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Weed management in rainfed lowland rice ecology in Nigeria – challenges and opportunities

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Review

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Abstract

Developing an effective weed management strategy is crucial to sustainable rice production in Nigeria. Rainfed lowland ecology contributes significantly to the volume of rice cultivated in terms of yield and land acreage. Nevertheless, increased weed infestation remains one of the major production constraints. This review highlights the strength and weaknesses of weed management practices in rainfed lowland ecology and research gaps, and examines the potential for developing a sustainable weed management strategy for lowland rice. In this review, a rainfed lowland situation is described (where water is limited) to engage flooding as a potential weed control option, due to the undulating land terrains. Effective weed management begins with creating a weed-free environment at the critical crop growth stages, such that broadcasted or transplanted rice seedlings can efficiently use water, nutrients, and light. Sustainable weed management practices in Nigerian lowland ecology would therefore imply that farmers begin to incorporate crop rotation to suppress problem weeds in continuous rice cropping systems; adopt conventional or minimum tillage to enhance herbicide efficacy and early establishment of rice; adopt weed-competitive and high-yielding cultivars; and practice appropriate spacing, seeding rate, and seeding methods that can support easy adoption of mechanical weeders and optimum plant population to suppress weed pressure at a later growth stage. This is feasible where farmers are supported with infrastructure, farm machinery, and other necessary inputs. Future research should engage lowland rice farmers in specific agroecological zones.

Introduction

Rice is the second most important cereal in the world after wheat in terms of production, with an average estimate of 520,000 kg being produced in 2022 (FAO 2022; Jones 1995). Rice is a major source of dietary energy for many households in Africa (Macauley and Ramadjit 2015), and Nigeria is the largest producer in West Africa, averaging 3.7 billion kg in 2018 (Soullier et al. 2020). Nevertheless, rice consumption has risen steadily by 2.3% per year in Nigeria (Soullier et al. 2020). Historically, rice cultivation in Nigeria began in the eighteenth century, when upland varieties were introduced to the high forest zone in western Nigeria (Grist 1965). Rainfed agriculture is the main production system (Daramola 2005), and rice cultivation in lowlands is favored within the country (Daramola 2005) due to the regular flooding of fresh water from rivers, streams, and rainfall into swamps all year round (Herdcastle 1959; Imeokparia 1989). Approximately, 6.7 billion kg of raw paddy were produced from 3.1 million hectares in Nigeria in 2014 (FAOSTAT 2014), out of which 47% was cultivated in the lowlands. Smallholder farmers contribute largely to the total volume of rice cultivated. However, as cultivated lowland areas begin to expand (9.1% and 19.4% per year) in Nigeria and other sub-Saharan countries (Soullier et al. 2020), grain yield has remained low, at 1400 kg ha^{-1} (Arouna et al. 2021). Several factors are responsible for such low yield, including the planting of low-yielding cultivars with high susceptibility to pests and diseases, poor agronomic practices (i.e., low plant population, non-uniform and wide spacing, low soil fertility, poor timeliness of operation, etc.), and above all, poor weed management practices (Dossou-Yovo et al. 2020; Imeokparia 1989).

Globally, reductions in rice yield attributed to poor weed management range from 10% to 100%, depending on the type of weed flora and level of infestation (Akobundu 1987; Chauhan 2012). This is higher than combined losses from insect pests and diseases of rice in Africa (Akobundu 1987). Yield reduction due to weed competition varies from country to country by weed species present, and agronomic practices (Arouna et al. 2021; Williams et al. 1990). Between 80% and 100% reduction in rice yield due to weed competition has been observed in Nigeria (Imeokparia 1994; Kehinde 2002). Moreso, the high infestation of noxious weeds continues to favor severe pests (Rodenburg et al. 2014) and disease infestation in many rice fields.

Apart from yield loss, the occurrence of high weed biomass during harvest indirectly incurs high harvesting costs and reduces rice quality (Akobundu 1981). Also, labor scarcity can further delay the timely removal of weeds in Nigeria. According to Chikoye et al. (2004), a shortage of labor for weed removal is a major production constraint among smallholder farmers in the Northern Guinea Savanna. Another reason for the low yield in the lowlands is improper land leveling, which limits the effectiveness of flooding to suppress weeds under rainfed conditions (Akobundu and Fagade 1978). Most paddy fields are situated along floodways; using such water resources to improve yield requires technical skills and heavy capital investment that is often unaffordable for farmers.

