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Potential of Herbicide-Resistant Rice Technologies for Sub-Saharan Africa

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Weed-inflicted yield losses in rice equate to half the current rice imports in sub-Saharan Africa (SSA) and African rice farmers have a limited range of effective and affordable weed management technologies. Herbicide-resistance (HR) technologies may have the labor-saving benefits of conventional chemical control without the concomitant phytotoxicity risks. To date, HR rice received only marginal attention in the context of SSA. Here, we review the literature on HR technologies and discuss their potential value for rice ecosystems in Africa. We conclude that HR technologies would provide technically sound solutions for the control of important yield-reducing weeds, such as wild rice in irrigated systems and rainfed lowlands and parasitic weeds in uplands. However, with respect to implementation, these technologies would require effective seed and microcredit systems as much as interested agro-industries. Public-private partnerships and government intervention may provide shortcuts where such conditions are not yet met.

Key words: weed control, herbicide-tolerant rice, broad-spectrum herbicides, glyphosate, glufosinate, imidazolinone, developing countries, poverty.

Introduction

Presently, rice is the fifth cereal in Africa in terms of area harvested and the fourth in terms of production (Food and Agriculture Organization of the United Nations [FAO], 2009b). Rice production in Africa is increasing faster than any other cereal. Over the past 30 years, harvested area has risen by 105% and production by 170%. Despite this growth, the region is not self-sufficient in rice, and increasing import costs are a concern. In West Africa, five main rice ecosystems are characterized: (1) rainfed upland rice on plateaus (pluvial) and hydromorphic (or phreatic) slopes, (2) rainfed (or fluxial) lowland rice in valley bottoms and floodplains, (3) irrigated rice in deltas and floodplains, (4) deep-water floating rice along major rivers, and 5) mangrove-swamp rice in lagoons and deltas (Windmeijer, Duivenbooden, & Andriesse, 1994). Irrigated rice of tropical highlands found in Central and East Africa (including Madagascar) complement these broad rice-ecosystem categories for sub-Saharan Africa (SSA). These rice ecosystems roughly break down as 39% (upland), 33% (rainfed lowland), 19% (irrigated), and 9% (deep water and mangroves) of the total area under rice in SSA (Table 1).

Weed competition is one of the main production constraints in any of the rice ecosystems in SSA (Rodenburg & Johnson, 2009). Weed problems are often due to inadequate land preparation, water, soil fertility, crop or fallow management, and the use of rice seed contaminated with weed seeds or rice seed of poor quality. High weed-inflicted yield losses in rice in Africa are attributable to the low inherent competitive ability of the crop (van Heemst, 1985), the limited number of effective and affordable weed-control options available to farmers (e.g., Rodenburg & Johnson, 2009), and delayed or insufficient weed control interventions due to labor shortages or financial constraints (e.g., Becker & Johnson, 2001b). Rice farmers in SSA mainly rely on hand weeding and herbicides (e.g., Rodenburg & Johnson, 2009). Hand weeding is time consuming and depends on the availability of labor (e.g., Ruthenberg, 1980), while the use of herbicides requires good application methods and timing in order to be effective and safe (Gitsopoulos & Froud-Williams, 2004; Johnson et al., 2004; Zimdahl, 2007). Herbicide-resistance (HR) technologies, combining post-emergence broad spectrum herbicides with HR rice varieties, may have the labor-saving benefits of conventional chemical control without the concomitant (phyto-)toxicity risks. To date, HR rice has not yet been considered as a potential technology for cropping systems in SSA. HR technologies did not appear in the short list of potentially most relevant and realistic biotechnological interventions for Africa that resulted from an expert poll held by the United Nations Industrial Development Organization (UNIDO) in 2003 (Thomson, 2008). In this article, we review the available evidence and analyze the reasons for the apparent hesitation concerning introduction of

Table 1. Estimated rice yields and weed-inflicted losses among ecosystems in sub-Saharan Africa, 2007.

Country	Rice area (10^3 ha)	Percentage of area by ecosystem				Production (10^3 t)	Yield (t/ha)
		RUR	RLR	IRR	DWM		
Angola	14	0	100	0	0	9	0.69
Benin	27	91	7	2	0	79	2.92
Burkina Faso	50	4	50	46	0	123	2.46
Burundi	21	4	74	21	0	70	3.31
Cameroon	40	0	5	95	0	49	1.23
Central African Republic	15	97	3	0	0	33	2.20
Chad	80	0	6	9	85	129	1.61
Comoros	14	-	-	-	-	17	1.21
Democratic Republic of Congo	418	89	11	0	0	315	0.75
Republic of Congo	2	0	100	0	0	1	0.68
Côte d'Ivoire	345	78	15	7	0	677	1.96
Ethiopia	7	0	15	85	0	13	1.81
Gabon	1	0	0	100	0	1	2.20
Gambia	19	16	63	7	14	40	2.11
Ghana	120	55	21	24	0	242	2.02
Guinea	789	44	23	10	23	1,402	1.78
Guinea-Bissau	65	27	27	1	45	89	1.36
Kenya	19	0	0	100	0	66	3.57
Liberia	120	92	6	2	0	155	1.29
Madagascar	1,300	29	18	52	1	3,596	2.77
Malawi	53	0	72	28	0	92	1.74
Mali	377	1	13	22	64	955	2.53
Mauritania	18	0	0	100	0	77	4.28
Mozambique	204	39	59	2	0	196	0.96
Niger	22	0	0	80	20	70	3.12
Nigeria	3,000	30	47	17	6	4,677	1.56
Rwanda	10	0	92	8	0	44	4.40
Senegal	80	0	40	50	10	215	2.70
Sierra Leone	630	68	28	0	4	650	1.03
Somalia	3	-	-	-	-	16	6.15
Sudan	8	-	-	-	-	30	3.95
Tanzania	665	23	73	4	0	1,240	1.86
Togo	45	80	19	1	0	74	1.65
Uganda	119	45	53	2	0	162	1.36
Zambia	14	0	100	0	0	18	1.31
Zimbabwe	0					1	2.40
Total sub-Saharan Africa	8,711	39	33	19	9	15,623	1.79
Estimated yield (t/ha)		1.04*	1.02*	4.19*	2.08*		
Standard error (t/ha)		0.20	0.16	0.20	0.41		
t-value		5.21	6.56	20.46	5.13		
Weed-inflicted yield loss[a]		16%	23%	15%	-	Total	
Annual production loss (10^3 t)		540	715	1,023	-	2,278	
Annual production loss (10^6 \$)[b]		259	342	490	-	1,091	

Sources: FAO (2009a; 2009b), Balasubramanian et al. (2007).

*Notes. * significant at the 0.001 confidence level; R^2 =0.99; RUR=rainfed upland rice; RLR=rainfed lowland rice; IRR=irrigated rice; DWM=deepwater and mangrove rice*

[a] *based on Haefele et al. (2000), Becker and Johnson (2001a; 2001b), and Becker et al. (2003)*

[b] *based on a world rice price (Thai 25%) of $479/t during January-March 2009 (FAO, 2009a).*

this technology in sub-Saharan Africa. We discuss the benefits, risks, and feasibility of HR technologies with relevance to rice production systems in SSA.

