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From rice-like plants to plants liking rice: A review of research on weeds and their management in African rice systems

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ABSTRACT

Competition from weeds is the most important yield reducing factor in African rice production systems. Generally important weed management practices in rice are controlled flooding and the use of herbicides. Smallholder rice farmers in Africa however often lack the necessary water management infrastructure, access to affordable, good quality herbicide products and knowledge and equipment for their safe and effective application. Against this challenging backdrop, effective and affordable weed management strategies are highly needed. The literature on weed ecology and management in African rice systems is systematically reviewed to assess achievements in the last quarter of the past 50 years of international rice research endeavours, the period since the last comprehensive review (2009), and to propose the way forward for research and development. Most published studies are from West Africa and focussed on rainfed upland (43% of all relevant studies) or rainfed lowland (32%) rice. Grasses are the most frequently studied weed types, closely followed by parasitic weeds and broadleaved weeds (*ex aequo*). Most research (75% of published studies) focussed on weed management, mostly referring to or including curative measures (e.g., chemical, manual) or preventive weed management options that improve weed competitiveness of the crop (e.g., crop establishment, cultivars), while less attention was observed for preventive measures aiming at reduced weed recruitment or seed bank sizes (e.g., crop rotations, intercropping, mulches) or integrated weed management approaches. Future research should invest more in developing integrated weed management strategies that achieve (1) reduced weed recruitment, (2) reduced weed seed bank sizes and (3) improved crop competitiveness and that are compatible with farmer's production resources, fairly independent of (agrochemical) industries and markets and benign to the environment and human health. We recommend research on parasitic weeds to focus on a further broadening of the range of currently available management options, with a particular focus on the role of soil fertility and more efficient fertiliser technologies that simultaneously improve crop productivity and quality. For research to contribute to the development of meaningful weed management strategies for African rice systems in the future, we believe it would be best to identify and focus on target-location specific weed-communities, and to reconcile field level weed management strategies with the preconditions set at higher system levels (e.g., farming and agricultural systems) and anticipated scenarios regarding changing demographics and biophysical and institutional environments.

1. Introduction

In Africa, the importance of rice increased in recent years to become the third most important food energy source in the region (Wopereis, 2013). It is predominantly grown in rural parts of Africa, where 59% of the population lives (compared to 38% in Asia, the world's most

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important rice growing and consuming region) and where the population density is relatively low (approximately 25 inhabitants/km^2, compared to 39 in Asia, based on: United-Nations, 2021; World-Bank, 2021).

Rice is a versatile crop species with a wide environmental adaptation. Rice growing environments in Africa are characterised according to the hydrology and the main water source, and broadly categorised in irrigated lowlands (26% of total area under rice), rainfed lowlands (38%) and rainfed uplands (32%; Diagne et al., 2013b). Regarding the hydrological categorisation, lowland environments have waterlogged soils whereas soils in the upland environment are free draining. The second categorisation distinguishes between environments where farmers have control over water (irrigated lowlands), by irrigation and sometimes drainage facilities, or rely fully on rainfall (uplands) or a combination of rainfall, high water tables and unregulated floods (rainfed lowland) for meeting the crop's water demands (Rodenburg et al., 2014). Rice cultivation in rainfed uplands and lowlands mostly coincides with the rainy season, whereas in irrigated lowlands rice can be grown during the off-season as well, enabling more than one crop a year, provided there is sufficient irrigation water (Saito et al., 2013). The importance of the rainfed rice growing environments in Africa, is sharply contrasting with the situation in Asia, where only an estimated 26% (lowland) and 9% (upland) of the area under rice is characterised as rainfed (Seck et al., 2012).

Rice production in Africa is limited by a wide range of biotic constraints, the most important of which is competition from weeds. An extensive survey conducted between 2009 and 2010, in 18 countries accounting for 87% of the area under rice in Africa (Africa), showed that this is also the perception of smallholder rice farmers across rice growing environments; 70% of the respondents marked weeds as a major problem, and 20% as an intermediate problem (Diagne et al., 2013a). Based on expert opinions and weed-inflicted yield loss estimates, the authors concluded that research leading to technological options addressing weed competition, could potentially lead to 35% yield loss abatement and nearly 5% of poverty reduction among smallholder farm households in Africa. While this illustrates the importance of weed research for smallholder rice production in Africa, it does not provide directions as to what the important areas of attention are in terms of rice growing environment, weed species or groups, farm types, management strategies and current and future challenges.

Following an overview of the important weed species, extent of weed-inflicted yield losses, management practices available and followed by smallholder farmers and a presentation of the main management issues, a strategy for future weed research was outlined before (Rodenburg and Johnson, 2009). Foundation for that strategy was the observation that rice farmers in Africa need labour-saving and affordable strategies to manage weeds. As most rice farmers work under rainfed conditions with no control over water, controlled flooding cannot be a prominent weed management component. Due to dysfunctional agrochemical supply markets, weed management cannot heavily rely on herbicides either. One of the ideas forwarded in this strategy was to prioritise research and development efforts by focussing on the most problematic weed species with broad continental distribution. Increasing the biological and ecological understanding of such species could provide clues for non-chemical management approaches. To operationalise the above strategy, the paper concluded by a list of research priorities which can be grouped into (1) plant-oriented and referred to as 'crop and weed ecology' and (2) management-oriented and referred to as 'weed management'. Under 'crop and weed ecology', research should focus on the plant biological elements, including weed species' distribution and agronomic importance as well as knowledge on biology, ecology and competitive mechanisms of weed species with current and future importance. Given the likely influence of climate change in the coming decades, effects of such changes should be considered. Under 'weed management', the focus is on what farmers can do to manage weeds and to minimize their negative impact on productivity of the crop. Here, attention should be paid to the development or adaptations of weed management technologies that anticipate or align with future changes such as the continuous urbanization and associated migration from rural areas (e.g. labour-saving) and climate change (e.g. water-saving). Achieving high levels of farmer-adoption should be one of the lead motives of these research and development efforts.

The current paper, written at the time when the Africa Rice Center (AfricaRice) celebrates its 50th anniversary, presents a systematic review of what has been done in this field during these 5 decades, with a particular focus on progress in the last quarter, representing the period since the last comprehensive review in 2009. The objective of this review is to assess achievements, identify important research gaps and propose a way forward for research and development efforts. By analysing the rice-weed literature focussing on Africa, we will follow the above-mentioned research priority areas. Field-based weed management strategies are the focus area of much of the research done on rice systems in Africa, and therefore also of this review. Following Bastiaans et al. (2008), we distinguish between *preventive weed management,* i.e.*,* measures that (1) reduce the recruitment of weed seedlings from the seedbank (e.g. cover crops, mulch), (2) reduce or deplete the seedbank (e.g., stale seed bed technique, false hosts of *Striga* spp. as rotation- or cover-crops) or (3) improve the weed competitiveness of the crop (e.g., weed competitive rice varieties, optimised sowing times or densities), and *curative weed management,* i.e.*,* interventions leading to killing or removing weeds (e.g., mechanical weeding). Following Zimdahl (2007), in this paper we use (weed) 'control' specifically as a synonym for curative weed management, whilst the more generic term (weed) 'management' is used to refer to the ensemble of curative and preventive approaches.

2. Systematic literature search

A systematic literature search in Web of Science (accessed: 1 June 2021) was done for the period 1970 - current, using two approaches. The first approach combined searches on four type of search terms, i.e. #1 Africa or names of individual African countries, #2 weeds or weed groups, #3 rice and synonyms and #4 control and synonyms. This was then refined to the Web of Science category "Agronomy" and the document type "articles", resulting in 150 sources (Table 1). A second approach was to search for the combination 'weed' AND 'rice' AND 'Africa', which resulted in 201 sources (Table 1). All 150 and 201 sources were combined, duplicates removed, and the remaining publications were scanned individually for their relevance and to ensure only research articles were selected. This resulted in a final cohort of 120 relevant research papers, published between 1980 and 2021. These 120 papers were then chronologically studied and scored in a matrix in Excel with year of publication as rows and content (e.g. main topics, weed types, environments, overarching themes, research methods/approaches and geographic origin) as columns.

3. Weed research in African rice systems

3.1. Geography and rice growing environments

Most studies (70%) on weeds in African rice systems are conducted in, or have relevance to, West Africa (Fig. 1A). The second most important geographic origin for such studies is East Africa (31%), which gained importance since 2009. This distribution corresponds to some extent with the importance of rice in different sub-regions, as roughly 62% of the cultivated area under rice in Africa is located in West Africa, and 24% of the area is located in East Africa (Diagne et al., 2013b). The increase in studies from East Africa in more recent years can be explained by the gradual expansion, in presence and activity, of the Africa Rice Center in that sub-region which started in 2004 (Rodenburg and Saito, This issue 2022).

Table 1
Web of Science search (accessed on 01/06/2021), showing results (in number of sources) for each search attempt between 1971 and 1 June 2021.