Despite these challenges, many weed control trials conducted in lowland ecologies across different agroecological zones in Nigeria have estimated a potential yield increase of 3,000 to 5,000 kg ha^{-1} (Akobundu 1987; Alhassan et al. 2015a; Imeokparia 1994; Imeokparia and Okusanya 1997; Imeokparia et al. 1992; Ismaila et al. 2014; Okafor 1986). Although several attempts have been made to recommend and replicate such yield benefits on farmers' fields, the outcome has not affected farmers' yields. It is therefore important to highlight possible weaknesses, and also harness the potential of research recommendations to achieve a sustainable weed management program under changing climate conditions. Hence, the goals of this review are to highlight the strengths and weaknesses of recommended weed management practices for lowland rice in different agroecological zones and propose further research directions for sustainable weed management in Nigerian lowland ecology.

Predominant Weed Flora of Nigerian Lowland Rice Fields

Establishing a rice weed database (Rodenburg et al. 2016) is critically necessary to achieve sustainable rice productivity in Nigeria. Weed flora dynamics in lowland ecological systems are influenced by different agronomic practices, which vary from one location to another (Akobundu 1987). However, a few weed species, such as in the genus *Echinochloa* and genus *Cyperus,* are now reported to be global prominent weeds in rice, irrespective of their cultures (Kraehmer et al. 2016). In Nigeria and other sub-Saharan African countries, weeds that exhibited high seeding output, high vigor, and aggressive morphological adaptation are difficult to manage in lowland rice fields with poor water control systems (Akobundu 1981; MacDonald 2003; Rodenburg and Johnson 2009).

Most of the reported weeds of Nigerian lowland ecologies are also weeds of global concern in rice (Kraehmer et al. 2016). Table 1 shows some prominent weed species across lowland ecologies in Nigeria. Prevalent grasses include junglerice [*Echinochloa colona* (L.) Link.], longstamen rice (*Oryza longistaminata* A.Chev. & Roehr.), *Sacciolepis africana* C.E. Hubb. & Snowden, and crabgrass (*Digitaria horizontalis* Wild).; broadleaves include tropical spiderwort (*Commelina benghalensis* L), swamp morningglory (*Ipomoea aquatica* Forsk), *Ludwigia* spp., and African mosquito fern (*Azolla africana* Desv).; and sedges include smallflower umbrella-sedge (*Cyperus difformis* L.), yellow nutsedge (*Cyperus esculentus* L.), purple nutsedge (*Cyperus rotundus* L.), and fimbry (*Fimbristylis littoralis* Gaudich). These weeds have resulted in significant yield losses (Rodenburg and Johnson 2009) and have been reported for decades, despite the use of various herbicides. Specifically, the invasion success of grassy weeds is relatively when soil conditions are poor and rice cropping systems are continuous (Alhassan 2015b; Imeokparia 1989; Ogborn 1978) due to increased tolerance of weeds to conventional agronomic practices. For instance, a survey of lowland rice weeds in the Sudan Savanna ecological zone of Nigeria shows that *D. horizontalis* constituted the highest total number of individual weeds and ranked highest in importance value index, followed by *E. colona* and other weed species (Alhassan et al. 2015b). Perennial rhizomatous or tuber-bearing species such as *S. africana, Leersia hexandra* Sw., wild rice (*O. longistaminata*), and sedges of the genus *Cyperus,* are hypothesized to possess a higher tendency to survive adverse environmental conditions (Rodenburg et al. 2011) in African lowland ecosystems.

Understanding the growth pattern, ecology, and herbicide tolerance/resistance status of important weed species (Figure 1) in Nigeria is necessary to develop an appropriate weed management strategy within a changing climate. Only a few studies have identified the biology of common weed species in Nigerian lowland ecology (Imeokparia 1989; Yakubu and Ayeni 2001). Furthermore, a good knowledge of the weed flora dynamics in specific lowland areas could be achieved by taking a periodic survey of the weed flora, weather conditions, and prevalent agronomic practices as they may affect weed distribution.

Chemical Weed Control

To cultivate rice on a large scale in Nigeria, chemical weed control represents a practical and economical alternative to hand weeding (Akobundu 1981; Alhassan et al. 2015a; Bakare et al. 2008a, 2008b, 2008c; Imeokparia and Okunsanya 1997; Jiya et al. 2019; Omovbude et al. 2020). Selective pre-emergence herbicides such as pretilachlor plus dimethametryn, oxadiazon, and butachlor, and postemergence herbicides such as piperophos plus propanil, thiobencarb, and propanil have been recommended for weed control in lowland rice at varying rates in different agroecologies (Akobundu 1987; Bakare et al 2008a, 2008b, 2008c; Enyinnia and Nwosu 1992; Jiya et al. 2019; Okafor 1981; Omovbude et al. 2020). The timely application of these herbicides has reduced weed infestation more effectively compared to manual weeding. However, achieving season-long weed control with these herbicides remains a challenge (Adigun et al. 2005, 2016). Weeds such as *O. longistaminata*, *S. africana*, *Echinochloa* spp., and *Cyperus* spp. have shown tolerance to recommended rice herbicides to date (Bakare et al 2008a, 2008b, 2008c; Imeokparia 1989; Jiya et al. 2019). Achieving season-long weed control with herbicides may further necessitate strategic integration of other weed management practices.

