CHAPTER FOUR

Weed Management in Rice-Based Cropping Systems in Africa

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Contents

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Abstract

Weed competition is a major constraint in all the rice production systems in Africa. In addition to the costs of weed control, weeds account for yield losses estimated to be at least 2.2 million tons per year in sub-Saharan Africa, valued at $1.45 billion, and equating to approximately half the current total imports of rice to this region. Important weeds in upland rice include the perennial species *Cyperus rotundus*, *Imperata cylindrica* and *Chromolaena odorata,* the annual species *Euphorbia heterophylla*, *Digitaria horizontalis*, and the parasitic weeds *Striga* spp. In lowland rice the perennial weeds: *Cyperus rotundus*, *C. esculentus* and *Oryza longistaminata* and annual weeds *Sphenoclea zeylanica*, *Echinochloa* spp., *Cyperus difformis, C. 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. Labor shortages and lack of access to information, inputs, and credits are widespread constraints for African farmers. To optimize financial, social and environmental costs and benefits, integrated and ecological management approaches are advocated. Locally adapted and affordable combinations of preventive measures and interventions should be targeted. Future weed research should aim to deliver the information and tools for the implementation of these approaches. This requires the generation of knowledge on weed biology and ecology and on the consequences of changes in management and the environment on weed populations. To address the diversity of rice-based cropping systems in Africa, priorities need to be set and products and information delivered that take full account of local conditions. This will require farmer participatory approaches that are inclusive with respect to resource-poor farmers and gender.

1. Introduction

1.1. Rice in Africa

Rice is the fifth most important cereal in Africa in terms of area harvested and the fourth in terms of production (FAO, 2008b). Rice production in Africa is increasing at the fastest rate of any cereal, and over the past three decades, harvested area has risen by 105% and production by 170% (Table 1). With respect to production and area statistics, important rice producing countries in Africa are Nigeria, Madagascar, Guinea, Sierra Leone, Egypt, Congo DR, Mali, Côte d'Ivoire, Tanzania, and Mozambique (Table 2). The majority of rice is consumed in West Africa, although the region is not self-sufficient in rice, and increasing import costs are a concern.

Rice-based cropping systems are diverse and vary among subregions, ecosystems, management input levels, farm scales, and traditional practices. Topography and hydrology are among the most important variables

Table 1 The five major cereals grown in Africa (data 2006) in terms of harvested area (×1000 ha), area under rice compared to total area under cereals (Area Share; %), production (×1000 t), rice production compared to total cereal production (Production Share; %), and increases in area (Δ Area; %) and production (Δ Production; %) between 1976 and 2006

Cereal	Area	Area share	Production	Production share	Δ Area	Δ Production
Maize	26,118	26	46,260	32	36	74
Sorghum	25,137	25	26,113	18	64	125
Millet	20,196	20	17,788	12	54	120
Wheat	10,175	10	25,096	17	11	144
Rice	8825	9	21,131	14	105	170
All	98,746		145,892		45	107

Source: FAOSTAT (2008).

determining differences in rice-based cropping systems in Africa. Five main rice ecosystems can be distinguished based on water supply and topography (Windmeijer *et al.*, 1994): (1) rain-fed upland rice on plateaus and hydromorphic slopes, (2) lowland rain-fed 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. Upland rice ecosystems roughly represent 39% of the total area under rice in SSA leaving 33% to rain-fed lowlands, 19% to irrigated lowlands and around 9% to deep water and mangroves (Balasubramanian *et al.*, 2007; updated with data from FAO, 2008b). Upland, rain-fed and irrigated lowland rice systems are widely distributed while deep water and mangrove systems are of only local importance such as the Niger River flood plains of Guinea, Mali, and Nigeria (deep water) or coastal zones of Sierra Leone, Liberia, and The Gambia (mangroves). Further distinction of the rice production systems can be based on the agroecological zones that differ in the length of the growing season (i.e., Sahel and Guinea savanna, derived savanna, and the humid forest zones).

Upland rice cropping systems are in the forest, savanna, and derived savanna zones. If the rainy season is of sufficient duration or if residual moisture is adequate after rice, subsequent crops like maize, cowpea, or soybean may be grown. In East African highlands, upland rice is rotated with wheat, maize, or potato. On hydromorphic areas, where the perched water table is within 50 cm of the soil surface for the majority of the growing season, rice and cash crops such as cotton are grown. In upland cropping systems of subsistence farmers, input levels are generally low, and low yields (mean: <1 t ha^{-1}; range: 0.1–3.5 t ha^{-1}) are commonly due to poor soil fertility and weed competition (Balasubramanian *et al.*, 2007;

Table 2 Major rice countries in Africa (2006 data) in terms of harvested area (×1000 ha), area under rice compared to total area under cereals (Area Share; %), production (×1000 t), rice production compared to total cereal production (Production Share, %), self-sufficiency (SS), and ranking (R) among 51 African countries (only top 10 countries by rice area shown and in decreasing order of importance)

Country	Area	R	Area share	R	Production	R	SS	Production share	R
Nigeria	2725	1	14	12	3924	2	–[a]	14	18
Madagascar	1250	2	94	2	3485	3	+	92	3
Guinea	758	3	89	3	1340	4	+	55	5
Sierra Leone	730	4	83	4	1062	5	+	92	2
Egypt	613	5	20	10	6500	1	+	29	10
Congo DR	418	6	16	11	316	9	+	21	12
Mali	401	7	12	13	1019	6	?	30	9
Côte d'Ivoire	370	8	47	5	700	8	–	50	6
Tanzania	355	9	10	14	784	7	+	15	16
Mozambique	180	10	9	17	174	13	–	10	21

[a] (–) Production < consumption; (+) production > consumption; (?) no consumption statistics available.
Source: FAOSTAT (2008)

Windmeijer and Andriesse, 1993). In rain-fed lowlands in the savanna and forest zones, fields are often unbunded and poorly leveled. Rice is grown during the wet season and land is often left fallow during the dry season. If the rainy season is long enough (>5 months) or if residual soil moisture in the valley bottom suffice, farmers use the dry season to grow groundnut, soybean, maize, or vegetables (Kent *et al*., 2001; Windmeijer and Andriesse, 1993). In irrigated lowlands, wet season rice is often followed by a second rice crop, or vegetables (Kent *et al*., 2001), or left fallow in the dry season. Some irrigated areas in the Sahel are double cropped with rice usually followed by a short fallow period (Defoer *et al*., 2004b). Double cropping is also practiced in the irrigated highlands of Central and East Africa (including Madagascar) either as rice–rice or rotated with vegetables, wheat, potatoes, or soybean (Balasubramanian *et al*., 2007).

1.2. Importance of weeds

Throughout Africa, from Senegal to Madagascar, weeds are cited among the main production constraints in any of the rice ecosystems (Adesina *et al*., 1994; e.g., Ampong-Nyarko, 1996; Becker and Johnson, 1999a; Diallo and Johnson, 1997). Common agronomic factors that contribute to weed problems are inadequate land preparation (soil tillage, soil leveling in lowland areas), rice seed contamination with weed seeds, use of poor quality rice seeds, broadcast seeding in lowlands, use of old rice seedlings for transplanting, inadequate water management, inadequate fertilizer management, mono-cropping, labor shortages for hand weeding and delayed herbicide applications and other interventions (Becker and Johnson, 1999a, 2001b; Diallo and Johnson, 1997). In the upland systems, crop intensification and inadequate fallow management are also contributory factors (Becker and Johnson, 2001b).

Worldwide, weeds are estimated to account for 32% potential and 9% actual yield losses in rice (Oerke and Dehne, 2004). The nature and severity of weed problems, however, vary according to the rice ecosystem. Likewise, weed management practices and the available options are often a function of biophysical and socioeconomic factors which, in turn, are determined by the agroecosystem. Weeds are the major constraints in rain-fed uplands and in the unbunded lowlands, for instance, where they cannot be controlled by flooding the soil surface. Similarly, rice in the deep-water rice systems along the major rivers can be severely affected by weeds prior to flooding as the crop is direct-seeded and farmers rely on hand weeding and use relatively little herbicides (Akobundu, 1987; Ampong-Nyarko and De Datta, 1991). In irrigated production systems where rice is direct-seeded, weeds are the major yield constraints (Becker *et al*., 2003; Diallo and Johnson, 1997). 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 in West Africa (Akobundu, 1980; Diallo and Johnson, 1997; Enyinnia, 1992; Imeokparia, 1994; Johnson *et al.*, 2004). In irrigated rice in West Africa, from the forest zone to the Sahel, poor weed management by farmers was estimated to be responsible for a yield reduction by at least 1 $t\,ha^{-1}$ and it was demonstrated that better weed control by farmers could raise yields by 15% (Becker *et al.*, 2003; Haefele *et al.*, 2000). In areas of rain-fed 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 and Johnson, 2001a,b). These estimates indicate that in sub-Saharan Africa weeds account for rice yield losses of at least 2.2 million tons per year at a value of $1.45 billion (Table 3), in addition to the costs of weed control. These estimated losses equate approximately to half the current imports of rice to the region.[1]

This chapter discusses the major weeds of African rice ecosystems and the various weed management options available to farmers. The objectives of this chapter are to provide an overview and source of reference with respect to weed problems and weed management, to assist with the identification of knowledge gaps and to contribute to the formulation of strategies for research to improve weed management options for rice farmers.

Table 3 Potential annual rice import savings from improved weed management in sub-Saharan Africa, 2008

	Irrigated lowland	Rain-fed lowland	Rain-fed upland
Rice area ('000 ha)[a]	1559	2707	3118
Rice area share SSA (%)	19	33	38
Average yield ($t\,ha^{-1}$)[b]	3.62	1.22	1.28
Annual production (10^3 t)	5648	3316	3998
Weed-inflicted yield loss (%)[c]	15	23	16
Annual production loss (10^3 t)	842	756	648
Potential annual import savings (M $)[d]	543	488	418

[a] Total area under rice in SSA is estimated at 8.2 million ha (FAO, 2008b).
[b] Calculated from Balasubramanian *et al.* (2007) and updated with FAO (2008b).
[c] Based on Becker and Johnson (2001a,b) and Becker *et al.* (2003).
[d] Based on a world rice price (Thai 25%) of \$645 t^{-1} in September 2008 (FAO, 2008a).

[1] FAO Rice Market Monitor (2008a); estimated annual rice imports in 2007 in SSA: 2.7 to 3.0 billion USD.

2. Weed Species in Rice in Africa

2.1. Major problem weeds

Each rice production system harbors weed species well adapted to the environment and management practices. While the weed flora of a specific production system (e.g., lowland or upland) may be similar across different agroecological zones, the abundance of individual species can differ substantially (Akobundu and Fagade, 1978). A review of the literature on weeds in rice-based cropping systems in Africa yielded 130 different weed species (upland: 61; hydromorphic: 31; lowland: 74), 57 of which were reported more than once (upland: 26; hydromorphic: 13; lowland: 30), and 12 were observed in more than one rice ecosystem. These 57 species are listed in Table 4. Most cited weed species of upland areas were *Rottboellia cochinchinensis* (Lour.) W. Clayton, *Digitaria horizontalis* Willd., *Ageratum conyzoides* L., and *Tridax procumbens* L., while *A. conyzoides* and *Panicum laxum* Sw. were most cited in the hydromorphic areas and *Cyperus difformis* L., *Sphenoclea zeylanica* Gaertner, *Fimbristylis littoralis* Gaudich, *Oryza longistaminata* A. Chev. & Roehr., *Echinochloa colona* (L.) Link and *E. crus-pavonis* (Kunth) Schultes were the most cited weeds of lowland rice. Gramineae (43%) and Cyperaceae (37%) were the most prevalent weeds of lowland rice while, in the uplands, weed species composition tended to be more diverse with Gramineae (36%) and Compositae (16%) most prevalent. Weed populations of upland rice are reported to be more dynamic than those of lowland rice areas (Johnson and Kent, 2002). Perennial species accounted for more than 45% of the weed species of lowland rice and only 31% in the upland or hydromorphic rice ecosystems (Table 4).

Commonly only a few weed species dominate the population in each rice ecosystem (Johnson and Kent, 2002) and consequently only a relative small proportion of the species found in rice are considered problem weeds (Diallo and Johnson, 1997). Characteristics that distinguish such species are high competitiveness, high multiplication rates, similarity in appearance with rice, and, in the lowland systems, submergence tolerance. Some problem weeds in rice are annuals with short growth cycles such as *C. difformis* and *D. horizontalis* (40–80 days) and are able to reproduce before rice harvest even when they emerge after the first weeding operation (Johnson, 1997). Such species, if not controlled, are able to build up populations very rapidly. Annual weeds causing problems in upland rice production are *Euphorbia heterophylla* (L.), *D. horizontalis* and the parasitic weeds *Striga* spp. (*S. hermonthica* [Del.] Benth. and *S. asiatica* [L.] Kuntze). Perennials *Cyperus rotundus* and *C. esculentus* as well as the annual *A. conyzoides* are frequently encountered on hydromorphic areas. Perennial weeds of rice in the upland forest and derived upland savanna zones tend to be those that are able to reestablish rapidly after disturbance and

Table 4 Weed species in rice production ecosystems in Africa: species (in decreasing order of citation) names, family, biology, and utility

Species	Fam.	Biology[a]	Use[b]
Upland			
Rottboellia cochinchinensis (Lour.) W. Clayton syn. *R. exaltata*	GRAM	A;C_4	
Digitaria horizontalis Willd.	GRAM	A	
Ageratum conyzoides L.	COMP	A	M, CP
Tridax procumbens L.	COMP	A	M
Eleusine indica (L.) Gaertner	GRAM	A;C_4	F
Euphorbia heterophylla (L.) syn. *E. geniculata* Ortega	EUPH	A	
Imperata cylindrica (L.) Raeuschel	GRAM	P;C_4	M
Paspalum scrobiculatum L.	GRAM	P	AF
Mariscus cylindristachyus Steudal	CYPE	P	
Trianthema portulacastrum L.	AIZO	A;C_4	F/M
Striga hermonthica (Del.) Benth.	OROB[c]	A/ohp	
Striga asiatica (L.) Kuntze	OROB	A/ohp	
Cynodon dactylon (L.) Pers.	GRAM	P;C_4	M
Amaranthus viridis L.	AMAR	A;C_4	
Euphorbia hirta (L.) syn. *E. pilulifera* (L.); *Chamaesyce hirta* (L.) Millsp.	EUPH	A;C_4	M, CP
Commelina benghalensis L.	COMM	A	M
Brachiaria lata (Schum.) C.E. Hubb.	GRAM	A	
Dactyloctenium aegyptium (L.) Willd.	GRAM	A;C_4	
Cyperus rotundus L.	CYPE	P;C_4	
Chromolaena odorata (L.) King & Robinson syn. *Eupatorium odoratum* L.	COMP	P	
Panicum laxum Sw.	GRAM	A	
Calopogonium mucunoides Desv.	LEGU	P	L
Aspilia bussei O. Hoffm. & Muschler	COMP[d]	A	
Pennisetum purpureum Schum.	GRAM[e]	A;C_4	
Boerhavia erecta L.	NYCT	P;C_4	M
Striga aspera (Willd.) Benth.	OROB	A/ohp	
Hydromorphic			
Ageratum conyzoides L.	COMP	A	M
Panicum laxum Sw.	GRAM	A	
Leersia hexandra Sw.	GRAM	P	
Cyperus rotundus L.	CYPE	P;C_4	
Digitaria horizontalis Willd.	GRAM	A	
Eclipta prostrata (L.) L. syn. *E. alba* (L.) Hassk.	COMP	A	
Spilanthes uliginosa Sw. syn. *S. acmella* A. Chev.	COMP	A	M