Search #	Search terms	Number of sources
#1	Africa OR Algeria OR Angola OR Benin OR Botswana OR "Burkina Faso" OR Burundi OR Cameroon OR "Cape Verde" OR "Central African Republic" OR Chad OR Comoros OR Congo OR "Côte d'Ivoire" OR "Ivory Coast" OR DRC OR "Democratic Republic of Congo" OR Djibouti OR Egypt OR Equatorial-Guinea OR "Equatorial Guinea" OR Eritrea OR Ethiopia OR Eswatini OR Gabon OR Gambia OR Ghana OR Guinea OR Guinea-Bissau OR "Guinea Bissau" OR Kenya OR Lesotho OR Liberia OR Libya OR Madagascar OR Malawi OR Mali OR Mauritania OR Mauritius OR Mayotte OR Morocco OR Mozambique OR Namibia OR Niger OR Nigeria OR Reunion OR Rwanda OR "Sao Tome and Principe" OR Senegal OR Seychelles OR "Sierra Leone" OR Somalia OR "South Africa" OR "South Sudan" OR Sudan OR Swaziland OR Tanzania OR Togo OR Tunisia OR Uganda OR Zambia OR Zimbabwe	883,842
#2	weed OR "parasitic weed" OR "aquatic weed" OR Striga OR Rhamphicarpa OR Cyperus OR Echinochloa OR grasses OR sedges OR "broad leaved" OR broadleaved OR "broad leaf"	173159
#3	rice OR paddy OR oryza OR "O. sativa" OR "O. glaberrima"	189,035
#4	#1 AND #2 AND #3 combined; refined by WEB OF SCIENCE CATEGORIES: (AGRONOMY) AND DOCUMENT TYPES: (ARTICLE)	150
#5	Weed AND rice AND Africa	201
#6	#4 and #5 combined and review papers and papers not dealing principally with rice, weed ecology or management, or not focusing on Africa removed	**120**

Regarding rice growing environments, 57% of the weed studies focussed on rainfed uplands (RU), while 43% and 34% were relevant to rainfed (RL) or irrigated lowlands (IL), respectively, with the former recently overtaking the latter (Fig. 1B). This distribution (weighted ratios RU:RL:IL - 43:32:25) is not entirely proportional to the distribution of estimated cultivated area under rice over these three environments, i.e. 32% uplands, 38% rainfed lowlands and 26% irrigated lowlands (Diagne et al., 2013b). The dominance of weed studies focussing on uplands is justified by the generally observed higher weed species diversity, weed infestation and perceived constraints that weeds impose in this rice growing environment (Okafor, 1986; Johnson and Kent, 2002; Diagne et al., 2013a), mainly because weeds cannot be managed by flooding, such as in lowlands.

3.2. Weed types and species

Compared to other weed types, parasitic weeds have not received much attention prior to 2009, but the number of studies steeply increased thereafter (Fig. 2). The prominence of broadleaved weeds in the literature is explained by their diversity, as they comprise many more families and species than the grasses (Gramineae) and sedges (Cyperaceae). The importance of grasses is explained by their broad environmental adaptation, their morphological resemblance to rice, in particular in the early crop stages, and the limited number of available herbicide solutions because of their taxonomic and physiological similarities with rice (Rodenburg and Johnson, 2009). The increased attention for parasitic weeds could be explained by a modest surge in externally funded projects on that topic, which in turn was partly driven by increasing awareness of the importance of parasitic weeds in rice in general (Rodenburg et al., 2010, 2016b), and that of *Rhamphicarpa fistulosa* in particular (Rodenburg et al., 2011, 2015b). The incidence of parasitic weeds is recently estimated at 6% of the area under rainfed lowland rice, for *R. fistulosa*, and 12% of the area under rainfed upland rice for *Striga* spp. (Rodenburg et al., 2016b), compared to 100% of both environments for ordinary weeds. The estimated annual economic losses caused by parasitic weeds in rice in Africa is around $0.2 billion (Rodenburg et al., 2016b), about 14% of the estimated total economic losses incurred from all weed groups combined (Rodenburg and Johnson, 2009). Therefore, at the present level of importance, the attention for parasitic weeds seems a bit skewed. The presence of parasitic weeds in rice is however one of the distinctive features of African rice systems, as from other regions no reports of such weeds have been found. This type of weeds also typically exerts greater damage to the crop, because of the direct extraction of resources from crop plants (e.g. Těšitel et al., 2010), compared to ordinary weeds that extract resources more indirectly, i.e. from the environment they share with crop plants. This provides a possible justification for the more than proportional attention for parasitic weeds.

3.3. Integration levels, study foci and methods

Weed research in rice in Africa has mainly focussed on the crop or field level (a total of 57% of the studies), with an increasing number of

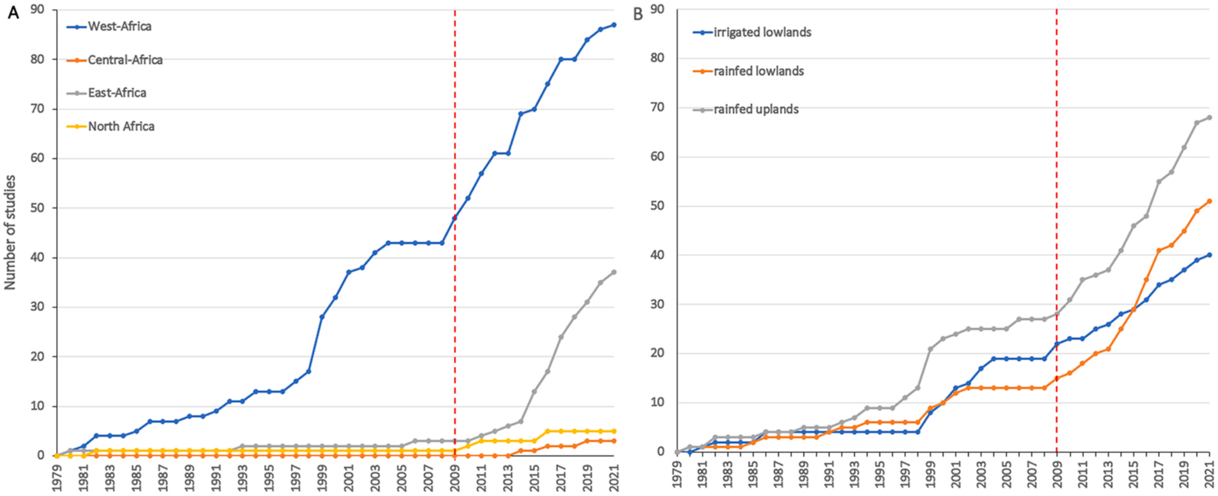

Fig. 1. A: Number (out of 120) of weed studies over time (1970-current) originating from a particular African region (i.e., West, East, Central and North). B: Number (out of 120) of weed studies over time (1970-current) focusing on a specific rice growing environment (i.e., irrigated lowland, rainfed lowland, rainfed upland). Multiple regions or environments can be covered by an individual study, explaining why the total sum of papers across categories in 2021 is larger than 120. Vertical red dashed line depicts 2009, the year of the review paper by Rodenburg and Johnson, against which progress is assessed.

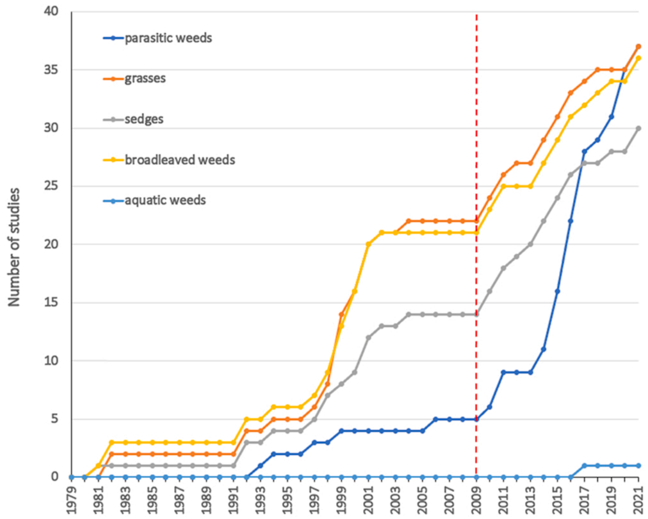

Fig. 2. Number (out of 120) of weed studies over time (1970-current) reporting or focussing on a particular weed type (i.e., grasses, sedges, broadleaved weeds, parasitic weeds, aquatic weeds). Multiple weed types can be covered by an individual study, explaining why the total sum of papers across types in 2021 is larger than 120. Vertical red dashed line depicts 2009, the year of the review paper by Rodenburg and Johnson, against which progress is assessed.

studies at lower (plant; 20%) or higher (farm; 25%) integration levels since the late nineties, and a more recent but modest increase of studies at yet higher integration levels, i.e., the landscape (7%), country (9%) and (sub-) regional levels (6%; Fig. 3A). The traditional dominant methodology of weed research focusing on African rice systems is experimental on-station work and researcher-led on-farm experiments (50% of all studies). In later years weed surveys (36%) became increasingly common, followed by other methodologies such as stakeholder interviews or workshops (15%), greenhouse or growth-chamber experiments (13%), farmer participatory experiments (10%) and modelling (8.4%; Fig. 3B).