Along with the rising living standard in Nigeria, consumers' demand for rice is shifting from quantity to quality. However, herbicide application has not been consistent with the recommended rate of herbicides. Farmers sometimes apply herbicides with little or no reference to the recommended rate (Alagbo and Akinyemiju 2018b; Rodenburg et al. 2019). For instance, glyphosate and a mixture of 2,4-D amine plus propanil (i.e., 47% and 65% respectively) were applied below recommended rates, whereas paraquat and 2,4-D (i.e., 34% and 200% respectively) were overused in lowland fields (Alagbo and Akinyemiju 2018b). The latter suggests some levels of risk to soil (Kaur et al. 2014), water, and aquatic life in Nigerian lowland ecologies. The environmental impacts of these conventional herbicides are rarely understood. Hence, there is a need to investigate farmers' resource use efficiency in Nigerian lowland ecologies.

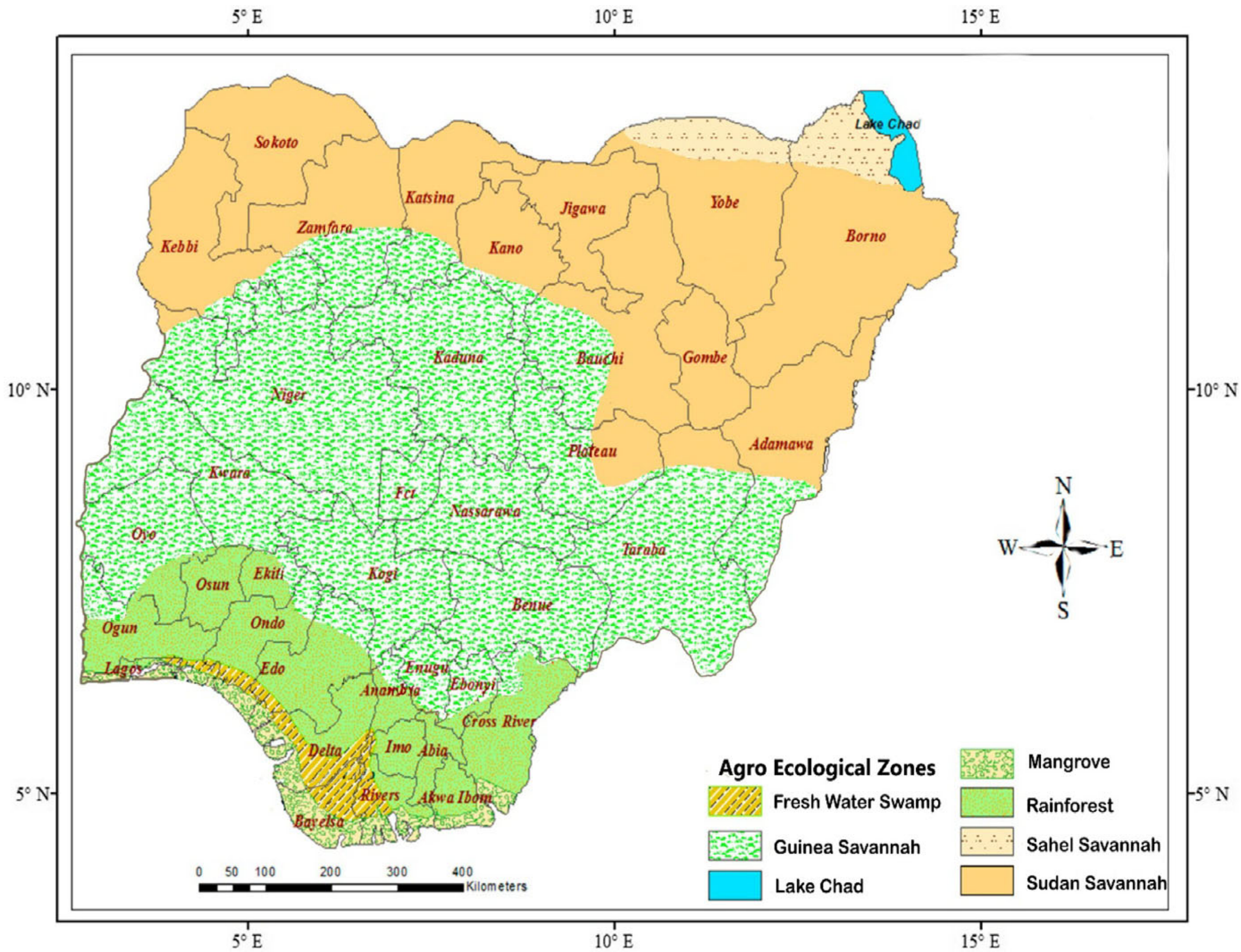

Figure 1. Nigerian map showing various agroecologies.

