reported losses in the range of 28–74% in transplanted lowland rice, 28–89% in direct-seeded lowland rice and 48–100% in upland ecosystems (Rodenburg & Johnson 2009). Improving weed control in farmers' fields was shown to increase rice yields by 15–23%, depending on agro-ecosystem, and it is estimated that weeds may account for annual rice yield losses in SSA of at least 2.2 million tonnes equating to US $1.45 billion (Rodenburg & Johnson 2009). Given that demand for food is projected to rapidly outpace increases in supply (e.g. von Grebmer *et al.* 2008), effective weed control is a priority in these systems.

Important weeds of upland rice include the perennials *Imperata cylindrica, Cyperus rotundus* and *Chromolaena odorata*, the annuals *Digitaria horizontalis* and *Euphorbia heterophylla* and the parasitic weeds *Striga hermonthica* and *Striga asiatica* (Table 1). In lowland rice, the perennial weeds *Oryza longistaminata* and *Cyperus* spp. and annual weeds *Echinochloa* spp., *Oryza barthii, Ischaemum rugosum, Cyperus difformis, Cyperus iria, Fimbristylis littoralis* and *Sphenoclea zeylanica* cause serious losses. Common weed management practices in rice-based cropping systems include soil tillage, flooding, fallow and crop rotations, clearance by fire, hand- or hoe-weeding and herbicides; these practices are often used in combination (Rodenburg & Johnson 2009).

Climate change is one of many risk factors affecting rice production and weed management. For the purpose of the present review, 'climate change' is used in the broad sense, including direct and indirect impacts of climate on the environment and on people. Major global changes include further increases in atmospheric greenhouse gases and likely changes in temperatures (> 0·2 °C/decade), soil degradation and competing claims for land and water (IPCC 2007). For Africa, climate trends suggest that variability in rainfall will increase and monsoon regions may become drier (Giannini *et al.* 2008), leading to a 5–8% increase in drought-prone areas in the Sahel and southern Africa by 2080 (IPCC 2007). Equatorial zones of Africa may receive more intense rainfall (Christensen *et al.* 2007). Spatial distribution of future rainfall, however, remains highly uncertain (Giannini *et al.* 2008), particularly for the Sahel for which there are a number of conflicting projections (e.g. Cook & Vizy 2006; Hoerling *et al.* 2006; Biasutti *et al.* 2008).

While many of the aforementioned changes began decades ago, the rates of changes have recently accelerated and impacts are increasingly apparent (Rozenzweig *et al.* 2008). This adds urgency to the required analyses of adaptation options for farmers and for policy and adaptation measures to be introduced (Meinke *et al.* 2009*b*). Changes in atmospheric carbon dioxide (CO_2), rainfall and temperature will affect weed species' distribution and prevalence within weed and crop communities. Climate changes may also necessitate adaptation of crop management practices, which in turn affect weed growth and the proliferation of certain species. Environmental conditions will impact on effectiveness of weed management operations such as chemical and mechanical control. Obviously, the magnitude of these effects will largely depend on the extent of local and regional changes to environmental conditions.

The present paper discusses (1) the likely effects of projected climate changes on the competitiveness and distribution of major weeds of African rice ecosystems and (2) the consequences of changing climates and changing weed community compositions for weed management in African rice production systems. The objectives are to describe likely climate change effects on weeds in African rice production systems and to identify potentially effective coping strategies for the resource-poor farmers in these systems.

CLIMATE CHANGE EFFECTS

Direct effects – weed competition, abundance and distribution

Temperatures, atmospheric CO_2 concentrations and rainfall irregularities will increase (IPCC 2007), and this will affect weed species in different ways, depending on their photosynthetic pathways and tolerance to environmental stress. 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 (e.g. Yin & Struik 2008). This competitive advantage of C_4 weeds diminishes or even reverses under conditions of high soil nitrogen or atmospheric CO_2 concentrations (e.g. Carter & Peterson 1983; Bazzaz & Carlson 1984). Of the 56 weed species most cited in relevant peer-reviewed literature (Rodenburg & Johnson 2009), 20 species (0·36 of total weed species) are C_4 types (Table 1). The C_4-type weed species are most reported

Table 1. *Names and biology of important weed species in the three most prevalent rice production ecosystems in Africa (upland, hydromorphic and lowland)*