Weed Control in African Rice Ecosystems

Commonly only a few species dominate the weed population in each rice ecosystem and can be considered problem weeds (Johnson & Kent, 2002). Examples of problem weeds are the wild rice species (e.g., *Oryza longistaminata* A. Chev. & Roehr. and *O. barthii* A. Chev. syn. *O. breviligulata* A. Chev. et Roehr.) in the irrigated and rainfed lowland rice-production systems and parasitic weeds in rainfed uplands (e.g., *Striga hermonthica* [Del.] Benth. and *S. asiatica* [L.] Kuntze) and lowlands (*Rhamphicarpa fistulosa* [Hochst.] Benth.). A more complete overview of important weeds in rice production systems of SSA is provided by Rodenburg and Johnson (2009).

Herbicides are important control methods in the irrigated rice and upland rice-cotton rotation systems (Johnson, 1997). Common herbicides used in rice in Africa are listed in Table 2. The use of herbicides is economically attractive, as it requires less overall weeding time and it enables the farmer to use time- and labor-saving planting methods such as direct (broadcast) seeding. Herbicides are likely to be particularly useful in areas where labor is in short supply. Farmers should also have sufficient financial resources to purchase herbicides, and the return of such investments should be high enough. Ecological research supports the use of a proportional damage function for modeling competitive pests, such as weeds (Archer & Shogren, 1996; Pannell, 1990; Swinton & King, 1994). Since yields are still comparatively low due to the slow progress of Africa's Green Revolution, the marginal benefits from crop protection against proportional damage are low, and farmers have reduced economic incentives for chemical forms of crop protection (Orr, 2003). Therefore, in SSA, (cheaper) labor often partly or entirely substitutes for expensive herbicides (Demont, Rodenburg, Diagne, & Diallo, 2009).

Effective and safe chemical weed control requires farmers to know exactly how and when to apply herbicides (e.g., Haefele, Johnson, Diallo, Wopereis, & Janin, 2000). They need to use the appropriate product, application equipment, and application rates (Zimdahl, 2007) and respect optimum growth stages of weeds (e.g., King & Oliver, 1992) and weather conditions (e.g., Hammerton, 1967). In Africa, where farmers generally have limited access to information and where literacy rates are low, herbicides are often inadequately applied. Herbicide applications are commonly too late, the rates incorrect, or the applications rendered ineffective by improper water management. This may result in inefficient weed control (Haefele et al., 2000), increased costs, and phytotoxicity damage to the crop (Gitsopoulos & Froud-Williams, 2004; Johnson et al., 2004). Again, this creates a potential market for efficiency-enhancing weed control technologies such as HR rice. However, in addition to limited access to information on weed biology, herbicide action, and proper application methods, African farmers often have limited market access. The markets are also often characterized by an insufficient range of products and intermittent supplies. In addition, African farmers often lack sufficient financial means for the purchase of the product and application and protection equipment (Balasubramanian, Sie, Hijmans, & Otsuka, 2007). The same constraints are expected to be binding in the case of HR rice, too.

Due to the constraints mentioned above, there is still substantial potential for enhancing weed-control strategies and reducing the yield gap in rice production in SSA. A rough estimate of the weed-inflicted damage despite control among rice ecosystems is presented in Table 1. Since disaggregated yield data from individual rice ecosystems in SSA are lacking, we need to disentangle them from national aggregates by running a linear regression combining secondary data on national production, area, and yields (FAO, 2009b) and area shares estimated in the literature (Balasubramanian et al., 2007). Consider countries i =1, …, 36 and ecosystems j=rainfed upland rice (RUR), rainfed lowland rice (RLR), irrigated rice (IRR), and deep-water and mangrove rice (DWM). The observed national rice production levels Q_i can be expressed as a linear function of the national areas under ecosystems j, i.e., the national area shares χ_{ij} of ecosystems j in country i multiplied by the national rice areas L_i, the unknown ecosystem-specific yield levels y_j, and an error term ε_i, i.e., $Q_i = \sum_{j=1}^{4} \chi_{ij} L_i y_j + \varepsilon_i$. In this equation, the unknown yield levels y_j can be interpreted as coefficients, and they can be estimated through ordinary least squares. Table 1 reports the results and indicates that the estimated average yields are all highly significant (P<0.001), and the coefficient of determination is very high (R^2=0.99). Yield levels in irrigated ecosystems (4.2 t/ha) are two- to four-times higher than those in other ecosystems (1.0-2.1 t/ha).

Table 2. Commonly employed herbicides in rice cultivation in Africa, ranked alphabetically.

Common name	Example of product	Rates (kg a.i./ha)	Timing	Target	Ecosystem
2,4-D	Dacamine Fernoxone Herbazol	0.5- 1.5	Late post	B/S	U/L
2,4-D + dichlorprop	Weedone	1-1.5 (l/ha)	Post	B/S	U/L
Bensulfuron	Londax	0.05-1.0	Post	B/S	L
Bentazon	Basagran	1.0-3.0	Post	B/S	U/L
Butachlor	Machete	1.0-2.5	Pre/early post	AG/(B)	U/L
Cinosulfuron	Set off 20WG	0.05-0.08	Post	S/B	U
Dymrone (K-223)	Dymrone	3.0-5.0	Pre	S/(G/B)	L
Glyphosate	Round-up	1.5-3.0	Pre/post	G	L
MCPA	Herbit	0.5-1.5	Post	B/S	U/L
Molinate	Ordram	1.5-4.0	Pre/early post	G/S/(B)	L
Oxadiazon	Ronstar 25EC Ronstar 12L	0.6-1.5	Pre/early post	G/B/S	U/L
Paraquat	Gramoxone	0.5-1.0	Pre/post	A	L
Pendimethalin	Stomp 500 Prowl	0.5-1.5	Pre	G/B/S	U/L
Piperophos	Rilof 500	0.5-2.0	Pre/early post	G/S	U/L
Piperophos + cinosulfuron	Pipset 35 WP	1.5	Post	G/S/B	U
Pretilhachlor + dimethametryne	Rifit extra 500 EC	1.5/0.5	Pre	G/B	U/L
Propanil	Stam F34 Propanil Surcopur Rogue	2.5-4.0	Early post	A	U/L
Propanil + bentazon	Basagran PL2	6-8 (l/ha)	Post	B/S	U/L
Triclopyr	Garil	5 (l/ha)	Post	G/S/(B)	U/L
Piperophos	Rilof S80 g/l	1.5			U
Oxadiazon	Ronstar PL	5 (l/ha)	Post	G/B/S	U/L
Quinclorac	Facet	0.25-0.5	Pre/post	G	L
Thiobencarb	Saturn	1.5-3.0	Pre/early post	G/B/S	U/L
Triclopyr	Garlon	0.36-0.48	Post	B/S	U

Notes. L=lowland; U=upland; B=broad-leaved weeds, S=sedges, G=grasses, A=annuals; weed types between brackets indicate that the product may control some species of that group or at some (early) stages; propanil is most often applied as a mixture with other products such as MCPA, molinate, oxadiazon, 2,4-D, fluorodifen, thiobencarb, bentazone, and butachlor.

Source: adapted from Rodenburg and Johnson (2009).