The state of farmers' knowledge of available herbicides for rice production is unknown. Most farmers in sub-Saharan Africa lack expert advice on herbicide application (Rodenburg et al. 2019). Tables 2 and 3 show some selected recommended herbicides for different agroecological zones in Nigeria, although it is still not clear whether these herbicides are available in the Nigerian market (Rodenburg et al. 2019). To increase rice yield sustainably, consistent evaluation of new rice herbicides against prevalent weeds is necessary, and such technology could be extended to farmers.

Cultural Weed Control

Water Requirement for Weed Management

Maintaining optimum water levels in a uniform, leveled field (where such is achievable) has been widely adopted to suppress weeds under anaerobic field conditions. Good water management is essential to minimize weed infestation in lowland rice because it significantly reduces the germination of weed seeds (Akobundu 1987; Ismaila et al. 2015). Timing, duration, and flooding depths will determine the degree of weed suppression under anaerobic conditions (Ismaila et al. 2015). In Nigeria, chemical weed control has proven to be effective under irrigated field conditions in the past (Imeokparia 1990) when integrated with good land preparation and proper water management (IITA 1974). Most lowland fields where rice is cultivated in Nigeria are rainfed, situated along coastal plains, and characterized by undulating land terrains without bunds or good drainage systems. Under these conditions, the use of water as a control strategy is difficult due to poor flooding control (Akobundu 1981; Akobundu and Fagade 1978). For instance, in southeastern Nigeria, the adoption of flooding as a weed management option under hydromorphic soil conditions is unrealistic due to impeded drainage (Enyinnia 1993; Pons 1982). Such uncontrolled drainage tends to favor the high proliferation of problem weeds (Enyinnia 1993) such that the cost of land clearing is high, particularly for subsistence-level farmers, and troublesome weed seeds are carried over to the next cropping season.

Weed control trials in Nigeria must factor in the poor drainage systems in major lowland ecologies. Effective weed management can be achieved through timely weeding interventions (other than flooding) at an early growth stage until rice is fully established to suppress weed growth at later stages (Akobundu 1981, 1987; Ismaila et al. 2014).

Use of Weed Competitive Cultivars

Crop competitiveness, being one of the most important features in achieving long-term weed control (Ferrell et al. 2006; Saito et al.

Table 1. Prominent weeds of Nigerian lowland rice fields.[a,b]

Prominent weeds				Agroecology			
Common names	Latin names	Class of weeds	Life cycle	Southern Guinea Savanna	Rain Forest	Sudan Savanna	Lake Chad Basin
African mosquito fern	*Azolla pinnata R. Br. Var. africana (*Desv.) Bak.	B	A	√	√	√	
Benghal	*Commelina benghalensis* L.	B	P		√	√	
Bermudagrass	*Cynodon dactylon* (L.) Pers.	G	P	√		√	
Smallflower umbrella sedge	*Cyperus difformis* L.	S	A	√	√	√	
Yellow nutsedge	*Cyperus esculentus* L.	S	P	√	√		√
Purple nutsedge	*Cyperus rotundus* L.	S	P	√	√	√	√
Crabgrass	*Digitaria horizontalis* Wild.	G	A	√	√	√	√
Japanese millet	*Echinochloa colona* (L.) Link.	G	A	√	√	√	√
Antelope grass	*Echinochloa pyramidalis* (Lam.) Hitchc. & Chase	G	P	√			
Globe fingerush	*Fimbristylis littoralis* Gaud.	S	A	√	√		
Swamp Morningglory	*Ipomoea aquatica* Forsk.	B	P	√	√	√	
Southern cutgrass	*Leersia hexandra* Sw.	G	P	√			
	Leptochloa caerulescens Steud	G	A	√			
Waterprimose	*Ludwigia* spp.	B	A/P	√	√		
Water lily	*Nymphaea lotus* L.	B	P	√	√		
Longstamen rice	*Oryza longistaminata* A.Chev.& Roehr.	G	P	√	√	√	√
	Sacciolepsis africana C.E. Hubb. & Snowden.	G	P	√	√		
Wedgewort	*Sphenoclea zeylanica* Gaertn.	B	A	√			
Hippo grass	*Echinochloa stagnina Beauv.*	G	P	√			
Low spikesedge	*Klinga pumila* Michx	S	A	√			
Fingergrass	*Chloris pilosa* Schumach	G	A			√	