Table 4 (*continued*)

Species	Fam.	Biology[a]	Use[b]
Commelina benghalensis L.	COMM	A	M
Fimbristylis littoralis Gaudich. syn. *F. miliacea* Vahl	CYPE	A;(C_4)	
Echinochloa colona (L.) Link syn. *E. colonum* (L.) Link; *Panicum colonum* L.	GRAM	A;C_4	AF/F/T
Cyperus esculentus L.	CYPE	P;C_4	
Cynodon dactylon (L.) Pers.	GRAM	P;C_4	M
Rhamphicarpa fistulosa (Hochst.) Benth.	OROB	A/fhp	
Lowland			
Sphenoclea zeylanica Gaertner	SPHE	A	
Cyperus difformis L.	CYPE	A	
Fimbristylis littoralis Gaudich. syn. *F. miliacea* Vahl	CYPE	A;(C_4)	
Oryza longistaminata A. Chev. & Roehr.	GRAM	P	
Echinochloa colona (L.) Link syn. *E. colonum* (L.) Link; *Panicum colonum* L.	GRAM	A;C_4	AF/F/T
Echinochloa crus-pavonis (Kunth) Schultes syn. *E. rostrata* (Stapf) Michael	GRAM	A	
Leersia hexandra Sw.	GRAM	P	
Oryza barthii A. Chev. syn. *O. breviligulata*	GRAM	A	
Cyperus iria L.	CYPE	A;C_4	I
Bolboschoenus maritimus (L.) Palla syn. *Scirpus maritimus* L., *Schoenoplectus maritimus* (L.) Lye	CYPE	P;(C_4)	
Ischaemum rugosum Salisb.	GRAM	A	
Panicum laxum Sw.	GRAM	A	
Ludwigia abyssinica A. Rich. syn. *Jussiaea abyssinica* (A. Rich.) Dandy & Brenan	ONAG	A	
Ammania prieureana Guill. & Perr.	LYTH	A	
Heteranthera callifolia Rchb. ex Kunth	PONT	A	M
Ipomea aquatica Forssk. syn. *I. reptans* Poiret	CONV	P	
Echinochloa pyramidalis Hitch & Chase	GRAM	P	AF/F/T
Cyperus esculentus L.	CYPE	P;C_4	F
Cyperus halpan L. syn. *C. haspan* L.	CYPE	P	
Sacciolepis africana C. E. Hubb. & Snowden	GRAM	P	
Acroceras amplectans Stapf	GRAM	A	
Diplachne fusca (L.) P. Beauv. ex Stapf	GRAM	P	
Panicum repens L.	GRAM	P;C_4	

(*continued*)

Table 4 (*continued*)

Species	Fam.	Biology[a]	Use[b]
Eleocharis spp. (*E. complanata* Boeck; *E. acutangula* (Roxb.) Schultes; *E. mutata* (L.) Roemer & Schultes; *E. dulcis* (Burm. f.) Henschel)	CYPE	A/P	
Fimbristylis ferruginea (L.) Vahl	CYPE	P;(C_4)	
Pycreus macrostachyos (Lam.) Raynal syn. *P. tremulus* (Poiret) C. B. Clarke; *P. albomarginatus* Nees	CYPE	A	
Schoenoplectus senegalensis (Steudel) Raynal syn. *Scirpus jacobii* C. Fischer	CYPE	A;(C_4)	
Ludwigia adscendens (L.) Hara syn. *Jussiaea repens* L.	ONAG	P	
Eclipta prostrata (L.) L. syn. *E. alba* (L.) Hassk.	COMP	A	
Rhynchospora corymbosa (L.) Britton syn. *R. aurea* Vahl; *Scirpus corymbosus* L.	CYPE	P;(C_4)	

[a] A, annual; P, perennial; fhp, facultative hemiparasitic; ohp, obligate hemiparasitic; C_4, C_4 photosynthetic pathway; (C_4), uncertainty about photosynthesis pathways; some species of the genus are C_3 some are C_4.
[b] AF, fodder (animal feed); CP, crop protection (bio-pesticides); F, food; I, insecticide (mosquito control); L, legume (green manure/improved fallow); M, medicinal; T, Thatching (roof material).
[c] Formerly: Scrophulariaceae.
[d] Papilionoideae.
[e] Poaceae.
Source: Akobundu and Fagade (1978), Ampong-Nyarko (1996), Becker and Johnson (1998, 1999a, 2001b), Buddenhagen and Bidaux (1978), Burkill (2004), Diallo and Johnson (1997), Dzomeku *et al.* (2007), Elliot *et al.* (1993), Elmore and Paul (1983), Haefele *et al.* (2000), Harahap *et al.* (1993), Hillocks (1998), Hong *et al.* (2004), Johnson (1997), Johnson and Kent (2002), Johnson *et al.* (1997, 1998a, 2004), Kent *et al.* (2001), Kent and Johnson (2001), Mallamaire (1949), Nyoka (1982), Okafor (1986), Parkinson (1989), Reneaud (1980), Schwartz *et al.* (1998), and Xuan *et al.* (2004).

these include *C. rotundus* L., *C. esculentus* L., *Imperata cylindrica* (L.) Raeuschel, and *Chromolaena odorata* (L.) King & Robinson. Parasitic species *Striga aspera* (Willd.) Benth. and *Rhamphicarpa fistulosa* (Hochst.) Benth. are locally important annual weed species in rice in hydromorphic areas. In forest and savanna lowlands in Africa *S. zeylanica*, *E. colona, C. difformis, C. iria*, and *F. littoralis* are important annual weeds (Kent *et al.*, 2001). In irrigated rice in the Sahel, important grass weeds are *E. colona* and *Ischaemum rugosum* and the wild rice species *O. longistaminata* and *O. barthii* (Diallo and Johnson, 1997). Notable sedges in irrigated rice in the Sahel are the annuals *C. difformis*, *C. iria* and *Pycreus macrostachyos* and the perennial *Cyperus haspan* (Diallo, 1999). Some of these species are discussed in more detail below.

2.1.1. Problem weeds of uplands and hydromorphic zones

a. *Cyperus* spp. In moist to hydromorphic upland areas some of the most intractable weed problems in rice are due to the perennial sedges *C. rotundus* L. (Purple nutsedge) and *C. esculentus* L. (Yellow nutsedge). Tubers and seeds can remain dormant to survive periodic flooding or dry seasons. These species are able to multiply rapidly through tubers which can be greatly accelerated by soil tillage (Holm *et al*., 1991). The tubers can grow from soil depths of more than 0.5 m (Johnson, 1997). Biomass of roots, tubers, and rhizomes of *C. rotundus* can be up to 40 $t\,ha^{-1}$ (Holm *et al*., 1991). The abovementioned characteristics make these species typical weeds of intensely cultivated lands and very difficult to control.

b. *Imperata cylindrica*. The perennial grass *I. cylindrica* (L.) Raeuschel (Speargrass) is a common and persistent weed in many upland crops like cassava, maize, sorghum, and rice. For more than 50% of the farmers surveyed by Chikoye *et al*. (1999) in West Africa, *I. cylindrica* was the most important weed. It reproduces through seeds and rhizomes. The species is particularly difficult to control as it is tolerant to fires and shallow cultivation due to the extensive underground network of rhizomes. The weed tends to be abundant where fields are regularly cultivated and burnt, as it recovers rapidly from disturbance, and burning induces flowering. It exerts great competition on crops (Chikoye *et al*., 2000; Johnson, 1997). The grass is common in the forest to savanna transition zone (Chikoye *et al*., 1999) and is widely adapted (Townson, 1991) but growth is suppressed by shade.

c. *Chromolaena odorata*. The perennial woody shrub *C. odorata* (L.) R. King & H. Robinson (Siam weed) of the Compositae (Asteraceae) family produces large quantities of seeds and is capable of rapid regrowth after being cut (Johnson, 1997). It is a common and dominant species in the upland fields and fallow vegetations of the forest zone and reported by many as a troublesome weed (e.g., Anthofer and Kroschel, 2007; Becker and Johnson, 2001a; Johnson, 1997; Kent *et al*., 2001). *C. odorata* gradually replaces indigenous species in fallow vegetation (Weise, 1995) and this in turn has consequences for the weed community in subsequent crops as it causes a predominance of broad-leaved species such as *A. conyzoides*, *T. procumbens*, and *Phyllanthus amarus* (Ikuenobe and Anoliefo, 2003).

d. *Digitaria horizontalis*. The annual grass species *D. horizontalis* Willd. (Jamaican crabgrass) is wide spread in upland and hydromorphic areas in the savanna and forest zones of Africa (Johnson, 1997; Mallamaire, 1949). It is capable of rapid growth and has become a dominant species in intensively cultivated fields (Johnson, 1997). *D. horizontalis* was observed to replace *I. cylindrica* over 5 years of rice cropping following fallow in Côte d'Ivoire (Johnson and Kent, 2002).

e. *Euphorbia heterophylla*. The annual species *E. heterophylla* L. (Mexican fireplant) of the Euphorbiaceae family is a common and very competitive weed of upland rice in the savanna zones of Africa. It can rapidly form a closed canopy, and it has a life cycle of only about 60 days from germination to seed setting contributing to a rapid buildup of the population. Seeds of *E. heterophylla* are dispersed explosively through its dehiscent seed capsules (Wilson, 1981). Germination occurs throughout the cropping season due to the variable dormancy of the seeds. *E. heterophylla* is particularly problematic in mechanized cropping systems as contamination of fields frequently occurs through machinery; other sources of infestation are seed supply and wild animals (Johnson, 1997). *E. heterophylla* was one of the species that was observed to increase with duration of rice cropping after fallow in Côte d'Ivoire (Johnson and Kent, 2002).

f. *Ageratum conyzoides*. The annual species *A. conyzoides* L. (Billy goat weed or Tropical white weed) is a member of the Compositae family. The species is widespread in moist uplands, hydromorphic and temporary, shallow flooded lands (Johnson, 1997). The tolerance to temporary flooding, abundant seed production, and rapid germination of this species makes it a successful weed in rain-fed rice cropping systems in Africa. *A. conyzoides* has been reported to have medicinal and bioherbicidal applications (Xuan *et al.*, 2004). Such uses however are not widespread.

g. *Striga* spp. Parasitic weeds of the family Orobanchaceae (formerly: Scrophulariaceae) are locally important biotic constraints to upland rice production in the savanna zone of Africa, and these include *Striga hermonthica* (Del.) Benth. (Purple or Giant witchweed), *S. asiatica* (L.) Kuntze (Asiatic or Red witchweed), and *S. aspera* (Willd.) Benth. The first two are almost entirely found in free draining uplands, while the latter is also found on hydromorphic areas (e.g., Ampong-Nyarko, 1996; Buddenhagen and Bidaux, 1978; Johnson, 1997). In West Africa, *S. hermonthica* and *S. aspera* are the most important *Striga* species in rice (e.g., Dugje *et al.*, 2006; Johnson *et al.*, 1997; Parkinson, 1989), while *S. hermonthica* and *S. asiatica* are the dominant species in East African countries like Tanzania, Kenya, and Madagascar (e.g., Elliot *et al.*, 1993; Fujisaka, 1990; Harahap *et al.*, 1993; Mbwaga, 1996; Reneaud, 1980).

Striga spp. (witchweeds) are annual, obligate hemiparasitic weeds on tropical cereal crops like maize, sorghum, and rice. Despite the presence of chlorophyll and photosynthetically active leaves (Press *et al.*, 1991), these parasitic plants can severely reduce growth and development of the infected host plant. They parasitize host roots through a xylem-to-xylem connection made by a special organ, the haustorium (Parker and Riches, 1993). Through this connection, the parasite subtracts host-plant metabolites, water, nutrients, and amino acids (e.g., Press *et al.*, 1987; Rogers and Nelson, 1962) and alters the hormone balance (Drennan and El Hiweris, 1979; Frost *et al.*, 1997; Taylor *et al.*, 1996). Most of the studies showing these effects have been conducted with C_4 hosts (e.g., sorghum and maize), but similar interactions are expected with C_3 hosts such as rice. Susceptible and sensitive rice varieties show stunted growth, low biomass production and failure to flower (Riches *et al.*, 1996). In a study by Cechin and Press (1994), rice plants infected with *S. hermonthica* did not produce any grain. This was partly attributed to reduced shoot growth and partly to reductions of up to 44% in photosynthesis compared to uninfected control plants. Severe crop damage (60–100%) has been reported in cases of heavy infestation with the parasitic weed *Striga asiatica* in Madagascar (e.g., Elliot *et al.*, 1993).

Striga spp. have a very successful life-cycle strategy including a wide host range, an out-crossing nature (with exception of *S. asiatica*), and prolific production of very small (0.2–0.35 mm) seeds (5000–85,000 per plant) with high off-season survival rates (e.g., Andrews, 1945; Krause and Weber, 1990; Parker and Riches, 1993; Stewart, 1990; Webb and Smith, 1996). Their germination depends on the availability of germination signals (xenognosins) (Saunders, 1933; Vallance, 1950; Yoder, 2001) that are exuded by suitable host plants, although some species (so-called false hosts) may provoke germination without supporting parasitism. Van Delft *et al.* (1997) calculated that it would only take 2–3 seeds producing *Striga* plants per m^2 to fully replenish the annual seed-bank losses.

There is evidence that parasitic weed problems are increasing in Africa and this is reported for *Striga* spp. in Nigeria (Dugje *et al.*, 2006) and Ghana (Aflakpui *et al.*, 2008). In Tanzania too, rice farmers witnessed a progressive decline in yields associated with an increased severity of *S. asiatica* infestations (Mbwaga and Riches, 2006).

