Food Security
https://doi.org/10.1007/s12571-018-0878-0

ORIGINAL PAPER

Status quo of chemical weed control in rice in sub-Saharan Africa

Jonne Rodenburg[1,2] · Jean-Martial Johnson[2,3] · Ibnou Dieng[2] · Kalimuthu Senthilkumar[4] · Elke Vandamme[5] · Cyriaque Akakpo[6] · Moundibaye Dastre Allarangaye[7] · Idriss Baggie[8] · Samuel Oladele Bakare[9] · Ralph Kwame Bam[10] · Ibrahim Bassoro[11] · Bayuh Belay Abera[12] · Madiama Cisse[13] · Wilson Dogbe[14] · Henri Gbakatchétché[15] · Famara Jaiteh[16] · Geophrey Jasper Kajiru[17] · Alain Kalisa[18] · Nianankoro Kamissoko[19] · Keita Sékou[20] · Ahouanton Kokou[2] · Delphine Mapiemfu-Lamare[11] · Fanny Mabone Lunze[21] · Jerome Mghase[22] · Illiassou Mossi Maïga[23] · David Nanfumba[24] · Abibou Niang[25] · Raymond Rabeson[26] · Zacharie Segda[27,28] · Fitta Silas Sillo[29] · Atsuko Tanaka[30] · Kazuki Saito[2]

Received: 14 November 2017 / Accepted: 9 December 2018

Abstract

If future rice production is to contribute to food security for the increasing population of sub-Saharan Africa (SSA), effective strategies are needed to control weeds, the crop's fiercest competitors for resources. To gain better insights into farmers' access to, and use of, herbicides as part of weed control strategies, surveys were conducted in key rice production locations across SSA. Farm surveys were held among 1965 farmers across 20 countries to collect data on rice yields, farmer's weed management practices, herbicide use, frequencies of interventions and information sources regarding herbicides. Markets were surveyed across 17 countries to collect data on herbicide availability, brand names and local prices (converted to US\$ ha^{-1}). Herbicides are used by 34% of the rice farmers in SSA, but adoption ranges from 0 to 72% across countries. Herbicides are more often used by men (40%) than by women (27%) and more often in irrigated (44% of farmers) than in rainfed lowland (36%) or upland rice growing environments (24%). Herbicides are always used supplementary to hand weeding. Following this combination, yield loss reductions in irrigated lowlands and rainfed uplands are estimated to be 0.4 t ha^{-1} higher than hand weeding alone. In rainfed lowlands no benefits were observed from herbicide use. Sixty-two percent of the herbicides sold at rural agro-chemical supply markets are unauthorized. These markets are dominated by glyphosate and 2,4-D, sold under 55 and 41 different brand names, respectively, and at relatively competitive prices (below average herbicide price of US \$17 ha^{-1}). They are also the most popular herbicides among farmers. For advice on herbicide application methods, farmers primarily rely on their peers, and only a few receive advice from extension services (<23%) or inform themselves by reading the product label (<16%). Herbicide application timings are therefore often (38%) sub-optimal. Herbicide technologies can contribute to reduced production losses in rice in SSA. However, through negative effects on crop, environment and human health, incorrect herbicide use may unintentionally counteract efforts to increase food security. Moving away from this status quo will require strict implementation and monitoring of national pesticide regulations and investment in research and development to innovate and diversify the currently followed weed management strategies, agricultural service provision and communications with farmers.

Keywords Herbicides · Glyphosate · 2,4-D · Farmers · Subsistence agriculture · Markets

1 Introduction

Food security in sub-Saharan Africa (SSA) is highly dependent on rice production systems (Seck et al. 2012). Competition from weeds is one of the main biophysical yield constraints in rice production systems in the tropics (Waddington et al. 2010). In SSA, weeds are conservatively estimated to result in annual losses of 2.2 million tons of milled rice (Rodenburg and Johnson 2009). Losses are not

✉ Jonne Rodenburg
j.rodenburg@gre.ac.uk

Extended author information available on the last page of the article

only caused by direct resource competition between weeds and the crop, but also because the presence of weeds may attract other biotic yield-reducing factors, such as diseases and grain-feeding birds (Heinrichs et al. 1997; Demont and Rodenburg 2016). Furthermore, while weed-inflicted yield losses may be diminished through weed control, these efforts depend on inputs such as labor (Ogwuike et al. 2014) which in turn imply additional indirect economic losses.

Previous studies have estimated yield loss reductions of at least 1 t ha^{-1} following improved weed management (Haefele et al. 2000; Becker et al. 2003; Nhamo et al. 2014). However the efficacy of actual weed management — in terms of yield loss prevention — in SSA is among the lowest in the world (Oerke and Dehne 2004). At farm level, weed-inflicted yield losses, despite control efforts by the farmer, were estimated to be still 15% in irrigated lowlands, 16% in rainfed uplands and 23% in rainfed lowlands (Becker and Johnson 2001a, b; Becker et al. 2003).

Weeds are mainly controlled manually, mechanically or chemically. The first option, hand weeding, is labor intensive; in upland rice systems hand weeding was estimated to take 173 to 376 person-hours per hectare, depending on the number of weeding interventions (Ogwuike et al. 2014). Mechanical tools for weeding, either person-driven, animal-driven or engine-driven, are scarce in rice systems in Africa (Rodenburg and Johnson 2009; Gongotchame et al. 2014), despite a latent interest from farmers (Johnson et al. 2018). Herbicide application, when applied well, is usually the most effective and least labor-intensive weed control method with the highest yield return (Rodenburg et al. 2015). This technology, however, relies heavily on the availability of well-functioning agro-chemical supply markets as well as on sufficient financial means and know-how on application techniques at the level of the farmer or service provider. These preconditions are often not met in smallholder rice systems in rural areas in SSA (Balasubramanian et al. 2007). Therefore, adoption rates of herbicides in SSA are estimated to be low (Gianessi 2013), and application characteristics i.e. herbicide choice, rate and timing, are assumed to deviate frequently from the recommendations (Rodenburg and Johnson 2009) with potential negative consequences for the environment, human health, crop performance (Zimdahl 2007) and hence food security.

Data on weed management practices, herbicide availability, prices and use in SSA are scarce (Rodenburg and Johnson 2009). This information gap in turn complicates the identification of entry points for innovations in weed control in African smallholder rice production systems. The objectives of this study were therefore, through a survey, to (1) assess the current importance of herbicides in weed management strategies of smallholder rice farmers in SSA, (2) find out whether this technology could contribute to productivity enhancement and therefore food security, (3) assess the availability and prices of rice herbicides on rural markets in SSA, (4) learn what types of herbicides are used by farmers, (5) find out what the sources of information are that farmers use concerning herbicide application, and (6) discover how all this is reflected in the actual use of these products in farmers' fields.

2 Materials and methods

2.1 Site and farmer selection

Farmer-surveys were conducted in 222 randomly selected villages in 36 sites divided over 20 countries in SSA (5 in East Africa: Ethiopia, Madagascar, Rwanda, Tanzania and Uganda, 12 in West Africa: Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Mali, Niger, Nigeria, Senegal, Sierra Leone, The Gambia and Togo, and 3 in Central Africa: Cameroun, DR Congo and Chad). In each country, sites were selected by the National Agricultural Research Institute (NARI) and its partners. Selected sites were considered priority intervention sites for national rice research and development (see: Niang et al. 2017; Tanaka et al. 2017). The sites covered five tropical agro-ecological zones: the arid zone (AR), the semi-arid zone (SA), the sub-humid zone (SH), the humid zone (HU) and the highland sub-humid zone (HL) (3.1.1, 3.1.2, 3.1.3, 3.1.4 and 3.2.3, respectively, of the classification by HarvestChoice 2010) (Fig. 1, Table 1). Most sites (27) are characterized by one rice-growing environment (either irrigated lowlands, rainfed lowlands or rainfed uplands). The remaining sites encompassed irrigated lowlands and rainfed lowlands (Lagdo in Cameroun, Savelugu in Ghana, Gaya in Niger, Kahama in Tanzania), rainfed lowlands and rainfed uplands (Glazoue in Benin, Sikasso in Mali, Kilombero in Tanzania, Namulonge in Uganda), or even all three environments (Navrongo in Ghana). Site categorization in either irrigated lowlands, rainfed lowlands or rainfed uplands was done by national experts of the NARIs. Location-specific names of production environments 'inland valley swamps' and 'riverine' in Sierra Leone were classified as rainfed lowland.