Around 75% (89 of 120) of the studies focussed on weed management (data not shown). The curative weed management approaches, i.e. manual and chemical weed control, have received most attention (30% and 27% respectively; Fig. 4A), with a particular focus on optimised intervention timing. In recent years however these curative approaches have featured often as benchmark treatments to compare other approaches against. From the mid-nineties onwards, an increasing number of studies have focussed on preventive management options involving the use of weed competitive or parasitic weed resistant cultivars (currently totalling 27%). Preventive practices associated with crop establishment, such as flooding, timing or spacing of planting and intercropping (12% of studies), preventive practices based on agroecological principles, such as crop rotation, cover crops and mulching (12%) and curative weed management based on mechanical control (10%), have been studied less frequently. Despite the broad consensus that weeds are best managed in an integrated way (combining preventive measures and, if needed, supplemented by curative weed management), the share of integrated weed management studies, although increasing since 2009, is still relatively low (9%; Fig. 3A). Among the 25% of studies not focussing on weed management, the majority presents weed species distribution data (13%), insights in weed biology or ecology (10%), weed botany/taxonomy or genetic insights (both 10%; Fig. 4B). Most of these studies are however still conducted in pursuit of novel weed management technologies.

4. Research priority areas

4.1. Crop and weed ecology

4.1.1. Dominant weed species

In rainfed or irrigated lowlands, the most observed sedges are *Cyperus haspan*, *C. difformis*, *C. iria* and *Fimbristylis littoralis* (Table 2). Most common grasses in these environments are the perennial *Oryza longistaminata* and *Leersia hexandra* and the annual *Echinochloa colona*. *Oryza longistaminata* is probably the most difficult grass weed to control because it is a wild species of rice, and therefore resembles most closely the cultivated species of rice in terms of morphology (at early stages) and ecology, while it multiplies both through seeds and through its rhizomes (Yoshida et al., 2016). Annual species *Sphenoclea zeylanica*, *Ipomoea aquatica* and *Ludwigia hyssopifolia* are three of the most common broadleaved weeds in the lowlands. *Rhamphicarpa fistulosa* is the only parasitic weed in the lowlands, but is only problematic in the rainfed lowlands where water control is suboptimal (Rodenburg et al., 2015b). It is an important weed species because of its severe negative impact on crop physiology, growth and productivity (Rodenburg et al., 2016a;

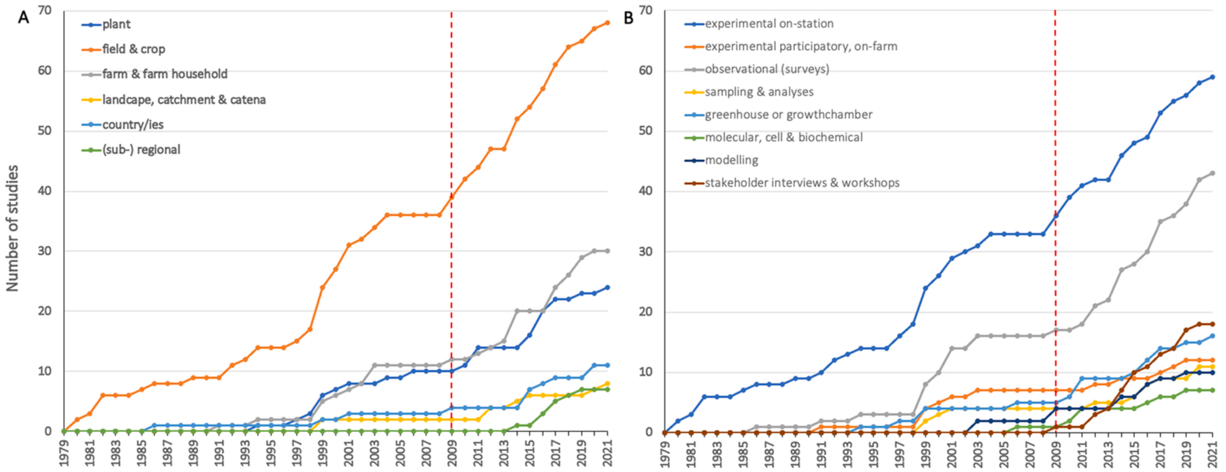

Fig. 3. A: Number of weed studies (out of 120) over time (1970-current) focussing on a particular integration level (i.e., plant, crop/field, farm/farm household, catena/landscape/catchment, country/ies, (sub-) regional). B: Number of weed studies (out of 120) over time (1970-current) following a particular methodological approach (i.e., experimental on-station, observational -surveys-, experimental farmer participatory, greenhouse/growth chamber, stakeholder interviews/workshops, sampling/lab analysis, molecular/biochemical, modelling). Multiple integration levels and methodological approaches can be covered by an individual study, explaining why total of summative percentages in 2021 is larger than 120. Vertical red dashed line depicts 2009, the year of the review paper by Rodenburg and Johnson, against which progress is assessed.

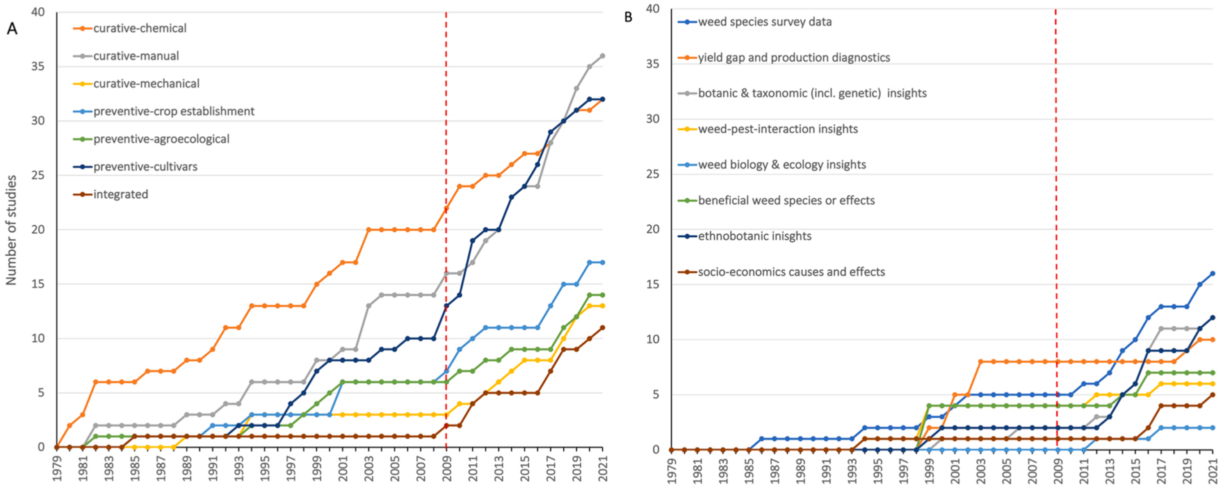

Fig. 4. A: Number (out of 120) of studies focussing on weed control approaches (i.e., chemical, manual, mechanical, preventive-crop establishment, preventive-agroecological, preventive-cultivars, integrated) over time (1970-current). 'Preventive-crop establishment' includes measures such as flooding, transplanting, timing or spatial arrangements of sowing. 'Preventive-agroecological' includes measures such as crop rotations, cover crops, mulching. B: Number (out of 120) of weed studies focusing on other aspects than control (i.e, weed species survey data, biology and ecology insights, botanic and taxonomic insights, socio-economic causes and effects, yield gap and production diagnostics, weed-pest interaction insights, beneficial weed species of effects, ethnobotanic insights) over time (1970-current). Multiple control approaches or topical areas can be covered by an individual study, explaining why total sum of studies in 2021 is larger than 120. Vertical red dashed line depicts 2009, the year of the review paper by Rodenburg and Johnson, against which progress is assessed.

Table 2
Weed species in upland and (rainfed or irrigated) lowland rice growing environments mentioned in more than two independent literature sources as most important/common, sorted on weed type (grasses, sedges, broadleaved, parasitic) and ontogeny (annual, perennial).