Upland		Hydromorphic		Lowland	
Widely adapted species					
Ageratum conyzoides	A	*A. conyzoides*	A		
Cynodon dactylon	P;C_4	*C. dactylon*	P;C_4		
Commelina benghalensis	A	*Commelina benghalensis*	A		
Cyperus rotundus	P;C_4	*C. rotundus*	P;C_4		
Digitaria horizontalis	A;C_4	*D. horizontalis*	A;C_4		
Panicum laxum	A	*Panicum laxum*	A	*Panicum laxum*	A
		Fimbristylis littoralis	A;C_4	*F. littoralis*	A;C_4
		Echinochloa colona	A;C_4	*E. colona*	A;C_4
		Leersia hexandra	P	*L. hexandra*	P
		Eclipta prostrata	A	*E. prostrata*	A
		Cyperus esculentus	P;C_4	*C. esculentus*	P;C_4
Ecosystem-specific species					
Mariscus cylindristachyus	P	*Spilanthes uliginosa*	A	*Oryza barthii*	A
Trianthema portulacastrum	A;C_4	*Rhamphicarpa fistulosa*	A/fhp	*Cyperus iria*	A;C_4
Striga hermonthica	A/ohp			*Bolboschoenus maritimus*	P
Striga asiatica	A/ohp			*Ischaemum rugosum*	A
Amaranthus viridis	A;C_4			*Ludwigia abyssinica*	A
Euphorbia hirta	A;C_4			*Ammania prieureana*	A
Brachiaria lata	A			*Heteranthera callifolia*	A
Chromolaena odorata	P			*Ipomoea aquatica*	P
Calopogonium mucunoides	P			*Echinochloa pyramidalis*	P;C_4
Aspilia bussei	A			*Cyperus halpan*	P
Pennisetum purpureum	A;C_4			*Sacciolepis africana*	P
Boerhavia erecta	P;C_4			*Acroceras amplectans*	A
Eleusine indica	A;C_4			*Diplachne fusca*	P
Imperata cylindrica	P;C_4			*Panicum repens*	P;C_4
Tridax procumbens	A			*Eleocharis* spp.	A/P
Euphorbia heterophylla	A			*Cyperus difformis*	A
Paspalum scrobiculatum	P;C_4			*Oryza longistaminata*	P
Dactyloctenium aegyptium	A;C_4			*Echinochloa crus-pavonis*	A
Rottboellia cochinchinensis	A;C_4			*Fimbristylis ferruginea*	P;C_4
				Pycreus macrostachyos	A
				Schoenoplectus senegalensis	A
				Ludwigia adscendens	P
				Sphenoclea zeylanica	A
				Rhynchospora corymbosa	P

Adapted from: Rodenburg & Johnson (2009). Additional sources on C_4 species: Downton (1975), Raghavendra & Das (1978), Elmore & Paul (1983) and Sage *et al.* (1999).
A = annual, P = perennial, fhp = facultative hemi-parasitic, ohp = obligate hemi-parasitic, C_4 = C_4 photosynthetic pathway.

in upland rice ecosystems (0·52) and least in the lowlands (0·23). For a C_3 crop such as rice, elevated CO_2 levels may have positive effects on crop competitiveness with C_4 weeds (Patterson *et al.* 1999; Fuhrer 2003), and tolerance to *Striga* infection (Watling & Press 2000). The latter may be caused by enhanced rates of photosynthesis which have been shown to play an important role in sustaining host tolerance against *Striga* (Gurney *et al.* 2002; Rodenburg *et al.* 2008). 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 have a greater increase in tillering, whereas C_4 grass species have a greater increase in leaf area (Wand *et al.* 1999). Tillering and leaf canopy development are important traits known to affect interspecific competition (e.g. Johnson *et al.* 1998; Saito *et al.* 2010). Increased atmospheric CO_2 levels are likely to be accompanied by higher temperatures favouring C_4 weeds over C_3 crops (Fuhrer 2003). A similar shift in weed species composition can also be expected under increased or prolonged drought conditions (Bjorkman 1976). Although precise changes in future precipitation are unknown, rainfall is likely to become more erratic with a higher frequency in the occurrences of droughts and floods (Giannini *et al.* 2008). Consequently, weeds adapted to these conditions will gain a comparative advantage. In the dry-land areas, besides drought tolerant C_4

weeds, parasitic weeds well adapted to low rainfall environments (e.g. *S. hermonthica*) or temporary flooded conditions (e.g. *Rhamphicarpa fistulosa*) could benefit from greater variability in rainfall (Rodenburg *et al.* 2010). *Striga* spp. infestations are often associated with low soil fertility (Vogt *et al.* 1991; Kroschel 1998), and should climate extremes lead to greater soil degradation (IPCC 2007) this might favour parasitic weeds. Such a scenario increases the importance of developing improved soil conservation and fertility management. Selection of appropriate soil conservation and fertility measures requires knowledge of local conditions and an understanding of the overall system dynamics. For instance, zero-tillage as a component of conservation agriculture, inappropriate fertilizer applications or the lack of fertilization can all lead to increased weed infestations, which in turn increase herbicide use or reduce fertilizer use efficiencies (e.g. Liebman & Davis 2000; Giller *et al.* 2009; Keating *et al.* 2010).

Temperature changes will impact the geographic distribution of weeds (Patterson *et al.* 1999), with some species moving to higher latitudes (Patterson 1995) and altitudes (Parmesan 1996). For instance, Witchweeds (*Striga* spp.) might extend their geographic range in this way (Mohamed *et al.* 2006). Based on genetic understanding and ecological niche modelling, Mohamed *et al.* (2007) suggest that the *Striga* area might expand to moderate climate zones. However, *S. asiatica* has been found to be relatively insensitive to temperature (Patterson *et al.* 1982) and distribution may be more affected by changes in the range of the host crop rather than directly by temperature (Cochrane & Press 1997). Phoenix & Press (2005) argued that this could be true for parasitic weeds in general. Recent progress in the development of heat, cold or drought tolerant rice germplasm increases the adaptive capacity of the crop to future environmental stress (Wassmann *et al.* 2009). This might enable rice to be grown in previously unfavourable conditions, which may cause a concomitant shift in the range of parasitic weeds.