2.1.2. Problem weeds in rain-fed and irrigated lowlands

a. *Sphenoclea zeylanica*. The annual broad-leaved plant *S. zeylanica* Gaertner (Goosweed or Chickenspike) of the Sphenocleaceae family is very common, widespread (observed from West Africa to Madagascar), and often serious weed, typical of lowland rice (Elliot *et al.*, 1993; Holm *et al.*, 1991; Johnson, 1997; Kent *et al.*, 2001). The species can be very competitive and this may be because of efficient uptake of nitrogen (Biswas and Sattar, 1991), is able to emerge from flooded soils (Kent and Johnson, 2001), and produces large numbers of miniscule seeds.

b. *Cyperus difformis*. The annual *C. difformis* L. (Variable flatsedge or Smallflower umbrella sedge) of the Cyperaceae family is one of the most important weeds in lowland rice in Africa (Diallo and Johnson, 1997; Johnson, 1997). In the irrigated rice areas in Senegal, it is the most common weed species together with *E. colona*. *C. difformis* can be particularly abundant where fields are only intermittently flooded or where land leveling is poor. The weed is well adapted to direct-seeded rice production methods (Johnson, 1997; Rao *et al.*, 2007). It is a problem weed because of its short growth cycle, and it can form dense stands in the rice crop (Johnson *et al.*, 2004) and produce large quantities of seed.

c. *Echinochloa* spp. Species of the genus *Echinochloa* constitute some of the most important and widespread grass weeds in rice worldwide

(Holm *et al.*, 1991). In Africa, the most important species are *E. colona* (L.) Link (Jungle rice or Awnless barnyard grass) and *E. crus-pavonis* (Kunth) Schultes (Gulf barnyard or Gulf cockspur grass). Distinguishing between *E. crus-pavonis* and E. *crus-galli* is difficult due to the morphological similarity and the high level of variation in the species which in turn can vary as a function of environment (Danquah *et al.*, 2002; Holm *et al.*, 1991). *E. colona* and *E. crus-pavonis* can both be found in rain-fed and irrigated lowlands and are often the most dominant species in a rice crop (Diallo and Johnson, 1997; Kent and Johnson, 2001). Like *C. difformis*, *E. colona* thrives on hydromorphic or lowland soils that are only temporarily flooded while *E. crus-pavonis* favors flooded conditions. These are problem weeds due to their close resemblance with rice at the early stages of growth which often causes confusion during transplanting or hand weeding. They are also highly competitive and have short life cycles (seed production within 70 days) and prolific seed production (Johnson, 1997). A single *E. crus-pavonis* plant, for example, can produce more than 20,000 seeds. *E. crus-pavonis* is reported as a host of a number of pathogens including Rice Yellow Mottle Virus and could therefore contribute to survival and spread of this important disease in African rice (Abo *et al.*, 2002).

d. *Oryza* spp. Wild and weedy rices are important weeds in the lowland rice growing areas in Africa. Weedy rices are weedy biotypes of the cultivated rice species *O. sativa* L. and *O. glaberrima* Steudel (Delouche *et al.*, 2007), while wild rices comprise the group of noncultivated rice species. Important wild rice species in Africa are the perennial *O. longistaminata* A. Chev. & Roehr., and the annuals *O. barthii* A. Chev. and *O. punctata* Kotschy ex Steud. (Johnson *et al.*, 1999). In Egypt, weedy/red rices (*O. sativa*) are more common (Delouche *et al.*, 2007).

Wild rice species constitute problems to lowland rice production due to their resemblance with the crop in the early stages and their competitiveness. In later stages, these species are easier to identify because they are tall, vigorous, and awned. Seeds shatter readily and they have variable seed dormancies, making them particularly difficult weeds to control in rice (Delouche *et al.*, 2007). The perennial *O. longistaminata* is difficult to control because of the well-developed underground rhizome system (Johnson *et al.*, 1999). Besides the competition for resources with the crop, wild and weedy rices are the only alternative hosts for the African Rice Gall Midge and important hosts for Rice Yellow Mottle Virus (Johnson *et al.*, 1999), two of Africa's most worrisome biological constraints in rice. Riches *et al.* (2005) reported problems with perennial wild rice (*O. longistaminata*) to be severe in Tanzania, where water cannot be fully controlled such as in the floodplains of the districts of Ifakara (east) and Kyela (south). In Mali, heavy infestation by *O. longistaminata* was reported to reduce rice yields on farmers' fields by up to 85% and also forced farmers to change management practices or abandon fields

(Johnson *et al.*, 1999). In Senegal, where rice is mainly grown in irrigated areas, it is estimated that 50% of the area sown to rice are infested by wild rice species *O. longistaminata* and *O. barthii* (Diallo, 1999). Yield reductions due to the annual wild rice *O. barthii* in Senegal are reported to be as high as 97% (Davies, 1984).

e. *Rhamphicarpa fistulosa*. *R. fistulosa* (Hochst.) Benth is an annual facultative hemiparasitic weed in hydromorphic and rain-fed lowland rice ecosystems of tropical Africa (Johnson *et al.*, 1998b). The plant has white flowers that only open at night time. Flowers are pollinated by moths (Cissé *et al.*, 1996; Parker and Riches, 1993). The seeds are very small (200–550 μm), numerous, and after ripening, the seeds are dormant for 6 months and then only germinate when exposed to humid conditions and daylight (Ouedraogo *et al.*, 1999). Flowering occurs between 70–140 days after sowing the crop (Ouedraogo *et al.*, 1999; Zossou, 2008). *R. fistulosa* is not a common weed but has been widely observed in West Africa (from Senegal to Benin) as well as in East and Southern Africa (e.g., Tanzania and Zimbabwe) (Bouriquet, 1933; Cissé *et al.*, 1996; Johnson *et al.*, 1998b; Kuijt, 1969; Ouedraogo *et al.*, 1999; Parker and Riches, 1993). Locally, it causes important yield reductions in rice, millet, sorghum, maize, and even cowpea (Cissé *et al.*, 1996; Gbehounou and Assigbé, 2003; Hoffmann *et al.*, 1997; Kuijt, 1969; Maiti and Singh, 2004; Neumann *et al.*, 1998; Ouedraogo *et al.*, 1999). As with *Striga* spp. it is difficult to reduce soil seed banks of this species due to its prolific seed production. In addition, *R. fistulosa* is a facultative hemi-parasite, and the control options are seriously limited by its wide host range and relative host independence.

Different studies have reported or predicted increasing problems with *R. fistulosa* in crops, including rice, in West and East Africa (e.g., Gbehounou and Assigbé, 2003; Gworgwor and Ndahi, 2004; Johnson *et al.*, 1998b; Raynal Roques, 1994) and more recently in Benin (Zossou, 2008) and Tanzania (J. Kayeke, personal communication).

2.2. The usefulness of weeds

There is a growing understanding of the importance of ecosystem services to human well-being, and that the world's poor has a disproportionate and direct reliance on these ecosystem services (MEA, 2005). Biodiversity has an important role in supporting and regulating ecosystem services such as nutrient cycling, pest and disease regulation, and pollination (UNEP-WCMC, 2007). Biodiversity describes the abundance and diversity of genes and species, ecosystems, and habitats within a region. Biological interactions are important in maintaining ecosystem services (e.g., relation of predators and prey) and, in this context, weeds have critical, yet poorly understood, roles in the landscape. Weeds are the first stage in the vegetative succession after land clearance or disturbance and, as such, recycle nutrients and protect the soil from erosion. Many weeds found in rice also have one or more direct benefits for African farmers in terms of domestic uses, crop protection and insect (mosquito) control (e.g., Akobundu, 1987; Burkill, 2004; Hillocks, 1998; Schwartz *et al.*, 1998) (Table 4). Some weeds of rice production systems in Africa have been reported useful for the control of other weeds. Examples are a bioherbicide based on *A. conyzoides* (Xuan *et al.*, 2004) or an improved fallow system with *Calopogonium mucunoides* Desv. (Akanvou *et al.*, 2001) or *C. odorata* (Ngobo *et al.*, 2004).

Rice farmers often leave useful species untouched or keep them apart during hand weeding operations (Both, 2006). Wild rice species (e.g., *O. longistaminata*) are sometimes purposely left in the field and harvested by rice farmers to complement cultivated rice production particularly when food is scarce (e.g., Nyoka, 1983). Wild rice species (including *O. barthii* and *O. punctata*) also possess potentially useful traits against a variety of biotic (e.g., drought) and abiotic (e.g., bacterial blight, brown planthopper, and green leafhopper) production constraints (Khush, 1997) and can as such be useful in rice breeding programs.

It has been speculated that wild rice species, and weed species like *E. colona* can, in theory, alleviate intensity of bird attack on rice (Treca, 1985), but the feasibility needs to be established before it could be advocated as a management practice. Weeds and mulches can have marked effects on the population dynamics of arthropods either through the influence of vegetation directly or through attraction of predator populations (Altieri *et al.*, 1985). ''Reliable natural enemy action'' is in part dependent for continuity on the proximity of year round nonrice habitats such as vegetation covered bunds (Way and Heong, 1994). Studies in West Africa showed that ants were the most abundant predators in the rice canopy and abundance of these were greater in areas where weeds occurred (Afun *et al.*, 1999b). Further, there was greater spider activity and beetles were more abundant where there was weed trash on the soil surface in rice fields (Afun *et al.*, 1999a). To enhance abundance and efficiency of natural enemies, some noncultivated plants can be planted as intercrop or in field margins. Examples are grasses, such as molasses grass (*Melinis minutiflora* Beauv.), Napier grass (*Pennisetum purpureum* Schum.), and Sudan grass (*Sorghum sudanensis* (Piper) Hitch.), that attract natural enemies (e.g., *Cotesia sesamiae*) of stem borers (*Chilo* spp.) (Khan *et al.*, 1997; 2000). Managing *Paspalum scrobiculatum* in the field margins may aid the control of African Rice Gall Midge by encouraging parasitoids (Nwilene *et al.*, 2008). Weeds may however serve as hosts and sources of infection for fungal and viral diseases of rice (Ou, 1985). A good understanding of such relations is therefore required to achieve greater regulation of pests, through the maintenance of natural enemies, while avoiding these deleterious effects.

3. Weed Management Practices in African Rice-Based Cropping Systems

3.1. Cultural weed control

3.1.1. Planting methods

Crop establishment is a key factor in determining the outcomes of weed–crop interactions and preventive weed management measures. A vigorous rice crop with a closed canopy denies weeds space and light. Crop establishment involves several steps of land preparation and sowing or planting depending on the agroecosystem. Crop establishment can be improved through soil tillage, land leveling, use of "clean seed," transplanting with healthy seedlings and timely flooding and nutrient management. Such integrated crop management (ICM) practices can reduce the weed problems in lowland rice fields and were shown to increase productivity by 4–25%, depending on the level of water control (Becker and Johnson, 1999a, 2001b; Haefele *et al*., 2000). In the following section, rice establishment methods relevant to rice cropping systems in Africa are discussed; whereas land preparation is discussed in Section 3.2.

In the traditional rice systems in Africa, particularly in the forest zones, shifting cultivation is still common practice (Balasubramanian *et al*., 2007). The crop is sown into the ashes after slash-and-burn, through direct-seeding either by broadcasting or dibbling in the uplands (Ampong-Nyarko, 1996) or by direct-seeding (dibbling) or transplanting on ridges or heaps in the inland valleys (Moormann and Juo, 1986; Windmeijer and Andriesse, 1993).

In irrigated lowland rice, direct-seeding or transplanting is practiced. In the Sahel, the areas under these establishment methods are approximately equal and, for example, in the lower- and middle delta of the Senegal River Valley in Senegal rice is mainly direct-seeded while in the upper delta it is largely transplanted (Diallo and Johnson, 1997). In the humid forest and savanna zones, irrigation schemes are usually smaller, compared to those in the Sahel, and rice is mostly transplanted (Balasubramanian *et al*., 2007). Transplanting is usually done with 25- to 30-day-old rice seedlings, although often much older, and these are either planted in rows or at random.

Compared to direct-seeding, transplanting saves seed, reduces the period the field is occupied and, importantly, it provides the crop with a competitive (size) advantage over weeds. Further, the soil can be flooded immediately after transplanting which suppresses the emergence of the majority of the potential weed species (see Section 3.1.2). Transplanting in rows facilitates the use of labor- and time-saving weeding equipment such as a hoe or a push weeder. Moreover, grasses that have similar appearance as rice, especially in the early stages, are easier to recognize if they occur outside the planting pattern.

Transplanting can cause a shock to rice seedlings which leads to longer growth periods and lower yield potentials (Poussin, 1997). Labor shortages in many areas however motivate farmers to continue to seed directly (Becker and Johnson, 1999a, 2001b). In direct-seeding, seeds may be sown dry as ungerminated seeds or "wet" as pregerminated seeds which are often sown into shallow water to reduce weed problems. Unless fields are well leveled, however, this may not result in effective weed control as the water layer will be of variable depth (Diallo and Johnson, 1997). Direct-seeded and transplanted rice have equivalent yields when weeds are properly controlled (De Datta *et al.*, 1968), and direct-seeding can save labor compared to transplanting (Akobundu and Fagade, 1978). An agroeconomic study on rain-fed lowland rice in Southern Senegal, however, concluded that, overall, transplanting is less time-consuming, fits in better with other farm activities, and requires less fertilizer than direct-seeding of rice (Posner and Crawford, 1991).

The "plasticity" of plants with respect to the available resources implies that there is a wide range of planting densities with more or less constant crop yield levels (Harper, 1977; Radosevich, 1987). Increasing the plant density within this range would in theory only increase a crop's competitive advantage over weeds with no concomitant negative consequences for crop yield. This is the case with rice, and varying the plant population density is an option for improving its competitiveness. Increased seeding rates have been proposed and tested as a component for improved weed management (e.g., Akobundu and Ahissou, 1985; Cousens, 1985; Fagade and Ojo, 1977; Kristensen *et al.*, 2008; Mohler, 1996). In the irrigated rice production schemes in the Sahel, (direct) sowing densities of up to 200 kg seed ha^{-1} have been observed (Diallo and Johnson, 1997). As seeding density surpasses a certain level, increased intraspecific competition may result in a poor crop growth (e.g., Rao *et al.*, 2007).

3.1.2. Flooding

Flooding is one of the most important weed management options in lowland rice (Diallo and Johnson, 1997) as many weeds will not germinate in anaerobic conditions. Maintaining a flood layer of 5–10 cm or more suppresses the growth of most species (Akobundu, 1987) and it is this means to limit weed growth that has enabled the sustainability of transplanted lowland rice. Even superficial flooding (2 cm of flood water) can reduce growth of one of the most noxious weeds, *Echinochloa crus-pavonis* (Kent and Johnson, 2001). This may require however that the soil remains flooded for prolonged periods throughout crop establishment as drainage or shallow flooding may encourage the emergence of grass weeds such as *Leptochloa chinensis* and *Echinochloa* spp. (Hill *et al.*, 2002).

It is the timing, duration, and depth of flooding that determines the extent of weed suppression by flooding (Mortimer *et al.*, 2005). Weeds tend to be recruited in the early stages of the rice crop and management of water at these stages can be critical in determining the nature and abundance of the weed flora. In a study of wet-seeded rice sown on puddled soil, where the soil was flooded 10–15 DAS after seeding, the recruitment of sedges and broad-leaves occurred in the early stages of the crop while grass weeds continued to increase in density up to 60 days after sowing (Hill *et al.*, 2002). In dry-seeded rice, the pattern of germination is likely to be determined by the moisture regime and the timing of flooding. As weed seedlings are reliant largely on the seed reserves to enable them to emerge from flooded conditions, seed size will influence the ability of species to establish under flooded conditions. *C. difformis* for instance might already be suppressed by 0.8 cm of turbid water while for suppression of *L. chinensis* 1.5 cm or more would be necessary and *Echinochloa crus-galli* has sufficient seed reserves to emerge from 8 cm of water (Chauhan and Johnson, 2008e; Mortimer *et al.*, 2005). Another variable is dormancy and while this may be pronounced or variable in some species, others (e.g., *Fimbristylis miliacea* and *E. colona*) exhibit no dormancy and germinate rapidly on the surface of puddled soil (Kim and Moody, 1989).

Farmers require appropriate field infrastructure to precisely manage flooding and drainage in the field to exploit differentials between rice and weeds. For effective control of weeds by flooding, fields need to be well leveled to ensure uniform water depth. Good land leveling requires skills and equipment not commonly available to resource-poor farmers in this region. As a result, uniform flooding is often difficult to achieve and therefore other control methods need to be integrated to provide adequate weed control (Akobundu, 1987).