2.2 Farm surveys

In each site the target community and farmers were selected by a team of socio-economic researchers of the local NARI and AfricaRice, following standardized protocols (see: Niang et al. 2017; Tanaka et al. 2017), whereby the leading criterion was for a farmer to manage at least one rice production field with a minimum size of 200 m^2. Attempts were made to come to a farmer selection that was considered representative of a

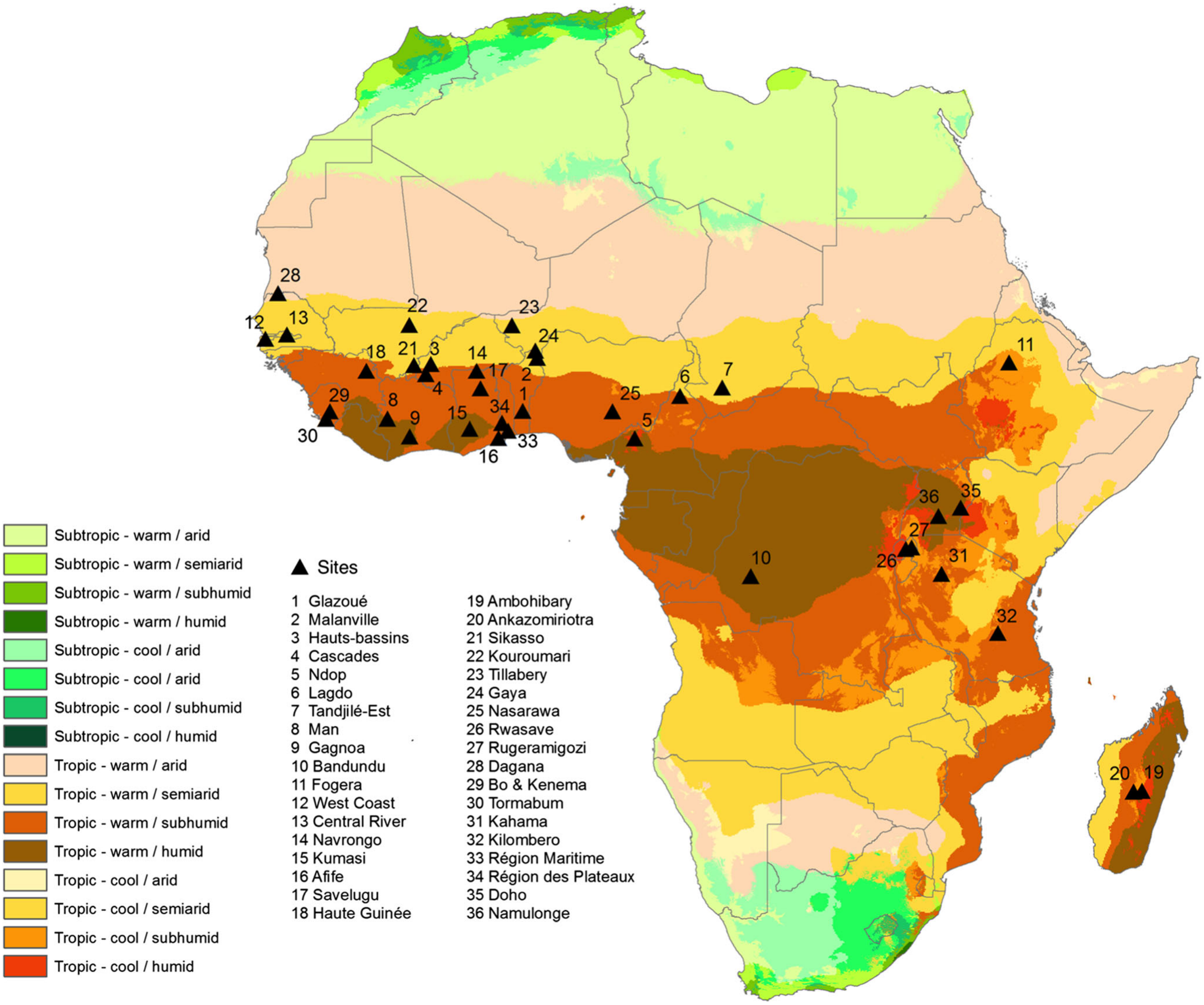


Fig. 1 Locations of the 36 study sites, in 20 countries, where the farmer-surveys were conducted (2012-2014), overlapped by the agro-ecological zones as defined and mapped by HarvestChoice (2010). The market study was conducted in site numbers 1-3, 5-15, 19, 21, 23-27 and 31-35

specific site. The sample size (number of farmers per community × number of communities surveyed) depended on the number of technicians available, the technicians' experience in field surveying, the budget, and the size of the site.

A rapid rural appraisal (RRA) was held on weed management practices during the wet seasons of 2012, 2013 or 2014 among 1965 individual rice farmers, using a structured questionnaire. Basic information was gathered in each site: (1) village names, (2) minimum and maximum altitude, (3) gender of participating farmers, (4) rice-growing environment the participating farmer operates in, and (5) the crop establishment method a farmer follows i.e. transplanting or direct sowing (i.e. dry-seeding in uplands, wet-seeding in lowlands). Leading follow-up questions of the farmer-survey were: (1) what weed management strategies do you apply (hand weeding, mechanical weeding, herbicide application), (2) how often do you conduct a weed management intervention during a season, (3) if you use herbicides, what kind of herbicides do you use, (4) do you apply herbicides yourself, and (5) if you apply them yourself, how do you obtain information on application methods (product label, agricultural extension, neighbor/colleague, other). The questions on weeding methods, herbicide choice and application timing (pre- or post- weed emergence), were asked for each weeding intervention stage within the season, including "Weeding

Table 1 Information on the survey conducted: agroecological zones (AEZ), countries, site names, villages (V), altitude range, and the number of surveyed farmers distributed over gender, rice growing environments and rice establishment methods.

AEZ	Country	Site	MS	V	Altitude (m)		Gender		Environment			Planting	
					Min.	Max.	F	M	IL	RL	RU	DS	TP
SA	Benin	Malanville	*	3	164	231	17	58	75	0	0	0	75
SH		Glazoue	*	7	155	249	34	29	0	34	29	63	0
SH	B. Faso	Cascades	*	5	272	361	23	21	0	44	0	33	11
SH		Hauts-bassins		2	–	–	0	21	0	0	21	21	0
HL	Cameroon	Ndop	*	4	1127	1202	30	20	0	50	0	1	49
SH		Lagdo	*	7	145	258	20	44	21	43	0	40	24
SA	Chad	Tandjilé-Est	*	5	–	–	14	34	0	48	0	48	0
HU	Côte d'Ivoire	Gagnoa	*	6	169	270	3	52	55	0	0	18	37
HU		Man	*	5	324	460	23	50	0	0	73	73	0
SH	DR Congo	Bandundu[a]	*	5	279	450	2	40	0	0	42	42	0
HL	Ethiopia	Fogera	*	5	–	–	11	29	0	40	0	39	1
SA	Gambia	Central River	*	6	0	125	31	39	70	0	0	12	58
SA		West Coast	*	5	12	63	33	37	0	0	70	55	15
HU	Ghana	Kumasi	*	4	225	247	7	27	0	34	0	22	12
SH		Afife		1	22	57	7	42	49	0	0	27	22
SH		Navrongo	*	8	95	336	28	58	32	42	12	65	21
SH		Savelugu		9	64	170	6	88	6	88	0	88	6
SH	Guinea	Haute Guinée		5	370	500	2	66	0	0	68	68	0
HL	Madagascar	Ambohibary	*	6	1545	1693	16	45	0	61	0	7	54
HL		Ankazomiriotra		4	1045	1180	3	40	0	0	43	36	7
SA	Mali	Kouroumari		5	299	319	8	45	53	0	0	6	47
SA		Sikasso	*	6	340	385	61	38	0	89	10	87	12
SA	Niger	Gaya	*	5	170	191	3	46	11	38	0	3	46
SA		Tillabery	*	5	210	269	1	64	65	0	0	9	56
SH	Nigeria	Nasarawa	*	5	116	209	9	42	0	51	0	42	9
HL	Rwanda	Rugeramigozi[b]	*	9	1760	1797	35	15	50	0	0	0	50
HL		Rwasave	*	1	1595	1804	21	29	50	0	0	0	50
AR	Senegal	Dagana		5	0	23	4	37	41	0	0	30	11
SH	S. Leone	Bo & Kenema		36	2	219	13	46	0	59	0	16	43
SH		Tormabum		6	5	14	10	40	0	50	0	41	9
SH	Tanzania	Kahama	*	5	1146	1208	15	41	8	48	0	13	43
SH		Kilombero	*	3	211	266	9	12	0	20	1	18	3
SH	Togo	Rég. Plateaux	*	3	257	328	21	27	0	48	0	25	23
SH		Rég. Maritime	*	3	39	75	10	29	39	0	0	7	32
HU	Uganda	Doho[c]	*	7	1054	1102	6	28	34	0	0	0	34
HU		Namulonge		16	1028	1132	7	43	0	38	12	50	0
	20	36	26	222	0	1804	543	1422	659	925	381	1105	860

AEZ refers to agro-ecological zones: *AR* arid, *HL* highland, *HU* humid, *SA* semi-arid, *SH* semi-humid; Environment refers to rice growing environment: *IL* irrigated lowland, *RL* rainfed lowland, *RU* rainfed upland; Planting refers to crop establishment method: *DS* direct seeded, *TP* transplanted; *MS* refers to market study, with * indicating sites where the market study was conducted; *V* refers to village, indicating the number of villages per site; Gender differentiates men (M) from women (F) farmers

[a] Kinshasa, Bas-Congo

[b] Rugeramigozi is also known as Gikonko II and Rwasave is known as Gikonko I

[c] Eastern Uganda

after land preparation, but before crop establishment" (W1), "1st weeding after crop establishment" (W2), "2nd weeding after crop establishment" (W3), "3rd weeding after crop establishment" (W4) and "4th weeding after crop establishment" (W5). This structured way of questioning reduced the likelihood of misconceptions between the enumerator and the farmer.