Indirect effects – crop management adaptations and weed management effectiveness

Water is an increasingly scarce resource in many parts of SSA (Seckler *et al.* 1999), and rice varieties and cropping methods need to be adapted accordingly (Ingram *et al.* 2008). For rain-fed rice, drought tolerance will be important not only to reduce losses due to moisture stress but also to maintain or improve the crop's competitiveness against weeds (Asch *et al.* 2005). Elsewhere, systems to conserve irrigation water, such as aerobic rice and alternate wetting and drying, may be adopted but will have consequences for weed abundance, and concomitant rice yield losses, due to the extended periods when the soil will not be flooded (Morita & Kabaki 2002; de Vries *et al.* 2010; Krupnik *et al.*, in press). Effective weed control technologies for such production systems will be required. Flooding is commonly the primary cultural means to suppress weeds in irrigated rice and even a few millimetres of water depth will prevent germination and emergence of the majority of the weeds, such as annual sedges (e.g. Akobundu 1987; Chauhan & Johnson 2009*a*). In Indonesia, Haden *et al.* (2007) observed an increased incidence of sedges due to reduced periods of flooding. Effective weed control by flooding requires the soil to remain flooded for prolonged periods throughout crop establishment. Drainage or shallow flooding may also encourage the emergence of grass weeds such as *Leptochloa chinensis* and *Echinochloa* spp. (Chauhan & Johnson 2008, 2009*b*). A shift to weed communities adapted to hydromorphic conditions may include species such as *Acroceras amplectans, Echinochloa* spp., *Leptochloa* spp., *Eleusine indica, Panicum repens, Cyperus esculentus, Eleocharis* spp., *Bolboschoenus maritimus, Ageratum conyzoides* and *Eclipta prostrata*. The need for hand weeding has been reported to increase by 35% as a result of temporary rather than permanent flooding (Latif *et al.* 2005). Where irrigation water is becoming scarcer, maintaining soil flooding to suppress weeds is likely to be increasingly difficult. In these circumstances, where farmers lack alternative means for effective weed control, yield losses are likely to rise (e.g. Barrett *et al.* 2004).

In rain-fed rice fields, a lack of rainfall in the early part of the wet season may result in inadequate land preparation or limited flooding of the soil in the early stages of the crop. In turn, this will limit the opportunity to suppress weeds through early flooding and early crop canopy closure. Such disruption is likely to be most acute in the rain-fed lowlands or inland valley systems, which is a major agro-ecosystem of Africa.

Effectiveness of weed management practices will change according to the environmental conditions. Unfavourable weather may increase the risk of herbicides either causing crop damage or not being effective (Patterson *et al.* 1999). Increased temperatures reduce herbicide persistence in the soil and likewise the 'windows' for herbicide effectiveness (Bailey 2004). If rainfall becomes more frequent and/or intense, 'rain-safe' intervals for herbicides application may become scarce and soil active herbicides may become less effective (e.g. Kanampiu *et al.* 2003). Herbicide use is expected to increase in the near future and with it resistant weed ecotypes are increasingly likely to emerge. Herbicide efficacy may also be affected by raised CO_2 levels, which have been shown to increase the tolerance of weeds to herbicides (Ziska *et al.* 1999; Ziska & Teasdale 2000). Changes in CO_2 concentrations may alter transpiration, number of leaf stomata or the thickness of the leaf and through that affect the absorption or uptake of the pesticide (Ziska 2008). In C_3 plants, Wong (1990) found increased concentrations of leaf starch under elevated CO_2 which in turn might reduce herbicide efficacy (Patterson *et al.* 1999).

Greater CO_2 concentrations may stimulate below-ground growth relative to that of above-ground growth (Ziska 2003). This will favour rhizome and tuber growth of perennial weeds, in particular those following the C_3 photosynthetic pathway (Oechel & Strain 1985), which may render their control more difficult (Patterson 1995; Patterson *et al.* 1999). Where tuber and rhizome growth is encouraged, increased tillage could lead to a multiplication of vegetative propagation material (Ziska 2008). This could mean increasing problems with perennial lowland weeds like *O. longistaminata, Leersia hexandra, B. maritimus, Sacciolepis africana* and *Cyperus halpan*. Other perennial weeds with difficult to control below-ground structures such as *I. cylindrica, Cynodon dactylon, C. esculentus* and *C. rotundus* that are found on upland and hydromorphic soils, are all of the C_4 type.