[a]References: Adeyemi et al. 2017; Ajala et al. 2019a, 2019b; Akobundu and Ahissou 1985; Alagbo and Akinyemiju 2018b; Alhassan 2015b; Bakare et al. 2008a, 2008b, 2008c; Daramola et al. 2020; Enyinnia 1993; Evbuomwan 1992; Gbanguba et al. 2011; Imeokparia 1994, 1989; Imeokparia and Okusanya 1997; Imeokparia et al. 1992; Ismaila et al. 2015; Jiya et al. 2019; Kamai et al. 2020; MacDonald 2003; Okafor 1986.
[b]Abbreviations: B, Broadleaf; G, Grass; S, Sedge; P, Perennial; A, Annual; √, Available weeds.

Table 2. Herbicides recommended for lowland rice in Nigeria.[a]

Common name	Rate, kg a.i. ha^{-1}	Timing	Ecosystem/ Zone	Source
Oxadiazon	1.0	PRE	SS	Alhassan et al. 2015a
Butachlor	1.25	PRE	RF	Omovbude et al. 2020
Pretilachlor + Pyribenzoxim	1.5	PRE	RF	Alagbo and Akinyemiju 2018b
Propanil + 2, 4-D	2.24	POST	SGS	Gbanguba et al. 2020; Jiya et al. 2019

[a]Abbreviations: RF, Rain Forest; SGS, Southern Guinea Savanna; SS, Sudan Savanna; POST, Postemergence; PRE, Preemergence.

2012), is a function of a cultivar's weed-competitive ability to maintain a high yield despite severe weed pressure (Jannink et al. 2000; Saito et al. 2012). Rice cultivars differ in weed competitiveness (Haefele et al. 2004) in different ecologies (Saito et al. 2012). To reduce a farmer's reliance on herbicides for weed control in water-limited lowland environments, the use of weed-suppressive cultivars has been suggested (Binang et al. 2011; Gibson et al. 2001; Saito et al. 2012) in combination with other favorable agronomic practices such as timely weed removal and good tillage operation. Rice cultivars that compete well against weeds are often tall with rapid vegetative growth, droopy leaves, and high leaf area (Akobundu and Ahiosu 1985; Binang et al. 2011; Haefele et al. 2004; Saito et al. 2012). For instance, the drooping leaves and higher tillering ability of the 'NERICA 1' cultivar resulted in good canopy formation, which contributed to its suppression of weed growth and higher grain yield compared to other NERICA cultivars (Kolo and Umaru 2012).

Unfortunately, studies on weed-competitive lowland rice cultivars in Nigeria are limited. 'FARO 55' (Usman et al. 2013) and 'FARO 59' are the only known cultivars with weed suppressive traits used in Nigeria (Oluwaseyi et al. 2016). Alternatively, cultivar mixtures have proven effective in suppressing weeds in lowland rice crops in Nigeria (Binang et al. 2011). For example, cultivar mixtures of 'Muduga' and 'FARO 15' at ratios of 1:4 and 3:2 produced significantly strong rice yields due to intraspecific competition among cultivars for light and growth resources and thus capable of reducing weed density (Binang 2010). The competitive potentials of such cultivar mixtures against weeds now depend on the choice of cultivars and transplanting intervals coupled with other agronomic practices (Binang 2010). To address the fast-growing problem of herbicide tolerance in rainfed lowland ecology, the role of rice cultivars in their ability to suppress weed growth in various agroecologies (Figure 1) should be studied further, and promising cultivars exploited for sustainable weed management in water-limited lowlands.

Cropping Pattern

The potential of good cultural practices to effectively suppress weeds, when used in combination with other weed control methods, cannot be underestimated in terms of reduced labor costs, weed aggressiveness, pest and disease control, and seeding input (Oyewole et al. 2010). Crop competitiveness with weeds can be improved by varying seed rates or seeding methods of rice (Hay and Walker 1989; Zimdahl 2004). For instance, low seeding rates of rice using productive cultivars ensures the establishment of

Table 3. Classes of herbicides recommended for lowland rice in Nigeria over three decades.[a,b]