Based on these regressions and weed-inflicted yield-loss figures in West Africa from various literature sources, the extent of weed problems despite control in rice production systems in sub-Saharan Africa can be estimated. In irrigated rice in West Africa, from the forest zone to the Sahel, better weed control by farmers could raise yields by 15% (Becker, Johnson, Wopereis, & Sow, 2003; Haefele et al., 2000). In areas of rainfed lowland rice without bunds, yields could be increased by 23% through improved weed control, while in the most widespread upland rice systems, yields could be raised by 16% (Becker & Johnson, 2001a, 2001b). These estimates indicate that in sub-Saharan Africa weeds account for rice yield losses of at least two million tons at a value of USD $1 billion per year, in addition to the costs of weed control, equating approximately to half the current imports of rice to the region. This estimate is conservative. Because of lack of data, it does not include yield losses in deep-water and mangrove rice ecosystems, comprising 9% of the total area. Nevertheless, the figures in Table 1 identify a potential market in SSA for enhanced weed-control technologies, such as HR rice.

Current and Potential HR Rice Technologies

Worldwide there are three commercial HR technologies, i.e. Clearfield® (imidazolinone resistance), commercialized by BASF, Roundup Ready® (glyphosate resistance), commercialized by Monsanto, and Liberty Link® (glufosinate resistance), commercialized by Bayer CropScience (Duke, 2005).

Clearfield® was developed through seed mutagenesis and confers resistance to imidazolinone herbicides (Sha, Linscombe, & Groth, 2007; Tan, Evans, Dahmer, Singh, & Shaner, 2005). These herbicides inhibit an essential plant enzyme called acetohydroxyacid synthase (AHAS) or acetolactate synthase (ALS). ALS-inhibiting herbicides control a broad spectrum of grass and broadleaf weeds, including parasitic weeds and weed species closely related to cultivated rice (Tan et al., 2005). Imidazolinone herbicides for which resistant crop cultivars are available include imazamox, imazethapyr, imazapyr, and imazapic. Imazapyr proved to be the most appropriate ALS-inhibiting herbicide for the control of parasitic weeds (Abayo et al., 1998). In East Africa, herbicide-coated imazapyr-resistant maize seeds are used for effective control of *Striga hermonthica* and *S. asiatica* (Kanampiu et al., 2003). This technology is now available under the name *StrigAway*® (African Agricultural Technology Foundation [AATF], 2007), and a similar technology could be developed for upland rice to control these parasitic weeds.

The technological breakthrough of transgenic rice in the early nineties (Christou, Ford, & Kofron, 1991) has led to the development of transgenic HR rice technologies. Two of them, Liberty Link® (compatible with glufosinate) and Roundup Ready® (compatible with glyphosate), currently await worldwide approval. New methods for the development of transgenic HR rice have recently been explored in Japan (Endo et al., 2007) and China (Lu & Snow, 2005). These new methods will probably lead to new HR technologies, including new varieties and other active ingredients. From the three groups of broad-spectrum herbicides, to our knowledge, only glyphosate is currently used in rice in SSA (Table 2).

Advantages of HR Technologies

HR technologies can contribute to the control of some typically problematic weeds—like weedy and wild rice—and other grasses that cannot be controlled selectively (Lanclos, Webster, Zhang, & Linscombe, 2003; Olofsdotter, Valverde, & Madsen, 2000), parasitic weeds that are difficult to target due to their initial underground growth stages (Berner, Ikie, & Green, 1997; Kanampiu, Ransom, & Gressel, 2001), and weeds that have already developed resistance against current herbicides (Kumar, Bellinder, Gupta, Malik, & Brainard, 2008b). HR technologies potentially lower the environmental footprint of chemical weed control (Devos et al., 2008; Sanvido, Romeis, & Bigler, 2007). Glyphosate and glufosinate are relatively environmentally benign, non-residual, post-emergence herbicides that target both monocotyledonous and dicotyledonous weed species. By using these herbicides, rice farmers have a wider period of application and doses can be adjusted to the actual weed pressure, thereby rendering crop management more flexible and reducing the amount and number of applications (Duke, 2005; Espinoza-Esquivel & Arrieta-Espinoza, 2007; Olofsdotter et al., 2000). This reduces environmental damage and facilitates weed management at the farm level, which generates important non-pecuniary benefits for farmers (Marra & Piggott, 2006). Glufosinate and glyphosate carry a relative low risk for development of herbicide-resistant weeds. HR technologies based on these products may therefore offer a valuable and environmentally friendly alternative for rice farmers to control weeds effectively and economically.

HR technologies are likely to be highly compatible with direct-seeded rice and conservation tillage (Delmer, 2005; Kumar et al., 2008b; Leon, Webster, Bottoms, & Blouin, 2008), which in turn potentially saves (transplanting and tillage) labor and contributes to resource conservation. HR technologies reduce rice production costs, increase productivity, and provide the opportunity to turn land into rice production that was formerly unsuitable due to excessive high wild rice infestation levels (Espinoza-Esquivel & Arrieta-Espinoza, 2007). Imidazolinone-resistance technologies, such as Clearfield®, can prevent crop damage caused by herbicide carryover from a previous rotation crop or herbicide-insecticide interactions (Tan et al., 2005).

HR crops, derived from gene transfer (Joel, Kleifeld, Losner Goshen, Herzlinger, & Gressel, 1995) or tissue culture (Berner et al., 1997), enable early, pre-attachment control of parasitic weeds by applying the herbicide with the maize seed (e.g., as coating). The advantage of ALS-inhibiting herbicides for the control of parasitic weeds is that they can be translocated through the phloem of host plants with target-site resistance (Hall & Devine, 1993) and reach the attached parasite. They are toxic to belowground stages of the parasite and are not degraded before the parasite has been reached (Joel et al., 1995). Thus, they prevent much of the usual early damage with these parasites. Seed treatment requires much smaller amounts of the product than with conventional herbicide spraying (Kanampiu et al., 2002), while no herbicide is applied off-target (Kanampiu et al., 2001). Seed-coating of imazapyr-resistant maize lowers *Striga* reproduction rates (Kanampiu et al., 2001) and parasite-inflicted crop yield losses (De Groote, Wangare, & Kanampiu, 2007). Consequently, the technology proved to be highly economically profitable.

Disadvantages and Risks of HR Technologies

Despite the possible attractions of HR technologies, there are a number of potential constraints and risks involved in their use. One of the major concerns—identified by many studies—is the likelihood of gene flow from an HR rice crop (or HR rice volunteers from the preceding cropping season) to wild and weedy rice species (or conventional *O. sativa* cultivars; e.g., Chen, Lee, Song, Suh, & Lu, 2004; Espinoza-Esquivel & Arrieta-Espinoza, 2007; Kumar, Bellinder, Brainard, Malik, & Gupta, 2008b; Lu & Snow, 2005; Olofsdotter et al., 2000; Shivrain et al., 2007; Zhang, Linscombe, Webster, Tan, & Oard, 2006). If HR rice is to be grown in close proximity to wild and weedy rice populations with overlapping periods of flowering, transgenes may accumulate in these populations with unwanted environmental consequences (Chen et al., 2004; Lu & Snow, 2005). Field studies in the United States with HR rice (Clearfield®) have shown that there is outcrossing to red rice (*O. sativa*), resulting in herbicide-resistant red rice biotypes (Rajguru, Burgos, Shivrain, & Stewart, 2005; Shivrain et al., 2007; Zhang et al., 2006). Cross-pollination usually occurs over a distance of no more than 30m (Gealy, Mitten, & Rutger, 2003; Song, Lu, Zhu, & Chen, 2003). Outcrossing rates between rice and weedy rice are usually less than 0.5% and drop dramatically beyond 5m (Gealy et al., 2003; Messeguer, Marfa, Catala, Guiderdoni, & Mele, 2004). Gene-flow frequencies between cultivated and wild rice are much more important, however (Chen et al., 2004; Song et al., 2003). They have been reported to range from 1.2-2.2% (Chen et al., 2004). In addition, if hybrids are formed, the HR gene may introgress into populations of wild relatives within a few generations (Gealy et al., 2003). Development of herbicide-resistant weeds would force farmers to use more persistent and more expensive herbicides, which can have serious economic and environmental costs (Lu & Snow, 2005). Farmers growing HR rice must maintain isolation zones with sufficient distances between HR rice varieties and wild rice populations (Chen et al., 2004) and try to de-synchronize flowering times between cultivated and wild rice (Lu & Snow, 2005). The latter may be very difficult, as natural populations of wild relatives of rice usually are heterogeneous with respect to developmental stages and, consequently, the periods during which flowering occurs can be long.