In the survey, the term hand weeding referred to the practice of uprooting weeds by hand, often combined with the use of a short-handled hoe, and removing them from the field by hand. Mechanical weeding referred to weeding operations that only made use of mechanical implements, either hand- animal- or fuel-driven. These implements included machetes, push or rotary weeders, sine hoes, harrows, spades, oxen ploughs, power tillers and tractor-mounted harrows.

2.3 Rice yield assessments

At each farm where a farmer survey was conducted, the rice (paddy) yield was assessed from three 12 m^2 harvesting areas (3 m × 4 m) that were randomly assigned to the field. Panicles were cut and threshed, and the collected grains were then winnowed and weighed. Grain moisture content was measured at the time of weighing using digital grain moisture meter (SATAKE Eng. Co., Tokyo; Model SS-7) to correct the grain weight to a standard moisture content of 14%. Grain weights were then extrapolated to tons of paddy ha^{-1}.

2.4 Market surveys

Between 2014 and 2015, an additional survey was conducted at markets among a sub-set of 26 sites (see Table 1), out of the 36 sites where farmer-surveys were held. This survey covered 17 countries. Of the 20 previously mentioned countries only Guinea, Senegal and Sierra Leone were not included in this survey. In each location at least three agro-chemical shops were visited and in each of these shops all available herbicide brands were listed. For each brand, country of origin, company information and recommendations concerning application provided on the label were noted down. In addition, for each herbicide brand the local price per bottle (local currencies) as well as the bottle volume was noted. Herbicide prices were converted from the local currency to US dollars ($) and from the bottle price to a price per ha, following recommended application rates.

Public consultations of available information sources were made to check for nine countries whether herbicide products were authorized before the date of the market study. For Benin, Burkina Faso, Chad, Côte d'Ivoire, Mali, Niger, The Gambia and Togo the list of herbicides authorized by the Comité Sahélien des Pesticides (CSP 2013) was used, while for Tanzania the list of registered pesticide products in Tanzania, of the Tropical Pesticide Research Institute (TPRI 2011), was used.

2.5 Data analyses

Descriptive statistics were generated for weed management practices, weeding timing and frequency, herbicide prices, herbicide types and sources of information for herbicide use. Where relevant, data were disaggregated by gender and/or rice growing environment. Pearson Chi-square (χ^2) tests of independence were performed to determine whether there were significant relationships ($P < 0.05$) among the data (i.e. number of weeding interventions, weed management practices and herbicide information sources) and gender (men, women) and/or environment (irrigated lowlands, rainfed lowlands, rainfed uplands). Two linear regression analyses were conducted to quantify variation in rice yields due to (1) the weeding frequency and (2) the weeding method. Both these analyses were done for each rice growing environment separately, but across agro-ecological zones. Weeding frequencies ranged from no-weeding (W0) to four or more weeding interventions (W4+), whereby W0 was used as the reference. The W4+ category comprised farmers following four, five and more than five weeding interventions because the sample sizes of these categories on their own were relatively small. Based on the available data, the weeding method followed by farmers comprised four categories: hand weeding only (HW), hand weeding and herbicide application (HW + H), hand weeding and mechanical weeding (HW + M), and hand weeding and herbicide application and mechanical weeding (HW + H + M). The first category (HW) was used as the reference situation. Coefficients of these two regressions, that represent the variation in the rice yields when switching from the reference category to any of the other categories, were estimated with their associated standard errors and *P* value. All data analyses were done using R software, Version 3.4.1 (R-Core-Team 2017).

3 Results

3.1 Farm characteristics

The altitude of rice production areas ranged from sea level to 1804 m above sea level (Table 1). The farmer selection was composed of 38% women and 62% men. The majority of farmers were producing rice in the rainfed lowlands (47%) followed by irrigated lowlands (34%) and rainfed uplands (19%). Slightly more than half of the farmers (56%) established their rice crop by direct sowing, whereas the others (44%) transplanted rice seedlings from nurseries. The importance of transplanting depends on rice growing environment. In irrigated lowlands 76% of the rice crops were established by transplanting, while in rainfed lowlands this was only 37%. In the uplands, all rice was established by direct sowing.

3.2 Weed management practices

The majority of rice farmers intervened only once (34%) or twice (39%) during a season to control weeds (Fig. 2). Only 5% of the farmers did not intervene at all, while 22% intervened three times or more. There was a significant difference in weeding intervention frequency between men and women

Fig. 2 Distribution of number of weeding interventions per farmer category, **a** Gender: men ($n = 1422$) or women ($n = 543$), $\chi^2 = 16.21$; $P = 0.0063$, **b** Environment: irrigated lowland ($n = 659$), rainfed lowland ($n = 920$) or rainfed upland ($n = 380$), $\chi^2 = 95.99$; $P < 0.0001$

(χ^2: 16.21; $P = 0.0063$). Compared with men, a higher share of women intervened twice, and a lower share of women intervened three times or more (Fig. 2a). There was also a significant difference in weeding intervention frequency between rice growing environments (χ^2: 95.99; $P < 0.0001$), in particular between the rainfed (both upland and lowland) and the irrigated environments. Compared with farmers in irrigated lowlands, a higher share of farmers in rainfed rice fields intervened only once or not at all, and a lower share intervened two or three times (Fig. 2b).

Weeding resulted in yield loss savings in all rice growing environments but the extent of these savings depended on the number of weeding interventions. In none of the environments was the yield loss reduction obtained after just one weeding significant (Table 2). In irrigated lowlands weeding significantly reduced yield losses after two or more weeding interventions. Compared with farmers who did not weed at all, farmers who weeded twice or three times gained around 1 t ha^{-1}. Close to 2 t ha^{-1} of yield loss reductions were estimated to be obtained in this environment by farmers intervening four or more times. In rainfed lowlands, weeding effects were smaller and less consistent. Farmers who weeded twice obtained an estimated 0.6 t ha^{-1} of yield loss reductions while farmers weeding three times did not see a significant positive effect. Farmers weeding four times or more obtained an estimated 1.5 t ha^{-1} yield savings. In rainfed upland, farmers weeding twice obtained an estimated yield loss reduction of 0.4 t ha^{-1}, and this improved to just below 1 t ha^{-1} after weeding three times and 1.2 t ha^{-1} after weeding four times or more (Table 2).

The most commonly used weed management practice by rice farmers was hand weeding (mean: 93%; weighted mean: 95%), followed, by a wide margin, by herbicide application (mean: 31%; weighted mean: 34%) and mechanical weeding (mean: 16%; weighted mean: 21%) using sine hoes, machetes, push or rotary weeders (Table 3). Herbicide use or mechanical weeding was always combined with hand weeding but only 3% of the farmers combined herbicides with mechanical weeding (not shown). Men (40%) used herbicides significantly ($P < 0.001$) more often than women (27%), while no gender differences were observed between the use of hand weeding or mechanical weeding (Fig. 3a). Both hand weeding and herbicides were significantly ($P < 0.001$) more frequently applied in irrigated lowlands, compared with upland or lowland rainfed rice environments (Fig. 3b). Herbicides were applied by 44% of the farmers in irrigated lowlands, compared with 36% in rainfed lowlands and only 24% in rainfed uplands. In rainfed lowlands a significantly ($P < 0.001$) lower share of the farmers used mechanical tools for weed control compared with farmers in irrigated lowland and rainfed uplands. There was also wide variation in the type of weed control interventions across countries (Table 3), in particular in herbicide use (ranging from 0 to 72%) and mechanical weeding (0 to 84%). In 12 countries, herbicide use ranged between 32 and 72% (with a mean of 51%) while in the remaining 8 countries (Ethiopia, Chad, Madagascar, The Gambia, Tanzania, DR Congo, Rwanda and Sierra Leone), herbicide use was only 3% or less. In The Gambia, and Madagascar this near absence of herbicide use was compensated by a high rate of mechanical control (>80%). In 11 of the 20 countries, mechanical weed control was not practised at all. This included five of the countries where farmers also hardly used herbicides (i.e. Ethiopia, Chad, DR Congo, Rwanda and Sierra Leone).