Common name	Mode of action	Group	Family
Bentazon	Inhibition of photosynthesis at photosystem II	6	Benzothiadiazinone
Propanil	Inhibition of photosynthesis at photosystem II	7	Amide
Silvex			
Butachlor	Inhibition of very-long-chain fatty acids (inhibition of cell division)	15	Chloroacetamides
Dimethametryn	Inhibition of photosynthesis at photosystem II	5	Triazine
Piperophos	Inhibition of very-long-chain fatty acids (inhibition of cell division)	15	Others
Pretilachlor	Inhibition of very-long-chain fatty acids (inhibition of cell division)	15	Chloroacetamides
Oxadiazon	Inhibition of PPO	14	Oxadiazole
Fluorodifen			
Bifenox	Inhibition of PPO	14	Diphenylether
Glyphosate	Inhibition of EPSPS	9	Glycine
2,4-D	Action like indole acetic acid (synthetic auxins)	4	Phenoxy-carboxylic-acid
Pyribenzoxim	Inhibition of ALS and AHAS	2	Pyrimidinyl(thio) benzoate
Thiobencarb	Inhibition of lipid synthesis	8	Thiocarbamate

[a]References: Akobundu 1981; Alhassan et al. 2015; Enyinnia 1993; Evbuomwan 1992; Imeokparia 1990, 1994; Imeokparia et al. 1992; Okafor 1986; WSSA 2010.
[b]Abbreviations: AHAS, acetohydroxyacid synthase; ALS, acetolactate synthase; EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase; PPO, protoporphyrinogen oxidase.

vigorous, competitive, and highly productive tillers that are capable of suppressing weeds at reduced seeding costs (Chauhan 2012; Gopal et al. 2010; Hay and Walker 1989). Crops are also known to gain more competitiveness over weeds when established in high densities (Danmaigoro et al. 2016). Studies have also shown that narrow interrow spacing (15 to 20 cm) effectively suppresses weeds (Ahmed and Moody 1980; Akobundu 1976; IRRI 1978) when combined with at least one weeding early in its life cycle. Such weed management strategies could result in increased yield with limited labor costs. However, optimizing such cropping practices among farmers may be limited due to non-uniform transplanting, wrong weeding timing, and the lack of technical knowledge, which remains a major bottleneck in bridging rice yield gaps in Nigeria.

In the Sudan Savanna agroecology (Figure 1) of Nigeria, the broadcast seeding method is reported to aggregate higher weed biomass when compared with the dibbling-and-drilling method (Alhassan et al. 2015a; Ismaila et al 2015; Phuong et al. 2005). On the other hand, increasing seeding rates in lowland rice fields aid the formation of a dense leaf canopy, which helps to suppress weed growth at a later growth cycle (Arce et al. 2009; Mahajan et al. 2010). It is a common practice that most farmers broadcast rice in a lowland field in a bid to reduce production costs. Increasing seed rates under such a situation may reduce weed pressure. However, such a result may be difficult to achieve in drought stress conditions (Kirkland et al. 2000). Studies on the effective practice of narrow spacing and increased seeding rate coupled with the best seeding method could be further evaluated under water-limited lowland field conditions across agroecological zones in Nigeria.

Crop Rotation

Weeds compete well with crops that have similar growth requirements, such that any cultural practices designed to enhance crop yield may also benefit the growth and development of weeds (Omafra 2006). Therefore, in a continuous monocropping system, adopting the best chemical and cultural practices as a weed management strategy may be unfavorable in the long term. The practice of crop rotation can significantly reduce the density of peculiar or problematic weed species in any continuous cropping system (Ball 1992; Gbanguba et al. 2020; Marenco et al. 1999). For instance, a six-time reduction of the weed seed bank was reported in a rotated cropping system when compared with a monocropping system in a study conducted over 7 yr (Forcella and Lindstrom 1988). Hence, synergizing crop rotation with other control practices (where it is possible) is key to developing a long-term weed control program across water-limited rainfed lowlands in Nigeria.

Rotation of vegetables and other arable crops (Gbanguba et al. 2011) in the late season followed by rice the following season could be beneficial in displacing herbicide-tolerant weed species in lowland ecosystems. For example, studies from the Guinea Savanna area in Nigeria have shown that cassava/legume intercrop, followed by lowland rice, reduced weed population and weed dry matter, and increased rice yield when compared with higher proliferation of troublesome weeds (*L. hexandra, E. colona,* and *E. stagnina*) when lowland rice was grown after a long fallow period (Gbanguba et al. 2011, 2020). In addition, rotating other crops with rice in the lowland ecology may benefit increased weed diversity, such that herbicide efficacy and other weed management strategies are enhanced in the long term. Despite such potentials of crop rotation as an integrated weed management (IWM) approach, there is a paucity of information on the economics and yield benefit of crop rotation for sustainable weed control in rainfed lowlands. Hence, on-farm field demonstration exercises may be necessary to actively engage farmers on the need to complement other weed management strategies with crop rotation in rainfed lowland fields in Nigeria.