OUTLOOK ON WEEDS AND THEIR MANAGEMENT IN AFRICAN RICE SYSTEMS

Rice is an inherently weak competitor with most weeds (e.g. van Heemst 1985) and consequently, yield losses due to weed competition can be high. Smallholder rice farmers in Africa have a limited number of options for preventing weed infestations and concomitant crop losses (Rodenburg & Johnson 2009). Changing environmental conditions may result in reduced efficiencies of existing weed control practices. If so, this requires timely identification and characterization of these emerging problems and the development of acceptable solutions that need to be implemented early to be most effective (Howden *et al.* 2007).

While there are uncertainties about future climate changes, it is likely that changes will have differential effects on weed species and alter the competitive balance between weed species and between weeds and rice in all production systems. Species response will be differentiated by the impact these changes have on the photosynthesis and resource-acquisition rates. Resulting changes in competitiveness and abundance are likely to differ between parasitic and non-parasitic weeds and between C_3- and C_4-type weeds. Further, agro-ecosystem characteristics will determine which of the environmental factors will have the dominant effect on crop and weed growth.

Irrigated systems are likely to be impacted mainly by indirect effects of climate change (e.g. reduced availability of irrigation water and increased herbicide tolerance in weeds). In these systems, herbicides are the primary weed control intervention and some of these are likely to become less effective due to CO_2 increases and more frequently occurring weather extremes. Moreover, the introduction of water-saving production methods at certain locations will likely cause severe increases in weed competition. In irrigated rice systems, temperature and rainfall variability increases may have less impact on weeds than CO_2 increases. Higher CO_2 concentrations may make rice and C_3 weed species (particularly rhizotomous perennials such as *O. longistaminata, L. hexandra, B. maritimus, S. africana* and *C. halpan*) more competitive against C_4 weeds, whereas mechanical control may become less effective due to the stimulating effect on their below-ground growth. To address the anticipated changes, integrated weed management strategies need to be developed that target the prevention of weed invasion, recruitment and reproduction. Such strategies may comprise combinations of optimal fertilizer timing and doses (Liebman & Davis 2000), off-season dry and deep tillage and land preparation (e.g. Sharma 1997), the use of irrigation water and rice seeds free of weed seeds (e.g. Dastgheib 1989; Rao & Moody 1990) and stale seed bed techniques (e.g. Rao *et al.* 2007), increased plant densities or improved arrangements (Phuong *et al.* 2005), transplanting of young seedlings (Becker & Johnson 1999*a*) and the use of adapted weed competitive rice cultivars (Haefele *et al.* 2004; Rodenburg *et al.* 2009). Effective approaches that harness available synergies could lessen dependency on irrigation water, chemical and mechanical control practices.

Direct effects of climate change are likely to have substantial effects on rain-fed rice areas as these systems harbour most of the C_4 and all of the parasitic weed species. These systems are most vulnerable to rainfall irregularities and soil degradation; in such areas infestations with parasitic weeds *S. asiatica, S. hermonthica, S. aspera* and *R. fistulosa* could increase (Rodenburg *et al.* 2010). Furthermore, because of the likely tolerance to drought and heat, C_4 species are likely to become more competitive in rain-fed rice. These may include the perennial grasses *I. cylindrica, Paspalum scrobiculatum* and *C. dactylon*, the annual grasses *Rottboellia cochinchinensis, D. horizontalis, E. indica, Dactyloctenium aegyptium, Pennisetum purpureum, Echinochloa colona* and the sedges *F. littoralis, C. rotundus* and *C. esculentus*. These weeds could be controlled through integrated approaches that combine preventive and curative measures. Examples of potential practices for these environments are the combined use of organic and inorganic soil fertility enhancers (e.g. Riches *et al.* 2005) with optimal fertilizer timing and doses (Liebman & Davis 2000), off-season dry and deep tillage (e.g. Chikoye *et al.* 2000), the use of weed (including parasitic species) suppressive intercrops, crop rotations and short fallows (e.g. Becker & Johnson 1999*b*) and the use of well-adapted, weed competitive and parasitic weed resistant/tolerant rice cultivars (Rodenburg & Johnson 2009; Rodenburg *et al.* 2010). Such cultivars should also possess drought and heat tolerance in order to successfully outcompete or withstand adapted C_4 and parasitic weeds under such conditions.

CONCLUSIONS

The net effect of climate change on weeds in rice production systems in Africa will be the result of a complex set of interactions between local environmental, ecological, biological and human factors such as the production ecosystem, the composition of weed communities, the management practices, atmospheric CO_2, ambient temperature and soil fertility and water availability. Interaction effects between key environmental factors (temperature, soil, water and CO_2) on different dominant weed species and communities should be systematically investigated.

It is desirable that weed management strategies are sufficiently diverse to lessen dependency on single strategies of irrigation water, herbicides and mechanical control, and approaches should target likely problem species such as hemi-parasitic and perennial rhizotomous weeds. Integrated approaches to prevent species invasion, recruitment and reproduction, and based on current knowledge of weed biology and ecology, are potentially most effective and sustainable. Future strategies for climate change adaptation for rice-based production systems, including novel cropping systems or improved stress-tolerant cultivars, should simultaneously address possible implications for weed control.

