Weed management in lowland rice systems in Africa[1]

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Introduction

Uncontrolled weed growth is one of the most frequently encountered biophysical production constraints to lowland rice production in Africa, causing huge economic losses to rice farmers and African economies. Common weed management practices in lowland rice systems include soil tillage, clearance by fire, hand- or hoe-weeding, herbicides and flooding and these are often used in combination. Labour shortages and lack of access to information, inputs and credits are widespread constraints for African farmers. Here we distinguish and discuss six main categories of weed management in lowland rice: (1) cultural, (2) mechanical, (3) varietal (genetic), (4) biological, (5) chemical and (6) integrated management.

1 Cultural Weed Control

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 leaves less space and light for weeds. Crop establishment involves several steps of land preparation and sowing or planting depending on the agro-ecosystem. Crop establishment can be improved through soil tillage, land levelling, 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, 1999, 2001; Haefele et al., 2000).

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. Transplanting in rows facilitates the use of labour- and time-saving weeding equipment such as a hoe or a push-weeder. Moreover,

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grasses that have similar appearance as rice, especially in the early stages, are easier to recognize if they occur outside the planting pattern.

In direct-seeding, seeds may be sown dry as un-germinated seeds or “wet” as pre-germinated seeds which are often sown into shallow water to reduce weed problems. Unless fields are well levelled, 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), hence direct-seeding can save labour compared to transplanting (Akobundu and Fagade, 1978). An agro-economic 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).

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). 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 intra-specific competition may result in a poor crop growth (e.g. Rao et al., 2007).

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 broadleaves 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. *Cyperus difformis* for instance might already be suppressed by 0.8 cm of turbid water while for suppression of *Leptochloa 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, 2008; 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 *Echinochloa colona*) exhibit no dormancy and germinate rapidly on the surface of puddled soil (Kim and Moody, 1989).

For effective control of weeds by flooding, fields need to be well levelled to ensure uniform water depth. Good land-levelling 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).

1.3. Soil fertility management

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). Improved soil fertility is important for the effective management of parasitic weeds such as *Striga* spp. (e.g. Ransom, 2000) and *Rhamphicarpa* (Rodenburg et al., 2011).

2. Mechanical Weed Control

Mechanical weed control can be applied as an intervention within the crop, and as a preventative measure as part of pre-season 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, levelling 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 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 to enable weeds to germinate, can limit following weed growth (Diallo and Johnson, 1997).

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.

Provided adequate labour 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 *Oryza longistaminata* and *Imperata 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, have already taken place. To prevent weed induced yield losses, three weeding operations are required for hydromorphic and flooded rice (Ampong-Nyarko and De Datta, 1991).

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 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 to mechanization in the Senegal River Valley have failed due to this constraint in addition to the limited financial resources of most rice farmers (Diallo and Johnson, 1997).

3. Rice Varietal Development for Improved Weed Control

3.1. Weed competitiveness

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., 1998).

On hydromorphic soils in Nigeria, the tall variety OS6, incurred 24% less yield reductions from weed competition than the semi-dwarf 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 screened lowland NERICA varieties, interspecific crossings of *O. sativa* and *O. glaberrima*, for weed competitiveness. Nine such lowland varieties of NERICA (NERICA-L-6, -32, -35, -37, -42, -53, -55, -58 and 60) have shown 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 (Table 1). 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.

3.2. Resistance and tolerance against parasitic weeds

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. For instance, *O. glaberrima* cultivar, CG14, showed resistance against *S. aspera* (Johnson et al., 1997). Genetic variation has also been observed for resistance and tolerance against *Rhamphicarpa fistulosa*, a parasitic weed adapted to temporary or permanently inundated lowlands (Table 1). The most resistant cultivars identified by Rodenburg et al. (2011) were (in decreasing order) Gambiaka, TOG5681, IR64 and NERICA-L-32, while NERICA-L-32 and NERICA-L-39 showed a higher tolerance level than other varieties, including their two genetic parents (IR64 and TOG5681).