Herbicide-resistant weeds can also be generated by the repeated use of a single class of herbicide. The resulting selection pressure will cause a shift in weed populations towards resistant biotypes (Gealy et al., 2003; Lu & Snow, 2005; Olofsdotter et al., 2000; Owen, 2008; Owen & Zelaya, 2005). Increased (single-product) herbicide use is thought to be a greater cause of development of herbicide-resistant weeds than pollen-mediated gene flow (Beckie, 2006). ALS-inhibiting imidazolinone herbicides carry the highest likelihood of resistance evolution in weeds. ALS-inhibitor resistance is by far the most frequently occurring type of resistance in weeds. The International Survey of Herbicide Resistant Weeds reports 98 cases of ALS-inhibitor-resistant weed biotypes out of a total of 324 (Heap, 2009). However, the same list also shows that 15 glyphosate resistant biotypes currently have already been identified, despite the fact that glyphosate carries a relative low risk for development of herbicide-resistant weeds. This may result from the relative low costs and the lack of soil residual activity of glyphosate, stimulating superfluous application rates (Duke & Powles, 2008). Although the number of weed species and regions (primarily the Americas and Asia) currently involved is still relatively low, more glyphosate-resistant biotypes are expected to evolve in the coming years, and diversity in weed-management strategies is advocated to avoid this spread and to maintain sustainability of glyphosate-based weed control (Powles, 2008). The use of additional herbicides based on other mechanisms would be necessary as well as application of integrated weed management, crop rotations, and early-season monitoring and removal of escapes (Beckie, 2006; Gealy et al., 2003; Olofsdotter et al., 2000; Zhang et al., 2006).

The use of glufosinate restricts the range of possible additional herbicides. Mixtures with triclopyr, for instance, may have severe adverse effects on HR rice (Sankula, Braverman, & Linscombe, 1997b). In addition, glufosinate has an optimal application time (3- to 4-leaf stage) to maximize weed control and minimize crop damage (Sankula, Braverman, Jodari, Linscombe,

& Oard, 1997b). Glufosinate applications at later growth stages (e.g., 5- to 6-tiller stage) may also negatively affect germination of seeds produced by the treated rice plants (Webster, Lanclos, & Zhang, 2003). For glyphosate on the other hand, the later growth stages should be targeted for effective weed control (Askew, Shaw, & Street, 1998). Farmers and seed producers should be well informed of these product specifics.

Part of the previously claimed environmental benefits of HR technologies, due to the facilitation of the use of relatively benign post-emergence herbicides, is reduced by the fact that, in practice, other products will still be compulsory. This proved to be the case for a residual herbicide like imazethapyr (Pellerin, Webster, Zhang, & Blouin, 2003), as well as non-residual glyphosate and glufosinate herbicides (Kumar et al., 2008a; Sankula et al., 1997a). Imidazolinone herbicides, based on ALS inhibition, are also broad-spectrum but have a residual effect. The use of ALS-inhibiting herbicides may therefore have unfavorable effects on the environment. For instance, Ahonsi, Berner, Emechebe, and Lagoke (2004) found that the ALS-inhibitors imazaquin and nicosulfuron have negative impacts on soil biology and natural suppression of *Striga* spp.

Climate Change Effects on Weed Populations and Management

Atmospheric greenhouse gases, including CO_2, are increasing worldwide. The climate changes this provokes may include a rise in temperature and an increase in the drought-prone area in the Sahel and southern Africa (Intergovernmental Panel on Climate Change [IPCC], 2007). Trends suggest that the variability of rainfall will increase with drier monsoon regions (Giannini, Biasutti, Held, & Sobel, 2008) and more frequent and intense rainfall in equatorial zones of Africa (Christensen et al., 2007).

The effect of changing climates on weeds will depend on the species involved (Ziska, 2008), the photosynthetic pathways (C_3, C_4 of CAM), and the interaction effects between CO_2, temperature, and water availability (Patterson, Westbrook, Joyce, Lingren, & Rogasik, 1999). High CO_2 environments may increase belowground root growth relative to aboveground shoot growth (Ziska, 2003) and favor rhizome and tuber growth of perennial weeds, rendering their control more difficult (e.g., Patterson et al., 1999). For rice production in Africa, this could mean increasing problems with perennial grass weeds like *Leersia hexandra* Sw. and the wild rice species *Oryza longistaminata* in irrigated and rainfed lowlands. Parasitic weeds, such as *Striga* spp., may extend their geographic range due to climate change (Mohamed et al., 2006). Parasitic weeds that thrive in erratic and low rainfall environments (e.g., *Striga hermonthica*) or temporary flooded conditions (e.g., *Rhamphicarpa fistulosa*) could be favored by the soil degradation (e.g., Kroschel, 1998) and rainfall extremes that are projected by the Intergovernmental Panel on Climate Change (IPCC, 2007).

Besides causing weed population shifts, projected climate changes are also likely to affect herbicide effectiveness and consequently affect the future of HR technologies. Increased temperatures negatively affect herbicide persistence in the soil and narrow the “windows” for herbicide effectiveness (Bailey, 2004). Extreme weather may increase the risk of herbicides either causing crop damage or not being effective (Patterson et al., 1999). With high rainfall events, for instance, imidazolinone herbicides may be diluted and cease to be effective (Kanampiu et al., 2003). Uncontrolled flooding, which might more frequently occur in the future, will reduce effects of glufosinate (Sankula et al., 1997b). On top of all this, raised CO_2 levels have been shown to increase the resistance of weeds to glyphosate (e.g., Ziska, Teasdale, & Bunce, 1999).

Discussion and Conclusions

Perennial weeds with extensive subterranean rhizome systems—like the wild rice species *Oryza longistaminata*—and parasitic weeds with wide geographic ranges and high genetic variation—like *Striga* spp.—are expected to become more important in future rice production in Africa (Rodenburg & Johnson, 2009). The ability to control such problem weed species efficiently makes HR rice an attractive technology for rice farmers in Africa. In addition to their effectiveness, HR technologies do not require substantial labor. If it can partly replace hand weeding and proves effective in the control of parasitic weeds, HR crops could be a highly relevant weed-management technology in developing countries (Duke, 2005). The labor-saving potential of HR rice is of high importance in SSA where hand- or hoe-weeding is taking a significant amount of the farmer’s time. These crop operations are often carried out by women and children and thus affect other economic activities and schooling rates. Any technology that relieves women and children from these time-consuming activities offers important societal benefits and should be seriously considered (Thomson, 2008). However, suitable technologies for subsistence rice farming in SSA should also be affordable, easy to learn and apply, and relatively independent of water control. HR technologies may not meet these criteria.