Current understanding suggests that perennial C_3 species such as *O. longistaminata, L. hexandra, B. maritimus, S. africana* and *C. halpan* will increase in irrigated rice production systems. Where water-saving production methods are adopted, the hydromorphic conditions will favour species such as *A. amplectans, E. colona, Echinochloa crus-pavonis, L. chinensis, Leptochloa caerulescens, E. indica, P. repens, C. esculentus, Eleocharis complanata, B. maritimus, A. conyzoides* and *E. prostrata*.

In rain-fed uplands parasitic weeds, such as *S. hermonthica* and *S. asiatica*, and C_4 grasses *I. cylindrica, P. scrobiculatum* and *C. dactylon, R. cochinchinensis, D. horizontalis, E. indica, D. aegyptium, P. purpureum* and *E. colona* and the C_4 sedges *F. littoralis, C. rotundus* and *C. esculentus* will become more dominant.

Timely efforts to fill the most important knowledge gaps on environment, management and weed interactions through strategic and applied research, and to generate and disseminate effective and locally applicable weed management strategies are required in order to raise or even sustain future rice production for the growing populations of Africa under changing climates. Design and implementation of such strategies requires interaction and collaboration between key stakeholders including scientists, extension services and farmers.

While atmospheric CO_2 levels and temperatures will increase, the spatial distribution of future rainfall remains much more uncertain. With the uncertainty surrounding water availability, combined with limited understanding of the interactions between changing environmental factors, the projections of future distribution and importance of particular plant species are conjecture and must be regularly reviewed. What is more certain is that in a future characterized by global changes (including climate change) resources such as water, land and labour will become increasingly scarce. Therefore, farmers will require management strategies including a wide range of technology options and decision support tools to tackle weeds and maintain livelihoods.

We thank (in alphabetical order), the UK Biotechnology and Biological Sciences Research Council (BBSRC), Common Fund for Commodities, the UK Department for International Development (DFID), the Dutch Directorate-General for International Cooperation (DGIS), the EU and the Netherlands Organisation for Scientific Research WOTRO Science for Global Development (NWO-WOTRO) for their past and continued financial support to our work. Views presented here are not necessarily shared by our donors or our host institutes.

REFERENCES

AKOBUNDU, I. O. (1987). *Weed Science in the Tropics – Principles and Practices*. Chichester, UK: John Wiley & Sons.

ASCH, F., DINGKUHN, M., SOW, A. & AUDEBERT, A. (2005). Drought-induced changes in rooting patterns and assimilate partitioning between root and shoot in upland rice. *Field Crops Research* **93**, 223–236.

BAILEY, S. W. (2004). Climate change and decreasing herbicide persistence. *Pest Management Science* **60**, 158–162.

BALASUBRAMANIAN, V., SIE, M., HIJMANS, R. J. & OTSUKA, K. (2007). Increasing rice production in sub-Saharan Africa: challenges and opportunities. *Advances in Agronomy* **94**, 55–133.

BARRETT, C. B., MOSER, C. M., MCHUGH, O. V. & BARISON, J. (2004). Better technology, better plots, or better farmers? Identifying changes in productivity and risk among Malagasy rice farmers. *American Journal of Agricultural Economics* **86**, 869–888.

BAZZAZ, F. A. & CARLSON, R. W. (1984). The response of plants to elevated CO_2 .1. Competition among an assemblage of annuals at two levels of soil moisture. *Oecologia* **62**, 196–198.

BECKER, M. & JOHNSON, D. E. (1999*a*). Rice yield and productivity gaps in irrigated systems of the forest zone of Côte d'Ivoire. *Field Crops Research* **60**, 201–208.

BECKER, M. & JOHNSON, D. E. (1999*b*). The role of legume fallows in intensified upland rice-based systems of West Africa. *Nutrient Cycling in Agroecosystems* **53**, 71–81.

BIASUTTI, M., HELD, I. M., SOBEL, A. H. & GIANNINI, A. (2008). SST forcings and Sahel rainfall variability in simulations of the twentieth and twenty-first centuries. *Journal of Climate* **21**, 3471–3486.

BJORKMAN, O. (1976). Adaptive and genetic aspects of C_4 photosynthesis. In *Metabolism and Plant Productivity* (Eds R.H. Burris & C.C. Black), pp. 287–309. Baltimore, MD: University Park Press.

CARTER, D. R. & PETERSON, K. M. (1983). Effects of a CO_2-enriched atmosphere on the growth and competitive interaction of a C_3 and a C_4 grass. *Oecologia* **58**, 188–193.

CHAUHAN, B. S. & JOHNSON, D. E. (2008). Germination ecology of Chinese sprangletop (*Leptochloa chinensis*) in the Philippines. *Weed Science* **56**, 820–825.

CHAUHAN, B. S. & JOHNSON, D. E. (2009*a*). Ecological studies on *Cyperus difformis, Cyperus iria* and *Fimbristylis miliacea*: three troublesome annual sedge weeds of rice. *Annals of Applied Biology* **155**, 103–112.

CHAUHAN, B. S. & JOHNSON, D. E. (2009*b*). Seed germination ecology of junglerice (*Echinochloa colona*): a major weed of rice. *Weed Science* **57**, 235–240.