3.1.3. Soil fertility management

Weeds have been observed to have less effect on adequately fertilized crops compared to unfertilized crops due to the more vigorous crop growth (e.g., McKenzie, 1996; Tollenaar *et al.*, 1994). It has also been demonstrated however that, for example, *Echinochloa* sp. responded more to fertilizer than the rice (Gibson *et al.*, 1999). Timing of fertilizer application may be very important with respect to its influence on the outcome of competition. Early fertilizer applications stimulate weed growth especially of weeds with small seed sizes that have little reserves (Liebman and Davis, 2000). In upland rice in the forest zone of West Africa, N application tended to increase weed growth and only benefited yields when it was accompanied by improved weed control (Becker and Johnson, 2001a). While farmers commonly recognize the importance of combining improved weed management with fertilizer applications, data from Africa on the impact of improved rice crop nutrition on competition with weeds are very limited.

Improved soil fertility is important for the effective management of parasitic weeds (e.g., Ransom, 2000). The application of urea at 3 weeks after sowing reduced the number on *S. asiatica* infections in rice in Tanzania

(Riches *et al.*, 2005). Further, application of 90–120 kg N ha^{-1} proved an adequate method to delay and reduce *S. hermonthica* infestation and ensure satisfactory crop yields in upland rice in Nigeria (Adagba *et al.*, 2002a). Improved yields may be the result of reduced and delayed parasitism rather than improved host performance (Cechin and Press, 1994), but the costs of these applications may be a constraint to farmer adoption (Riches *et al.*, 2005).

3.1.4. Mulching

Mulching is a feasible option in upland rice but not widely practiced in Africa. Mulching with residues from trees (Budelman, 1988; Kamara *et al.*, 2000; MacLean *et al.*, 2003) or crops (e.g., Iwuafor and Kang, 1993; Singh *et al.*, 2007) has shown to suppress weeds in cereal crops, including rice. Mulching can inhibit weed seed germination by shading and in some cases through the release of allelopathic substances (e.g., Akobundu, 1987; Singh *et al.*, 2003). Rice straw proved an effective mulch material to reduce weed growth (Lal, 1975). A limitation of this practice is the limited availability of suitable mulching material in many parts of Africa. Rice straw, for instance, also has an economic value in many areas as it is often used for forage or fuel. Mulching can also hinder rice establishment, encourage pests such as termites (Akanvou *et al.*, 2000) or, in the case of rice straw, facilitate the survival and spread of rice diseases over the off-season.

3.1.5. Mixed cropping, rotations, and fallow

Intensifying cropping systems can result in an increase in weed growth, increasing losses due to weeds and, with inadequate control, larger soil seed banks (Akobundu *et al.*, 1999; Ekeleme *et al.*, 2000). Traditionally, rain-fed rice farmers in Africa use fallow and rotations to interrupt the buildup of weeds. Rotations with noncereal crops like cowpea and soybean in the savanna and forest uplands and groundnut, soybean, cassava, potato, sweet potato, or vegetables in the rain-fed lowlands are often practiced in subsistence rice-based production systems. Changes in management and crop rotations help prevent the buildup of crop-specific weeds (Akobundu, 1987). Improved fallows and intercropping can be effective measures but their introduction, where these are not already traditional practice, has met with limited success (see below).

In the humid forest zones, African rice farmers traditionally manage weeds and other stresses through long fallow periods in shifting cultivation systems. In the Taï forest in Côte d'Ivoire, for instance, a single crop of rice may be followed by many (up to 20) years of fallow (de Rouw, 1995). In such extensive systems, weed population buildup is limited and farmers need little effort for additional control (de Rouw, 1995). Such practice is still common in some areas (Ampong-Nyarko, 1996; Johnson, 1997) but becoming less frequent. With human population growth and concomitant increased pressure on land, fallow lengths are progressively being reduced (Braimoh, 2006; de Rouw, 1995; Demont *et al*., 2007). Cropping intensification in these systems may lead to an increase in the losses due to weeds (Becker and Johnson, 2001a). Consequently, there is a clear trade-off between fallow length and weeding labor requirements (Dvorak, 1992). The significance of weed management in the traditional upland rice production systems is underscored by the fact that weeding can require 29% of all the time needed for cropping operations including clearing, soil tillage, planting, harvest, and transport (Windmeijer and Andriesse, 1993).

To facilitate intensification in upland rice systems, relay cropping with weed-suppressing legumes may be a viable alternative to reduce weed growth and improve soil fertility (Becker and Johnson, 1999b). Species choice and planting date need to be carefully chosen to avoid the threat of severe competition for resources between the legume and the rice. Sowing of *Cajanus cajan* 56 days after rice proved an appropriate management practice in this respect (Akanvou *et al*., 2002). Legumes may continue to grow after rice harvest and thereby suppress weeds during the off-season. Such "short fallow" rotation systems were shown to increase rice yields (20–30% across agroecosystems) and lower weed pressure in the forest and savanna zones of West Africa (Akanvou *et al*., 2000; Becker and Johnson, 1998, 1999b). Legume species proposed for improved fallows in rice-based cropping systems in Africa are summarized in Table 5. Best-bet legumes for upland cropping systems in different agroecological zones have been proposed (Becker and Johnson, 1998, 1999b). Fallow species including *Cassia occidentalis* L. (Mallamaire, 1949) and *Aeschynomene histrix* (Merkel *et al*., 2000) were reported to control *S. hermonthica*. *A. histrix* acted as "trap crop" in infested fields by stimulating the germination of *Striga* seeds without supporting parasitism.

Intercropping with a legume crop is another cultural practice to reduce weed problems. For instance in India, Sengupta *et al*. (1985) showed that intercropping upland rice with black gram (*Vigna mungo* [L.] Hepper) contributed to improved weed suppression compared to rice monoculture. Successful examples of intercropping in rice-based systems in Africa are scarce. For the control of *Striga* spp., rotations or the use of intercrops especially with "trap crops" like cowpea (e.g., Carsky *et al*., 1994b), yellow gram (Oswald *et al*., 2002), pigeon pea (e.g., Oswald and Ransom, 2001), soybean (e.g., Carsky *et al*., 2000; Robinson and Dowler, 1966), groundnut (Carson, 1989), or cotton (e.g., Murdoch and Kunjo, 2003) has been proposed. Most of these crops grow in similar environments as upland rice and could fit existing cropping systems. For example, rotations with *Crotalaria ochroleuca* or pigeon pea in Tanzania resulted in improved rice productivity in *S. asiatica* infested fields, reduced *Striga* infection and the number of weeding operations required (Riches *et al*., 2005). Intercropping with the fodder legumes Silverleaf (*Desmodium uncinatum*) and Greenleaf

Table 5 Suitable legume species for weed-suppressive fallow rotations or intercrops in African rice-based cropping systems

Species	Ecosystem	Spatial and temporal arrangement	Characteristics and traits	Sources
Aeschynomene afraspera	Rain-fed lowland	Off-season fallow	Biomass accumulation Weed suppressive	Becker and Johnson (1999b)
Aeschynomene histrix	Savanna and forest upland	Relay seeding or off-season fallow, burning of residues	High N accumulation Forage value Weed suppression *Striga hermonthica* trap crop	Becker and Johnson (1999b), Becker and Johnson (1998), and Merkel *et al.* (2000)
Cajanus cajan	Forest and savanna upland	Off-season fallow, burning or mulching of residues	High N accumulation Weed suppressive	Becker and Johnson (1998) and Akanvou *et al.* (2000)
Canavalia ensiformis	Savanna and forest upland	Off-season fallow	High N accumulation Forage value Weed suppression	Becker and Johnson (1999b), Becker and Johnson (1998), and Akanvou *et al.* (2000)

Cassia occidentalis	Upland	1 year fallow	*Rhamphicarpa fistulosa* and *Striga* spp. control	Mallamaire (1949)
Crotalaria anagyroides	Forest upland	Off-season fallow	Weed suppressive	Becker and Johnson (1998)
Crotalaria juncea	Savanna upland and rain-fed lowland	Off-season fallow	Weed suppressive	Becker and Johnson (1999b) and Becker and Johnson (1998)
Crotalaria ochroleuca	Upland	Rotation	*Striga asiatica* control	Riches *et al*. (2005)
Mucuna spp.	Savanna upland	Off-season fallow	High N accumulation Weed suppressive	Becker and Johnson, (1999b) and Becker and Johnson (1998)
Sesbania rostrata	Rain-fed lowland	Off-season fallow	Biomass accumulation Weed suppressive	Becker and Johnson (1999b)
Stylosanthes guianensis	Savanna and forest upland	Relay seeding or off-season fallow, burning of residues	High N accumulation Weed suppressive	Becker and Johnson (1999b) and Becker and Johnson (1998)

(*D. intortum*) was also shown to reduce *S. hermonthica* infestations in maize in East Africa (Khan *et al*., 2006). *Desmodium* spp. is suggested to have an allelopathic effect on *Striga* spp. (Khan *et al*., 2002). Further, a modeling study showed that the use of a ''trap crop'' to reduce the *Striga* soil seed bank was more effective when the legume was being intercropped rather than grown separately in a rotation (van Mourik *et al*., 2008).

Legumes or cover crop species need to be rotated to avoid the buildup of detrimental weeds and pests (Teasdale, 2003). At the end of the fallow period, legumes may be cut and burnt, removed, incorporated in the soil, or mulched in order to avoid unnecessary competition to the subsequent rice crop. The best residue management, from a weed management perspective, appeared to be burning in the forest zones (Akanvou *et al*., 2000; Tonye *et al*., 1997) and incorporation in the soil in the savanna zones (Akanvou *et al*., 2000). Residue burning results in less weed infestation in subsequent crops than soil incorporation (Akanvou *et al*., 2000). Burning, however, causes substantial loss of nitrogen to the atmosphere (e.g., Juo and Mann, 1996), and destruction of the protective surface litter layer increases the risk of erosion (e.g., Alegre and Cassel, 1996).

Intercropping, improved fallow systems, relay cropping or rotations with legumes have had low farmer adoption rates in Africa. Some reasons for this are the additional labor and energy required for clearing and incorporation of the legume into the soil, a poor fit with traditional cropping systems, lack of land tenure, subsequent poor crop establishment and additional costs of inputs (Faulkner, 1934; Langyintuo and Dogbe, 2005; Tarawali *et al*., 1999). *Desmodium* spp., for instance, may have little potential for adoption as the species has proved difficult to establish, has a limited geographical range, and would only have any economic value as a fodder in mixed farming systems (Gressel and Gebrekidan, 2007). Direct economic benefit proved imperative for legumes to be acceptable for farmers in West Africa (Becker and Johnson, 1999b).

3.2. Mechanical weed control

Mechanical weed control can be applied as an intervention within the crop, and as a preventative measure as part of preseason land preparation or as off-season dry-soil tillage. Preventive mechanical weed control options can be differentiated as either off-season soil tillage between harvest and establishment of the next crop or land preparations prior to crop establishment that may include tillage, leveling, and puddling. Off-season dry-soil tillage at sufficient depth may help breaking and drying subsoil rhizomes of perennial weeds. Tillage in dry-soil tillage is often however too superficial to bury weed seeds or control perennial species (Diallo and Johnson, 1997) particularly where mechanization is limited. When soil is sufficiently moist, for instance, after the first rains at the onset of the rainy season, several tillage passes with sufficient time intervals enable weeds to germinate can limit following weed growth (Diallo and Johnson, 1997).

Land preparation on small-scale farms in rain-fed systems is usually undertaken manually and commonly with a short-handled hand hoe. In some inland valleys (e.g., in Sierra Leone, Côte d'Ivoire) animal traction or small power tillers have been introduced (Ampong-Nyarko, 1996) but many rice farmers in Africa are restricted by scarce resources and limited availability of animals. The latter may be determined by the presence of the Tsetse fly. In larger, irrigated schemes as found in Egypt, Madagascar, and Nigeria, however, land preparation is often mechanized (Akobundu, 1987) with medium and large, twin-axle tractors (Wanders, 1986). In these situations, land may be prepared by wet rotovation (Ampong-Nyarko, 1996) or by using disc ploughs or harrows (van der Meijden, 1998).

Due to a common lack of equipment and mechanization in the rain-fed lowland production systems, fields are often inadequately tilled, bunded, and leveled. Unleveled land and the absence of bunds in the inland valleys result in uneven flooding and patchy conditions which favors weed growth and increases weed control costs (Akobundu and Fagade, 1978; Ampong-Nyarko, 1996). Puddling, or the thorough tillage of flooded soil, besides controlling any established weeds, promotes vigorous rice growth and enhances crop competitiveness with weeds (De Datta and Baltazar, 1996). Soil puddling is not widely practiced in Africa, as it is in Asia, which is perhaps primarily due to the lack of draught animals and small power tillers noted above.

Hand weeding is the most widely practiced intervention against weeds on small-scale rice farms in Africa (e.g., Adesina *et al*., 1994), yet this is labor demanding, and requires 250–780 man h ha^{-1} (Akobundu, 1987; Akobundu and Fagade, 1978; Stessens, 2002). Using this labor requirement, and assuming eight working hours a day at a daily wage of €1.5 per person, weeding costs range from €48 up to €149 per ha. This, however, assumes that farmers have alternative opportunities for employment that pay €1.5 per person or more. Vissoh *et al*. (2004) showed that hand weeding costs (€57 per ha) were comparable to the costs of applying herbicide (Garil) to rice (€58 per ha) in Benin. On subsistence farms, weeding is mostly carried out by women from the farm household and involvement of children is common. On larger farms, labor for hand weeding may be hired from outside the farm family and, in these cases, costs can exceed those for herbicide use.

Provided adequate labor is available, hand weeding is an effective method to prevent weeds from producing seeds. In deep-water rice, for instance, it is suggested as the most effective management practice for *O. barthii* (Catling, 1992). However, for most perennial weeds, such as *O. longistaminata* and *I. cylindrica*, hand weeding alone is unlikely to provide adequate control (Akobundu, 1987) as these are capable of rapid regrowth from rhizomes. A further disadvantage of hand weeding is that weeds need to grow tall enough to be hand pulled, by which time competition for resources, extraction of metabolites, or phytotoxic effects in case of parasitic weeds has already taken place.

Hand hoes or push weeders are often used in row sown crops providing rows are spaced wide enough (Rijn, 2001), and the implements are available to farmers. A shortcoming of such devices is that it does not target weeds in the row and when used close to the rice plant they may also cause crop damage (Navasero and Khan, 1970). The use of power tillers or tractors for mechanical weeding is not common in West Africa and, for instance, only 4% of the rice area is mechanized in Senegal (van der Meijden, 1998). In irrigated systems in river deltas, such as the Senegal and Niger rivers, the clay soils seriously limit the effectiveness of mechanized weeding during the cropping season. Attempts at mechanization in the Senegal River Valley have failed due at this constraint in addition to the limited financial resources of most rice farmers (Diallo and Johnson, 1997).

To prevent weed induced yield losses, two to three weeding operations are required for upland and three for hydromorphic and flooded rice (Ampong-Nyarko and De Datta, 1991). Despite recommendations to the contrary however, weeding is frequently inadequate or delayed, often due to labor shortages or conflicts between on- and off-farm activities (Johnson *et al.*, 1998a).