Outcrossing success between HR rice and wild rice species present in African rice production systems has not yet been tested (Lu & Snow, 2005). The risk of gene flow between HR and wild rice is relevant, however, for both common wild rice species in SSA—*Oryza longistaminata* and *O. barthii*—as they share the AA genome with cultivated rice species *O. sativa* (Khush, 1997). For another closely related rice species sharing the AA genome, *O. rufipogon*, hybridization with *O. sativa* naturally occurs (Chen et al., 2004; Song et al., 2003) and introgression with genes from HR rice has been shown to be possible (Wang et al., 2006). The above considerations regarding gene flow suggest that HR technologies may have a limited lifetime at a particular location, unless its introduction and use are carefully managed (Rodenburg & Johnson, 2009). In the case of parasitic weeds, model predictions show that, on average, five resistant *Striga* plants per ha will survive herbicide treatment (Gressel, Segel, & Ransom, 1996). Although this is a manageable number, careful and consistent hand rouging would be required to prevent a rapid seedbank buildup of resistant biotypes. Farmers using HR technologies would need to strictly follow stewardship recommendations to avoid evolution of herbicide-resistant weeds on a field (e.g., by meticulous herbicide use and hand-rouging of escaped weeds) and community level (e.g., mitigating gene flow between farms by quarantine and containment agreements) and apply HR technologies as a component of integrated weed management. The lack of human and financial resources in SSA to adequately identify a case of herbicide resistance in weeds in an early stage, implies a high additional risk if gene flow or the long-term use of a single herbicide will indeed lead to the development of an herbicide-resistant weed population.

HR rice technologies may also lack compatibility with existing rice-based cropping systems in SSA, as many farmers use crop or species mixtures within their fields (Delmer, 2005; Thomson, 2008). In northern Côte d'Ivoire for instance, harboring hot-spots of *Striga*-spp.-infested upland rice fields, maize is often intercropped. The rice varieties or intercrops used in rice-based cropping systems in SSA will most probably not be resistant to any of the broad-spectrum herbicides such as glufosinate, glyphosate, or imidazolinone. The carryover and neighbor effects could possibly be reduced if the herbicides can be applied with the seed. A minimum distance between intercrops, however, should still be respected as was shown when imazapyr-resistant maize was intercropped with cowpea, yellow gram, or field bean (Kanampiu et al., 2002). The use of rice variety mixtures in a field or different rice varieties in neighboring fields might cause gene flow from HR to conventional rice varieties. Gene flow to conventional rice varieties may cause a subsequent indirect flow of transgenes to wild rice in adjacent fields (Lu & Snow, 2005). Prevention of this indirect gene flow would require community-based regulation and information systems and good communication between rice producers. It should be noted however that the likelihood of longer-distance gene flow and resulting problems with seed purity in neighboring fields is small (Rong et al., 2007).

In the context of developing countries, HR seems to be a trait that is more tailored to large-scale farms that have both access to reliable markets and the financial means to purchase the required chemicals and seed each season (Delmer, 2005). Rice production in SSA is mainly subsistence (Poulton et al., 2008) and we did not find any published evidence of relevance of these technologies for such farming systems. The costs and investment risks of high-quality certified seeds pose a real constraint for poor farmers working under unreliable environmental and financial conditions, especially when technology licensing fees are added (Delmer, 2005).

For SSA, currently the only reported application of HR technologies that we are aware of is in the *Striga*-infested maize production systems in East Africa (De Groote, et al., 2007; De Groote et al., 2008; Kanampiu et al., 2003). HR technologies to control *Striga* spp. in maize systems in East Africa may be successful because several conditions are met that are still lacking for rice production systems or for other parts of SSA, such as West Africa. These conditions may include a substantial commercial market, an interested agro-industry, well developed seed production and distribution systems, and relatively low seed prices. In the case of HR maize in East Africa, De Groote et al. (2008) showed that even poor farmers are interested in the technology. They also argue that availability of a private seed sector would be a precondition for success. However, the interest of the agro-industry also depends on the scope for intellectual property right (IPR) protection. Hybrid maize's intellectual property is biologically protected, as reusing saved seed from harvest entails significant yield reductions. Therefore, it is expected that in developing countries with weak governance of IPRs, the agro-industry will first target hybrid seed markets for commercializing HR technologies. The biological IPR protection in hybrids may substitute existing weak regulatory IPR protection

(Goldsmith, Ramos, & Steiger, 2003). Therefore, if hybrid rice is introduced in Africa in the future, the interest for HR technologies may increase.

The use of HR technologies may partially remove the timing requirement and lower the risks of phytotoxicity and negative effects on environment and human health, but in turn would require meticulous stewardship to prevent outcrossing of HR rice with rice weeds (Lu & Snow, 2005; Madsen, Valverde, & Jensen, 2002; Tan et al., 2005). Consequently, in order to follow stewardship recommendations, the farmer would need to understand the risks and consequences of gene flow and be willing to sacrifice some of his valuable time and land (in case of rotations). Effective stewardship may also require well-functioning markets for the farmer to be able to purchase any additional or alternative chemical products to eradicate weeds escaping the first chemical treatment. In addition to this, the existing HR technologies require the farmer to purchase new (certified) seeds for each new cropping season (Olofsdotter et al., 2000; Tan et al., 2005). The advantage of such a system is that the use of certified seed, produced on quality-controlled production farms, will be free of weed seeds (like wild relatives of rice), and as such, will minimize the spread of wild-rice infestations and resistant weedy and wild-rice biotypes (Gealy et al., 2003; Tan et al., 2005). However, in SSA very few, if any, of such certified seed-production services exist for rice; even if they did, such a system would add to the seasonal financial investments a farmer would need to make.

Transfer and adoption success of HR rice technologies in the developing world will depend on profitability and farmer perceptions towards binding agreements with agro-industries (Olofsdotter et al., 2000) on one hand, and willingness of agro-industries and the public sector to invest or build strategic partnerships on the other hand. As suggested earlier, large private seed companies are not likely to invest in crops that do not have an interesting, well-developed and IPR-protected market (Delmer, 2005). A recent case-study on the potential economic impact of HR rice in the irrigated rice production systems in Senegal concluded that farmers could substantially gain from access to these technologies (Demont et al., 2009). However, potential institutional constraints to introduction of these technologies are existing subsidy arrangements on chemical input and seed. These subsidies reduce farmers' costs of conventional weed control programs and erode the competitive position and profitability of HR rice. In turn, this would discourage private investments in the required biotechnology capacity, unless the government would shift existing subsidies to HR technologies. Estimating the value of HR rice in other regions and ecosystems requires detailed data on herbicide expenditures and opportunity costs of weeding labor. To our knowledge, such a comprehensive database is not available for SSA. Cross-sectional and panel databases of farmer practices and production costs exist, but cover scattered areas and are generally not publicly available. In particular, survey evidence on heterogeneity of weed control costs over a wide range of farming conditions is needed in order to capture the effect of population pressure and market access on the opportunity costs of weeding labor (Demont, Jouve, Stessens, & Tollens, 2007; Ruthenberg, 1980). Moreover, since women often provide an important part of weeding labor (Bassett, 2002), the impact of HR rice is not expected to be gender-neutral.