Weed type	Ontogeny	Upland	Lowland
Grasses	Annual	*Digitaria horizontalis; D. sanguinalis; Eleusine indica; Panicum laxum; P. maximum; Rottboellia cochinchinensis; Dactyloctenium aegyptium; Pennisetum purpureum; P. polystachion*	*Echinochloa colona; E. crus-pavonis; Oryza barthii; Pentodon pentandus*
	Perennial	*Cynodon dactylon; Imperata cylindrica; Paspalum scrobiculatum*	*Oryza longistaminata; Leersia hexandra*
Sedges	Annual		*Cyperus difformis; C. iria; Fimbristylis littoralis; Schoenoplectus senegalensis*
	Perennial	*Cyperus rotundus; C. esculentus; Mariscus alternifolius*	*Cyperus haspan; Fimbristylis ferruginea*
	Annual/ Perennial		*Fimbristylis spp.; Pycreus spp.*
Broadleaved	Annual	*Ageratum conyzoides; Euphorbia heterophylla; E. hirta; Commelina benghalensis; Tridax procumbens; Richardia brasiliensis; Acanthospermum hispidum; Cleome viscosa; Hyptis spicigera; Oldenlandia herbacea; Portulaca oleracea*	*Sphenoclea zeylanica; Ipomoea aquatica; Ludwigia hyssopifolia; Alternanthera sessilis; Bacopa decumbens; Basilicum polystachyon*
	Perennial	*Chromolaena odorata; Boerhavia spp.*	
Parasitic	Annual	*Striga asiatica; S. hermonthica*	*Rhamphicarpa fistulosa*

Kabiri et al., 2017, 2021), and difficult to control because of the abundant production of minute seeds (Ouedraogo et al., 1999).

In rainfed uplands, the perennial sedges *Cyperus rotundus* and *C. esculentus*, and perennial grasses *Cynodon dactylon*, *Imperata cylindrica* and *Paspalum scrobiculatum* are the most reported in the literature and among the most problematic weeds (Table 2). Again, these weeds, in particular the grasses, are difficult to control because they are rice-like species in terms of their morphological appearances, and they reproduce both sexually, through seeds, and asexually, through belowground rhizomes (*C. dactylon* and *I. cylindrica*) or aboveground rooted tillers (*P. scrobiculatum*). The broadleaved weed *Chromolaena odorata* complements the shortlist of most common perennial species. Among the annual weed species in the uplands, *Digitaria horizontalis*, *Eleusine indica*, *Panicum laxum*, *Rottboellia cochinchinensis* and *Panicum maximum* (mainly in fallows) are the most common grasses and *Ageratum conyzoides*, *Euphorbia heterophylla, Commelina benghalensis* and *Tridax procumbens* are the most common broadleaved weeds. *Striga asiatica* and *S. hermonthica* are the most common parasitic weeds species in these environments, inflicting high yield losses in rice (Johnson et al., 1997; Rodenburg et al., 2016b). Because of their very successful reproduction strategy they require a combination of control measures (Goldwasser and Rodenburg, 2013).

4.1.2. Weed distribution and agronomic and economic importance

Based on our systematic literature review an estimated 13% of the literature on weeds in rice systems in Africa presents weed survey data that provide insights in existing weed community diversity, weed distribution, agronomic or economic importance of weeds. Half of these studies focused on parasitic weeds, in particular *R. fistulosa*.

Weed species surveys have not been conducted in a regionally coordinated manner, but rather in particular countries, subregions, or environments or addressing a specific crop- or pest-ecological research question. A recent study from East Africa (i.e., Kenya, Tanzania, Uganda, Rwanda), by Irakiza et al. (2021), showed some similarity and differences in common species with those observed in West Africa (Okafor, 1986; Kent et al., 2001; Johnson and Kent, 2002; Toure et al., 2014). Most prominently, frequently observed lowland species in West Africa not found in East Africa are: the grasses *Panicum repens*, *Digitaria sanguinalis, Sorghum aethiopicum* (in Nigeria; Okafor, 1986) and *Panicum laxum* (in Benin; Toure et al., 2014), the broadleaved *Bacopa decumbens* (in Côte d'Ivoire; Kent et al., 2001; Johnson and Kent, 2002), and the sedge *Cyperus sphacelathus* (in Benin; Toure et al., 2014). Conversely, the grasses *Leptochloa squarrosa*, broadleaved species *Sphaeranthus suaveolens, Crepidorhopalon hepperi, Crassula granviki* and sedges *Eleocharis atropurpurea,* and *Kyllinga polyphylla*, prominent in East Africa (Irakiza et al., 2021), were not observed in West Africa.

The composition of weed communities depends highly on the environment. Clear differences are observed between the main rice growing environments (Okafor, 1986), even within the same catchment area along a hydrological gradient (Johnson and Kent, 2002), with species abundant in one environment but absent in another. This is mainly a result from differences in soil hydrology (e.g. water-logged vs free-draining soils, shallow vs deep water tables) and associated water management options, as these are important determinants for species occurrences or absences (Kent et al., 2001). But also within a similar rice growing environment, different species compositions are encountered between different agroecological zones, e.g. forest or savannah (Kent et al., 2001), or between altitudes (Irakiza et al., 2021). These findings allow more tailored weed management approaches.

Despite an identified need for more information about distribution, agronomic and economic importance of prominent or problematic weed species in African rice systems (Rodenburg and Johnson, 2009), progress has only been made for the parasitic weed species Striga spp. and *R. fistulosa*. A spatial analysis, based on geo-referencing herbarium specimen of parasitic weeds in Africa and existing rainfed rice maps, was followed by a stochastic impact assessment based on data derived from the literature (Rodenburg et al., 2016b). *Striga* spp. were found in 31 countries where rice is grown under rainfed conditions, whereas *R. fistulosa* was found in 28 rainfed rice producing countries in Africa. The rice area infested with any one of these parasitic weeds was estimated at 1.34 million ha and was predicted to increase in the future.

4.1.3. Biology, ecology and competitive mechanisms of current and future weeds

Only about 10% of the published studies on weeds of African rice systems have focussed on weed biology or ecology, two-thirds of which have looked at parasitic weeds (mainly *R. fistulosa*). Kone et al. (2013) showed associations between nutsedge species (*Cyperus rotundus*, *C. esculentus* and *C. sphacelathus*) and soil traits. It was concluded that soil carbon and magnesium contents were negatively correlated with nutsedge presence, whereas sand content, iron and available phosphorus showed a positive correlation. Previously, Kent and Johnson (2001) showed that increasing the flood layer or increasing flood duration decreased the abundance of *E. colona* and *E. crus-pavonis* while a number of associated common broadleaved weed species (i.e., *Heteranthera callifolia* and to a lesser extent *Sphenoclea zeylanica* and *Ammannia prieureana*) became more abundant or maintained their relative presence. Intermittent but deeper flood layers had a relatively stimulating effect on *Fimbristylis littoralis* and *A. prieureana.* For a number of other common species (e.g. upland weeds *Eleusine indica*, *Chromolaena odorata, Tridax procumbens, Portulaca oleraceae* and lowland weeds *Ludwigia hyssopifolia*, *Cyperus difformis* and *C. iria*), studies on their biology or ecology have been conducted in the past (e.g. Chauhan and Johnson (2008a), Chauhan and Johnson (2008b) (2009b), Chauhan and Johnson, 2009a; Chauhan and Johnson, 2009c; elaborated in Rodenburg and Johnson, 2009) but not within the context of African rice systems. In addition, whilst focussing on rice production in Asia, three studies showed competitiveness of weed species that are also common in Africa. *Cyperus iria* showed to be a highly competitive weed, able to outgrow rice through stem elongation in direct-seeded lowland rice (Chauhan and Johnson, 2010b). Through competition for light, *Echinochloa colona* and to a latter extent L. *hyssopifolia* proved to be competitive weeds to direct-seeded lowland rice where the crop misses the head start provided by transplanting (Chauhan and Johnson, 2010a).

Whereas increased knowledge on biology, ecology and competitive mechanisms is important, developing feasible and effective control strategies based on these insights may be complicated by the commonly observed diversity in weed species and the inherent adaptability of the weed community as a whole. For parasitic weeds a targeted approach of understanding their biology, ecology and host effects may be more relevant as these weeds cause greater direct damage and may also be more difficult to manage using common practices (Tippe et al., 2017a).

Most biology and ecology studies have focussed on the facultative parasite *R. fistulosa*. While it shares its geographic distribution and host-range with that of *Striga asiatica* and *S. hermonthica*, the ecological niche of *R. fistulosa* is distinctly different; whereas *Striga* spp. can be found on free-draining uplands soils, *R. fistulosa* is mainly found in the middle and lower parts of the upland-lowland continuum (Kabiri et al., 2015). The species has been observed to favour relatively coarse-textured soils with a relatively high potassium content and pH (Houngbedji et al., 2020). *Rhamphicarpa fistulosa* is characterised by a high genetic diversity as distinct ecotypes are observed among populations in Benin and Senegal (Zossou et al., 2016). It also has a broad host range, which includes several rice weeds. Some common weeds that are associated with *R. fistulosa* (no proven hosts) are the grass *Acroceras zizanioides,* the sedge *Cyperus difformis*, and the broadleaved *Eclipta prostrata* and *Bacopa decumbens* in Togo (Houngbedji et al., 2016) and the grass *Oryza longistaminata*, the sedges *Scleria vogelii*, *Fimbristylis littoralis* and *Cyperus distans* and the broadleaved *Ammannia auriculata* in Tanzania (Kabiri et al., 2015). In contrast with the obligate parasitic weed Striga spp., seeds of *R. fistulosa* do not need any biochemical cues from a potential host plant to germinate (Ouedraogo et al., 1999; Kabiri et al., 2016). The seeds are about four times larger than *Striga* spp. seeds, have a minimum dormancy period of 6 months (Ouedraogo et al., 1999) and germination requires moist conditions and exposure to light (Kabiri et al., 2016). Only developed seedlings can find a host plant to parasitise on and therefore it takes around 35 days for *R. fistulosa* to attach to a host and about 42 days for negative effects on the host to become apparent, considerably longer than with the obligate *Striga* spp. which starts parasitisation and host damage infliction within few days after seed germination (Kabiri et al., 2017). Compared to independently growing individuals, *R. fistulosa* plants able to parasitise a suitable host can quadruple their seed production and increase the size of individual seeds by about 15% (Kabiri et al., 2016).