3.3. Rice varietal development for improved weed control

In rice systems where farmers have scarce resources and use few external inputs, as often found in Africa, rice varieties that suppress weeds maintain high yields under weedy conditions and are well adapted to the local conditions would bring considerable advantages to resource-poor farmers (Johnson *et al.*, 1998a). In morphological terms, weed competitive rice varieties are suggested to be those that are tall and have a high tillering ability, a high specific leaf area (SLA = leaf area per leaf dry weight), erect to droopy leaves and relative long crop durations to compensate from losses suffered during early weed competition (Asch *et al.*, 1999; Dingkuhn *et al.*, 1998, 1999; Fofana and Rauber, 2000). Cultivars of the African rice species *Oryza glaberrima* have shown yield advantages under weedy conditions compared to the Asian *O. sativa* varieties (Johnson *et al.*, 1998a). There are possible trade-offs between various competitive characteristics (e.g., Dingkuhn *et al.*, 1999; Perez de Vida *et al.*, 2006) or between competitive traits and yield potential (e.g., Jannink *et al.*, 2000; Jennings and Aquino, 1968; Kropff *et al.*, 1997). Although some studies showed that such trade-offs are no general phenomena (e.g., Garrity *et al.*, 1992; Haefele *et al.*, 2004; Pernito *et al.*, 1986), many desirable morphological characteristics with respect to weed competitiveness may have negative effects on yield potential. For instance, characteristics associated with high yielding modern varieties, such as short stature and erect leaves, are considered to be unfavorable for weed suppression (Johnson *et al.*, 1998a). Droopy leaves, on the other hand, may shade out weeds but limit light penetration to lower rice leaves, while tall rice plants may compete for light more effectively than shorter plants but these may be more prone to lodging (Bastiaans *et al.*, 1997). While *O. glaberrima* can be competitive with weeds, they have low yield potentials and yield losses are incurred due to lodging and grain shattering (Dingkuhn *et al.*, 1998; Jones *et al.*, 1997; Koffi, 1980). Interspecific hybrids of *O. sativa* and *O. glaberrima* were developed with higher yield potential and without the seed shattering characteristic. Varieties derived from these interspecific crosses were named New Rice for Africa (NERICA) and currently comprise 18 upland and 60 lowland varieties (Rodenburg *et al.*, 2006b), of which 17 upland and 11 lowland varieties have been released in SSA (I. Akentayo, personal communication). Early observations on these varieties, developed for the upland areas, have shown that some putative traits of the *O. glaberrima* parent, contributing to weed suppressiveness, and traits of the *O. sativa* parent, contributing to yielding ability, are heritable (Dingkuhn *et al.*, 1999; Johnson *et al.*, 1998a; Jones *et al.*, 1997). In a recent study carried out in two upland environments in Nigeria, compared to the popular check variety ITA150 and the NERICA parents (WAB56-104 and CG14), NERICA-1, -2, and -4 generally had slightly higher weed infestation levels and relative yields losses due to weed competition (Ekeleme *et al.*, 2009). In the same study, however, all three NERICA varieties had higher yields than CG14 and ITA150 when the crop was weeded one or two times. Another recent study carried out in a lowland environment in Benin, showed that nine lowland varieties of NERICA (NERICA-L-6, -32, -35, -37, -42, -53, -55, -58, and 60) have significant higher yields than both lowland NERICA parents under weedy and weed-free conditions, and comparable yield performances as the high yielding and weed competitive check variety Jaya (Rodenburg *et al.*, 2009).

Even though varietal differences in weed competitiveness have been found in rice (Fischer *et al.*, 2001; Garrity *et al.*, 1992; Zhao *et al.*, 2006a), so far, only a limited number of varieties are confirmed to combine superior weed competitiveness with good adaptation to African rice ecosystems. In upland fields in Côte d'Ivoire, *O. glaberrima* varieties IG10 (Fofana and Rauber, 2000), CG14, and CG20 (Jones *et al.*, 1996) were found to be superior in suppressing weeds but also had low yield potential. On hydromorphic soils in Nigeria, the tall variety OS6, incurred 24% less yield reductions from weed competition than the semidwarf cultivar ANDNY11 (Akobundu and Ahissou, 1985). In Senegal, Haefele *et al.* (2004) reported that lowland rice variety Jaya was weed competitive and high yielding compared to a range of varieties. Jaya incurred lower yield losses due to weeds (<20%) compared to popular Sahel 108 (>40%). Superior performance of Jaya under both weedy and weed-free conditions was confirmed in a study carried out in Benin (Rodenburg *et al.*, 2009). This study also identified nine superior lowland NERICA varieties as noted above. Table 6 lists some *O. glaberrima*, *O. sativa*, and interspecific rice varieties that have shown to be weed competitive in Africa. Varieties with superior levels of weed competitiveness have been confirmed in other regions, such as Apo and UPLRi-7 in Asia (Zhao *et al.*, 2006a; 2007), Oryzica Sabana 6 in Latin America (Fischer *et al.*, 2001), and M-202 in north America (Gibson *et al.*, 2001), and these could be tested under African rice production conditions in the future.

It was suggested, but not demonstrated, that the weed-suppressive ability of IG10 (*O. glaberrima*) may be, in part, due to allelopathy (Fofana and Rauber, 2000). A large number of reviews has already been published on crop allelopathy (e.g., Belz, 2007; Olofsdotter *et al.*, 2002; Singh *et al.*, 2003; Weston and Duke, 2003; Xuan *et al.*, 2005). Crop allelopathy refers to the process of the release of chemical compounds by living and intact roots of crop plants that affect plants of other species (Belz, 2007; Olofsdotter *et al.*, 1999a; Weston and Duke, 2003). Allelopathy is suggested by many as one of the potential mechanisms to suppress weeds and as a possible component in integrated weed management (IWM) (e.g., Belz, 2007; Fofana and Rauber, 2000; Jordan, 1993; Olofsdotter *et al.*, 2002; Weston, 1996; Weston and Duke, 2003). Weed suppressiveness and allelopathy may, however, be confounded and they may coexist in the same variety (e.g., Olofsdotter *et al.*, 1999a). Indeed, as Rao *et al.* (2007) suggest, the significance of allelopathy for weed management in rice will remain conjecture until it is clearly demonstrated that differences observed in bioassays also occur in the field.

The use of weed competitive varieties is unlikely to be feasible as a stand-alone technology but rather it may be a valuable component of integrated measures. Suitable varieties should, in addition to weed competitiveness, also possess other traits (Dingkuhn *et al.*, 1999) like resistance or tolerance to other biotic and abiotic stresses. Furthermore, a suitable variety needs to be well adapted to the environment and have the specific characteristics desired by farmers and consumers.

Rice varietal development may contribute to the management of parasitic weeds in rice. Differences among *O. sativa* and *O. glaberrima* in the interaction with *Striga* spp. have been observed, and a selection of African rice species (*O. glaberrima*) showed greater *Striga* resistance than *O. sativa* varieties (Johnson *et al.*, 1997, 2000; Riches *et al.*, 1996). An *O. glaberrima* cultivar, CG14, showed resistance against *S. hermonthica* and *S. aspera* (Johnson *et al.*, 1997; Kaewchumnong and Price, 2008). This was not expressed in the progenies (F7) from interspecific hybrid of CG14 with the *O. sativa* WAB56-104 and it appeared that the resistance to *Striga* may have been lost during the repeated back-crossing (Johnson *et al.*, 2000). In another study carried out by Gurney *et al.* (2006), many of the *O. glaberrima* varieties (including CG14) that showed resistance in the field

Table 6 A selection of rice varieties with proved superior levels of weed competitiveness in African production systems

Ecosystem	Variety	Species	Main superior traits	Sources
Upland	IG10	*O. glaberrima*	Biomass; Tiller number; LAI; SLA; Early vigor; Yield under weedy conditions; Root length density	Johnson *et al.* (1998a) and Fofana and Rauber (2000)
	CG14	*O. glaberrima*	SLA; Tillering; Early vigor; Weed suppression	Asch *et al.* (1999), Dingkuhn *et al.* (1998), and Jones *et al.* (1996)
	CG20	*O. glaberrima*	SLA: Tillering; Early vigor; Weed suppression	Jones *et al.* (1996)
	ACC102257	*O. glaberrima*	Root length density	Fofana and Rauber (2000)
	WAB96-1-1	*O. sativa*	Height; Weed suppression	Jones *et al.* (1996)
	SP4	*O. sativa*	Height; Weed suppression	Jones *et al.* (1996)
Lowland	Jaya	*O. sativa*	Yields under weedy and weed-free conditions; Weed suppression	Haefele *et al.* (2004) and Rodenburg *et al.* (2009)
	TOG5681	*O. glaberrima*	Weed suppression	Rodenburg *et al.* (2009)
	NERICA-L -6, -32, -35, -37, -42, -53, -55, -58, and -60	interspecific	Yields under weedy and weed-free conditions	Rodenburg *et al.* (2009)

in Côte d'Ivoire were found to be susceptible in the lab. This could be due to differences in *Striga* species and strains, growing conditions, or differences in screening methods used (detail or moment of observation). It has been observed earlier that the expression of *Striga* resistance or tolerance may differ between pot and field trials (e.g., Omanya *et al.*, 2004; Riches *et al.*, 1996; Rodenburg *et al.*, 2005). As even highly resistant crop varieties have been shown to be susceptible to infection by *Striga* spp., breeders should aim at incorporation of tolerance into the resistant material (Haussmann *et al.*, 2001; Pierce *et al.*, 2003; Rodenburg *et al.*, 2005).

3.4. Biological weed control

No published evidence is available on farmer adoption of biological weed control in rice in Africa. The possible reasons for this are yet to be validated but the implementation of biological control has a number of intrinsic constraints and, further, smallholder farmers have limited access to the technologies. Biological control agents are generally very host specific and their use requires a relative high skill level to put them in practice. This knowledge is often lacking among poor farmers in Africa (e.g., Abate *et al.*, 2000; Riches *et al.*, 1993).

Outside of Africa, suitable candidate pathogens have been identified for the biological control of weeds that also occur in African rice systems, such as *Dactylaria higginsii* against *C. rotundus* and *C. iria* (Kadir and Charudattan, 2000) and *Alternaria alternata* to control *S. zeylanica* (Masangkay *et al.*, 1999). Hong *et al.* (2004) found allelopathic properties in some wild plants in Vietnam that could be used for biological control. Two of these plants (*Bidens pilosa* and *Euphorbia hirta*) are also found as upland rice weeds in Africa and therefore may have relevance for biological control in rice cropping systems. Another rice weed with putative potential for use in a bioherbicide is *A. conyzoides* (Xuan *et al.*, 2004). The leaf-feeding moth *Pareuchaetes pseudoinsulata/insulata* has been released in Ghana, Nigeria, and South Africa for the control of *C. odorata* in plantations (Gunasekera and Rajapakse, 1994; Kluge and Caldwell, 1993). No reports are available however on the use of such biological agents in rice cropping systems in Africa.

Biological control may have a role in the management of invasive weeds and, for example, some biological control methods tested on *Striga* spp. in maize and sorghum could be applied in rice-based cropping systems. Larvae of the weevil *Smicronyx* spp. (Coleoptera: Curculionidae) feed on *Striga* spp. seeds inside their capsules and prevent seed production (Pronier *et al.*, 1998) but their effectiveness as biological control agent is limited (Smith *et al.*, 1993). Pathogenic fungi like *Fusarium* spp. may be used as biological control against *Striga* spp. (Ahmed *et al.*, 2001). The low virulence of some plant pathogens is reported as a constraint to the application of biological control, and control agents are rarely able to eradicate an established weed population or reduce the invasion of weed species into new areas (Sands *et al.*, 2007). This may in part be due to the evolutionary necessity of allowing some host plants to persist in order for the pathogen itself to survive (Gressel *et al.*, 2007; Sands *et al.*, 2007). Some promising results with fungal pathogens have however been obtained and, for example, *Fusarium* (i.e., *F. oxysporum* and *F. solani*) was shown to reduce *Striga* emergence by up to 98% (Abbasher *et al.*, 1995; Kroschel *et al.*, 1996). The use of rhizobacterial strains such as *Pseudomonas fluorescens* and *P. putida* isolates, as seed treatments, may be useful as biological control agents (Ahonsi *et al.*, 2002) if phytotoxic effects on the crop can be precluded. Field inoculation with arbuscular mycorrhizal fungi was found to be an effective biological control method against *S. hermonthica* in sorghum (Lendzemo *et al.*, 2005).

These options could have useful applications in rice-based cropping systems although there are major ''bottlenecks'' for these technologies that include the lack of availability of the pathogens and their limited suitability for smallholder systems. For example, inoculum needs to be brought to the field and incorporated into the soil in sufficiently high quantities. This could be achieved either through seed coatings (Ciotola *et al.*, 2000) or via granular formulations (Elzein, 2003; Marley and Shebayan, 2005) at time of crop sowing. The formal seed-supply systems in sub-Saharan Africa are, however, weak (Balasubramanian *et al.*, 2007) and specialized agro-industries limited, and hence technologies dependent on such infrastructures are unlikely to become widely available to farmers in the near future. Establishment of public–private partnerships or training programs for on-farm production of inoculum and application-media might provide a necessary shortcut for such developments.

3.5. Chemical weed control

3.5.1. Conventional chemical weed control

Herbicides are important control methods in the lowlands, and in upland rice grown in rotation with cotton (Johnson, 1997). 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 (e.g., Akobundu and Fagade, 1978; Babiker, 1982; Riches *et al.*, 2005). Herbicides are likely to be particularly useful in areas where labor is in short supply. Farmers should also have sufficient financial resources to invest in herbicides and the return of such investments should be high enough. In the rain-fed rice production systems in the Casamance (South Senegal) herbicides were found to be a profitable investment on fertile soils (Posner and Crawford, 1991). Herbicides are often used in combination with other control options and, for example, in the irrigated rice systems in Senegal, most farmers rely on chemical weed control followed by hand weeding (e.g., Haefele *et al.*, 2002).

For effective and safe herbicide use, the appropriate product, application equipment and application rates are important (Zimdahl, 2007). Moreover, herbicide application requires good timing with respect to crop and the growth stage of weeds (King and Oliver, 1992), weather conditions (Hammerton, 1967) and flooding. Interactions between flooding and herbicides tend to be product specific (Ampong-Nyarko and De Datta, 1991). Good chemical weed control under conditions of imperfect water management has been reported with different mixtures of propanil with thiobencarb, oxadiazon, and fluorodifen (Akobundu, 1981).

Farmers require the knowledge on exactly how and when to apply herbicides to achieve effective control (Haefele *et al.*, 2000; Hill *et al.*, 2002). In Africa, where farmers generally have limited access to information and where literacy rates are low, the knowledge of proper herbicide use is often inadequate. Due to this, it is common that herbicide applications are too late, the herbicides poorly applied, 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 (e.g., Gitsopoulos and Froud-Williams, 2004; Johnson *et al.*, 2004; Riches *et al.*, 2005). In turn, this may cause reduced crop vigor or plant population densities and increased weed competition. 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 *et al.*, 2007). The incorrect use of herbicides, caused by the above cited problems, may accelerate the evolution of herbicide resistance in weeds (Johnson, 1995).