Because of the reasons discussed above, government intervention and establishment of effective public-private partnerships (PPP) might be a precondition to transfer this technology (Basu & Qaim, 2007; Demont et al., 2009; Graff, Roland-Holst, & Zilberman, 2006; Tollens, Demont, & Swennen, 2004; World Bank, 2008). As similar conclusions were derived from an *ex ante* impact assessment of HR rice technologies in Uruguay (Hareau, Mills, & Norton, 2006), this seems applicable to a wider range of developing countries. A model for effective PPP could consist of the private sector developing beneficial traits in major commercial crops, and the public sector providing a range of adapted germplasm into which these traits can be introduced (Delmer, 2005). Required support from government and non-governmental organizations would involve credit, training, and seed and herbicide supply systems, preferably with private sector participation (De Groote et al., 2008). Microcredit or two-tiered price systems, where technology fees will be charged as proportional to the scale of the farm, could alleviate some of the investment risks for small-scale farmers (Delmer, 2005).

Alternatively African countries could develop collaborative initiatives, for instance, with regional and international research and development organizations, such as the Africa Rice Center (AfricaRice) and the newly founded regional centers like Biosciences for East and Central Africa (BECA) and the African Agricultural Technology Foundation (AATF), to develop and disseminate HR rice varieties independently of existing multi-national agro-industries. This could be achieved through a multidisciplinary, step-wise approach, such as followed in Costa Rica (Espinoza-Esquivel & Arrieta-Espinoza, 2007). However, in the case of transgenic HR rice, the major constraints for adoption will be the fact that most countries in Africa do not yet have the capacity to conduct full biosafety assessments. Some of these African nations even enacted a ban on GM crops or have implemented regulations limiting the use of GM cereal grains donated as food aid (Falck Zepeda, 2006).

We conclude that HR technologies might provide technically sound and effective solutions to control wild rice in the irrigated systems and parasitic weeds in the rainfed uplands of sub-Saharan Africa. However, development, introduction, and farmer adoption of these technologies have a long way to go. The great number of prerequisites for success renders the future of HR rice technologies in SSA ambiguous. Innovations like these, however, are urgently needed for the continent to alleviate poverty and raise food security. New collaborative initiatives and financial support for research and development efforts targeted to technological and organizational solutions adapted to the local context are therefore required.

References

African Agricultural Technology Foundation (AATF). (2007, December). Strides in *Striga* management (*African Agricultural Technology Foundation Newsletter*). Nairobi, Kenya: Author. Available on the World Wide Web: http://www.aatf-africa.org/UserFiles/File/Strides_Issue-1_Dec07.pdf.

Abayo, G.O., English, T., Eplee, R.E., Kanampiu, F.K., Ransom, J.K., & Gressel, J. (1998). Control of parasitic witchweeds (*Striga* spp.) on corn (*Zea mays*) resistant to acetolactate synthase inhibitors. *Weed Science*, *46*(4), 459-466.

Ahonsi, M.O., Berner, D.K., Emechebe, A.M., & Lagoke, S.T. (2004). Effects of ALS-inhibitor herbicides, crop sequence, and fertilization on natural soil suppressiveness to *Striga hermonthica*. *Agriculture, Ecosystems and Environment*, *104*(3), 453-463.

Archer, D.W., & Shogren, J.F. (1996). Endogenous risk in weed control management. *Agricultural Economics*, *14*(2), 103-122.

Askew, S.D., Shaw, D.R., & Street, J.E. (1998). Red rice (*Oryza sativa*) control and seedhead reduction with glyphosate. *Weed Technology*, *12*(3), 504-506.

Bailey, S.W. (2004). Climate change and decreasing herbicide persistence. *Pest Management Science*, *60*(2), 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.

Bassett, T.J. (2002). Women's cotton and the spaces of gender politics in northern Côte d'Ivoire. *Gender, Place and Culture*, *9*(4), 351-370.

Basu, A.K., & Qaim, M. (2007). On the adoption of genetically modified seeds in developing countries and the optimal types of government intervention. *American Journal of Agricultural Economics*, *89*(3), 784-804.

Becker, M., & Johnson, D.E. (2001a). Cropping intensity effects on upland rice yield and sustainability in West Africa. *Nutrient Cycling in Agroecosystems*, *59*(2), 107-117.

Becker, M., & Johnson, D.E. (2001b). Improved water control and crop management effects on lowland rice productivity in West Africa. *Nutrient Cycling in Agroecosystems*, *59*(2), 119-127.

Becker, M., Johnson, D.E., Wopereis, M.C.S., & Sow, A. (2003). Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. *Journal of Plant Nutrition and Soil Science*, *166*(1), 61-67.

Beckie, H.J. (2006). Herbicide-resistant weeds: Management tactics and practices. *Weed Technology*, *20*(3), 793-814.

Berner, D.K., Ikie, F.O., & Green, J.M. (1997). ALS-inhibiting herbicide seed treatments control *Striga hermonthica* in ALS-modified corn (*Zea mays*). *Weed Technology*, *11*(4), 704-707.

Chen, L.J., Lee, D.S., Song, Z.P., Suh, H.S., & Lu, B.R. (2004). Gene flow from cultivated rice (*Oryza sativa*) to its weedy and wild relatives. *Annals of Botany*, *93*(1), 67-73.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., et al. (2007). Regional climate projections. In S. Solomonet et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assesment report of the intergovernmental panel on climate change* (pp. 847-940). New York: Cambridge University Press.

Christou, P., Ford, T.L., & Kofron, M. (1991). Production of transgenic rice (*Oryza sativa* L) plants from agronomically important Indica and Japonica varieties via electric-discharge particle-acceleration of exogenous DNA into immature zygotic embryos. *Bio-Technology*, *9*(10), 957-962.

De Groote, H., Wangare, L., & Kanampiu, F. (2007). Evaluating the use of herbicide-coated imidazolinone-resistant (IR) maize seeds to control *Striga* in farmers' fields in Kenya. *Crop Protection*, *26*(10), 1496-1506.

De Groote, H., Wangare, L., Kanampiu, F., Odendo, M., Diallo, A., Karaya, H., & Friesen, D. (2008). The potential of a herbicide resistant maize technology for *Striga* control in Africa. *Agricultural Systems*, *97*(1-2), 83-94.

Delmer, D.P. (2005). Agriculture in the developing world: Connecting innovations in plant research to downstream applications. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(44), 15739-15746.

Demont, M., Jouve, P., Stessens, J., & Tollens, E. (2007). Boserup versus Malthus revisited: Evolution of farming systems in Northern Côte d'Ivoire. *Agricultural Systems*, *93*(1-3), 215-228.

Demont, M., Rodenburg, J., Diagne, M., & Diallo, S. (2009). *Ex ante* impact assessment of herbicide resistant rice in the Sahel. *Crop Protection*, *28*(9), 728-736.