CHIKOYE, D., MANYONG, V. M. & EKELEME, F. (2000). Characteristics of speargrass (*Imperata cylindrica*) dominated fields in West Africa: crops, soil properties, farmer perceptions and management strategies. *Crop Protection* **19**, 481–487.

CHRISTENSEN, J. H., HEWITSON, B., BUSUIOC, A., CHEN, A., GAO, X., HELD, I., JONES, R., KOLLI, R. K., KWON, W. T., LAPRISE, R., MAGAA RUEDA, V., MEARNS, L., MENENDEZ, C. G., RAISANEN, J., RINKE, A., SARR, A. & WHETTON, P. (2007). Regional climate projections. In *Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. M. B. Tignor & H. L. Miller), pp. 847–940. Cambridge: Cambridge University Press.

COCHRANE, V. & PRESS, M. C. (1997). Geographical distribution and aspects of the ecology of the hemiparasitic angiosperm *Striga asiatica* (L.) Kuntze: a herbarium study. *Journal of Tropical Ecology* **13**, 371–380.

COOK, K. H. & VIZY, E. K. (2006). Coupled model simulations of the West African monsoon system: twentieth- and twenty-first-century simulations. *Journal of Climate* **19**, 3681–3703.

DASTGHEIB, F. (1989). Relative importance of crop seed, manure and irrigation water as sources of weed infestation. *Weed Research* **29**, 113–116.

DE VRIES, M. E., RODENBURG, J., BADO, B. V., SOW, A., LEFFELAAR, P. A. & GILLER, K. E. (2010). Rice production with less irrigation water is possible in a Sahelian environment. *Field Crops Research* **116**, 154–164.

DOWNTON, W. J. S. (1975). Occurrence of C_4 photosynthesis among plants. *Photosynthetica* **9**, 96–105.

ELMORE, C. D. & PAUL, R. N. (1983). Composite list of C4 weeds. *Weed Science* **31**, 686–692.

FAO (2009). FAO Statistical Databases. Available at: http://faostat.fao.org/ (verified 15 Dec 2010).

FUHRER, J. (2003). Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. *Agriculture, Ecosystems and Environment* **97**, 1–20.

GIANNINI, A., BIASUTTI, M., HELD, I. M. & SOBEL, A. H. (2008). A global perspective on African climate. *Climatic Change* **90**, 359–383.

GILLER, K. E., WITTER, E., CORBEELS, M. & TITTONELL, P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Research* **114**, 23–34.

GURNEY, A. L., TAYLOR, A., MBWAGA, A., SCHOLES, J. D. & PRESS, M. C. (2002). Do maize cultivars demonstrate tolerance to the parasitic weed *Striga asiatica*? *Weed Research* **42**, 299–306.

HADEN, V. R., DUXBURY, J. M., DITOMMASO, A. & LOSEY, J. E. (2007). Weed community dynamics in the system of rice intensification (SRI) and the efficacy of mechanical cultivation and competitive rice cultivars for weed control in Indonesia. *Journal of Sustainable Agriculture* **30**, 5–26.

HAEFELE, S. M., JOHNSON, D. E., M' BODJ, D., WOPEREIS, M. C. S. & MIÉZAN, K. M. (2004). Field screening of diverse rice genotypes for weed competitiveness in irrigated lowland ecosystems. *Field Crops Research* **88**, 39–56.

HOERLING, M., HURRELL, J., EISCHEID, J. & PHILLIPS, A. (2006). Detection and attribution of twentieth-century northern and southern African rainfall change. *Journal of Climate* **19**, 3989–4008.

HOWDEN, S. M., SOUSSANA, J-F., TUBIELLO, F. N., CHHETRI, N., DUNLOP, M. & MEINKE, H. (2007). Adapting agriculture to climate change. *Proceedings of the National Academy of Sciences USA* **104**, 19691–19696.

INGRAM, J. S. I., GREGORY, P. J. & IZAC, A. M. (2008). The role of agronomic research in climate change and food security policy. *Agriculture, Ecosystems and Environment* **126**, 4–12.

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Eds R. K. Pachauri & A. Reisinger). Geneva, Switzerland: IPCC.

JOHNSON, D. E., DINGKUHN, M., JONES, M. P. & MAHAMANE, M. C. (1998). The influence of rice plant type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*. *Weed Research* **38**, 207–216.

KANAMPIU, F. K., KABAMBE, V., MASSAWE, C., JASI, L., FRIESEN, D., RANSOM, J. K. & GRESSEL, J. (2003). Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls *Striga* spp. and increases yields in several African countries. *Crop Protection* **22**, 697–706.

KEATING, B. A., CARBERRY, P. S., BINDRABAN, P. S., ASSENG, S., MEINKE, H. & DIXON, J. (2010). Eco-efficient agriculture: concepts, challenges, and opportunities. *Crop Science* **50**, S109–S119.

KROSCHEL, J. (1998). *Striga* – How will it affect African agriculture in the future? – An ecological perspective. In *Agroecology, Plant Protection and the Human Environment: Views and Concepts* (Eds K. Martin, J. Muther & A. Auffarth), pp. 137–158. Weikersheim, Germany: Margraf Verlag.