Table 1. A selection of rice varieties with superior levels of weed competitiveness, resistance or tolerance against *Rhamphicarpa fistulosa.*

Variety	Species	Characteristic	Source
Jaya	*O. sativa*	Yields under weedy and weed-free conditions; Weed suppression	1,2
TOG5681	*O. glaberrima*	Weed suppression	2
NERICA-L -6, -32, -35, -37, -42, -53, -55, -58 and 60)	interspecific	Yields under weedy and weed-free conditions	2
Gambiaka and IR64	*O. sativa*	Resistance against *R. fistulosa*	3
TOG5681	*O. glaberrima*	Resistance against *R. fistulosa*	3
NERICA-L-32	interspecific	Resistance and tolerance against *R. fistulosa*	3
NERICA-L-39	interspecific	Tolerance against *R. fistulosa*	3

1= (Haefele et al., 2004), 2= (Rodenburg et al., 2009), 3= (Rodenburg et al., 2011)

4. Biological Weed Control

Biological control may play a role in the management of invasive weeds and, for example, some biological control methods tested on *Striga* spp. in upland cereal systems (e.g. maize and sorghum) could perhaps be applied to control parasitic weeds in rice in lowlands and hydromorphic areas, such as *S. aspera* and *Rhamphicarpa fistulosa* (e.g. Rodenburg et al., 2010). 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

Cyperus rotundus and *C. iria* (Kadir and Charudattan, 2000) and *Alternaria alternata* to control *Sphenoclea 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 *Ageratum conyzoides* (Xuan et al., 2004). No reports are available however on the use of such biological agents in lowland rice cropping systems in Africa.

5. Chemical Weed Control

5.1. Conventional chemical weed control

Herbicides are important control methods in the lowlands (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 labour-saving planting methods such as direct (broadcast) seeding (e.g. (e.g. Akobundu and Fagade, 1978; Riches et al., 2005). Herbicides are likely to be particularly useful in areas where labour is in short supply. Farmers should have sufficient financial resources to invest in herbicides and the return of such investments should be high enough. In the rain-fed lowland 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 (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). Commonly used herbicides in rice in Africa can be found in Table 2.

Table 2. Herbicides (alphabetic order) used in rice in Africa: common name, product names, application rates, timing and target weeds.

Common name	Example of product	Rates (kg a.i. ha^{-1})	Timing	Target
2,4-D	Dacamine	0.5-1.5	Late post	B/S

2,4-D + dichlorprop	Weedone	1-1.5 (l ha^{-1})	Post	B/S
bensulfuron	Londax	0.05-1.0	Post	B/S
bentazon	Basagran	1.0-3.0	Post	B/S
bifenox	As a mixture= Foxpro D	1.5-2.4	Pre	B/(G)
butachlor	Machete	1.0-2.5	Pre/early post	AG/(B)[b]
dymrone (K-223)	Dymrone	3.0-5.0	Pre	S/(G/B)
fluorodifen	Preforan	2.0-3.5	Pre	AB
glyphosate	Round-up	1.5-3.0	Pre/post	G
MCPA	Herbit	0.5-1.5	Post	B/S
molinate	Ordram	1.5-4.0	Pre/early post	G/S/(B)
oxadiazon	Ronstar 25EC	0.6-1.5	Pre/early post	G/B/S
paraquat	Gramoxone	0.5-1.0	Pre/post	A
pendimethalin	Stomp 500	0.5-1.5	Pre	G/B/S
piperophos	Rilof 500	0.5-2.0	Pre/early post	G/S
pretilhachlor + dimethametryne	Rifit extra 500 EC	1.5/0.5	Pre	G/B
propanil[c]	Stam F34	2.5-4.0	Early post	A
propanil + bentazon	Basagran PL2	6-8 (l ha^{-1})	Post	B/S
triclopyr	Garil	5 (l ha^{-1})	Post	G/S/(B)
oxadiazon	Ronstar PL	5 (l ha^{-1})	Post	G/B/S
quinclorac	Facet	0.25-0.5	Pre/post	G
thiobencarb	Saturn	1.5-3.0	Pre/early post	G/B/S

Sources: (Akobundu, 1987; Akobundu and Fagade, 1978; Ampong-Nyarko, 1996; Babiker, 1982; Diallo and Johnson, 1997; Grist, 1968; Johnson, 1997; Okafor, 1986; Rijn, 2001; Wopereis et al., 2007; Zimdahl, 2007)

[a] 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.