Farmers in irrigated lowlands obtained significantly higher yield loss reductions from their weeding efforts when they supplemented hand weeding with herbicide applications (0.4 t ha^{-1}) or a combination of herbicide applications and mechanical weeding (1.1 t ha^{-1}; Table 2). In rainfed lowlands farmers supplementing hand weeding with mechanical weeding obtained significant

Table 2 Regression analyses output, quantifying the variation in rice yields due to the (1) Weeding Frequency and (2) the Weeding Method

	Environ.	Level	n	Estimate	SE	*P*
Weeding frequency	IL[a]	(Intercept: W0)	14	2.999	0.428	<0.0001
		W1	160	0.580	0.448	0.1954
		W2	327	0.934	0.437	0.0329
		W3	113	1.045	0.454	0.0218
		W4+	45	1.970	0.491	<0.0001
	RL[b]	(Intercept: W0)	65	2.131	0.216	<0.0001
		W1	345	0.196	0.235	0.404
		W2	293	0.568	0.240	0.018
		W3	141	0.301	0.259	0.246
		W4+	76	1.512	0.290	<0.0001
	RU[c]	(Intercept: W0)	24	1.159	0.190	<0.0001
		W1	161	0.211	0.204	0.302
		W2	136	0.403	0.206	0.052
		W3	45	0.963	0.235	<0.0001
		W4+	14	1.249	0.321	0.0001
Weeding method	IL[d]	(Intercept: HW)	239	3.725	0.107	<0.0001
		HW + H	247	0.377	0.148	0.0109
		HW + M	123	0.039	0.182	0.829
		HW + H + M	36	1.070	0.288	0.0002
	RL[e]	(Intercept: HW)	439	2.567	0.083	<0.0001
		HW + H	290	−0.232	0.132	0.0783
		HW + M	115	0.684	0.176	0.0001
		HW + H + M	11	0.059	0.507	0.908
	RU[f]	(Intercept: HW)	191	1.495	0.073	<0.0001
		HW + H	75	0.397	0.136	0.0037
		HW + M	84	0.044	0.130	0.7338
		HW + H + M	6	−0.502	0.407	0.2187

Both analyses are broken down in rice growing environments: irrigated lowland (IL), rainfed lowland (RL) and rainfed upland (RU). Weeding Frequency has four levels, ranging from no-weeding (W0) —taken as reference— to four or more weeding interventions (W4+); Weeding Method has four levels: Hand Weeding (HW) —taken as reference—, Hand Weeding + Herbicides (HW + H), Hand Weeding + Mechanical Weeding (HW + M) and Hand Weeding + Herbicides + Mechanical Weeding (HW + H + M). Output shows the regression coefficients (Estimate, i.e. estimated yield or yield changes in t ha^{-1}), standard errors (SE) and *P*-values showing significance of contributions

[a] Residual standard error (RSE): 1.601; Degrees of freedom (DF): 637 degrees of freedom (DF); Observations deleted due to missing data (MD): 17

[b] RSE: 1.648; DF: 838; MD: 77

[c] RSE: 0.931; DF: 363; MD: 12

[d] RSE: 1.605; DF: 624; MD: 17

[e] RSE: 1.657; DF: 781; MD: 70

[f] RSE: 0.982; DF: 340; MD: 12

(0.7 t ha^{-1}) higher yields than farmers pursuing hand weeding only. Compared with the control group (hand weeding only), farmers who supplemented hand weeding with herbicides obtained an estimated 0.2 t ha^{-1} lower yields, while farmers combining all three methods obtained no significant yield advantage. In rainfed uplands supplementing hand weeding by herbicide application resulted in a significant yield advantage (0.4 t ha^{-1}), while combining hand weeding with mechanical or combinations of chemical and mechanical weed control did not result in significantly different yields compared with hand weeding only.

Table 3 Percentage of farmers using different weed control interventions in the surveyed countries

		Type of weed control intervention		
Country	n	Hand	Mechanical	Chemical
Benin	138	100	46	59
Burkina Faso	65	97	0	72
Cameroon	114	89	2	43
Côte d'Ivoire	128	99	1	41
Chad	48	100	0	2
DR Congo	42	60	0	0
Ethiopia	40	100	0	3
Gambia	140	100	84	1
Ghana	263	95	36	55
Guinea	68	90	0	49
Madagascar	104	99	82	2
Mali	152	93	0	43
Niger	114	100	15	58
Nigeria	51	84	0	37
Rwanda	100	100	0	0
Senegal	41	88	0	68
Sierra Leone	109	84	0	0
Tanzania	77	92	28	1
Togo	87	100	0	57
Uganda	84	96	17	32
Mean		93	16	31
Weighted mean		95	21	34
Min		60	0	0
Max		100	84	72

3.3 Chemical weed control

Herbicides were mainly applied during the first weeding intervention, before crop establishment, only (W1: 61% of cases), during the first and second weeding intervention (W1,2: 26%) or during the second intervention only (W2: 7%) but there were differences among rice growing environments (Fig. 4). Compared with rainfed environments, in irrigated lowlands a relatively larger share of farmers applied herbicides at more or later stages than before crop establishment only (W1). Compared to other environments, in rainfed lowlands the share of farmers applying at W1 only was the highest, while in the upland relatively more farmers applied herbicides during W1,2, and the first four weeding interventions (W1,2,3,4; Fig. 4).

The 677 herbicide users (34%) used a total of 18 known herbicide formulations (Table 4). The most frequently used formulations were glyphosate (with 176 farmers at W1, 45 farmers at W2 and 4 farmers at W3), 2,4-D (118 farmers at W1, 47 at W2 and 4 at W3) and bensulfuron (112 farmers at W1, 38 at W2 and 7 at W3). In 39 cases (20 at W1, 2 at W2 and 17 at W3) farmers were not able to tell the name of the herbicide formulation used (Table 4, 'unknown').

Farmers more often applied herbicides post weed emergence (W1: 56%; W2: 65%) than pre-emergence (Table 4). Based on the farmers' responses, we estimated the proportion of potentially wrong application timings at 38% (Table 4). This 'potential misuse frequency' is the number of cases where the herbicide application timing, indicated by the farmer, did not match with the

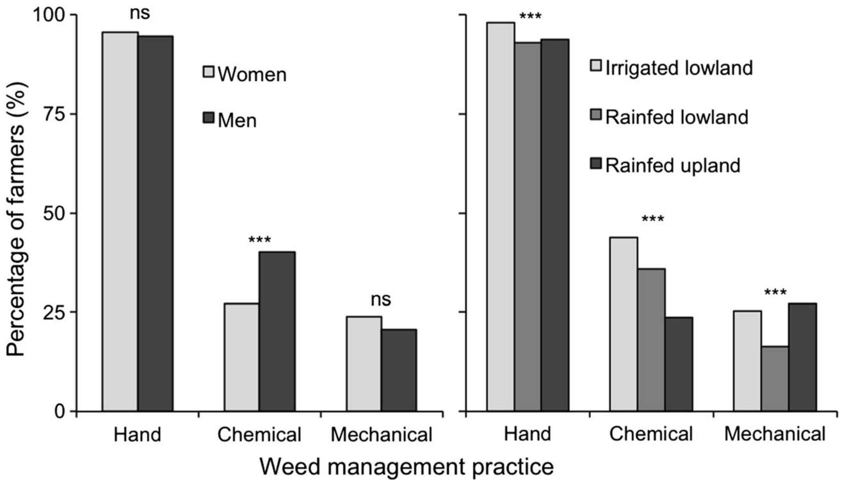


Fig. 3 Percentages of farmers managing weeds by hand, herbicides or mechanical implements in each of the farmer category, **a** Gender: women ($n = 512$) or men ($n = 1322$), and **b** Environment: irrigated lowland ($n = 645$), rainfed lowland ($n = 841$) or rainfed upland ($n = 342$); Indications of significant effects following Chi-square (χ^2) tests refer to comparisons within categories of weed management practices, whereby 'ns' means not significant and *** indicates significance at $P < 0.001$; Gender: $\chi^2_{\text{Hand weeding}} = 1.020$; $\chi^2_{\text{Chemical control}} = 26.124$; $\chi^2_{\text{Mechanical weeding}} = 2.341$; Environment: $\chi^2_{\text{Hand weeding}} = 1.020$; $\chi^2_{\text{Chemical control}} = 39.603$; $\chi^2_{\text{Mechanical weeding}} = 2.341$