KRUPNIK, T. J., RODENBURG, J., SHENNAN, C., MBAYE, D. & HADEN, V. R. (2010). Trade-offs between rice yield, weed competition and water productivity under recommended and water-saving rice production practices in the Sahel. In *Abstracts. Africa Rice Congress 2010: Innovation and Partnerships to Realize Africa's Rice Potential, 22–26 March 2010, Bamako, Mali* (Eds P. Kiepe, M. Diatta & D. Millar), p. 66. Cotonou, Benin, Africa: Africa Rice Center.

LATIF, M. A., ISLAM, M. R., ALI, M. Y. & SAEQUE, M. A. (2005). Validation of the system of rice intensification (SRI) in Bangladesh. *Field Crops Research* **93**, 281–292.

LIEBMAN, M. & DAVIS, A. S. (2000). Integration of soil, crop and weed management in low-external-input farming systems. *Weed Research* **40**, 27–47.

MEINKE, H., BASTIAANS, L., BOUMAN, B., DINGKUHN, M., GAYDON, D., HASEGAWA, T., HEINEMANN, A. B., KIEPE, P., LAFARGE, T., LUQUET, D., MASOOD, A., VAN OORT, P., RODENBURG, J., YAN, J. & YIN, X. (2009*a*). An international collaborative research network helps to design climate robust rice systems. In *Crop Production under Heat Stress: Monitoring, Impact Assessment and Adaptation. Proceedings of the MARCO Symposium 2009 held in Tsukuba, Japan, 5–9 October 2009* (Eds T. Hasegawa & H. Sakai), pp. 1–12. Tsukuba (Japan): National Institute for Agro-Environmental Sciences (NIAES). Available online at: http://www.niaes.affrc.go.jp/marco/marco2009/ws2proc.pdf (verified 17 Feb 2011).

MEINKE, H., HOWDEN, S. M., STRUIK, P. C., NELSON, R., RODRIGUEZ, D. & CHAPMAN, C. S. (2009*b*). Adaptation science for agricultural and natural resource management – Urgency and theoretical basis. *Current Opinion in Environmental Sustainability* **1**, 69–76.

MOHAMED, K. I., BOLIN, J. F., MUSSELMAN, L. J. & TOWNSEND PETERSON, A. (2007). Genetic diversity of *Striga* and implications for control and modeling future distributions. In *Integrating New Technologies for Striga Control – Towards Ending the Witch-hunt* (Eds G. Ejeta & J. Gressel), pp. 71–84. Singapore: World Scientific Publishing.

MOHAMED, K. I., PAPES, M., WILLIAMS, R., BENZ, B. W. & PETERSON, T. A. (2006). Global invasive potential of 10 parasitic witchweeds and related Orobanchaceae. *Ambio* **35**, 281–288.

MORITA, H. & KABAKI, N. (2002). Effects of soil moisture conditions on the emergence of weeds and rice plants from rain-fed paddy soils in north-east Thailand. *Weed Biology and Management* **2**, 209–212.

OECHEL, W. C. & STRAIN, B. R. (1985). Native species responses to increased atmospheric carbon dioxide concentration. In *Direct Effects of Increasing Carbon Dioxide on Vegetation* (Eds B. R. Strain & J. D. Cure), pp. 117–154. Washington, DC: U.S. Department of Energy.

PARMESAN, C. (1996). Climate and species' range. *Nature* **382**, 765–766.

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

PATTERSON, D. T., MUSSER, R. L., FLINT, E. P. & EPLEE, R. E. (1982). Temperature responses and potential for spread of witchweed (*Striga lutea*) in the United States. *Weed Science* **30**, 87–93.

PATTERSON, D. T., WESTBROOK, J. K., JOYCE, R. J. V., LINGREN, P. D. & ROGASIK, J. (1999). Weeds, insects, and diseases. *Climatic Change* **43**, 711–727.

PHOENIX, G. K. & PRESS, M. C. (2005). Effects of climate change on parasitic plants: The root hemiparasitic Orobanchaceae. *Folia Geobotanica* **40**, 205–216.

PHUONG, L. T., DENICH, M., VLEK, P. L. G. & BALASUBRAMANIAN, V. (2005). Suppressing weeds in direct-seeded lowland rice: effects of methods and rates of seeding. *Journal of Agronomy and Crop Science* **191**, 185–194.

RAGHAVENDRA, A. S. & DAS, V. S. R. (1978). Occurrence of C4-photosynthesis – supplementary list of C4 plants reported during late 1974-mid 1977. *Photosynthetica* **12**, 200–208.

RAO, A. N., JOHNSON, D. E., SIVAPRASAD, B., LADHA, J. K. & MORTIMER, A. M. (2007). Weed management in direct-seeded rice. *Advances in Agronomy* **93**, 153–255.

RAO, A. N. & MOODY, K. (1990). Weed seed contamination in rice seed. *Seed Science and Technology* **18**, 139–146.