4.2. Weed management

Integrated weed management (IWM) is generally considered the most effective and sustainable approach in rice (e.g., Jabran and Chauhan, 2015). IWM is defined as an approach to weed management whereby all possible means are integrated (Shaw, 1982). Given the concomitant complications of herbicide use (see below under *curative weed management*), IWM ideally focusses primarily on ecological interactions and should therefore be strongly based on preventive weed management measures (Bàrberi, 2019). Only when a prevention-oriented IWM is insufficient, it should be followed by curative weed management interventions, preferably labour-saving and non-chemical (Touré et al., 2021). In the literature on rice systems in Africa there are however few tangible examples of IWM that are strongly based on multiple preventive weed management practices; most IWM comprises one preventive with one curative measure. In irrigated lowlands prominent components of Integrated Crop Management (e.g., transplanting, levelling, flooding) could be considered as IWM (e.g., Toure et al., 2009), and effectiveness of this approach could for instance be enhanced by growing a weed competitive rice cultivar. In rainfed uplands, an example of IWM composed of preventive measures is the use of the weed-competitive legume species *Stylosanthes guianensis*, as a relay crop and short-term fallow followed by slashing and burning of the fallow biomass in the next season and rice sowing without prior tillage (Saito et al., 2010a). A variation of this practice, whereby the fallow and crop residue biomass is mulched instead of burnt also proves an effective IWM approach, and again this can be combined with a weed competitive or Striga-resistant rice cultivar (Randrianjafizanaka et al., 2018).

4.2.1. *Preventive management focussed on weeds*

Preventive management that focusses on the weeds, includes all measures that reduce weed seedlings recruitment or the size of the weed seedbank. Fallow management, crop rotations, the use of cover crops and mulching are examples of preventive measures that are most frequently studied in rice within the African context, and these are mainly tested and implemented in upland rice environments.

Traditional fallow periods between rice cropping seasons (Nyoka, 1982; Adesina et al., 1994) are increasingly shortened or abandoned (de Rouw, 1995; Demont et al., 2007). Alternatives are the shorter, off-season fallows with (leguminous) plant species that are sown for the purpose of weed control, such as *Aeschynomene* spp., *Crotalaria* spp., *Mucuna* spp., *Cajanus cajan*, *Canavalia ensiformis* or *Sesbania rostrata* (see: Rodenburg and Johnson, 2009; and Table 3). Improved (short) fallows using such legume species resulted in lower weed biomass in the following rice crop, compared to natural fallow (Akanvou et al., 2000).

In recent years, *Stylosanthes guianensis* is one of the more extensively studied cover crop species of rice-based systems in Africa, in particular as part of a Conservation Agriculture (CA) approach whereby the use of cover crops is combined with no-till and crop residue mulching. Stylosanthes is a perennial legume that produces relatively large amounts of aboveground biomass. The species has shown to be highly weed suppressive when used as a short-term fallow, relay-cropped into rice, in particular in a no-till system (Saito et al., 2010a). Conventional annual tillage contributes to good weed control but also renders soils vulnerable to erosion. Practising no-tillage however generally leads to higher weed biomass (Olofintoye, 1989; Saito et al., 2010a). In a rice-maize rotation a Conservation Agriculture (CA) approach with *Stylosanthes guianensis* as cover crop and source for mulch, controls erosion (Rodenburg et al., 2020) while the loss of weed control from refrained tillage can be compensated by its weed suppression (Randrianjafizanaka et al., 2018). Crop residue mulching may contribute to weed suppression, but earlier work showed that removal (Becker and Johnson, 1999b) or burning of residues (Akanvou et al., 2000) resulted in lower weed biomass levels in the following crop. Ranaivoson et al. (2019) demonstrated that weed suppression by mulching could work, but only when the soil is sufficiently covered. This requires biomass in excess of 10 t ha^{-1} which may be difficult to source, as the typical amount of biomass produced per ha is around 4–5 tonnes (Ranaivoson et al., 2018). Prolific biomass producers like *Stylosanthes guianensis* in the uplands and *Vicia villosa* in the lowlands appear good sources of such quantities (Naudin et al., 2012).

Table 3
Suitable legume species for weed-suppressive fallow rotations or intercrops in African rice-based cropping systems per rice growing environment (RGE: RU= rainfed upland; RL=rainfed lowland; IL= irrigated lowland) and agroecological zone (AEZ) if applicable (F= forest, S=savannah). Updated from Rodenburg and Johnson (2009).

Species	RGE (EAZ)	Timing	Traits	Source[a]
Aeschynomene afraspera	RL	Off-season fallow	Biomass accumulationWeed suppressive	1
Aeschynomene histrix	RU (F&S)	Relay seeding or off-season fallow	High N accumulationForage valueWeed suppression*Striga hermonthica* trap crop	1,2, 3
Cajanus cajan	RU (F&S)	Off-season fallow	High N accumulationWeed suppressive	2, 4
Canavalia ensiformis	RU (F&S)	Off-season fallow	High N accumulationForage valueWeed suppression	1,2, 4
Crotalaria anagyroides	RU (F)	Off-season fallow	Weed suppressive	2
Crotalaria juncea	RU, RL (S)	Off-season fallow	Weed suppressive	1, 2
Crotalaria ochroleuca	RU	Rotation	*Striga asiatica* control	5
Mucuna spp.	RU (S)	Off-season fallow	High N accumulationWeed suppressive	1, 2
Sesbania rostrata	RL	Off-season fallow	Biomass accumulationWeed suppressive	1
Stylosanthes guianensis	RU (F&S)	Relay seeding or off-season fallow; intercrop; residue mulching	High N accumulationWeed suppressive, *S. asiatica* suppression	1, 2, 6, 7, 8, 9, 10, 11
Vigna umbellata	RU	Rotational intercrop	Weed suppressive, *S. asiatica* suppression	7
Dolichos lablab	RU	Residue mulching	Weed suppressive	9, 10, 11
Vicia villosa	RL/IL	Weed suppression		11

[a] Sources: 1 = (Becker and Johnson, 1999b), 2 = (Becker and Johnson, 1998), 3 = (Merkel et al., 2000), 4 = (Akanvou et al., 2000), 5 = (Riches et al., 2005), 6 = (Saito et al., 2010a), 7 = (Randrianjafizanaka et al., 2018), 8 = (Rodenburg et al., 2020), 9 = (Ranaivoson et al., 2018), 10 = (Ranaivoson et al., 2019), 11 = (Naudin et al., 2012)

Conservation Agriculture practices in a rice-maize rotation have also shown to suppress infestation levels of the parasitic weed *Striga asiatica*. This is particularly the case with *Stylosanthes guianensis* as the cover crop species, but also with rice bean (*Vigna umbellata*) as intercrop in maize good *Striga* control in both maize and the subsequent rice crop is obtained (Randrianjafizanaka et al., 2018). The mechanistic explanation for reduced *S. asiatica* numbers, i.e., whether the cover crop and mulch cause suppression, suicidal germination or other effects, still needs to be elucidated.

4.2.2. *Preventive management focussed on the crop*

Preventive weed management can also include agronomic measures that contribute to a weed-competitive crop. Transplanting, increased crop plant densities, flooding and the use of cultivars that are more competitive (e.g., because of early vigour, superior height or tillering) are prominent examples of such preventive measures in rice.

One of the first lines of defence is the crop density (Dass et al., 2017). Evidence from Africa for this idea is however scant. Reduced interrow spaces have only been tested by Akobundu and Ahissou (1985) in Nigeria, who concluded that reducing the spacing from 25 × 30 to 25 × 15 cm increased the competitiveness of the crop, but (slightly) reduced yields of rice on hydromorphic lowland soils. The timing of rice planting may also be modified for weed control purposes, but the only published study we found on the application of sowing time in African rice systems refers to parasitic weeds in rainfed rice. Tippe et al. (2017b) showed that in uplands *S. asiatica* infestation is reduced with a delayed sowing time, whereas in lowlands *R. fistulosa* infestation is reduced when rice sowing is brought forward.