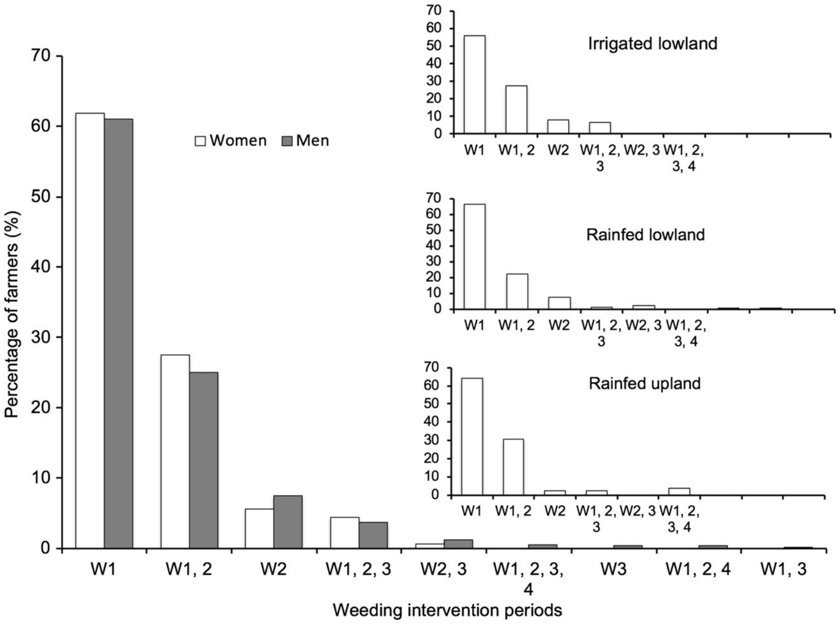


Fig. 4 Frequency and timing of herbicide application for all farmers applying herbicides (large chart left; $n = 719$) and per rice growing environment (smaller charts right): Irrigated lowland ($n = 333$), rainfed lowland ($n = 301$) and rainfed upland ($n = 81$). Categories indicate the weed intervention periods, with W1 = After land preparation but before crop establishment, W2 = 1st intervention after crop establishment, W3 = 2nd intervention after crop establishment, W4 = 3rd intervention after crop establishment

Table 4 Herbicide application according to farmers; Number of farmers applying herbicides prior to crop establishment (W1), first application after crop establishment (W2) and second application after crop establishment (W3); Farmers were asked whether the herbicide was applied pre-emergence (PRE) or post-emergence (POST) of the weeds

Formulations	Type	Number of farmers reporting	Applied before crop establishment (W1)		First intervention after crop establishment (W2)		Second intervention after crop establishment (W3)	Potential misuse frequency[a]	Potential misuse percentage
			PRE	POST	PRE	POST	POST		
Glyphosate	PP[b]	225	139	37	28	17	4	188	84
2,4-D	POST	169	15	103	7	40	4	22	13
Bensulfuron	POST	157	46	66	11	27	7	57	36
Propanil +2,4-D	POST	60	1	40		16	3	1	2
Butachlor	PRE	43	18	4	17	3	1	8	19
Propanil	POST	39		20	1	15	3	1	3
Propanil + Triclopyr	POST	26	2	19	2	1	2	4	15
Pendimethalin	PRE	23	16	3	3	1		4	17
Paraquat	PP	15	8	7					
Metolachlor + Terbutryn	PRE	10	3	1		6		7	70
Propanil + Butachlor	PRE[c]	8		8				8	100
Pretilachlor + Pyribenzoxim	POST	4				3	1	0	0
Oxadiazon	PRE	2	1	1				1	50
Haloxyfop	PRE	1		1				1	100
Paraquat + Pendimethalin	PRE	1		1				1	100
Trifluralin	PRE	1	1					0	0
Propanil + Bentazon	POST	1		1				0	0
Glyphosate + Oxyfluorfen	PRE	1				1		1	100
Unknown	–		7	13	1	1	17	(39)[d]	
Total number		786	257	325	70	131	42	312	38

[a] Potential misuse frequency (%) is the number of cases where the herbicide application timing, indicated by the farmer, does not match with the recommended herbicide application timing, indicated on the product label, divided by the total number of herbicide applications and multiplied by 100

[b] PP = Pre-planting, the herbicide should be applied pre planting but post weed emergence, the assumed correct use is therefore only under W1 as POST

[c] Can be applied early post-emergence

[d] Famers not knowing the product, indicate a lack of awareness and a high risk of misconception/misuse, or concern cases where herbicide application was outsourced to service providers (like in Rwanda). These cases ('unknown') were not included in the calculation of the potential misuse frequency

Table 5 Sources of information for the farmers using herbicides during the first weed management intervention time (W1) and the second weed management intervention time (W2)

		Product label		Agricultural Extension		Neighbor farmer		Other sources	
		Women	Men	Women	Men	Women	Men	Women	Men
W1	Consulted[a]	11	12	23	18	63	66	2	4
	Not-consulted	89	88	77	82	37	34	98	96
	χ^{2} [b]	0.091 (ns)		1.669 (ns)		0.377 (ns)		0.385 (ns)	
W2	Consulted	16	14	21	16	56	63	2	5
	Not-consulted	84	86	79	84	44	37	98	95
	χ^{2}	0.009 (ns)		0.236 (ns)		0.581 (ns)		0.183 (ns)	

[a] Responses are independent, meaning that multiples sources may have been consulted by the same farmer

[b] Pearson's Chi-square (χ^{2}) test statistic indicating a gender effect on the way farmers inform themselves on the application practices of herbicides; ns = not significant

recommended timing of herbicide, indicated on the product label, divided by the total number of herbicide applications. Of the top-ten most frequently used herbicides, the highest percentage of potential misuse was observed with glyphosate (84% of cases where it was applied), followed by metolachlore + terbutryn (70%) and paraquat (53%).

For farmers, the most consulted sources of information on herbicide application were neighboring farmers (Table 5). Some 63% of the women and 66% of the men turned to their neighbor for advice during the first weeding intervention (W1) and 56% of the women and 63% of the men solicited neighbor advice during the second intervention (W2). At any intervention time, no more than 23% of the farmers sought advice from extension services and no more than 16% read the herbicide product labels before applying herbicides (Table 5). When broken down to countries (only those with at least

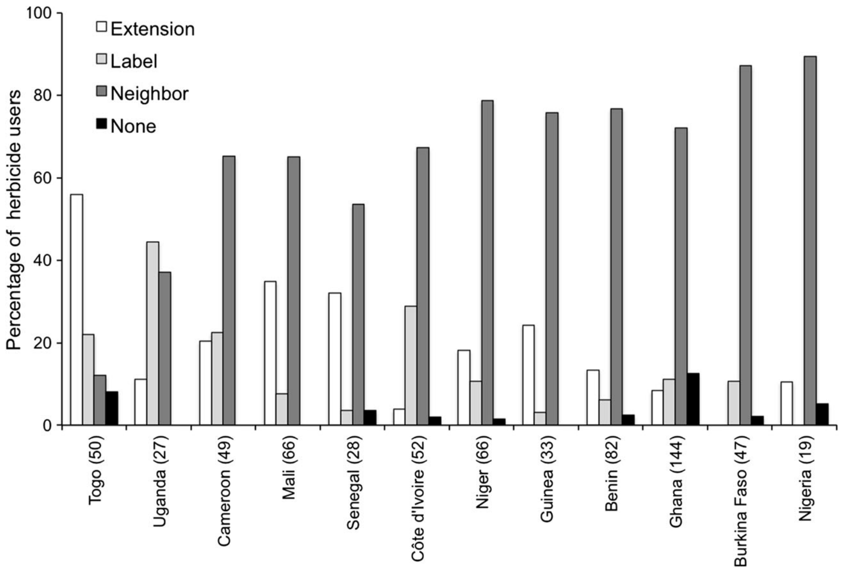


Fig. 5 Information sources of herbicide-using farmers (HU) (Extension services, Product label, Neighboring farmers, None) for the application of herbicides, broken down per country for the countries with more than 30% of herbicide users ($N = 713$): Togo (HU = 57%), Uganda (HU = 32%), Cameroun (HU = 43%), Mali (HU = 43%), Senegal (HU = 68%), Côte d'Ivoire (HU = 41%), Niger (HU = 58%), Guinea (HU = 49%), Benin (HU = 59%), Ghana (HU = 55%), Burkina Faso (HU = 72%), and Nigeria (HU = 37%). Values between parentheses behind country names represent the number of herbicide users (n). The category 'other sources' was too insignificant to be shown here

Table 6 Formulations and brand names of the herbicides available in agrochemical supply shops in rice growing areas of SSA