RICHES, C. R., MBWAGA, A. M., MBAPILA, J. & AHMED, G. J. U. (2005). Improved weed management delivers increased productivity and farm incomes from rice in Bangladesh and Tanzania. *Aspects of Applied Biology* **75**, 127–138.

RODENBURG, J., BASTIAANS, L., SCHAPENDONK, A. H. C. M., VAN DER PUTTEN, P. E. L., VAN AST, A., DINGEMANSE, N. J. & HAUSSMANN, B. I. G. (2008). CO_2-assimilation and chlorophyll fluorescence as indirect selection criteria for host tolerance against *Striga*. *Euphytica* **160**, 75–87.

RODENBURG, J. & JOHNSON, D. E. (2009). Weed management in rice-based cropping systems in Africa. *Advances in Agronomy* **103**, 149–218.

RODENBURG, J., RICHES, C. R. & KAYEKE, J. M. (2010). Addressing current and future problems of parasitic weeds in rice. *Crop Protection* **29**, 210–221.

RODENBURG, J., SAITO, K., KAKAI, R. G., TOURE, A., MARIKO, M. & KIEPE, P. (2009). Weed competitiveness of the lowland rice varieties of NERICA in the southern Guinea Savanna. *Field Crops Research* **114**, 411–418.

ROZENZWEIG, C., KAROLY, D., VICARELLI, M., NEOFOTIS, P., WU, Q., CASASSA, G., MENZEL, A., ROOT, T. L., ESTRELLA, N., SEGUIN, B., TRYJANOWSKI, P., LIU, C., RAWLINS, S. & IMESON, A. (2008). Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453**, 353–357.

SAGE, R. F., LI, M. & MONSON, R. K. (1999). The taxonomic distribution of C4 photosynthesis. In *C4 Plant Biology* (Eds R. F. Sage & R. K. Monson), pp. 551–584. San Diego, CA: Academic Press.

SAITO, K., AZOMA, K. & RODENBURG, J. (2010). Plant characteristics associated with weed competitiveness of rice under upland and lowland conditions in West Africa. *Field Crops Research* **116**, 308–317.

SECKLER, D., BARKER, R. & AMARASINGHE, U. (1999). Water scarcity in the twenty-first century. *International Journal of Water Resources Development* **15**, 29–42.

SHARMA, A. R. (1997). Effect of integrated weed management and nitrogen fertilization on the performance of rice under flood-prone lowland conditions. *Journal of Agricultural Science, Cambridge* **129**, 409–418.

VAN HEEMST, H. D. J. (1985). The influence of weed competition on crop yield. *Agricultural Systems* **18**, 81–93.

VOGT, W., SAUERBORN, J. & HONISCH, M. (1991). *Striga hermonthica* distribution and infestation in Ghana and Togo on grain crops. In *Proceedings of the 5th*

International Symposium on Parasitic Weeds (Eds J. K. Ransom, L. J. Musselman, A. D. Worsham & C. Parker), pp. 372–377. Nairobi, Kenya: CIMMYT.

von Grebmer, K., Fritschel, H., Nestorova, B., Olofinbiyi, T., Pandya-Lorch, R. & Yohannes, Y. (2008). *Global Hunger Index. The Challenge of Hunger 2008*. Bonn, Washington, DC & Dublin: Welt Hunger Hilfe, IFPRI & Concern Worldwide.

Wand, S. J. E., Midgley, G. F., Jones, M. H. & Curtis, P. S. (1999). Responses of wild C_4 and C_3 grass (Poaceae) species to elevated atmospheric CO_2 concentration: a meta-analytic test of current theories and perceptions. *Global Change Biology* **5**, 723–741.

Wassmann, R., Jagadish, S. V. K., Heuer, S., Ismail, A., Redona, E., Serraj, R., Singh, R. K., Howell, G., Pathak, H. & Sumfleth, K. (2009). Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. *Advances in Agronomy* **101**, 59–122.

Watling, J. R. & Press, M. C. (2000). Infection with the parasitic angiosperm *Striga hermonthica* influences the response of the C_3 cereal *Oryza sativa* to elevated CO_2. *Global Change Biology* **6**, 919–930.

Wong, S. C. (1990). Elevated atmospheric partial pressure of CO_2 and plant growth. 2. Non-structural carbohydrate content in cotton plants and its effect on growth parameters. *Photosynthesis Research* **23**, 171–180.

Yin, X. & Struik, P. C. (2008). Applying modelling experiences from the past to shape crop systems biology: the need to converge crop physiology and functional genomics. *New Phytologist* **179**, 629–642.

Ziska, L. H. (2003). Evaluation of the growth response of six invasive species to past, present and future carbon dioxide concentrations. *Journal of Experimental Botany* **54**, 395–404.

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

Ziska, L. H. & Teasdale, J. R. (2000). Sustained growth and increased tolerance to glyphosate observed in a C-3 perennial weed, quackgrass (*Elytrigia repens*), grown at elevated carbon dioxide. *Australian Journal of Plant Physiology* **27**, 159–166.

Ziska, L. H., Teasdale, J. R. & Bunce, J. A. (1999). Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science* **47**, 608–615.