As mentioned before, transplanting in rows, levelling and bunding allowing the use of a homogeneous and continuous flood water layer, are all part of general crop management recommendations for lowland rice (referred to as Integrated Crop Management, ICM, or Good Agricultural Practices, GAP), that are mostly studied as integrated measures (e.g. Becker and Johnson, 1999a; Toure et al., 2009; Senthilkumar et al., 2018). The lack of factorial experiments in the literature under review, prevents an analysis of the contribution of individual practices to weed control. One could however argue whether that would be valuable and relevant information to have, as the different practices are mutually enabling and enforcing one another and should therefore not be recommended in isolation. Transplanting at optimum spacings (e.g. 20 × 20 cm) provides a dense, homogeneous and quick soil coverage and thereby a competitive advantage of the crop over weeds. Transplanting also enables early flooding, while field levelling and bunding allows homogeneous flooding, both important weed control measures.

Conversely, in crop management innovations where any of these recommended principles under ICM are modified, the vulnerability to weed competition may be increased. This is the case with the System of Rice Intensification (SRI), where more space for weeds is created because of the wider plant distances (25 × 25 or 30 × 30 vs 20 × 20 cm with ICM) and the use of fewer seedlings (one vs three with ICM) and younger seedlings (2 weeks old vs 3–4 weeks old with ICM), and where the weed-suppressive continuous flooding practice is replaced by alternate wetting and drying (AWD; e.g., de Vries et al., 2010). Increased weed pressure resulting from this led to an average of 28% lower yields and 38% lower water productivity under SRI compared to ICM (Krupnik et al., 2012a). Additional weed management technologies would then be needed, such as weed competitive rice cultivars (e.g. Jaya and Sahel-202; Krupnik et al., 2012a) and curative measures such as mechanical weeders, alone or combined with spot-application of post-emergence herbicides (Krupnik et al., 2012b).

The combination of (timely) fertiliser application and weeding is a prominent and profitable ICM recommendation in irrigated rice (Donovan et al., 1999; Wopereis et al., 1999; Haefele et al., 2000; Becker et al., 2003). In upland rice, split application of organic fertilisers (cattle manure) combined with weeding interventions, minimises weed interference and improves yields (Dada et al., 2017). Mineral nitrogen fertiliser application can increase weed infestation, which in turn diminishes the fertiliser effect on yield, but when fertiliser application is combined with one (early) post-emergence herbicide application (butachlor) and a manual weeding intervention, the yield is similar to that of a weed-free crop (Kolo et al., 2021). It is evident from all these studies, that weed growth can be stimulated by fertiliser applications, and thereby completely cancel out any yield advantage that one would expect from fertilization. Parasitic weeds may form an exception to that rule. Under (semi-) controlled experimental conditions infection of rice by the obligate parasite *Striga* spp. and the facultative parasite *R. fistulosa* were reduced by mineral fertiliser applications (Jamil et al., 2011a; Rodenburg et al., 2011). Evaluations of this potential management option in a rainfed upland and a rainfed lowland field in the same location, showed indeed moderate fertiliser-induced reductions in *S. asiatica* infections, but increasing numbers and biomass production of *R. fistulosa* (Tippe et al., 2020).

Considerable progress has been made regarding the identification of cultivars with superior levels of weed competitiveness and parasitic weed resistance or tolerance, as well as with understanding the underlying mechanisms (Table 4). Only part of the identified lines (i.e., the interspecific NERICAs) are actual fruits of deliberate breeding attempts to generate more weed competitive cultivars. The idea behind the first generation of NERICAs, adapted to the rainfed uplands, was the development of a dynamic plant type that would resemble the morphology of the weed competitive African cultivated rice species *O. glaberrima* in the vegetative phase and the more productive Asian species *O. sativa* during the reproductive stage through interspecific crossings (Jones et al., 1997; Dingkuhn et al., 1999). While some interspecific offspring indeed inherited the weed competitiveness of *O. glaberrima* parents (Johnson et al., 1998), no published data are available to show to what extent this is true across all 18 upland NERICA cultivars. For all other upland rice cultivars shown in Table 4, weed competitiveness was not explicitly part of the breeding objectives.

In contrast with the upland cultivars, the NERICA cultivars developed for the lowlands were all screened for weed competitiveness and nine of them showed superiority in this trait (Rodenburg et al., 2009; Saito et al., 2010b). However, the explicit breeding objectives of the lowland NERICAs, were environmental adaptation, yield, grain quality and insect and disease resistance, but not weed competitiveness (Rodenburg et al., 2009).

Alongside cultivar identification, screening protocols for both weed tolerance (ability to maintain high yields despite weed competition) and weed suppressiveness (ability to reduce weed growth through competition), as components of weed competitiveness (Jannink et al., 2000), are developed (Haefele et al., 2004; Saito, 2014; Saito and Futakuchi, 2014). Comparing the test cultivar bordered at each side by a row of a known weak competitor and natural weed growth, to the test cultivar grown alone and without weeds, was shown to be a good set-up for weed tolerance screening (Haefele et al., 2004). Grain yield, growth vigor and plant height at maturity under weed-free conditions proved reliable selection measures for weed competitiveness (Saito et al., 2010b). To find lines with superior weed suppressive abilities, large numbers of lines can undergo initial screening in unbordered single rows without weeds, followed by a smaller subset of lines screened with rice cultivars as substitute weeds to increase homogeneity of competition (Saito, 2014).

Since 2009, many parasitic weed resistant and tolerant rice cultivars are identified that are adapted to African rice growing environments (Table 4). Among the earlier mentioned interspecific upland cultivars, NERICA-1, −2, −4 and −10 had broad-spectrum resistance against *Striga asiatica* and *S. hermonthica* (Rodenburg et al., 2015a, 2017). NERICA-1 combined pre-attachment resistance based on low Striga seed germination stimuli (strigolactone) production (Jamil et al., 2011b), with post-attachment resistance based on less penetrable root endodermis layers (Cissoko et al., 2011) and tolerance, based on reduced Striga-inflicted yield losses compared to other cultivars (Rodenburg et al., 2015a). Several rice cultivars adapted to rainfed lowlands, proved suitable for use in *R. fistulosa* infested fields. Among the lowland NERICAs several showed either good levels of resistance or tolerance (Table 4) and two (i.e., NERICA-L-31 and −40) combined low infection levels with good crop yields (Rodenburg et al., 2016a).

4.2.3. *Curative weed management*

Weeding by hand or hand-held hoe is still the main weeding intervention by rice farmers in Africa (Rodenburg et al., 2019). In upland rice, a continent-wide survey showed that hand weeding takes on average close to 300 h per hectare (Ogwuike et al., 2014). Optimising timing and number of weeding interventions could imply labour savings, however a modelling exercise showed that weeding more than once significantly increases rice yields (by 27%) and labour efficiencies (by 37%) of rice farms (Ogwuike et al., 2014). At the field level, best weed control is achieved by weeding twice, well before the maximum tillering stage of the crop (e.g., at 21 and 42 days after sowing; Ekeleme et al., 2009; Toure et al., 2011).

Herbicides are the most obvious and effective labour-saving approach among the curative weed management alternatives (Olofintoye, 1989; Posner and Crawford, 1991; Rodenburg et al., 2015c). But the (effective and safe) use of herbicides implies an additional (monetary) cost on farm budgets for the product, application equipment and protective gears, and an availability of the right, quality-controlled, products at an affordable price. Such requirements are often not met in rural parts of Africa (Rodenburg et al., 2019). From the literature on weed management in rice in Africa, no herbicide innovations have emerged since the last comprehensive review by Rodenburg and Johnson (2009). With the exception of a fairly recent study that explicitly compared effectiveness of different herbicides (Saleh and Oyinbo, 2017), none of the recent studies focussed on herbicide effectiveness or innovations in terms of formulations or applications. Herbicides were included in on-farm experiments to test integrated crop management (Toure et al., 2009; Senthilkumar et al., 2018) or improve fertiliser use efficiency (Kolo et al., 2021), as additional weed control intervention in water saving production approaches (de Vries et al., 2010; Krupnik et al., 2012b) or as benchmark to test the labour-saving potential of mechanical weeders (Rodenburg et al., 2015c). In a recent continent-wide survey, a number of herbicide products have been observed that were not reported before in the literature on African rice production systems (Table 5), but these do not comprise newly developed formulations. The lack of herbicide innovations (Duke, 2012) and limited product diversity (Davis and Frisvold, 2017) is not unique for

Table 4

Adapted rice cultivars with proven superior levels of weed competitiveness (WC) and parasitic weed resistance and tolerance (PW) in African production systems per rice growing environment (RGE: RU= rainfed upland; RL=rainfed lowland; IL= irrigated lowland). Updated from Rodenburg and Johnson (2009) and Rodenburg et al. (2010).