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. Johnson et al., 2004; Riches et al., 2005). In turn this may cause reduced crop vigour or plant population densities, and increased weed competition. The incorrect use of herbicides, caused by the above cited problems, may also 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 pre-emergence 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).

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). The herbicide 2,4-D was found to be effective against *Striga* spp. and *Rhamphicarpa fistulosa* (e.g. Rodenburg et al., 2010). Glyphosate, another common herbicide in preparation for rice, is effective against *O. longistaminata* and *O. barthii* as pre-emergence 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). Post-emergence 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 pre-emergence applications of dymrone or thiobencarb in the Lake Chad Basin in Nigeria (Okafor, 1986), and bifenox or oxadiazon in Sudan (Babiker, 1982). Chemical weed control is best used in conjunctions with other weed management components within an integrated weed management approach (Rijn, 2001).

5.2. Herbicide resistant rice technologies

Rice varieties with resistance against post-emergence non-selective or broad-spectrum herbicides could facilitate improved weed management in some situations (e.g. Fernandez-Quintanilla et al., 2008). World-wide 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. Development of transgenic rice has led to two additional HR rice technologies, namely Liberty Link® (compatible with glufosinate) and Roundup Ready® (compatible with glyphosate).

HR rice technologies have the potential to control a wide range of weeds (broad leaf, grasses and sedges) causing problems in lowland rice in Africa, including problem weeds like *Echinochloa* spp. and weedy rice (e.g. Rodenburg and Demont, 2009). Glyphosate and glufosinate are considered as relatively environmentally benign and, as post-emergence herbicides, the application rates can be adjusted to the weed population, and the technology has a wider herbicide application time window compared to conventional technologies which is an attractive characteristic for farmers dealing with labour peaks (Olofsdotter et al., 1999). 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). 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 (e.g. Chen et al., 2004; Lu and Snow, 2005). 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 (Rodenburg and Demont, 2009).

6. Integrated Weed Control

Many of the above discussed technologies can be combined in an integrated weed management strategy. integrated weed management (IWM) may combine preventive measures with interventions, and short-term with long-term approaches, in order 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 et al., 2008). Obvious combinations are the use of pre-emergence herbicides with improved crop establishment and competitive varieties.

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, 1999).

Combining a weed-suppressive genotype with an optimum seeding rate (e.g. 300 viable seeds m-2) improves weed management (Zhao et al., 2007). Integrated approaches are particular useful to control weedy and wild rice in African rice cropping systems. 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 ploughing prior to the next rainy season destroy rhizomes. Manual weeding in addition to herbicides, pre-irrigation, 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 traditional "under-water mowing" of *O. longistaminata* during the fallow periods in Mali (Nyoka, 1983).

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Weed management in rice-based cropping systems in Africa. Advances in Agronomy 103, 149â€“218.CrossRef Google Scholar. Rodenburg, J., Riches, C. R. & Kayeke, J. M. (2010).Â Effect of integrated weed management and nitrogen fertilization on the performance of rice under flood-prone lowland conditions. Journal of Agricultural Science, Cambridge 129, 409â€“418.CrossRef Google Scholar. van Heemst, H. D. J. (1985). The results indicate that in rainfed, low-input, lowland rice production systems, cultivar mixtures can improve the competitive ability of rice, reducing weed biomass production and diminishing rice biomass losses. Across both cultivars, the population of weeds was reduced by 39.7% when Faro 15 was introduced 2 weeks after Muduga in a 3:2 ratio, but the effect on weed biomass was not significant.Â Rice cultivar mixtures have a number of benefits from their use in low-input systems such as practiced in Nigeria (Binang et al., 2010a, b). While it is known that cultivar mixtures generally stabilize crop yields and reduce lodging, their influence on weeds have not been investigated to any significant extent. photosynthetic pathway. 429Weed management in African rice systems. weeds, parasitic weeds well adapted to low rainfall. environments (e.g. S. hermonthica) or temporary.Â The net effect of climate change on weeds in rice. production systems in Africa will be the result of a. complex set of interactions between local environ-. mental, ecological, biological and human factors such.