Timing of Operations

A major setback in the implementation of an IWM strategy is the poor timing of operations (Alagbo and Akinyemiju 2018a). Weed control at an early crop growth stage is important to enhance rice yield (Ajala et al. 2019b; Nojima 1966). Weeds are better controlled during periods of crop establishment (when crop plants and weeds are tender) provided planting or transplanting takes place within a short time after land preparation (Adigun et al. 2005; Imeokparia and Okusanya 1997). For instance, early weed interference in irrigated rice could result in potential yield loss if not addressed (Okafor 1982). Unfortunately, poor smallholder farmers underrate the timeliness of operation (Alagbo and Akinyemiju 2018a). Rice must remain weed-free during the critical period of biomass development (Ajala et al. 2019a) to support panicle initiation and grain filling. Once the tillering is adversely affected by weeds, the yield will be reduced (Ajala et al. 2019b; Imeokparia and Okusanya 1997). Achieving such timeliness would imply that farmers have the required weed control inputs ahead of time. Therefore, the timely intervention of government and nongovernmental organizations (NGOs) in providing an enabling platform for smallholder

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farmers to explore the available IWM technology will successfully bridge the rice yield gap, thus, enhancing rice productivity.

Physical Weed Control

Tillage Practices

Land preparation (either mechanical or manual) is important to provide the weed-free seedbed needed for effective weed control at the initial cropping stage before broadcasting or transplanting rice (Jiya et al. 2019; Okafor 1986). The knowledge and feasibility of good tillage practices among rice farmers are crucial for sustainable weed management in the lowland.

For decades, the practice of no-till systems has been common among smallholder rice growers in Nigeria. It serves as an alternative to conventional or minimum tillage, which is believed to be labor and capital intensive due to the scarcity of tractors (Ajah 2014) and increased cost of manual operations. Many studies have supported that high labor costs and weed density reductions could be achieved in lowland rice if a no-till system is adopted (Akobundu 1987; Jiya et al. 2019; Magani and Shave 2011; Zakaria and Dzomeku 2018). Particularly, the use of pre-plant (nonselective) herbicides such as glyphosate and paraquat to clear vegetation is widely adopted in Nigeria for this purpose (Akobundu 1987; Alagbo and Akinyemiju 2018a). Under such practices, the increased prevalence of noxious perennial grasses (Table 1) is becoming more serious. A no-till system is predicted to result in a shift in the weed community structure over a while (Buhler 1992). The successful proliferation of perennial weeds under no-till conditions has encouraged a low weed species diversity in lowland ecosystems (Sans et al. 2011; Shrestha et al. 2002). This possible eco-shift in the weed community under no-till situations is still not addressed in most rice fields in Nigeria. Hence, introducing minimum or deep tillage practices may further enhance the burial of surface seeds and better efficacy of herbicides and/or alternative weed management approaches.

Mechanical Weed Control

Introducing mechanical weed control in lowland rice fields is necessary to complement conventional weeding practices (herbicide and hand weeding). Manual mechanical weeding tools such as rotary weeders can help farmers to save weeding time (Rodenburg et al. 2015) and remove herbicide-tolerant weeds. For instance, rotary weeders such as straight-spike and twisted-spike floating weeders were reported to reduce weeding time by 32% to 49% and by 32% to 56%, respectively, with better weed control efficacy compared with hand weeding (Rodenburg et al. 2015). Nevertheless, the adoption of mechanical weeders under rainfed field conditions may be challenging (Senthilkumar et al. 2018) considering poor leveling of land, inadequate flooding, and non-uniform seeding practices by smallholder farmers. A recent study from Tanzania shows that more than 80% of farmers adopt rotary weeders under irrigated rice fields compared with 20% in rainfed lowlands (Senthilkumar et al. 2018). Similarly, farmers in Nigeria also encountered difficulty in adopting the ring hoe technology in upland rice fields due to non-uniformity in seeding, even though it was perceived to be best in saving weeding time (Johnson et al. 2019). These suggest that the easy adoption of mechanical weeders could boost good agronomic practices where capital infrastructures such as rice seeders and transplanters are procured for farmers to seed or transplant rice in a uniform manner. It is therefore important for the government and other NGOs to provide infrastructural support in rural farming communities.

Precision Weed Management

Precision weed management is gaining wider acceptance globally because it promises a significant reduction in herbicide load in the environment (Gerhards 2019). Solving the problem of suboptimal or over-usage of herbicides (Alagbo and Akinyemiju 2018a; Rodenburg et al. 2019), and the long-term persistence of problem weed species in rainfed lowland fields would further necessitate the development of smart spraying technology for future farms in Africa. In high-income countries, offline weed mapping data in connection with a decision support system have been deployed for site-specific weed spraying in winter cereals resulting in higher yield and better weed control efficacy compared with conventional spraying (Gerhards and Quebel 2006).