			Herbicide brands	
Formulations	Number of observations	Frequency	Number	Examples
Glyphosate	98	41.7	55	Adwumaye; Agasate; Agriherb; Destroyer; Detru-Herb; Frankosate; Gly Star; Glycel; Glycot; Glyfort; Glyphader; Herbo Total; Heros; Kalach; Lamachette; Nwura Wura; Puissance; Roundup; Sunphosate; Tackle; Touch Down; Uproot; Weed Kill; Weedall
2,4-D	63	26.8	41	Agriselect; Amino Force; Ascomine; Bextra; Cotomine; Dekade Plus; Devaweed; Herbafor; Herbazol; Herbextra; Herbus Plus; Hond; Stopstar; Sun; Ultra 2;4-D; Weed Kill; Weed Killer
Propanil + Triclopyr	18	7.7	10	Calriz; Garil; Maloflora; Phytoriz; Pyranyl; Rigold; Rivitex; Sakaril; Tripro; Tropiryle
Propanil +2,4-D	13	5.5	8	Baccara; Orizo Plus; Pronil Plus; Propa Gold; Propa Plus; Propacal Plus; Propocalpus; Vespanil Plus
Paraquat	7	3.0	6	Gramoquat Super; Gramoxone; Kabquet; Para Q; ParaCot; Weed Crusher
Pendimethalin	7	3.0	5	Activus; Alligator; Kayanga; Pendimenthalin; Stomp
Butachlor	5	2.1	5	Buta Force; Butachruseh; Butaplus; Surplus; Ultrachlore
Propanil	4	1.7	4	Propanil; Propanil Plus; Propercare; Yuperstar
Oxadiazon	4	1.7	4	Topstar; Callistar; Oxariz; Ronstar
Bensulfuron	4	1.7	3	Condax; Dadyax; Samory
Bispyribac	3	1.3	2	Bounty; Nominee Gold
Bensulfuron + Pretilachlor	2	0.9	1	Londax
Haloxyfop-R	2	0.9	1	Gallanfort
Propanil + Thiobencarb	2	0.9	2	Herbivore; Rical
Pretilachlor + Pyribenzoxim	1	0.4	1	Solito
Penoxsulam	1	0.4	1	Rainbow
Glyphosate + Oxyfluorfen	1	0.4	1	Zoomer
Total	235	100	150	

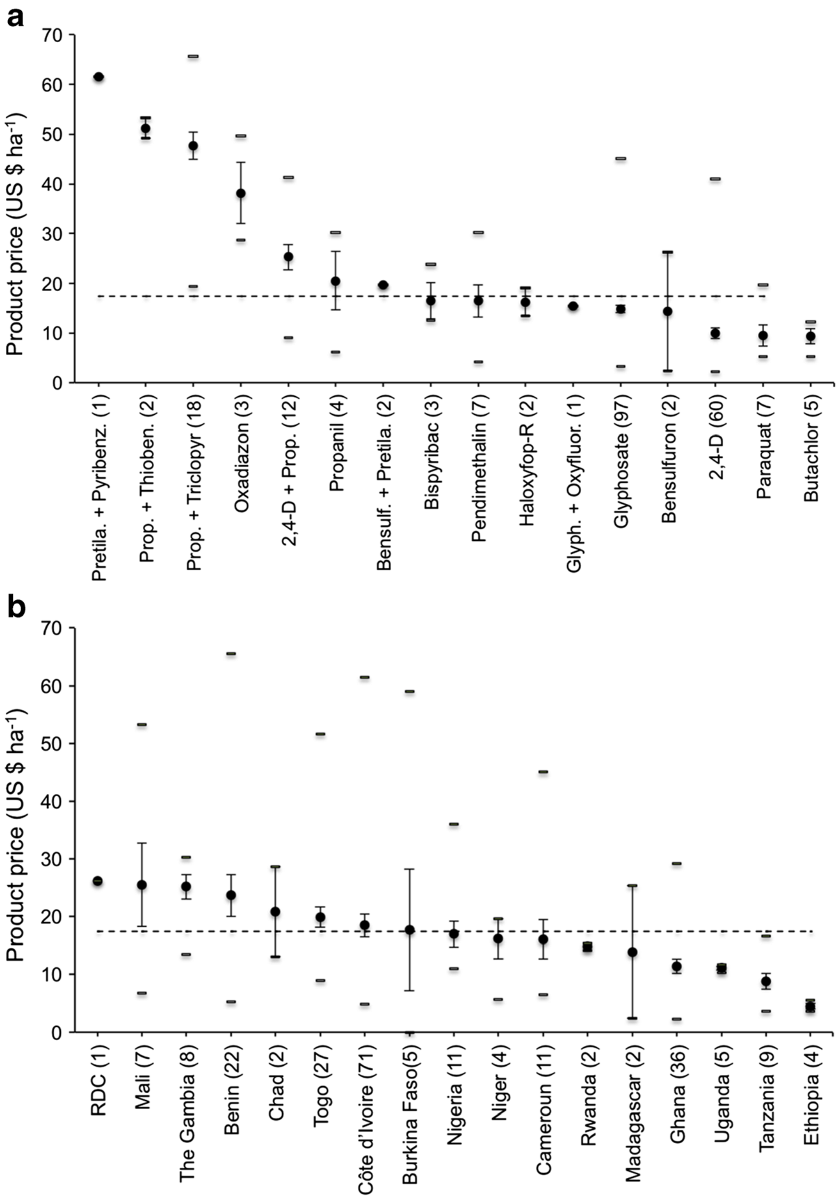
30% of farmers using herbicides), the data show that extension services were important information sources in Togo, Mali and Senegal, while in Uganda farmers mostly relied on the product label and farmers in Burkina Faso and Nigeria more often consulted their neighbors (Fig. 5).

3.4 Herbicides on the market

During the market-survey, in 26 locations, a total of 235 herbicide brands were encountered and examined. These brands encompassed 17 different herbicide formulations, 11 single-formulations and 6 combined-formulations (Table 6). By far the most common formulation found on the market was glyphosate. The formulation was found in 42% of the herbicides. Second, 2,4-D amine, was found in 33% of the herbicides (stand-alone: 27%, combined: 6%) and the third formulation, propanil, was found in 16% of the herbicides (stand-alone: 2%, combined: 14%). Herbicide formulations were available under a wide diversity (150) of brands, in particular glyphosate, with 55 different brands, and 2,4-D, with 41 brands (Table 6). In some cases different herbicide formulations were sold under the same or very similar brand names (although not at the same location); e.g. Weed Kill for 2,4-D in Cameroon and for glyphosate in Uganda and Weed Killer for 2,4-D in Ethiopia.

Apart from being the most widely available formulations, 2,4-D (\$10 ha^{-1}; $n = 60$) and glyphosate (\$15 ha^{-1}; $n = 97$) were also among the cheapest herbicides on the market (Fig. 6a). Mean prices of the third and fourth most widely available herbicides; i.e. combinations of propanil + triclopyr

Fig. 6 Herbicide prices per ha per product (**a**) and per country (**b**) with the number of observations per product or country (n) between parentheses. Black dots indicate means, error bars indicate standard error of means, hyphens indicate minimum and maximum values and the dashed line indicates the weighted mean (US $17.4 ha^{-1}). Absence of some herbicide products is caused by missing or incomplete data for conversion in price per ha



($48 ha^{-1}; $n = 18$) and propanil +2,4-D ($25 ha^{-1}; $n = 12$), were both well above the overall mean herbicide price of US $17.4 ha^{-1}. Large price differences among countries were observed (Fig. 6b). Mean herbicide prices in Mali ($26 ha^{-1}; $n = 7$), The Gambia ($25 ha^{-1}; $n = 8$) and Benin ($24 ha^{-1}; $n = 22$), were above average, while in Ethiopia ($4 ha^{-1}; $n = 4$), Tanzania ($9 ha^{-1}; n = 9), Uganda ($11 ha^{-1}; $n = 5$) and Ghana ($11 ha^{-1}; $n = 36$) they were well below average.

Of the available herbicide brands on the market, 62% appeared not to be authorized by a recognized pesticide regulatory organization such as TPRI in East or CSP in West Africa (Table 7). There are important differences among countries however; in Tanzania all herbicide brands were authorized (by TPRI) but in The Gambia nine out of ten (90%) were not (by CSP). In Togo, 21 of the 26 brands (hence 81%), Côte d'Ivoire, 42 of the 60 brands (70%), and Benin, 13 of the 21 brands (62%), brands did not feature on the CSP list. The two most important herbicide-providing countries were China and France, with the first exporting 50 individual herbicide brands and the second 17. Among the 50 brands of Chinese origin only three were authorized in the CSP list, hence 94% were not. Twenty-four brands were from unknown origin and unregistered.