Devos, Y., Cougnon, M., Vergucht, S., Bulcke, R., Haesaert, G., Steurbaut, W., & Reheul, D. (2008). Environmental impact of herbicide regimes used with genetically modified herbicide-resistant maize. *Transgenic Research*, *17*(6), 1059-1077.

Duke, S.O. (2005). Taking stock of herbicide-resistant crops ten years after introduction. *Pest Management Science*, *61*(3), 211-218.

Duke, S.O., & Powles, S.B. (2008). Glyphosate: A once-in-a-century herbicide. *Pest Management Science*, *64*(4), 319-325.

Endo, M., Osakabe, K., Ono, K., Handa, H., Shimizu, T., & Toki, S. (2007). Molecular breeding of a novel herbicide-tolerant rice by gene targeting. *Plant Journal*, *52*(1), 157-166.

Espinoza-Esquivel, A.M., & Arrieta-Espinoza, G. (2007). A multidisciplinary approach directed towards the commercial release of transgenic herbicide-tolerant rice in Costa Rica. *Transgenic Research*, *16*(5), 541-555.

Falck Zepeda, J. (2006). Coexistence, genetically modified biotechnologies and biosafety: Implications for developing countries. *American Journal of Agricultural Economics*, *88*(5), 1200-1208.

Food and Agriculture Organization of the United Nations (FAO). (2009a, February). *Rice market monitor* (Volume 7, Issue 1). Rome, Italy.

FAO. (2009b). FAOSTAT [Database]. Rome, Italy: Author. Available on the World Wide Web: http://faostat.fao.org.

Gealy, D.R., Mitten, D.H., & Rutger, J.N. (2003). Gene flow between red rice (*Oryza sativa*) and herbicide-resistant rice (*O. sativa*): implications for weed management. *Weed Technology*, *17*(3), 627-645.

Giannini, A., Biasutti, M., Held, I.M., & Sobel, A.H. (2008). A global perspective on African climate. *Climatic Change*, *90*(4), 359-383.

Gitsopoulos, T.K., & Froud-Williams, R.J. (2004). Effects of oxadiargyl on direct-seeded rice and *Echinochloa crus-galli* under aerobic and anaerobic conditions. *Weed Research*, *44*(4), 329-334.

Goldsmith, P.D., Ramos, G., & Steiger, C. (2003). A tale of two businesses: Intellectual property rights and the marketing of agricultural biotechnology. *Choices*, *Third Quarter*, 25-30.

Graff, G., Roland-Holst, D., & Zilberman, D. (2006). Agricultural biotechnology and poverty reduction in low-income countries. *World Development*, *34*(8), 1430-1445.

Gressel, J., Segel, L., & Ransom, J.K. (1996). Managing the delay of evolution of herbicide resistance in parasitic weeds. *International Journal of Pest Management*, *42*(2), 113-129.

Haefele, S.M., Johnson, D.E., Diallo, S., Wopereis, M.C.S., & Janin, I. (2000). Improved soil fertility and weed management is profitable for irrigated rice farmers in Sahelian West Africa. *Field Crops Research*, *66*(2), 101-113.

Hall, L.M., & Devine, M.D. (1993). Chlorsulfuron inhibition of phloem translocation in chlorsulfuron-resistant and chlorsulfuron-susceptible *Arabidopsis thaliana*. *Pesticide Biochemistry and Physiology*, *45*(2), 81-90.

Hammerton, J.L. (1967). Environmental factors and susceptibility to herbicides. *Weeds*, *15*(4), 330-336.

Hareau, G.G., Mills, B.F., & Norton, G.W. (2006). The potential benefits of herbicide-resistant transgenic rice in Uruguay: Lessons for small developing countries. *Food Policy*, *31*(2), 162-179.

Heap, I.M. (2009). *International survey of herbicide resistant weeds*. Corvallis, OR: International Survey of Herbicide Resistant Weeds Accessed on April 1, 2009 from http://www.weedscience.org.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change 2007: Synthesis report. A contribution of working groups I,II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.)]. Geneva, Switzerland: Author.

Joel, D.M., Kleifeld, Y., Losner Goshen, D., Herzlinger, G., & Gressel, J. (1995). Transgenic crops against parasites. *Nature*, *374*(6519), 220-221.

Johnson, D.E. (1997). *Weeds of rice in West Africa*. Bouaké: WARDA.

Johnson, D.E., & Kent, R.J. (2002). The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in West Africa. *Weed Research*, *42*(2), 89-99.

Johnson, D.E., Wopereis, M.C.S., Mbodj, D., Diallo, S., Powers, S., & Haefele, S.M. (2004). Timing of weed management and yield losses due to weeds in irrigated rice in the Sahel. *Field Crops Research*, *85*(1), 31-42.

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*(5), 697-706.

Kanampiu, F.K., Ransom, J.K., Friesen, D., & Gressel, J. (2002). Imazapyr and pyrithiobac movement in soil and from maize seed coats to control *Striga* in legume intercropping. *Crop Protection*, *21*(8), 611-619.

Kanampiu, F.K., Ransom, J.K., & Gressel, J. (2001). Imazapyr seed dressings for *Striga* control on acetolactate synthase target-site resistant maize. *Crop Protection*, *20*(10), 885-895.

Kanampiu, F.K., Ransom, J.K., Gressel, J., Jewell, D., Friesen, D., Grimanelli, D., & Hoisington, D. (2002). Appropriateness of biotechnology to African agriculture: *Striga* and maize as paradigms. *Plant Cell Tissue and Organ Culture*, *69*(2), 105-110.

Khush, G.S. (1997). Origin, dispersal, cultivation and variation of rice. *Plant Molecular Biology*, *35*(1-2), 25-34.

King, C.A., & Oliver, L.R. (1992). Application rate and timing of acifluorfen, bentazon, chlorimuron, and imazaquin. *Weed Technology*, *6*(3), 526-534.

Kroschel, J. (1998). *Striga* - How will it affect African agriculture in the future? - An ecological perspective. In K. Martin, J. Muther, & A. Auffarth (Eds.), *Agro-ecology, plant protection* *and the human environment: Views and concepts* (pp. 137-158). Weikersheim, Germany: Margraf Verlag.

Kumar, V., Bellinder, R.R., Brainard, D.C., Malik, R.K., & Gupta, R.K. (2008a). Risks of herbicide-resistant rice in India: A review. *Crop Protection*, *27*(3-5), 320-329.

Kumar, V., Bellinder, R.R., Gupta, R.K., Malik, R.K., & Brainard, D.C. (2008b). Role of herbicide-resistant rice in promoting resource conservation technologies in rice-wheat cropping systems of India: A review. *Crop Protection*, *27*(3-5), 290-301.

Lanclos, D.Y., Webster, E.P., Zhang, W., & Linscombe, S.D. (2003). Response of glufosinate-resistant rice (*Oryza sativa*) to glufosinate application timings. *Weed Technology*, *17*(1), 157-160.

Leon, C.T., Webster, E.P., Bottoms, S.L., & Blouin, D.C. (2008). Water management and chemical control of red rice (*Oryza punctata*) in water-seeded imidazolinone-resistant rice. *Weed Technology*, *22*(1), 132-135.

Lu, B.R., & Snow, A.A. (2005). Gene flow from genetically modified rice and its environmental consequences. *Bioscience*, *55*(8), 669-678.