Recent studies in Nigeria show that deep-weed, learning-based algorithms such as fuzzy logic (Olaniyi et al. 2020) and a single-shot multi-box detector (SSD) network models (Olaniyi et al. 2021) have shown high precision and accuracy in making weed management decisions and thus showing their potential for smart spraying in lowland rice. The SSD neural network-based algorithm resulted in 86% accuracy, 84% precision, and 92% sensitivity performance in object (weeds and rice) differentiation at varying resolutions (Olaniyi et al. 2021). The fuzzy logic-based expert system depends on weed density signals (thresholds) to make herbicide spraying decisions in lowland rice with a mean absolute error (decision accuracy) of 0.9 (Olaniyi et al. 2020). Both studies demonstrate the possibilities of developing an autonomous weed management system for rice production in sub-Saharan Africa.

Integrated Weed Management

IWM systems are perhaps the most appropriate weed control strategy for resource-poor rice farmers in the tropics. Combining various measures (i.e., cultural, chemical, physical, etc.) to control weeds at a subsistence level depends on the technical efficiency of adopted agronomic practices, availability of farm inputs to time, and the economic status of individual rice growers. Any time lag, deficiency, or absence of either or any of these automatically forfeits the possibility to optimize IWM principles for effective weed control at the subsistence level. Such deficits possibly explain the increased yield gap between researchers' and farmers' yields over decades (Daramola 2005). Harnessing the potential of recommended IWM strategies under different lowland ecologies across agroecological zones in Nigeria could sustainably bridge the yield gap.

In Nigeria, cultural practices such as land preparation, crop rotation, and adoption of a weed-competitive cultivar are most widely recommended practices in lowlands in combination with an appropriate chemical weed-control method (Ajala et al. 2019a, 2019b; Danmaigoro et al. 2016; Imeokparia and Okusanya 1997; Jiya et al. 2019). Emphasis given to each weed control method would depend on the peculiarity of rice ecosystems across each agroecological zone (Figure 1) in which rice is cultivated. For example, the cultivation of rice under hydromorphic soil conditions resulted in the proliferation of problem weeds (Imeokparia and Okusanya 1997). Hence, the need for a weed-suppressive IWM strategy.

A farmers' participatory research engagement is necessary to ascertain the potential of IWM under field conditions. It is equally important that necessary infrastructure facilities and farming inputs are supplied for the timely implementation of field operations.

Conclusions and Recommendations

It is clear that poor flood control systems combined with continuous cropping practices have benefited a shift in weed species from annuals to stable perennials that continually threaten lowland rice ecosystems. Sustainable weed management intervention in lowland ecology systems requires smart integration of cultural, physical, and chemical weed control methods that can mitigate heavy weed pressure in the long run (i.e., weeds are drastically suppressed, and yield is significantly enhanced).

To achieve better weed suppression and enhanced rice yield in Nigerian rainfed lowland environments, incorporating regular rotation with legumes (Gbanguba et al. 2011, 2020) could reduce the pressure of problem weeds and enhance the biodiversity of weed flora. The practice of conventional or minimum tillage operations as a substitute for no-till practices would further allow the burial of perennial weed propagules and heavy weed seed deposits within shallow soil depths. Promoting such tillage methods would enhance the emergence of uniform weed seeds and promote higher efficacy of the recommended postemergence and preemergence herbicides. Such a technique is necessary to reduce weed pressure and enhance the vigor of weed-competitive cultivars at early growth stages.

Uniform plant spacing, precise seeding rate, and seeding methods are prerequisites for ease of adopting mechanical weeders and optimum plant population as target weed suppression. Availability of rice seeders or a transplanting machine is needed for precise seeding in this case rather than the usual manual transplanting or broadcasting.

Future Outlook

The weed community structure in the key rice-producing areas in Nigeria must have changed with time due to poor agronomic practices. Unfortunately, there are few documented surveys of weed flora dynamics (i.e., current weed species richness, abundance, and diversity) across agroecological zones. Knowing the weed flora dynamics is necessary for site-specific weed management precision. On the other hand, new studies on the biology and ecology of existing problem weeds with multi-propagative mechanisms are needed to guide farmers to adopt appropriate control strategies.

Existing or newly released rice cultivars should be screened for site-specific weed competitiveness across agroecological zones in Nigeria. It is important to validate recommended herbicides with those present in the market (Rodenburg et al. 2019). Future studies of herbicide field trials should factor in poor water management systems under rainfed, inundated, and hydromorphic lowlands. Furthermore, the environmental impacts of herbicides on nontarget lowland communities should be investigated (i.e., future studies should focus on herbicide persistence status in lowland soil, water, and rice grain quality).

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