Table 7 Number of registered (R) and unregistered (U) herbicides[a] available in rural markets of importing countries in sub-Saharan Africa[b], from different herbicide producing countries

Herbicide producing countries	Herbicide importing countries																		Individual products	
	BJ		BF		TD		CI		ML		NE		GM		TG		TZ			
	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	R	U	Total	Unregistered
China	1	7		1			3	15			1			9	2	15			50	47
France	4		1				9		5	3			1		2	1			17	4
India	1	1					2					2							5	3
Burkina Faso			5																5	0
Côte d'Ivoire	1							3	1										5	3
Ghana		1						1								3			5	5
USA							2		2								1		4	0
Tanzania																	4		3	0
Singapore	1	1														1			2	1
Germany						1											1		2	1
Kenya																	2		2	0
Mali									1	1									2	1
Nigeria																2			2	2
Switzerland							2												2	0
Malaysia								1											1	1
Israel			1																1	0
South Africa								1											1	1
UK		1																	1	1
Zambia																	1		1	0
Unknown		2				1		21											16	16
Overall	8	13	7	1	0	2	18	42	9	4	1	2	1	9	5	21	9	0	127	86

[a] Following the TPRI (2011), for Tanzania and the CSP (2013), for the other countries

[b] BJ: Benin; BF: Burkina Faso; TD: Chad; CI: Côte d'Ivoire; ML: Mali; NE: Niger; GM: The Gambia; TG: Togo; TZ: Tanzania

4 Discussion

4.1 Weed management in rice: Importance of herbicides

Weeds are perceived by farmers as the most important overarching production constraint in rice in SSA (Diagne et al. 2013). Rice systems in SSA are characterized by diverse weed communities. A recent study in East Africa observed 222 species belonging to 46 plant families, with the Poaceae (39 species) and Cyperaceae (38 species) as the most represented ones (Makokha et al. 2017). In a synopsis of the literature on weed species in rice in Africa, Rodenburg and Johnson (2009) reported the five most important species in uplands to be: *Rottboellia cochinchinensis*, *Digitaria horizontalis*, *Ageratum conyzoides*, *Tridax procumbens* and *Eleusine indica*. In hydromorphic environments, the top five comprised *A. conyzoides*, *Panicum laxum*, *Leersia hexandra*, *Cyperus rotundus*, and *D. horizontalis* and in the lowlands the most frequent species were *Sphenoclea zeylanica*, *Cyperus difformis*, *Fimbristylis littoralis*, *Oryza longistaminata*, and *Echinochloa colona*. The reported species diversity makes weed control a complex task.

Weed control proved to be an important management practice for safeguarding rice yields and therefore is an important contributor to increased food security. Based on the data of the current study, it was estimated that farmers in irrigated rice systems could save 1 t ha^{-1} of grain following a minimum of two weed control interventions. This range of yield loss reductions obtained by weed management corroborates previous studies on irrigated rice (Haefele et al. 2000; Becker et al. 2003). In the rainfed uplands, the rice yield estimate following two weeding interventions was 1.6 t ha^{-1}, a yield loss reduction of 0.4 t ha^{-1} compared with the no-intervention reference, while three interventions resulted in an estimated yield of 2.1 t ha^{-1},a loss reduction of nearly 1 t ha^{-1}. These yield savings are similar to estimates from a previous study on weeding in upland rice, conducted by Ogwuike et al. (2014).

For obtaining yield loss reductions, hand weeding alone proved overall less efficient than hand weeding supplemented by either herbicide application or mechanical weed control technologies. In rainfed lowlands, higher yield loss reductions

Table 8 Herbicides (formulations, alphabetical order) reported to be available and used in rice in Africa prior to 2009 [according to Rodenburg and Johnson 2009, Akobundu 1987 and Diallo and Johnson 1997] in comparison with the current market survey in 17 countries (26 locations) and farmer survey in 20 countries (36 sites, 1965 farmers) conducted from 2012 to 2015

Herbicide formulations	Literature[a]	Markets	Farms
2,4-D	x	x	x
2,4-D + dichlorprop	x		
2,4-5-TP	x		
Bensulfuron	x	x	x
Bentazon	x		
Bifenox	x		
Butachlor	x	x	x
Cinosulfuron	x		
Dymrone	x		
Fluorodifen	x		
Glyphosate	x	x	x
MCPA	x		
Molinate	x		
Oxadiazon	x	x	x
Paraquat	x	x	x
Pendimethalin	x	x	x
Piperophos	x		
Piperophos + Cinosulfuron	x		
Pretilhachlor + Dimethametryne	x		
Propanil	x	x	x
Propanil + Bentazon	x		x
Propanil + Fluorodifen	x		
Propanil + MCPA	x		
Propanil + Molinate	x		
Propanil + Triclopyr	x	x	x
Propanil + Piperophos	x		
Propanil + Oxadiazon	x		
Propanil + Thiobencarb	x	x	
Quinclorac	x		
Thiobencarb	x		
Triclopyr	x		
Bensulfuron + Pretilachlor		x	
Bispyribac		x	
Glyphosate + Oxyfluorfen		x	x
Haloxyfop-R		x	x
Metolachlor + Terbutryn			x
Paraquat + Pendimethalin			x
Penoxsulam		x	
Pretilachlor + Pyribenzoxim		x	x
Propanil +2,4-D		x	x
Propanil + Butachlor			x
Trifluralin			x
Number	31	17	18

[a] Rodenburg and Johnson (2009), Akobundu (1987) and Diallo and Johnson (1997)

were obtained when hand weeding was supplemented by mechanical weeding, while supplementary herbicide applications did not further reduce yield losses. Herbicides may be less effective here because of the lack of control over water levels as shown before by Toure et al. (2009). Uncontrolled and therefore untimely floods or droughts may cancel out the effectiveness of herbicide applications (Zimdahl 2007). In irrigated lowlands and rainfed upland environments rice yields benefited from herbicide applications as supplementary technology to hand weeding. The survey data however revealed that in order to fulfil the potential of herbicides, the adoption of the technology as well as application practices of the technology need to be improved.

This farm survey showed that 34% of rice farmers in SSA use herbicides to control weeds, although always combined with hand weeding. Wide variation was observed in herbicide use frequencies across countries, confirming an earlier report by Sheahan and Barrett (2017). The low adoption of herbicides in some countries (e.g. DR Congo, Chad, Rwanda, The Gambia, Madagascar and Ethiopia) may have different underlying reasons. In DR Congo, Chad and Rwanda, herbicide availability on the markets seems limited, while in The Gambia herbicides are widely available but come at above-average prices and a large proportion of farmers control weeds mechanically. In Madagascar, farmers rely heavily on cheap family labor for hand weeding (R. Rabeson, *personal communication*) and rotary weeders are widely adopted (Rodenburg et al. 2015), which is reflected in a high frequency of mechanical weeding. The poor adoption of herbicides in Ethiopia is more difficult to explain, as the herbicide prices are lower than anywhere else in SSA. In teff, a much more traditional and widely grown cereal in the country, a recent and steep increase in herbicide use was observed (Tamru et al. 2017). Among farmers growing rice, which is a relatively new crop, the awareness of this technology could be lower.

Not only in Ethiopia but also in Mali a recent increase in herbicide use in subsistence cereal production was observed (Haggblade et al. 2017a). For rice there is a scarcity of data on herbicide use, which makes it difficult to compare the herbicide adoption figures of the current study to those of the past. Limited reports available on herbicide use by rice farmers in the past however suggest no noteworthy change. Already in the early nineties, herbicides were used by 42% of the rice farmers across rice growing environments in Côte d'Ivoire (compared with 41% in this study), although again mostly combined with hand weeding (Adesina et al. 1994). In the irrigated rice systems of the Senegal River Valley, herbicide use in the late nineties ranged from 60% in Mauritania, to 100% in Senegal (Haefele et al. 2000). The current study showed that herbicides are more often used by men than by women and this confirms the more general observation made by Sheahan and Barrett (2017), that male-headed households more frequently use modern inputs across SSA. This is probably due to gender differences in access to such inputs (Achandi et al. 2018). Also the higher herbicide use observed in irrigated compared with rainfed rice growing environments seems to be a more general feature, as it was previously observed in India (Rao and Nagamani 2010) and the Philippines (Beltran et al. 2013).

Based on the dominance of postemergence herbicides, or post-emergence application of herbicides, it can be concluded that farmers use herbicides more often as a curative control measure, than as a preventive measure. With an observed 38%

of likely cases of wrong application timings, the current survey results also indirectly show the weak level of awareness and knowledge at the farmer level concerning herbicides. This is a persistent problem as it was already observed twenty years ago in the Senegal River Valley where farmers were frequently applying herbicides too late and in sub-optimal doses (Haefele et al. 2002). From the current study, particularly worrisome is the high proportion of potential misuse of the controversial broad-spectrum herbicides glyphosate and paraquat.