	RGE	Cultivar	Rice species	Main superior traits	Source[a]
Weeds					
	RU	IG10	*O. glaberrima*	Biomass; Tiller number; LAI; SLA; Early vigor; Weedy yields; Root length density	1, 2, 3
		CG14	*O. glaberrima*	SLA; LAI; Tillering; Early vigor; Weed suppr.	3, 4, 5, 6, 7, 10
		CG20	*O. glaberrima*	SLA: Tillering; Early vigor; Weed suppr.	6, 9
		ACC102257	*O. glaberrima*	Root length density	2
		WAB96–1–1	*O. sativa*	Height; Weed suppr.	6
		SP4	*O. sativa*	Height; Weed suppr.	6
		ITA 150	*O. sativa*	Height; Tillering; Weed suppr.	7
		IR 74371–3–1–1	*O. sativa*	Weed suppr.; Weedy yield	8
		B 6144 F-MR-6–0–0	*O. sativa*	Weedy yield	8
		NERICA-1	Interspecific	Weed suppr.	10
		WAB56–104	*O. sativa*	Weed suppr.	10
		Chhomrong Dhan	*O. sativa*	Weed suppr.	11
		FOFIFA 167	*O. sativa*	Weed suppr.	11
		Aus 257		Weed suppr.; Weed-free yields	12, 13
		IR 1552		Weed suppr.	12
	IL	Jaya	*O. sativa*	Weedy and weed-free yields; Weed suppr.; Weed competitive	14, 15, 16
		Sahel-202	*O. sativa*	Weed competitive	16
	IL/ RL	TOG5681	*O. glaberrima*	Weed suppr.; Weed competitive	9, 15
		WITA 4	*O. sativa*		8
		WAB1159–4–10–15–1–3	Interspecific		8
		NERICA-L-6	Interspecific	Weed suppr.; Weed yields	8, 15
	RL	NERICA-L-32, −35, −37, −42, −53, −55, −58 and 60	Interspecific	Weedy and weed-free yields	15
		Adny 11	*O. sativa*	Tillering	17
Parasitic weeds					
STRHE, STRAS*	RU	ACC102196	*O. glaberrima*	T * *	18
		Makassa		T, R/T	18
		IG10		T, R/T	18
		M27		T	18, 21
		T2		T	18, 21
		CG14		R (pre- & post attachment)	19, 21, 24, 25
		WAB951–1	Interspecific	R	19
		IR49255-B-B-5–2	*O. sativa*	R	18, 20
		IR47255-B-B4		R	18, 20
		IR47697–4–3–1		R	18, 19
		WAB928–22		R	19
		WAB935–5		R	19
		WAB937–1		R	19
		B3913F-16–5-ST-42		R	18, 20
STRHE		Ble Chai		R	20, 31
		Nipponbare		R (post-attachment)	21, 24, 32
		FARO 40		R	22
		FARO 11		T	23
		NERICA-2, −3, −4, −12, −13, −17		R	27
		NERICA-1, −10, 17		T	27
		NERICA-5		R	27, 30
		Umgar		R	30
STRHE, STRLU		NERICA-1		R (pre- & post-attachment)	24, 25, 27
		NERICA-10		R (post-attachment)	24, 27, 31
		NERICA-2, −4		R	31
		SCRID090–60–1–1–2–4		R	31
STRLU		Botrabe		T	26
		3293		R	26
		Ra-JL		R	26
		NERICA-2, −5, −17		R	27
		NERICA-1, −9, −17		T	27
		Ble Chai		R	31
		ACC102196		T	31
		WAB928–22-2-A-A-B		T	31
RPCLO	RL	Gambiaka		R	28
		NERICA-L-39	Interspecific	T	28, 29
		NERICA-L-20		T	29
		Supa India (Kilombero)		T	29
		TOG5681		R	29
		IR64		R	29
		NERICA-L-23, − 31, − 40, − 48		R	29

* EPPO codes parasitic weed species: *Striga hermonthica* (STRHE), *S. asiatica* (STRLU), *S. aspera* (STRAS), *Rhamphicarpa fistulosa* (RPCLO); * * R= resistant, T = tolerant

[a] *Sources*: 1 = (Johnson et al., 1998), 2 = (Fofana and Rauber, 2000), 3 = (Dingkuhn et al., 1999), 4 = (Asch et al., 1999), 5 = (Dingkuhn et al., 1998), 6 = (Jones et al., 1996), 7 = (Ekeleme et al., 2009), 8 = (Saito et al., 2010b); 9 = (Moukoumbi et al., 2011), 10 = (Toure et al., 2011), 11 = (Raboin et al., 2014), 12 = (Saito,

2014), 13 (Saito and Futakuchi, 2014), 14 = (Haefele et al., 2004), 15 = (Rodenburg et al., 2009), 16 = (Krupnik et al., 2012a) 17 = (Akobundu and Ahissou, 1985), 18 = (Johnson et al., 1997), 19 = (Johnson et al., 2000), 20 = (Harahap et al., 1993), 21 = (Gurney et al., 2006), 22 = (Adagba et al., 2002b), 23 = (Adagba et al., 2002a), 24 = (Cissoko et al., 2011), 25 = (Jamil et al., 2011b), 26 = (Rodenburg et al., 2010), 27 = (Rodenburg et al., 2015a), 28 = (Rodenburg et al., 2011), 29 = (Rodenburg et al., 2016a), 30 = (Samejima et al., 2016), 31 = (Rodenburg et al., 2017); 32 = (Mutuku et al., 2019)

Source:Adapted rice cultivars with proven superior levels of weed competitiveness (WC) and parasitic weed resistance and tolerance (PW) in African production systems per rice growing environment (RGE: RU= rainfed upland; RL=rainfed lowland; IL= irrigated lowland).

Table 5
Herbicide formulations (in alphabetical order) reported to be available at local agrochemical supply (ACS) shops and used at rice farms in Africa, based on a continent-wide survey across 20 countries (Source: Rodenburg et al., 2019). Timing of application (POST=post-emergence, PRE=pre-emergence, PP= pre-planting), weed types targeted by the product (G=grasses, S=sedges, B=broadleaved, A=all) and rice growing environment (RGE; U= rainfed upland, L= rainfed/irrigated lowland, A=all). The last column indicates whether the formulations were reported in previous reviews (Y=yes; N=No; C =Not in combined formulation), i.e., Rodenburg and Johnson (2009), Akobundu (1987) and Diallo and Johnson (1997). Herbicide names in bold are not reported before in this context (African rice systems) and could be considered as newly emerged in the last 12 years.

Herbicide formulations	Application timing	Weed types	RGE	ACS shops	Used on farms	Observed before 2009
2,4-D	POST	B, S	A	*	*	Y
Bensulfuron	PRE/POST	B, S	L	*	*	Y
Butachlor	PRE/POST	B, G	A	*	*	Y
Glyphosate	PP	A	A	*	*	Y
Oxadiazon	PRE	A	A	*	*	Y
Paraquat	PP	A	A	*	*	Y
Pendimethalin	PRE	A	A	*	*	Y
Propanil	POST	G (B)	A	*	*	Y
Propanil + Bentazon	POST	A	A		*	Y
Propanil + Thiobencarb	POST	A	A	*		Y
Propanil + Triclopyr	POST	A	U	*	*	Y
Bensulfuron + Pretilachlor	PRE/POST	A	L	*		N
Bispyribac	POST	A	L	*		**N**
Glyphosate + **Oxyfluorfen**	PRE	A	A	*	*	**N**
Haloxyfop-R	PRE	G	U	*	*	**N**
Metolachlor + **Terbutryn**	PRE	A	U		*	**N**
Paraquat + Pendimethalin	PRE	A	A		*	C
Penoxsulam	POST	B (S, G)	L	*		**N**
Pretilachlor + **Pyribenzoxim**	PRE/POST	A	L	*	*	**N**
Propanil + 2,4-D	POST	A	A	*	*	C
Propanil + Butachlor	POST	B, G	A		*	C
Trifluralin	PRE	G, B	A		*	**N**

Africa, but rather a globally observed phenomenon.

Mechanical weeders are another type of labour-saving curative weed management technologies. Research on such weeders in Africa commenced in the period 2009–2021, and a wide range of weeder types are developed and tested both for upland and lowland rice systems (Gongotchame et al., 2014; Johnson et al., 2019). In lowland rice, mechanical weeders have experimentally been assessed to reduce weeding time by 32–56% (Rodenburg et al., 2015c). Feedback from farmers using a ring hoe, which is the most simplified version of a mechanical weeder particularly useful in upland rice, indicated at least 31% of time savings compared to hand weeding (Johnson et al., 2019). Mechanical weeders have gained popularity in Africa through research and promotion activities around SRI of which mechanical weeders are a prominent component (Krupnik et al., 2012b; Ndiiri et al., 2013). Promotion and research activities by the Africa Rice Center has also led to an increased use of mechanical weeders, although more by men than by women farmers (Achandi et al., 2018). Adoption of weeders by smallholder rice farmers in lowlands may be hindered by fears over plant damage by passing through the crop and by difficulty of operation, in particular when they lack experience or when they have suboptimal control over water to flood their fields, as shown in Tanzania (Senthilkumar et al., 2018). The use of mechanical weeders requires row planting, land levelling and flooding (Rodenburg et al., 2015c; Senthilkumar et al., 2018). Because of these requirements, farmers that are already using herbicides may be less likely to adopt weeders. In a weeder try-out workshop in Benin, farmers who used herbicides indicated a preference for their own practice (Gongotchame et al., 2014). Across Africa, mechanical weeding, including mechanical weeders, as weeding intervention is currently done by 21% of rice farmers, but this varies widely between countries (0–84%; Rodenburg et al., 2019).