As mentioned above, good water control in lowland rice is important for effective herbicide use. The combination of a preemergence herbicide with effective water management can provide season-long weed control (Ampong-Nyarko, 1996). In fields prone to uncontrolled flooding, such as in hydromorphic areas and unimproved inland valleys, herbicide efficiency may however be very low (Akobundu, 1987). Formulations that can be applied directly to the irrigation or flood water rather than spraying, and hence not requiring equipment, may be particularly suitable for resource-poor rice farmers (Johnson, 1995).

For parasitic weeds, in addition to the above constraints, the use of postemergence herbicides has two major limitations. Firstly, detrimental effects on the crop have already occurred before the parasite emerges aboveground and, secondly, there are few effective herbicides available. The herbicide 2,4-D was found to be effective against *S. hermonthica* (Carsky *et al.*, 1994a) and *S. asiatica* (Delassus, 1972). However, 2,4-D has a low selectivity and, like many other herbicides, requires multiple applications to affect *Striga*. These constraints may be overcome by rice seed treatment with herbicide. In upland rice in Nigeria, cinosulfuron (0.2–0.6 $g l^{-1}$) and CG152005 (0.064 $g l^{-1}$) delayed and reduced *S. hermonthica* infection, and it was suggested this could be used in combination with resistant varieties (Adagba *et al.*, 2002b). Possible drawbacks to such approaches are unfavorable effects on the environment as, for instance, Ahonsi et al (2004) found that the ALS-inhibitors imazaquin and nicosulfuron have negative impacts on soil biology and natural suppression of *Striga* spp.

Commonly used herbicides in rice in Africa can be found in Table 7. Herbicide use in rice in Africa is poorly documented and recent publications covering currently used products are not available. Herbicides targeting broad-leaved weed species in rice in Africa are 2,4-D and MCPA, while, butachlor, molinate, oxadiazon, and thiobencarb are commonly used against grass weeds (Johnson, 1997; Rao *et al.*, 2007). Glyphosate, a herbicide used in land preparation for rice, is effective against *O. longistaminata* and *O. barthii* as preemergence treatment (Davies, 1984; Riches *et al.*, 2005). Propanil is a popular herbicide for use in tank mixtures and, for example, one of the most frequently used combinations in rice production schemes of the Senegal River Valley is propanil and 2,4-D + dichlorprop (e.g., Haefele *et al.*, 2000). Postemergence applications of propanil mixed with piperophos (Imeokparia, 1994), molinate (Babiker, 1982), thiobencarb, fluorodifen, or oxadiazon (Akobundu, 1981; Okafor, 1986) proved successful in irrigated rice in various other African countries. In irrigated direct-seeded rice, good weed control was obtained with preemergence applications of dymrone or thiobencarb in the Lake Chad Basin in Nigeria (Okafor, 1986), and bifenox or oxadiazon in Sudan (Babiker, 1982). In upland rice in Nigeria, good weed control has been reported by using mixtures of pretilachor with dimethametryne and piperophos with cinosulfuron (Enyinnia, 1992; Ishaya *et al.*, 2007). Chemical weed control is best used in conjunctions with other weed management components within an IWM approach (Rijn, 2001). In this respect, however, herbicides may not lend themselves to be combined with other practices such as mixed cropping systems (Akobundu and Fagade, 1978) or biological pest control (e.g., Afun *et al.*, 1999b; Taylor *et al.*, 2006).

3.5.2. Herbicide resistant rice technologies

Rice varieties with resistance against postemergence nonselective or broad-spectrum herbicides could facilitate improved weed management in some situations (e.g., Fernandez-Quintanilla *et al.*, 2008). These may be particularly useful for the control of problem weeds like wild and weedy rice species. Worldwide there are three herbicide resistance (HR) technologies. One of them, known under the commercial name Clearfield®, was developed through mutagenesis and Clearfield® rice possesses resistance to broad-spectrum imidazolinone herbicides (e.g., Sha *et al.*, 2007; Tan *et al.*,

Table 7 Herbicides (alphabetic order) used in rice in Africa: common name, product names, application rates, timing, target weeds, and production ecosystem

Common name	Example of product	Rates (kg a.i. ha^{-1})	Timing	Target	Ecol.
• 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^{-1})	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[a]
• Bifenox	As a mixture = Foxpro D	1.5–2.4	Pre	B/(G)	U/L
• Butachlor	Machete	1.0–2.5	Pre/early post	AG/(B)[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
• Fluorodifen	Preforan	2.0–3.5	Pre	AB	U/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 12 L	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[c]	• Stam F34 • Propanil • Surcopur • Rogue	2.5–4.0	Early post	A	U/L
• Propanil +					
◦ Bentazon	Basagran PL2	6–8 ($l\ ha^{-1}$)	Post	B/S	U/L
◦ Triclopyr	Garil	5 ($l\ ha^{-1}$)	Post	G/S/(B)	U/L
◦ Piperophos	Rilof S80 $g l^{-1}$	1.5			U
◦ Oxadiazon	Ronstar PL	5 ($l\ ha^{-1}$)	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

[a] L, lowland; U, upland; B, broad-leaved weeds; S, Sedges; G, Grasses; A, Annuals.
[b] Weed types between brackets indicate that the product may control some species of that group or at some (early) stages.
[c] Propanil is most often applied as a mixture with other products such as MCPA, molinate, oxadiazon, 2,4-D, fluorodifen, thiobencarb, bentazone, and butachlor.
Sources: Akobundu (1987), Akobundu and Fagade (1978), Ampong-Nyarko (1996), Babiker (1982), Diallo and Johnson (1997), Grist (1968), Ishaya *et al.* (2007), Johnson (1997), Okafor (1986), Rijn (2001), Wopereis *et al.* (2007), and Zimdahl (2007).

2005). Development of transgenic rice has led to two additional HR rice technologies, namely Liberty Link® (compatible with glufosinate) and Roundup Ready® (compatible with glyphosate) which are currently awaiting worldwide approval.

HR rice technologies have the potential to control a wide range of weeds (broad leaf, grasses, and sedges) including problem weeds like *Echinochloa* spp. and weedy rices. Glyphosate and glufosinate are considered as relatively environmentally benign and, as postemergence herbicides, the application rates can be adjusted to the weed population (Olofsdotter *et al.*, 1999b). In addition, the technology has a wider "window" for herbicide application compared to conventional technologies which is an attractive characteristic for farmers dealing with labor peaks (Olofsdotter *et al.*, 1999b).

A recent case study on the potential economic impact of HR rice in the irrigated rice production systems in Senegal, pointed out that farmers could substantially gain from access to these technologies (Demont *et al.*, 2009). The authors concluded that introduction of HR rice should be combined with farmer training on the proper use of it to assure the long-term effectiveness. They also identified potential institutional constraints to introduction of this technology, such as the existing subsidy arrangements on chemical input and seed, which would result in very small marginal profits for commercial seed industries, which in turn would discourage private investments in the required biotechnology capacity. Establishment of effective public–private partnerships might therefore be a precondition to transfer of this technology (Demont *et al.*, 2009).

Despite the possible attractions of HR options, there are concerns regarding the likelihood of gene flow from HR rice to wild and weedy rice species. If HR rice is to be grown in close proximity to wild and weedy rice populations with overlapping periods of flowering the question has been raised as to how quickly fitness-enhancing transgenes will accumulate in these populations and whether unwanted environmental consequences will result from this (Chen *et al.*, 2004; Lu and Snow, 2005). Field studies in the USA with HR rice (Clearfield®) have shown that there is outcrossing to red rice (*O. sativa*) resulting in resistant plants (Shivrain *et al.*, 2007). A further concern is the evolution of herbicide tolerance or resistance in other weeds, which has widely occurred in rice systems (Rao *et al.*, 2007), due to the repeated use of the same herbicide. The ability to control problem weed species efficiently makes HR rice an attractive technology and farmers may rapidly adopt it in many cases. The above considerations regarding gene-flow also suggest, however, that the reliance on HR technology for effective weed control in rice is likely to have a limited life, at a particular location, unless its introduction and use are carefully managed.

3.6. Integrated weed control

IWM describes the integration of multiple control options based on the knowledge of weed biology and ecology, with other crop management practices (Sanyal *et al.*, 2008). IWM may combine preventive measures with interventions, and short-term with long-term approaches, to sustainably reduce yield losses due to weeds. It is opined that this can contribute to reductions in input expenses and to the robustness of long-term weed management (Swanton and Weise, 1991). Rice cropping systems in Africa may often be suitable for integrated approaches to pest management. Farmers are often constrained by a lack of finance, information, and inputs and therefore are often reliant on traditional methods. Weed management practices based on cultural and integrated approaches may be more compatible with farmers' resources than single-component technologies requiring high levels of external inputs (Johnson, 1995).

In Côte d'Ivoire, in lowland rice fields with poor water control, options such as transplanting of young seedlings and timely weed control interventions made investments in additional herbicides or improved water control less urgent (Becker and Johnson, 1999a). Combining a weed-suppressive genotype with an optimum seeding rate (e.g., 300 viable seeds m^{-2}) can improve weed management (Zhao *et al.*, 2007). Rice varieties may play an important role in an integrated approach, and besides improving weed competitiveness, plant breeding can contribute to better weed management through the development of shorter duration (90–100 days) rice varieties. These varieties may allow farmers to grow two crops a year and open up the possibility of introducing a weed suppressive fallow legume into the rotation (Balasubramanian *et al.*, 2007). Short crop cycles allow crop diversification (rotations) which may improve weed management. Prerequisite to such approach is effective early weed control as short duration varieties which have little time to recover from early competition. Integrated approaches are particular useful to control weedy and wild rice in rice cropping systems in Africa. For instance, dry season tillage and the stale seedbed method using rotary cultivation can be used for the management of the perennial *O. longistaminata* (Johnson *et al.*, 1999). Farmers in Mali, when confronted with heavy infestations of *O. longistaminata* in lowland rice, were observed to burn rice straw in their fields right after crop harvest followed by thorough plowing prior to the next rainy season to destroy rhizomes (M. Dembele, personal communication). Manual weeding in addition to herbicides, preirrigation, the use of clean seed, transplanting in a standing water layer, and crop rotations were used by Senegalese rice farmers in fields with heavy infestations of wild rice (Diallo, 1999). Other examples of integrated practices in African rice systems are zero- or reduced tillage combined with herbicides (Kegode *et al.*, 1999) and "under-water mowing" of *O. longistaminata* during the fallow periods in Mali (Nyoka, 1983).

4. Emerging Weed Problems and Weed Management Issues

4.1. Likely effects of demography on weed management

Future weed management issues will be influenced by changing human and environmental factors, and perhaps most prominent among these will be demographic and climate changes. Africa has a higher population growth than any other continent. With a current annual average growth rate of 2.2% (compared to the world's rate of 1.2%) the population is expected to increase by 170% between 2005 and 2030 (UN, 2007), hence there is a growing need to produce more food. As a consequence of population growth and changing consumption patterns, the rice area in Africa is increasing (Table 1) although, at the same time, rural to urban migration is causing labor shortages in some rural rice growing areas. These changes are likely to cause a shift away from labor-intensive practices and to favor the implementation of direct-seeding (Rao *et al.*, 2007), increased herbicide applications, reduced soil tillage operations, and increased cropping intensities. As a result, there are likely to be shifts in the composition in weed flora, a greater risk of herbicide resistance, and an increase in the incidence of challenging weed problems.

4.2. Effect of changing climates on weed management

There are different scenarios projected for future climate changes (Biasutti *et al.*, 2008; Giannini *et al.*, 2008), but whatever the changes, they are likely to affect weed problems in rice in Africa. Major global changes may comprise a rise in atmospheric greenhouse gases and an increase (>0.2 °C decade^{-1}) in temperature (IPCC, 2007). Trends suggest that the variability of rainfall will increase and the 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). Equatorial zones of Africa may receive more intense rainfall (Christensen *et al.*, 2007). The spatial distribution of future rainfall remains uncertain, however (Giannini *et al.*, 2008), particularly for the Sahel for which there are a number of contrasting predictions (Biasutti *et al.*, 2008; Cook and Vizy, 2006; Held *et al.*, 2005; Hoerling *et al.*, 2006). It has been suggested that higher temperatures alone may already be responsible for 10–40% yield losses (Tubiello *et al.*, 2000). Combined with heavy precipitation events and increased frequency of droughts, rising temperatures are estimated to cause yield reductions of up to 50% in rain-fed agriculture in Africa by 2020 (IPCC, 2007). Increased atmospheric CO_2 levels may have different consequences for species depending on their photosynthetic pathways (C_3 vs C_4). For a C_3 crop like rice, elevated CO_2 levels may have positive effects on crop growth rates, resource-use efficiency, competitiveness with C_4 weeds, and tolerance to *Striga* infection (Fuhrer, 2003; Patterson *et al.*, 1999; Watling and Press, 2000). Many weed species in rice production systems in Africa, however, have the C_3 pathway and so are likely to be favored by these changes (Table 3, adapted with information from Elmore and Paul, 1983). With elevated atmospheric CO_2 levels, both C_3 and C_4 grasses showed increased biomass production, C_3 species had a greater increase in tillering while C_4 species had a greater increase in leaf area (Wand *et al.*, 1999). Tillering and leaf canopy development are likely to be important traits affecting interspecific competition, and therefore, change in the outcome of this is anticipated.

Increased CO_2 levels are likely to be accompanied by higher temperatures favoring C_4 weeds over C_3 crops, accelerating plant development and increasing crop water consumption (Fuhrer, 2003). Drought (Liu *et al.*, 2006) or increased temperatures (Jagadish *et al.*, 2007), combined with elevated CO_2 levels (Matsui *et al.*, 1997), may increase spikelet sterility in rice and consequently reduce crop yields. Certain weed species are likely to be better adapted to these environmental changes and, for instance, dry conditions are found to favor C_4 weeds (Bjorkman, 1976).

The net effect of changing climates on weeds is uncertain (Tubiello *et al.*, 2007) and due to the interrelated factors difficult to predict. The outcome will depend on the species involved (Ziska, 2008), the photosynthetic pathways and the interaction effects between CO_2, temperature, and water availability (Patterson *et al.*, 1999). Changes in precipitation patterns will significantly impact crops (Tubiello *et al.*, 2007) and weeds. Temperature will affect the geographic ranges of weeds (Patterson *et al.*, 1999), with some species moving to higher latitudes (Patterson, 1995) and altitudes (Parmesan, 1996). Such changes are, for instance, likely for Sahelian species (Wittig *et al.*, 2007).

Witchweeds (*Striga* spp.) may extend their range as a result of climate change (Mohamed *et al.*, 2006). Parasitic weeds of the *Orobanchaceae* family (including *Striga* spp.) have a wide host range with high genetic variability enabling rapid adaptation to changing environments (Kroschel, 1998), production systems, and control methods. Parasitic weeds that thrive in erratic and low rainfall environments (e.g., *S. hermonthica*) or temporary flooded conditions (e.g., *R. fistulosa*) could be favored by future climate extremes. *Striga* spp. problems are associated with low soil fertility (Ejeta, 2007; Kroschel, 1998; 1999; Vogt *et al.*, 1991), and hence if climate extremes indeed lead to greater soil degradation in Africa (IPCC, 2007) this might favor parasitic weeds. Aspects of climate change that will have the greatest effect on parasitic weeds are, as yet, however unknown. *S. asiatica* has been found to be relatively insensitive to temperature (Patterson *et al.*, 1982) and distribution may be affected by changes in the geographic range of the host crop rather than directly by temperature (Cochrane and Press, 1997). Phoenix and Press (2005) argued that this could be true for parasitic weeds in general.

