Adapting weed management in rice to changing climates

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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 rice in Africa.

Elevated CO_2 levels may have positive effects on rice competitiveness with C_4 weeds, but these are generally outnumbered by C_3 species in weed populations of rice in Africa. Moreover, higher temperatures and drought will favor C_4 over C_3 plants. Increased CO_2 levels may also improve tolerance of rice against parasitic weeds, while invasiveness of such species may be stimulated by soil degradation and more frequent droughts or floods. Elevated CO_2 may increase belowground relative to aboveground growth, in particular of perennial (C_3) species, rendering mechanical control less effective or even counterproductive. Increased CO_2 levels, rainfall and temperature may also reduce the effectiveness of chemical control. The implementation of climate change adaptation technologies, such as drought-tolerant germplasm and water-saving irrigation regimes, will also have consequences for rice–weed competition.

Rainfed production systems are hypothesized to be most vulnerable to direct effects of climate change (e.g. changes in rainfall patterns) and are likely to face increased competition from C_4 and parasitic weeds. Biotic-stress-tolerant rice 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 rhizotomous (C_3) weeds. Water-saving production methods that replace the weed-suppressive flood water layer by intermittent or continuous periods of aerobic conditions, necessitate additional weed management strategies to address the inherent increases in weed competition.

Introduction

Rice is an increasingly important commodity in sub-Saharan Africa (Balasubramanian *et al.*, 2007). Five main ecosystems for rice production can be distinguished based on water supply and topography: (1) rainfed upland rice on plateaus and hydromorphic slopes (39%), (2) rainfed lowland rice in valley bottoms and floodplains (33%), (3) irrigated rice in deltas, floodplains and highlands (19%), (4) deep-water floating rice along major rivers, and (5) mangrove-swamp rice in lagoons and deltas (9%) (Balasubramanian *et al.*, 2007, updated with data from FAO, 2009).

Uncontrolled weed growth is reported to cause yield losses in the range of 28–74% in transplanted lowland rice, 28–89% in direct-seeded lowland rice and 48–100% in upland ecosystems, and improved weed control has been estimated to raise rice yields by 15–23%, depending on production ecosystem (for references, see Rodenburg and Johnson, 2009). In sub-Saharan Africa (SSA), weeds may account for annual rice yield losses of at least 2.2 million tonnes equating to US$ 1.45 billion (Rodenburg and Johnson, 2009). Important weeds in upland rice include the perennials *Cyperus rotundus*, *Imperata cylindrica* and *Chromolaena odorata*, the annuals *Euphorbia heterophylla* and *Digitaria horizontalis*, and the parasitic weeds *Striga asiatica* and *S. hermonthica* (Table 1). In lowland rice, the perennial *Cyperus* spp. and *Oryza longistaminata* and annual *Sphenoclea zeylanica*, *Echinochloa* spp., *Cyperus difformis*, *Cyp. iria*, *Fimbristylis littoralis*, *Ischaemum rugosum* and *O. barthii* cause serious losses. Common weed management practices in rice-based cropping systems include soil tillage, clearance by fire, hand- or hoe-weeding, herbicides, flooding, fallow and crop rotations, and these are often used in combination (Rodenburg and Johnson, 2009).

Future rice production and weed management issues will be affected by changing environmental conditions. 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 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, 2007). For Africa, historical climate trends suggest that the variability in rainfall will increase and that some monsoon regions may become drier (Giannini *et al.*, 2008) leading to a 5–8% increase in drought-prone area in the Sahel and southern Africa by 2080 (IPCC, 2007).

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Table 1. Names and biology of important weed species in the three most prevalent rice production ecosystems in Africa (upland, hydromorphic and lowland). Only species that were mentioned more than once in relevant peer-reviewed articles are listed here (in decreasing order of citation numbers)

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

Adapted from: Rodenburg and Johnson (2009); Additional sources on C_4 species: Downton (1975), Raghavendra and Das (1978), Elmore and 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.

Equatorial zones of Africa may receive more intense rainfall (Christensen *et al.*, 2007). However, the spatial distribution of future rainfall remains uncertain (Giannini *et al.*, 2008), particularly for the Sahel for which there are a number of conflicting projections (e.g. Biasutti *et al.*, 2008; Cook and Vizy, 2006; Hoerling *et al.*, 2006).

This paper discusses (1) the likely effects of projected climate changes on rice production, and on the competitiveness and distribution of major weeds of African rice ecosystems; and (2) the consequences of changing climates and changing weed population compositions for weed management in African rice production systems.

Climate change effects

Direct effects — weed competition, abundance and distribution

The CO_2 concentration in the atmosphere will increase further. 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 (e.g. Bazzaz and Carlson, 1984; Carter and Peterson, 1983). Of the 56 weed species most cited in relevant peer-reviewed literature (see Rodenburg and Johnson, 2009), 20 species (36%) are C_4 types (Table 1). 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 interspecific competition. Increased CO_2 levels are likely to be accompanied with 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. *Striga* spp. problems are also associated with low soil fertility (Kroschel, 1998); if climate extremes indeed lead to greater soil degradation in Africa (IPCC, 2007) this might favor parasitic weeds. Such a scenario increases the urgency for improved soil conservation and fertility management.

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, *Striga* spp. might extend their geographical range as a result 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 — crop management adaptations and weed management effectiveness

Water is becoming a scarcer 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 upland rice, drought tolerance will be important not 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 (de Vries *et al.*, 2010; Krupnik *et al.*, 2011), requiring more crop management skills and better access to production resources. Haden *et al.* (2007) observed weed populations to shift, 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 flood-water layer to suppress weeds is likely to become increasingly difficult in many areas as water becomes scarcer; as a consequence, farmers lacking the means for effective weeding are likely to suffer severe yield losses (Barrett *et al.*, 2004).

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 in the near future 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 (e.g. 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 *Cyp. rotundus* on upland and hydromorphic soils) are all C_4 types.

Outlook on weeds and their management in rice in Africa

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 rhizotomous 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 are expected to be more impacted by the direct effects of climate change as these systems harbor most of the C_4 and all of 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 *Cyp. 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 hemi-parasitic) 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 × temperature × 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 rhizotomous 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.

Note

The material from this study has also been published in the *Journal of Agricultural Science* (Rodenburg *et al.*, 2011).

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