5. Synthesis and conclusions

Competition from weeds is the most important biotic constraint to rice production worldwide and there are many similarities between regions in terms of weed species, management strategies and future challenges. Yet, several features that are unique to rice systems in Africa justify targeted investments in weed research in this specific region: (1) the dominance of rainfed rice growing environments, (2) the presence of parasitic weeds in those rainfed rice growing environments (*Striga* spp. in the rainfed uplands, *Rhamphicarpa fistulosa* in the rainfed lowlands), (3) the relative low population density combined with low levels of mechanisation and agrochemical use by smallholder farmers. Each of these unique features can be considered drivers for research and development endeavours.

The dominance of rainfed rice systems implies that most rice farmers in Africa cannot apply controlled flooding as a weed management practice. In the rainfed environments the weed species diversity is also generally higher than in irrigated lowlands making weed management even more difficult. Rainfed lowlands should be marked as a high-priority area for the future development of adapted, preventive weed management strategies (e.g., identification of competitive cultivars, short-fallow cover crops). This is the largest rice growing environment in terms of area under cultivation, with the most limited number of weed management practices with proven effectiveness. The rainfed uplands are suitable target environments for the preventive weed management approaches that are based on agroecology (e.g., cover crops, rotations, intercropping, short fallows, mulching). The implication is that for rainfed uplands, future research should aim at widening these weed management options, in terms of (cover-, inter-, rotation-) crop species and applications (e.g. timing, spatial arrangements, crop residue management). Ideally, such solutions should both reduce weed seedling recruitment, by suppression, and reduce or deplete the weed seedbank (e.g., cover crop species that out-shade weeds and cause suicidal germination of *Striga* spp.). Perhaps more importantly, the options generated by research should serve smallholder rice farmers; they should address multiple objectives (e.g., weed control, pest and disease management, soil fertility or conservation management, market or production value) and be accessible, affordable and feasible to manage. This requires inclusion of a diversity of selection and assessment criteria of preventive weed management solutions that are put to test, and participation of farmers and extension in different phases of research. Data on farmer adoption, and perceptions of preventive weed management practices is scant and this should also be addressed in future research for informed and purposeful technology development efforts.

Regarding research on parasitic weeds of rice, tremendous progress has been made since 2009. For the newly emerged facultative parasite *R. fistulosa*, the biology (e.g. seed germination requirements, host impact on biomass and reproduction, genetic variation), ecology (e.g. environmental affinity, weed community association) and virulence (e.g. timing and extent of effects on host physiology, biomass partitioning) as well as the geographic distribution, agronomic and economic importance have been elucidated to a great extent. Moreover, research on preventive management, generated tangible solutions for smallholders, ranging from early sowing to the use of identified resistant or tolerant cultivars. This is good news for affected smallholders, who previously had limited options for control of *R. fistulosa* other than laborious hand weeding. In environments where *R. fistulosa* is a problem (i.e., rainfed lowlands), controlled flooding is not a feasible management option. Because of their facultative parasitic nature and broad host range, the effectiveness of rotation or cover crops is also less likely. In addition, the characteristics of their environments, with uncontrolled seasonal flooding, limit the range of secondary crop choices and the feasibility of mulching. For the obligate parasitic *Striga* spp. the range of potential control options is wider and has been further enhanced in recent years. Delayed sowing, organic and mineral fertiliser application, the use of cover crops with or without soil tillage and crop residue mulching, and a range of adapted resistant and tolerant cultivars, are some of the most effective and affordable management options farmers now have available. For both type of parasitic weeds, future research should focus on fine-tuning fertiliser technologies (improving the composition and delivery methods, lowering input levels) to enhance host-plant resistance and nutrient-use efficiencies, optimising preventive management approaches and generating locally adaptable, integrated management approaches that reconcile the multiple production objectives of rice smallholders.

The low availability and use of mechanisation and herbicides observed in smallholder rice systems across Africa, implies that weed management interventions are still overwhelmingly done by hand or hand-held tools. Hand weeding is highly time consuming and therefore often done too late or inadequately. Research efforts should therefore continue to focus on the development of affordable and feasible labour-saving weed technologies. Herbicides are perhaps the most obvious technologies, but preconditions for the safe and effective use of herbicides are often not met in rural parts of Africa. Priority should therefore be given to the development of weed management practices that are feasible, less reliant on (agrochemical) industries and markets and benign to the environment and human health. Since 2009, progress has been made on testing and disseminating mechanical weeders for both upland and lowland rice farmers. The impact of this work could be enhanced by training local blacksmiths in the production and servicing of mechanical weeders, and by informing agricultural extension, and farmers about their availability and benefits. Another approach is to intensify research on preventive weed management options. Research has shown that following Integrated Crop Management (also known as Good Agricultural Practices) already reduces weed competition and weeding labour inputs, while improving yields to a great extent. Future research can focus on fine-tuning specific combinations (e.g., planting space and competitive cultivars, timing of crop establishment and fertiliser application) or identifying feasible and durable additional components such as compatible preventive weed management options focusing on reduced weed recruitment and seed bank sizes (e.g., off-season cover crops with above- or belowground weed suppressive properties) or improved crop competitiveness (e.g., weed competitive cultivars). We observe some research gaps as well as some untapped potential regarding the use of weed competitive cultivars. For instance, the impact from the use of such cultivars on weeding labour or herbicide requirements in the current and following season, is largely unexplored. Also, while a great number of cultivars have now been identified, the options are more restricted when narrowed down to specific rice growing environments. Moreover, very few of the identified cultivars combine multiple traits, such as weed tolerance and weed suppressive ability or parasitic weed resistance and tolerance. In addition, weed competitive or parasitic weed resistant or tolerant cultivars do not necessarily comprise other desirable characteristics such as disease resistance, grain quality traits, submergence or drought tolerance. To play a significant role in future weed management programs in African rice systems, cultivars need to meet a range of such criteria and be acceptable for farmers and consumers. The identified germplasm and developed screening protocols, farmer participatory variety selection approaches and contemporary biomolecular breeding tools (e.g., CRISPR/Cas), paved the way for more targeted progress in this respect. This will however require substantial financial investments in research and development.

The above synthesis provides directions for future research regarding weed management technologies on the crop and field level. For relevance and impact of such future research work, a contextual and thematic focus is needed. In the previous review in 2009, it was proposed that weed research should focus on (biology, ecology, distribution and management of) problematic weed species with broad geographic relevance. The first observation is that, with the exception of parasitic weeds, this proposal has not clearly been followed up as very few studies on other weed types are published. Perhaps the most notable associated observation is the total absence of studies on weedy rice, which is one of the most prominent weed problems in other parts of the world. Whether weedy rice is indeed much less of a problem in rice in Africa or perhaps an eminent problem that is simply overlooked as a result of limited human and financial resources for weed research in smallholder rice systems, would merit future investigation. The second observation is that weed communities are generally diverse and dynamic and therefore the recommendation to focus on single (problematic) weed species has perhaps limited relevance; successful control of the most dominant species may create opportunities for other species to become the next most dominant species. Identification of dominant weed communities associated to specific target-locations (i.e., associated to rice growing environments, further subdivided into regions, agro-climatic zones, elevation levels and even farm typologies) would probably provide more relevant foci for weed management technology development, resulting in more durable outcomes. Another recommendation by the 2009 review was to adapt weed management technologies to future changes. Apart from identification of labour-saving mechanical weeders and weed competitive varieties that perform well in plots following the water-saving irrigation regime of alternate wetting and drying, little progress is made. Most remarkable is the limited research attention for climate change effects on weeds and weed management efficacy in African rice systems over the period under review here. In addition, in the period under review no reports have been published on herbicide resistant weed ecotypes in African rice systems, while such reports are rather common from other parts of the world. This could be explained by the relative low herbicide use intensity among smallholder rice farmers in Africa, or again be a feature that has so far been overlooked because of limited resources for systematic weed research on smallholder rice systems in the continent. The 2009 review also emphasised that research should address farmer-adoption of weed management technologies.

There is an increased notion that hampered farmer-adoption cannot be explained by farm-level issues alone, and that stakeholders and factors at higher hierarchical levels of the agricultural system play pivotal roles as well. Addressing this effectively requires transdisciplinary weed research and development approaches (such as followed in the PARASITE project, e.g., Schut et al., 2015; Jordan et al., 2016).

We conclude that future agronomic research addressing weeds in rice systems in Africa would best identify and address target-location specific weed-communities, ensure potential solutions are aligned with opportunities or limitations at prevailing higher system levels (e.g., farming and agricultural systems) and address likely future scenarios regarding changing demographics and biophysical and institutional environments.

CRediT authorship contribution statement

D.T., J.K. and J.R. initiated the study; D.T., J. K. and J.R. reviewed papers; J.R. assembled and analyzed data and generated tables and figures; D.T., J.K., R.I., A.T., L.B. and J.R. collectively wrote the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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