Water is becoming a scarcer resource in many parts of Africa (Seckler *et al*., 1999; UNDP, 2007) and rice varieties and cropping methods need to be adapted accordingly (Ingram *et al*., 2008). The challenges are likely to differ for upland and lowland rice production (Manneh *et al*., 2007). For upland rice, drought tolerance will be important not just to reduce losses due to moisture stress but also, under stress, rice may become less competitive with weeds (Asch *et al*., 2005). In irrigated rice, approaches to conserve irrigation water, such as aerobic rice and alternate wetting and drying (AWD), which is also an integral part of the system of rice intensification (SRI), may be adopted but these are likely to have consequences for weed management. Haden *et al*. (2007) observed weed populations to shift to an increased incidence of sedges under the reduced flooding regimes of the SRI. As the season-long flooding of lowland rice fields is replaced by only temporary flooding or aerobic conditions, increased weed infestations are anticipated (e.g., Morita and Kabaki, 2002). Hand weeding requirements increased by up to 35% with temporary rather than permanent flooding in lowland systems (Latif *et al*., 2005). Maintaining the flooding to suppress weeds is likely to be increasingly difficult in many areas as water becomes scarcer however and, as a consequence, farmers lacking the means for effective weeding are likely to suffer severe yield losses (Barrett *et al*., 2004).

Increased temperatures affect herbicide persistence in the soil and the "windows" for herbicide effectiveness (Bailey, 2004). Extreme weather may affect the risk of herbicide by either causing crop damage or by reducing the efficacy (Patterson *et al*., 1999). With high rainfall events, for instance, herbicides may be diluted and cease to be effective (e.g., Kanampiu *et al*., 2003).

High CO_2 environments may increase belowground plant growth relative to aboveground shoot growth (Ziska, 2003) and favor root, 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 weeds like the grasses *O. longistaminata* and *Leersia hexandra* in the lowlands. Other perennial weeds with difficult to control belowground structures (e.g., *I. cylindrica*, *Cynodon dactylon*, *Cyperus esculentus* and *C. rotundus* on upland and hydromorphic soils and *Bolboschoenus maritimus* in the lowlands) are all of the C_4 type.

4.3. Herbicide resistance in weeds

There are few confirmed reports of weeds in Africa that have evolved resistance to herbicides (ISHRW, 2008) and in none of these cases are rice implicated. In Egypt, *Conyza bonariensis* (Hairy fleabane) is reported to be resistant to paraquat, but this weed is of no significance in rice. Rice farmers in Africa do however indicate that herbicides have become less effective against certain species. For instance, propanil has been observed to be less effective to control *E. colona* in Senegal than in the past (Haefele *et al*., 2000). A survey of rice farms in Benin in 2006 revealed disadoption of a once popular herbicide (Garil, a mix of propanil and triclopyr) as it became less efficient (Kouazoundé, 2006). Further investigation indicated that the herbicide had become ineffective against *D. horizontalis* perhaps as a result of propanil resistance. Resistance may be accelerated by the continuous use of a single product which in turn can be a consequence of the limited range of products available on the local market; a common constraint to small farmers in Africa.

Despite the absence of confirmed resistance to herbicides in weeds of rice in Africa, the problem may already exist and is a threat for the near future. The few active weed scientists in Africa often lack facilities and resources to validate herbicide resistance. Little information is available to farmers and the choice of herbicides to manage the risks of resistance is not available. Herbicide use is expected to increase in the near future and, with it, resistance is likely to develop. Environmental changes can accelerate this and, for example, raised CO_2 levels have been shown to increase the tolerance of weeds to herbicides (Ziska *et al*., 1999; Ziska and Teasdale, 2000). Reasons behind this effect are not clear, however, rising CO_2 levels may alter transpiration, reduce the number of leaf stomata or alter the thickness of the weed leaf, and thereby reduce the absorption or uptake of the pesticide (Ziska, 2008). Increased leaf starch concentrations caused by elevated CO_2, as found in C_3 plants (Wong, 1990), might also affect herbicide activity (Patterson *et al*., 1999).

Following with earlier suggestions (Haefele *et al*., 2000), the emergence of resistant weed populations in rice production systems in Africa needs to be monitored in areas where farmers are reporting herbicides to be less effective. In this way timely and effective coping strategies for farmers could be identified and introduced.

5. A Strategic Vision for Weed Management and Research in African Rice Production Systems

5.1. Weed management strategy

Levels of literacy among rice farmers in Africa tend to be low which limit the options for effective information transfer to farmers. Furthermore, there are institutional constraints ranging from absent or malfunctioning commodity markets, seed-supply systems, agro-industries, and transport facilities to unfavorable subsidy and trade arrangements. Other important constraints to weed control, typical of rice farms in Africa, are the limited access to capital intensive inputs and information, and a lack of time or manpower.

Weed problems are particularly severe where controlled flooding for weed control is not an option, such as in rain-fed cropping systems. In Africa, this is the case for roughly two thirds of the rice growing area. Even in irrigated systems rice farmers may have limited control over water (Kent and Johnson, 2001). Rice farmers in Africa would be best served by effective weed control options that do not require substantial labor, that are affordable, easy to learn and apply and that are relatively independent of markets and (agro-) industries and of the level of water control. Effective weed management strategies are likely to build on knowledge on weed ecology, biology, competition mechanisms, and the effectiveness of control methods. Rather than achieving weed-free fields, the emphasis should be on optimizing resource use which may result in minor rice yield losses being incurred. Problematic weed species may be targeted with preventive management practices, back stopped with strategically timed weeding interventions. Some considerations for appropriate weed management strategies are outlined below.

5.1.1. Prioritization of weed species

A range of wild species has value as medicinal, food, or other functions and is therefore not controlled (e.g., Hillocks, 1998). Moreover, in each rice production ecosystem, there are usually only a few problem weeds in terms of the severity of competition or difficulty of control (Johnson and Kent, 2002). Targeting the limited number of problem weed species, rather than all species occurring in a field, could help reduce labor requirements without compromising farm profits.

Certain weed species are likely to become significant constraints as cropping systems intensify. The emergence of a particular species as dominant weeds will be largely influenced by the environment and especially seasonal soil moisture regimes, and will be likely to reflect the crop management. *E. colona*, *Digitaria* spp., *R. cochinchinensis*, *I. cylindrica*, *Dactyloctenium aegyptium*, and *Eleusine indica* are considered to be some of the most important grass weeds in rice worldwide (Moody, 1991), and they all occur in Africa. The perennial sedges *C. esculentus* and *C. rotundus* will be favored where the systems intensify, particularly where there is regular soil tillage. There is also evidence from Asia that *C. rotundus* has become adapted to wetter environments (Pena-Fronteras *et al.*, 2008). *E. heterophylla* is a broad-leaved weed capable of rapid growth and multiplication that can become a serious problem in upland rice-based rotations, and *Striga* spp. and *R. fistulosa* can cause serious losses in certain environments.

In the lowland rice systems it is likely that some of the same weeds that pose problems elsewhere in the world (Rao *et al.*, 2007) will be an increasing constraint in Africa. These will likely include the annual grasses

Echinochloa spp., *L. chinensis*, and *I. rugosum* and the annual sedges *Fimbristylis* spp., *C. difformis*, and *Cyperus iria* among others. A number of these species are already established problems in Africa. Successful management of these will likely follow the application of practices that integrate cultural measures of land preparation, water management and rotations, and, especially in the direct-seeded systems, the judicious use of herbicides.

Weed management strategies for particular species may consider the ecology and biology of the species. Certain management practices (e.g., seed burial or submergence depth due to soil tillage or flooding) are likely to provoke differential responses among the key weed species and this can be employed as a basis to develop more sustainable management practices. Many species are capable of prolific seed production (e.g., *Echinochloa* spp., *Striga* spp.) and reducing the number of weeds that produce seed or multiply after harvest can contribute to decreased weed problems in the subsequent seasons (e.g., Diallo and Johnson, 1997; Haefele *et al.*, 2000). As an example, if environmental conditions are favorable, *S. hermonthica* continues to reproduce after crop harvest, contributing considerably to the total seed production (Rodenburg *et al.*, 2006a). To prevent a buildup of the weed seed bank, a preflowering or a postharvest weed control operation may be required (e.g., Diallo and Johnson, 1997; Haefele *et al.*, 2000). Farmers however may have other priorities after crop harvest or may not be aware of the longer term impact on weed populations.

Greater understanding of species biology can contribute to weed management in different ways. Obligate hemiparasitic weeds like *Striga* spp., for instance, require a suitable host for survival and development after germination. Infestation levels of these parasitic weeds can therefore be reduced through rotations with nonhost crops. ‘‘Trap crops’’ like cowpea, bean, soybean, yellow gram, groundnut, or bambara groundnut (e.g., Oswald *et al.*, 2002) are particularly effective as these provoke seed germination of *Striga* spp., but do not support subsequent infection and development of the parasite. Facultative hemiparasitic weeds, such as *R. fistulosa* and *Buchnera hispida*, require a different approach however as they are fairly independent of the presence of a suitable host to develop and multiply. Seeds of *R. fistulosa* and *B. hispida* require sunlight for germination (Nwoke and Okonkwo, 1980; Ouedraogo *et al.*, 1999) and it is possible that a cover crop or mulch might prevent these from germinating. Perennial wild rice, *O. longistaminata,* has underground rhizomes that enable it to survive superficial weed control operations especially when the soil is moist, but deep tillage in the dry season brings rhizomes to the surface where they desiccate and die (e.g., Johnson, 1997; Johnson *et al.*, 1999). Annual wild rice such as *O. barthii*, on the other hand, reproduce only through seed and their control requires the use of rice seed free of wild rice as a contaminant and hand rouging of wild rice in the field before seed setting and shattering occurs (Delouche *et al.*, 2007). Knowledge of seed germination ecology of different weed species with relevance to rice production systems in Africa (e.g., Chauhan and Johnson, 2008a–d) is useful for the design of targeted control options, such as tillage practices or crop residue management.

The development of knowledge-based technologies is often hampered by limited understanding of weed ecology and biology (Fernandez-Quintanilla *et al.*, 2008). There are also large gaps between "scientific understandings" and the information available to the farmer. Farmers often lack information on parasitic weeds for instance (Frost, 1995; Reichmann *et al.*, 1995), and, in this respect, women often have less access to information than men (Gehri *et al.*, 1999). This lack of available information is likely to limit implementation by farmers of any control methods that are developed.

5.1.2. Integrated crop and weed management approaches

Weed management strategies that are financially, socially, and environmentally cost effective are only likely to be achieved through integrated approaches. Such approaches will combine crop management practices to achieve good crop establishment with optimum plant population densities and vigorous crop growth together with weed management options that prevent, suppress, and control weeds. The choice of management practices is largely predetermined by the type of production environment and system. Good crop establishment and vigorous growth can in part be achieved through good land preparation, adequate soil leveling to the best of farmers' means, use of weed-free rice seeds of good quality, transplanting of young seedlings or sowing of pregerminated seeds in rows, maintaining soil flooding until maximum tillering, and split fertilizer applications (e.g., Becker and Johnson, 1999a, 2001b). Complementary weed management can include one or more of the following components:

- Weed competitive or parasitic weed resistant and tolerant crop varieties (e.g., Fofana and Rauber, 2000; Johnson *et al.*, 1997)
- Crop rotations with a noncereal crop (e.g., Oswald *et al.*, 2002; Sengupta *et al.*, 1985)
- Weed-suppressive fallows (e.g., Akanvou *et al.*, 2000; Merkel *et al.*, 2000)
- Weed-suppressive mulches (e.g., Iwuafor and Kang, 1993; Kamara *et al.*, 2000)
- Postharvest weeding to prevent buildup of weed seed bank (e.g., Diallo and Johnson, 1997; Haefele *et al.*, 2000)
- Increased plant densities and improved plant arrangements (e.g., Akobundu and Ahissou, 1985; Phuong *et al.*, 2005)

5.1.3. Timing of weed control and crop management interventions

Timing is critical to effective integration of crop and weed management. For instance, correct rates and timing of fertilizer provides adequate nutrients without a surplus soon after rice sowing or planting which would encourage weed growth (e.g., Liebman and Davis, 2000). Another example is timing of transplanting; careful transplanting of young rice seedlings reduces transplanting shock and results in better crop establishment and a more competitive crop as compared to older seedlings (e.g., Poussin, 1997).

Timing is imperative for effective weed control interventions. Herbicides, for instance, often have "windows" for application as, for example, postemergence applications usually need to be applied in the early stages of crop growth to be efficient and minimize crop damage (e.g., Haefele *et al.*, 2000). Timing of interventions is important also with respect to crop–weed competition. Crops have critical periods during which weed competition affects yield and beyond which effects are minimal. In irrigated rice in the Sahel, this critical weed period varied markedly between the two seasons of study, but fell between 14 and 56 DAS (Johnson *et al.*, 2004), while in upland rice in the Guinea Savannah the critical weed period assessed with two varieties of NERICA, fell between 21 and 42 DAS (Dzomeku *et al.*, 2007). Few of such studies have been undertaken and there is a dearth of information on the critical periods for weed competition for other production systems, rice varieties, and weed species.

5.2. Weed research strategy

Despite weeds being the most widespread biotic production constraints of rice in Africa, data on distribution and importance of specific weed species are lacking. Such data are an initial requirement for improved priority setting for weed research in the context of these production systems. Moreover, as rice systems in Africa are diverse, general recommendations tend to be flawed. Weed research therefore needs to have regional relevance while also generating outputs (e.g., technologies, knowledge) that are locally applicable and validated with farmers.

Improved approaches to weed management will discriminate between the uplands, and the rain-fed and irrigated lowlands in which hydrology and degree of water control have decisive impacts on weed species and the range of applicable management options. In each environment, compiling basic knowledge on the biology and ecology of the most troublesome weeds for each ecosystem will provide insights on which management options could be developed. Some of the options discussed in this review have yet to be validated for rice systems in Africa.

Changing weed populations, water, and labor shortages will be key future issues for weed research. These can be addressed by genetic and management improvements, but such developments also require a thorough understanding of underlying ecological and biological principles and interactions between crop, weeds, management options, and the environment. The following sections discuss some research topics relevant for enhancing the effectiveness of weed management practices to meet the future challenges.

5.2.1. Climate change

Many studies have been carried out on the effects of CO_2 enrichment on plant species (Bunce, 2005; Navas *et al.*, 1999; Wand *et al.*, 1999; Ziska, 2001; 2003). Fewer studies have focused on temperature rise effects on weeds (Tungate *et al.*, 2007) or on combined effects of CO_2 and temperature increases (Coleman and Bazzaz, 1992; Nonhebel, 1996; Williams *et al.*, 2007). Fewer still peer-reviewed studies report on specific investigations of the effect of drought or water-stress on crop–weed interactions (Moffett and McCloskey, 1998). Studies have not been undertaken on the combined effects of the three main anticipated climate change causes/effects (e.g., CO_2, temperature and drought) on rice-weed competition. Controlled experiments with field crops and weeds are however difficult and costly to conduct, and the absence of the resources and facilities to conduct such experiments in Africa suggests that partnerships with institutes and universities elsewhere would be advantageous. Anticipated climate changes will bring changes in species distribution and predicting these changes is an important task for weed science (Fernandez-Quintanilla *et al.*, 2008). The anticipated changes will need to be considered in the context of emerging constraints such as demographic changes and water shortages. Integrated management options should be developed that on one hand arrest potential increased losses to weeds due to changing climatic and environmental conditions and that prevent climate change to aggravate on the other hand (Ingram *et al.*, 2008).