Madsen, K.H., Valverde, B.E., & Jensen, J.E. (2002). Risk assessment of herbicide-resistant crops: A Latin American perspective using rice (*Oryza sativa*) as a model. *Weed Technology*, *16*(1), 215-223.

Marra, M.C., & Piggott, N.E. (2006). The value of non-pecuniary characteristics of crop biotechnologies: A new look at the evidence. In R.E. Just, J.M. Alston, & D. Zilberman (Eds.), *Regulating agricultural biotechnology: Economics and policy* (pp. 145-177). New York: Springer.

Messeguer, J., Marfa, V., Catala, M.M., Guiderdoni, E., & Mele, E. (2004). A field study of pollen-mediated gene flow from Mediterranean GM rice to conventional rice and the red rice weed. *Molecular Breeding*, *13*(1), 103-112.

Olofsdotter, M., Valverde, B.E., & Madsen, K.H. (2000). Herbicide resistant rice (*Oryza sativa* L.): Global implications for weedy rice and weed management. *Annals of Applied Biology*, *137*(3), 279-295.

Orr, A. (2003). Integrated pest management for resource-poor African farmers: Is the emperor naked? *World Development*, *31*(5), 831-845.

Owen, M.D.K. (2008). Weed species shifts in glyphosate-resistant crops. *Pest Management Science*, *64*(4), 377-387.

Owen, M.D.K., & Zelaya, I.A. (2005). Herbicide-resistant crops and weed resistance to herbicides. *Pest Management Science*, *61*(3), 301-311.

Pannell, D.J. (1990). Responses to risk in weed control decisions under expected profit maximization. *Journal of Agricultural Economics*, *41*(3), 391-403.

Patterson, D.T., Westbrook, J.K., Joyce, R.J.V., Lingren, P.D., & Rogasik, J. (1999). Weeds, insects, and diseases. *Climatic Change*, *43*(4), 711-727.

Pellerin, K.J., Webster, E.P., Zhang, W., & Blouin, D.C. (2003). Herbicide mixtures in water-seeded imidazolinone-resistant rice (*Oryza sativa*). *Weed Technology*, *17*(4), 836-841.

Poulton, C., Tyler, G., Hazell, P., Dorward, A., Kydd, J., & Stockbridge, M. (2008). *Commercial agriculture in Africa: Lessons from success and failure* (Background paper for the Competitive Commercial Agriculture in Sub-Saharan Africa [CCAA] Study). Washington, DC: World Bank.

Powles, S.B. (2008). Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. *Pest Management Science*, *64*(4), 360-365.

Rajguru, S.N., Burgos, N.R., Shivrain, V.K., & Stewart, J.M. (2005). Mutations in the red rice ALS gene associated with resistance to imazethapyr. *Weed Science*, *53*(5), 567-577.

Rodenburg, J., & Johnson, D.E. (2009). Weed management in rice-based cropping systems in Africa. *Advances in Agronomy*, *103*, 149-217.

Rong, J., Lu, B.R., Song, Z.P., Su, J., Snow, A.A., et al. (2007). Dramatic reduction of crop-to-crop gene flow within a short distance from transgenic rice fields. *New Phytologist*, *173*(2), 346-353.

Ruthenberg, H. (1980). *Farming systems in the tropics* (3rd ed.). Oxford, England: Clarendon Press.

Sankula, S., Braverman, M.P., Jodari, F., Linscombe, S.D., & Oard, J.H. (1997a). Evaluation of glufosinate on rice (*Oryza sativa*) transformed with the BAR gene and red rice (*Oryza sativa*). *Weed Technology*, *11*(1), 70-75.

Sankula, S., Braverman, M.P., & Linscombe, S.D. (1997b). Glufosinate-resistant, BAR-transformed rice (*Oryza sativa*) and red rice (*Oryza sativa*) response to glufosinate alone and in mixtures. *Weed Technology*, *11*(4), 662-666.

Sanvido, O., Romeis, J., & Bigler, F. (2007). Ecological impacts of genetically modified crops: Ten years of field research and commercial cultivation. *Advances in Biochemical Engineering and Biotechnology*, *107* 235-278.

Sha, X.Y., Linscombe, S.D., & Groth, D.E. (2007). Field evaluation of imidazolinone-tolerant Clearfield rice (*Oryza sativa* L.) at nine Louisiana locations. *Crop Science*, *47*(3), 1177-1185.

Shivrain, V.K., Burgos, N.R., Anders, M.M., Rajguru, S.N., Moore, J., & Sales, M.A. (2007). Gene flow between Clearfield (TM) rice and red rice. *Crop Protection*, *26*(3), 349-356.

Song, Z.P., Lu, B.R., Zhu, Y.G., & Chen, J.K. (2003). Gene flow from cultivated rice to the wild rice species *Oryza rufipogon* under experimental field conditions. *New Phytologist*, *157*(3), 657-665.

Swinton, S.M., & King, R.P. (1994). The value of pest information in a dynamic setting: The case of weed control. *American Journal of Agricultural Economics*, *76*(1), 36-46.

Tan, S.Y., Evans, R.R., Dahmer, M.L., Singh, B.K., & Shaner, D.L. (2005). Imidazolinone-tolerant crops: History, current status and future. *Pest Management Science*, *61*(3), 246-257.

Thomson, J.A. (2008). The role of biotechnology for agricultural sustainability in Africa. *Philosophical Transactions of the Royal Society B-Biological Sciences, 363*(1492), 905-913.

Tollens, E., Demont, M., & Swennen, R. (2004). Agrobiotechnology in developing countries: North-south partnerships are a key. *Outlook on Agriculture, 33*(4), 231-238.

van Heemst, H.D.J. (1985). The influence of weed competition on crop yield. *Agricultural Systems, 18*(2), 81-93.

Wang, F., Yuan, Q.H., Shi, L., Qian, Q., Liu, W.G., et al. (2006). A large-scale field study of transgene flow from cultivated rice (*Oryza sativa*) to common wild rice (*O. rufipogon*) and barnyard grass (*Echinochloa crusgalli*). *Plant Biotechnology Journal, 4*(6), 667-676.

Webster, E.P., Lanclos, D.Y., & Zhang, W. (2003). Influence of glufosinate on seed weight, seed germination, and seedling vigor of glufosinate-resistant rice. *Weed Technology, 17*(1), 51-54.

Windmeijer, P.N., Duivenbooden, N., & Andriesse, W. (1994). *Characterization of rice-growing agro-ecosystems in West Africa: Semi-detailed characterization of inland valleys in Côte d'Ivoire.* Wageningen, The Netherlands: SC-DLO-Wageningen Agricultural University.

World Bank. (2008). *World development report 2008*. Washington, DC: Author.

Zhang, W.Q., Linscombe, S.D., Webster, E., Tan, S.Y., & Oard, J. (2006). Risk assessment of the transfer of imazethapyr herbicide tolerance from Clearfield rice to red rice (*Oryza sativa*). *Euphytica, 152*(1), 75-86.

Zimdahl, R.L. (2007). *Fundamentals of weed science* (3rd ed.). London: Academic Press.

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*(381), 395-404.

Ziska, L.H. (2008). Rising atmospheric carbon dioxide and plant biology: The overlooked paradigm. *DNA and Cell Biology, 27*(4), 165-172.

Ziska, L.H., Teasdale, J.R., & Bunce, J.A. (1999). Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science, 47*(5), 608-615.

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