5.2.2. Crop management

More detailed information on the mechanisms of competition (nutrients, water, light and space) is required to provide the basis on which to develop new elements of IWM. This might include investigating effects of management practices such as the quantity, method, and timing of fertilizer application on weed development. Detailed guidelines are needed on how to optimize crop growth without unduly favoring weeds. This could derive from a better understanding of the effects of fertilizer timing on problem weeds and crop–weed competition and how this in turn might be influenced by season and rice ecosystem.

More nonchemical, labor-saving weed management technologies need to be explored and local innovations validated. This might include examples such as removing flower heads of weeds as observed in Bende, Abia state, Nigeria (E. A. Maji and M. Tokula, personal communication), the combined burning and off-season dry tillage in Zéguésso, Sikasso, Mali (M. Dembele, personal communication) or the application of locally produced bioherbicides in Glazoué, Collines in Benin (Kouazoundé, 2006). Such weed control practices are typically based on cultural and integrated approaches and inherently have a high compatibility with farmers' resources and, as such, are likely to be more successful (Johnson, 1995).

Cultural weed management practices such as relay cropping or rotations with legumes have often been proved technically sound but generally face low farmer adoption rates (e.g., Tarawali *et al.*, 1999). Participatory approaches could help develop more appropriate options and help identify and alleviate reasons for low adoption rates of otherwise effective management practices. Relay cropping, intercropping and improved fallows should have additional benefits and good adaptation to agro-climatic and ecological ranges. These were typical weaknesses of the *Striga* control practice using *Desmodium* spp., for instance (Gressel and Gebrekidan, 2007). Legume species may be tested under local on-farm conditions and more research should be conducted on residue management practices to minimize competition effects and maximize weed suppression and reduction of the weed seed bank. Suitable and effective rice-intercrop practices, improved crop residue management like mulching (e.g., Iwuafor and Kang, 1993; Singh *et al.*, 2007) and alternative establishment methods like line sowing and plant densities (Phuong *et al.*, 2005) merit further study in rice systems in Africa. Further, *ex ante* analyses of the likely impacts and farmer adoption of potential technologies are required to guide strategic decisions on the allocation of scarce research resources.

Finally, interactions of water management and weeds need further study. Weed germination could be reduced if the period between sowing/planting and flooding could be shortened by several days. This can be achieved by drill-planting imbibed or pregerminated rice seeds (Counce and Burgos, 2006), land leveling to allow earlier shallow flooding, or by transplanting in (shallow) flooded fields (Poussin, 1997). Differential responses to timing and depth of flooding among species, as shown by different studies (e.g., Kent and Johnson, 2001; Mortimer *et al.*, 2005), provide opportunities to target weed species or groups of species through better water management. Knowledge and understanding is however required on the precise limits of the depth and timing of flooding for particular species and conditions to allow establishment of rice while suppressing weeds.

5.2.3. Varietal development

Studies show that varieties with high yields under weed-free conditions are also likely to have superior yields under weed competition (e.g., Lemerle *et al.*, 2001; Zhao *et al.*, 2006a,b, 2007). Local adaptation is therefore an important characteristic for weed competitiveness (Lemerle *et al.*, 2001) and weed-free yield may be an efficient indirect selection trait to find germplasm capable of high yield under weed competition (Zhao *et al.*, 2006a). Combining yield potential with the ability to reduce losses to weeds would make a valuable contribution to IWM programs. There have only been limited efforts, compared to the challenges faced, to develop locally adapted rice varieties suitable for Africa, however. A preferred approach would be to intensify research and breeding activities to enlarge the range of available germplasm with desirable traits in addition to increased weed competiveness or resistance and tolerance to parasitic weeds. It is likely that suitable rice varieties will combine different weed competitive or suppressive traits (Dingkuhn *et al.*, 1999), including early vigor and efficient nutrient and water uptake, together with other desirable traits such as improved resistance or tolerance to other biotic or abiotic stresses and high yields and grain quality.

To realize such advances in the near term may require that available screening measures (e.g., Haefele *et al.*, 2004; Zhao *et al.*, 2006b) are adapted or enhanced. Indirect selection measures and novel experimental designs may be utilized to screen desired traits, but the number of easily identifiable traits responsible for increased weed competitiveness needs to be enhanced (Pester *et al.*, 1999). A better understanding of physiological traits conferring competitiveness may help to identify the related molecular markers and suitable parents for marker-assisted breeding programs. Few studies to date have reported advanced biomolecular methods such as employed by Gurney *et al.* (2006) and Kaewchumnong and Price (2008) for the improvement of resistance against parasitic weeds, or such as used by Jensen *et al.* (2001) for the development of weed competitive rice varieties. In this respect, the gene pools of the African wild and cultivated rice species and the currently available NERICA varieties are yet to be fully explored.

5.2.4. Herbicides

Herbicide formulations that can be directly applied to the irrigation water or soil, rather than foliar applied postemergence applications might be particularly suited to rice systems in Africa (Johnson, 1995). Such formulations (e.g., granular or dry flowable) do not require spraying equipment and they also carry lower risks of herbicide contamination compared to liquid formulations (Akobundu, 1987; Zimdahl, 2007). An inexpensive but effective preemergence and slow-release granular formulation of an herbicide would have great potential for these cropping systems. A promising approach may also be to focus on herbicide seed treatment. Seed treatment has the advantage that farmers do not need to apply herbicides in the field anymore. Moreover, through seed coatings, herbicide application is well targeted and doses are therefore relatively low. This option, combined with herbicide resistant germplasm has been successful in *Striga* control in maize in East Africa (e.g., Kanampiu *et al.*, 2001). A possible disadvantage of such a technology is the increased dependency on the commercial seed systems and agro-industries that this technology would require. Furthermore the approach may not be effective in lowland rice or high rainfall areas as there may be rapid leaching of the product. Conversely, phytotoxicity may occur with low rainfall (Kanampiu *et al.*, 2003). Further development may focus on seed treatment methods that can be applied by farmers and on products with low toxicity to rice and coating methods that prevent the product from quickly dissolving and leaching away.

Bioherbicides based on locally abundant weed species may be an attractive alternative to chemical herbicides for rice farmers in Africa. Potentially suitable weed species for production of bioherbicides are *B. pilosa* and *E. hirta* (Hong *et al.*, 2004) and *A. conyzoides* (Xuan *et al.*, 2004). It is important however to recognize the likely institutional, economic, and physical constraints to the use of bioherbicides in many of the rice environments in Africa.

5.2.5. Weed ecology and rice ecosystems

Knowledge of the biology and ecological requirements of target species will be the starting point for the development of effective, appropriate, and affordable weed control technologies. Species-specific weed management options need to account for any negative consequences on the dynamics of the weed population and competition with the rice crop (Mortensen *et al.*, 2000) as the removal of a key species may result in undesirable population shifts in the remaining species. The dynamics following species-specific weed management is as yet poorly understood.

Wild and weedy rices (*Oryza* spp.), perennial weed species, particularly those with extensive subterranean rhizome systems (*Cyperus* spp. and *I. cylindrica*), parasitic weeds with wide geographic ranges and high genetic variation (e.g., *Striga* spp.), and annual species such as *Digitaria* spp., *Echinochloa* spp., and possibly also *I. rugosum* and *Leptochloa* spp., are expected to become more important in future rice production in Africa. Such species merit further research attention. Weed research needs to focus on elucidating biology, taxonomy, and control measures of wild and weedy rices. In addition, to overcome problems of contaminated seed supplies, possibilities for the initiation of community-based seed systems should be investigated in different countries. More research efforts should be undertaken to predict and anticipate spread of parasitic weeds. Parasitic weeds like *Striga* spp. in uplands and hydromorphic lands and *R. fistulosa* in hydromorphic lands and rain-fed lowlands are likely to become more important in rice in Africa in the near future. The minor parasitic weeds of today can be the major ones tomorrow (Raynal Roques, 1994).

Weed research for rice systems in Africa may focus more on rain-fed and semi-irrigated lowland ecosystems (inland valleys) where flooding cannot, or only partially, be controlled. The inland valleys comprise a huge production potential that is yet underexploited. In these areas, weeds are a major constraint as water control is poor, and the soil is fertile and either wet or moist for much of the year. Rice production in the inland valleys is mainly for subsistence (Windmeijer and Andriesse, 1993). Land preparation is mostly done by hand and fields are often inadequately bunded and leveled resulting in uneven flooding and patchy conditions favoring weed growth (Akobundu and Fagade, 1978; Ampong-Nyarko, 1996). Uncontrolled flooding also renders the use of herbicides less effective (Akobundu, 1987). The lack of a permanent and adjustable water layer favors weed infestations, such as observed with wild rice in Tanzania (Riches *et al.*, 2005), and leads to severe crop–weed competition. Few suitable weed control technologies are yet available for farmers in these rice production ecosystems and developing these should be a priority. Rice production in inland valleys is considered very suitable for integrated management approaches.

Relatively little is known about the interactions between weeds and other biotic constraints such as birds, insects (stem borers), and pathogens like Rice Yellow Mottle Virus and African Rice Gall Midge, and in selective cases these may merit further study. In a recent survey carried out in Senegal, farmers indicated that weeds attract birds (M. Diagne and Y. de Mey, personal communication). Weeds, like *E. colona* or wild rice species, provide shelter and food to grain-feeding birds such as *Quelea quelea* (Luder, 1985; Treca, 1985; Ward, 1965) especially in the period before rice grain filling and after harvest. More effective weed control could therefore contribute to reduced bird pressure (Luder, 1985; Treca, 1985). This would however require further study. In Asia, ducks are used to control weeds in rice and were shown to reduce herbicide use without compromising farm profits (Liu *et al.*, 2004; Men *et al.*, 2002). In rice–fish production systems, fish (mainly common carp, *Cyprinus carpio*, and Nile tilapia, *Oreochromis niloticus*) can control weeds through direct feeding and increased water turbidity, while the permanent flooding required for fish culture also adds to weed management (Halwart, 2001). Integrations of rice with poultry or fish may need to be adapted or tested for compatibility with prevailing rice farming systems. Concepts of the management of vegetation to regulate the natural enemies of insect pests, noted above (Afun *et al.*, 1999b; Nwilene *et al.*, 2008), warrant further investigation, particularly with regard to the practical implications for farmers and farm management in rice-based cropping systems.

5.2.6. Socioeconomics and gender

Integration of socioeconomic sciences with agronomic practice is important if the impact and relevance of outcomes of weed science is to be increased. Such integration is currently often lacking (De Groote, 2007; Fernandez-Quintanilla *et al.*, 2008). Socioeconomic perspectives may improve the targeting of the appropriate weed species and be necessary for setting priorities for the development of weed technologies. Data are lacking on distribution and economic losses caused by weeds in rice production systems, and further, impact studies (*ex ante* or *ex post*) on weed control technologies are scant. Social sciences could also have a greater role in identifying potential constraints to adoption and in developing approaches to overcome these.

Weed management in the rice systems of Africa is mainly carried out by women. Including all crops, women in Africa collectively spend an estimated 20 billion hours a year on (hand) weeding while still suffering crop yield losses to weeds of between 20 and 100% (Gianessi, 2008). Weeding is the most labor-intensive crop operation and therefore weighs heavily on women's time which in turn impacts other economic activities (e.g., Gehri *et al.*, 1999). Further, women are often also accompanied by children and therefore weeds impact across the generations as this impinges on opportunities for education. Farmers' view on the importance of weed control relative to the overall farm operations is poorly understood. Information about these farm priorities, strategies, and choices could help identify the constraints to adoption, the development of weed technologies, and farmer extension efforts.

Besides their effectiveness to control weeds, for technologies to be acceptable to farmers, they need to fit in the local social context and be affordable. Involvement of female farmers in weed research is extremely important to effectively reach the target group and get their input in the design and development of suitable weed management strategies (e.g., Gehri *et al.*, 1999). There is a great need for farmers, extension agents and scientists to exchange views and identify expertise and knowledge gaps in order to better target problem weeds, and develop improved approaches and control options. Such interactions might already improve farmers' decision making and consequently enhance weed management, as this is highly dependent on exposure to technologies and access to information (e.g., Becker *et al.*, 2003; Haefele *et al.*, 2002; Rao *et al.*, 2007). Due to the diversity of rice systems in Africa, farmers require locally adapted solutions.

An example of a successful participatory approach to improve farmers' crop management, stimulating farmer experimentation, and identifying researchable issues is the curriculum for Participatory Learning and Action Research (PLAR) for Integrated Rice Management (IRM) in inland valleys of sub-Saharan Africa as developed by WARDA and IFDC. This method consists of a technical manual (Wopereis *et al.*, 2007) and a facilitators' guide (Defoer *et al.*, 2004a) containing modules on water, crop, and pest management issues. Many of the integrated rice management practices discussed throughout this curriculum contribute directly (through modules on weed recognition, IWM, and the use of herbicides) or indirectly (through modules on land preparation, transplanting, and water management) to improved weed management. This approach could be expanded with modules for example on weed biology and ecology, rice-weed competition, and improved weed management. Currently, PLAR-IRM modules are converted into training videos in various local languages (WARDA, 2008). This medium ensures an easier and probably cheaper means of technology transfer than traditional extension, leading to rapid and massive dissemination among rice farmers (Van Mele, 2006). PLAR-IRM can contribute to more efficient and sustainable weed management in rice for resource-poor farmers and merits promotion and wider application through diverse media.

6. Concluding Remarks

Critical research issues are implicated in the challenge to realize the potential productivity of some underutilized areas, such as the inland valleys of West Africa. For rice systems to be sustainable, ecological approaches to weed management must be applied. Components of such approaches may comprise effective land preparation and establishment of a competitive crop, managing flooding at critical stages in crop or weed growth, depletion of the soil seed bank, minimizing the ingression of undesirable species, and timely interventions against weeds that escaped the preventive measures. The implementation of such knowledge-based systems may build on experiences and results gathered from elsewhere and may also require adaptive research with farmers to identify and address local constraints and successful application of the options. Such initiatives are a likely prerequisite to the sustainable development of these underexploited areas.

Approaches to improving weed management in rice farming systems in Africa can benefit from extending activities through participatory farmer learning and research activities. Farmers often lack knowledge on weed biology and control while at the same time, as daily practitioners, they may possess traditional knowledge that could provide useful insights for the development of sustainable management options. Enhancing exchange between farmers and scientist could lead to greater knowledge on some of the most important or troublesome species and management practices and is expected to achieve substantial gains. Parasitic weeds (in uplands) and weedy and wild rices (in lowlands) would be suitable subjects for pilot projects on participatory farmer training on weed biology and control.

Finally, the economic importance of weeds in African rice production systems ($1.45 billion a year in addition to costs of weed control) is currently not reflected in the resources dedicated to reducing these losses and improving weed management. It is envisaged that weed research could generate a considerable impact on the lives of the rural poor, and economies of developing countries through the development of knowledge-based management practices. To realize this requires long-term investments in human and financial resources focused on the development of more productive farming systems.

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