4.2 Herbicide products: Availability and use

Based on the weed management literature, before 2009 there were 31 herbicide formulations available and used by rice farmers in SSA (Table 8). The current surveys showed market availability of 17 formulations, while farmers were using 18. Of these 18 herbicide formulations, five were not found in the market survey. Three of these, i.e. propanil + butachlor, paraquat + pendimethalin and trifluralin, were observed at locations where no market study was conducted, i.e. Namulonge (Uganda), Hauts-bassins (Burkina Faso) and Afife (Ghana). The other two herbicide formulations, i.e. propanil + bentazon and metolachlor + terbutryn, were probably either out of stock or obtained at other places or through other ways than the agro-chemical supply shops. Eleven herbicide formulations were established (observed before 2009) and the same number of formulations were new (since 2009), or not reported before. Twenty formulations that were cited in the literature did not feature in any of the surveys.

Farmers' access to information and improved technologies is key to reach the necessary increase in rice production for food security in the region (Haefele et al. 2002). Concerning farmer's access to information, the high illiteracy rate in SSA is likely to be part of the problem. According to UNESCO (2017), out of the 20 countries surveyed in our study, 11 have an adult literacy rate below 50% and only six have a literacy rate between 70 and 79% (i.e. Cameroon, DR Congo, Ghana, Madagascar, Tanzania and Uganda). A recent study on agricultural technologies used by rice farmers in East Africa, with partly the same respondents as in the current study, confirmed the UNESCO reports on Tanzania, Madagascar and Ethiopia (Achandi et al. 2018). The high illiteracy rates in most of the survey countries could explain the low number of farmers who indicated that they had read the product labels to inform themselves about herbicide use.

With respect to access to herbicides a crucial role should be played by the rural supply markets. The market study showed that currently these markets are dominated by only a hand-full of formulations (albeit under many different herbicide brand names) such as glyphosate and 2,4-D. This confirms recent studies in Mali and Ethiopia, summarized by Haggblade et al. (2017a), in which concomitant to an increasing number of mainly Chinese brands on the African markets, the herbicide prices have dropped. Indeed, as the current market survey showed, these products are sold at very competitive prices, i.e. well below the average herbicide price of US \$17 ha^{-1}. More than a decade ago, US \$10 ha^{-1} was the average actual level of expenditure on pesticides (mainly herbicides) in SSA (Oerke and Dehne 2004), and therefore this does seem like a price smallholder farmers may be willing to pay. The frequently postulated and observed complaint by farmers that herbicides are too expensive (e.g. Adesina et al. 1994; Tippe et al. 2017) therefore cannot be generalized. On the contrary, herbicides appear to be generally cheaper than wages, as shown in Ethiopia (Tamru et al. 2017), and in Mali where the cost of applying herbicides was less than half the cost of hand weeding (Haggblade et al. 2017b). The comparison between herbicide and hand weeding costs seem to be country specific however. For rice systems in Senegal, Demont et al. (2009) estimated the costs of hand weeding at 15 € ha^{-1}, which was 25% cheaper than their cost estimate for herbicide application.[1]

Without good stewardship, the heavy reliance on a limited number of herbicide formulations (glyphosate and 2,4-D) may accelerate the development of herbicide resistant weed ecotypes (Davis and Frisvold 2017). The evolution of glyphosate-resistant weed ecotypes illustrates this (Duke and Powles 2008). Apart from the risks concerning the development of herbicide-resistant weed ecotypes, there are concerns about negative herbicide-related impacts on human health and the environment. A number of herbicides that are used by farmers in rice systems in SSA are controversial in this respect. Most prominent are the concerns over the use of glyphosate (Myers et al. 2016), but also 2,4-D has been critically assessed (Peterson et al. 2016) while paraquat is even officially banned in many countries (Haggblade et al. 2017a). Many of the herbicides currently sold on the market are postulated by Haggblade et al. (2017a) to be counterfeit or at least unregistered in the African countries where they are sold. While results of the current study confirm this (62% of available brands were unauthorized), the study also highlighted important differences among countries in terms of the number of unauthorized herbicides. This in turn points to differences in capacities of countries to monitor and regulate pesticide developments at their markets. It has recently been observed that such regulatory capacities of African countries cannot always keep pace with the influx of new herbicide brands, imported from Asia (Haggblade et al. 2017b; Tamru et al. 2017), and this again raises concerns with respect to health and environmental safety.

4.3 The status quo of herbicides in Africa

This study showed that (1) herbicides are potentially important technologies to reduce yield losses and therefore to contribute to food security, (2) herbicides are commonly (32-72%) used

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[1] *Conversion rate on 29 May 2018: 1 Euro = 1.16 USD*

by rice farmers in 13 of the 20 countries covered by the survey, and often at multiple application times during the season but, (3) there is a limited diversity of herbicide formulations in supply shops in rural Africa, (4) the most widely available herbicide formulations are glyphosate and 2,4-D and they are among the cheapest available herbicides, (5) herbicide market availability and prices are reflected by what farmers are using in their rice crop, as the same products are predominantly observed here, (6) herbicides are often applied at the wrong time, and (7) farmers make limited use of formal sources of information for the correct application of herbicides. A clear trade-off was observed between the use of formal sources (extension and product labels) and the consultation of neighboring farmers. Suboptimal market processes and communication flows seem to be the most important impediments to the fulfillment of the potential these technologies hold with respect to their contribution to food security and poverty alleviation in the region. As long as this situation does not change, the status quo of poor chemical weed control in rice in SSA will likely be maintained. Prospects for changes are not bright.

For the promotion of modern technologies and good agricultural practices, well-functioning and accessible extension services are imperative (Emmanuel et al. 2016). However, in reality, extension services in SSA are often understaffed, underequipped and often lack the relevant knowledge on, for instance, weed management (e.g. Schut et al. 2015). Alternative means of information transfer, like programs or applications based on information and communication technologies (ICT) such as computers and smart-phones (e.g. Aker 2011; Saito et al. 2015; Rodenburg et al. 2016) or farmer-to-farmer instruction videos (e.g. Zossou et al. 2012) are promising in this respect.

On the supply side, the developments are not conducive either. Globally, innovations in herbicide formulations have been seemingly non-existent since the 1990s (Duke 2012), resulting in an overall low diversity of herbicide formulations even in industrial, developed countries (Davis and Frisvold 2017). Although some recent developments have been noted that point to a renewed interest in herbicide innovations, potential new formulations will likely be much more expensive than existing ones (Haggblade et al. 2017b). The marginal attainable profits for the agro-industry in rural Africa, also do not attract innovative private investments in this area (Demont et al. 2009) and the regional herbicide market is not likely to expand and diversify with already available herbicide formulations in the near future either. The recent trend of increasing imports of cheap herbicides mainly from China and, to a lesser extent, India (Haggblade et al. 2017b), does not contribute to product diversity and quality. Rural Africa is populated by smallholder farmers with small financial margins, who are often unable or reluctant to invest. They will be attracted by the same cheap herbicides imported from Asia and not be incentivized or able to pay more for a new herbicide for which the efficacy has not been proven to them yet. The status quo of herbicides in rice in SSA, is therefore likely to endure.

5 Conclusions

Herbicides are commonly used (32-72%) technologies in 12 of the surveyed countries, while in eight of the countries i.e. Ethiopia, Chad, Madagascar, The Gambia, Tanzania, DR Congo, Rwanda, and Sierra Leone, adoption is less than 3%. Herbicides are more often used by men than by women and more often in irrigated lowland rice than in rainfed rice growing environments.

Herbicides are never used as stand-alone weed technology but rather as a supplement to hand weeding. Compared with hand weeding only, this supplementary use of herbicides can further reduce yield losses by 0.4 t ha^{-1} in irrigated lowlands and rainfed uplands. Herbicides could therefore play an important role in reaching food security in the region. Based on surveys and recent trends reported in the literature, we however observe a number of problems regarding the sustainability implications of this technology. The global stagnation in herbicide innovations and the poor diversity in available herbicide formulations on local rural markets result in the dominance of few herbicides being used by rice farmers in SSA. Moreover, the rural herbicide supply markets in SSA are dominated by cheap and unregistered herbicide brands, there is a shortfall in effective national regulatory capacities to monitor environmental and health safety related to these products, and we observed a very low rate of users consulting reliable information sources concerning proper and safe herbicide use. The latter is reflected by a high rate of assumed wrong spraying timings.

Overreliance on a small range of herbicide formulations and the frequent use of these formulations in herbicide brands of unknown quality applied at sub-optimal timings/methods may cause negative impacts on the environment, human health, and the crop, and may accelerate the evolution of herbicide resistant weed ecotypes. All these factors jeopardize the future food security in sub-Saharan Africa. Moving away from this status quo, will require (1) improvements in national pesticide regulation procedures and investments for their effective implementation and monitoring of environmental and health impact, (2) innovations in herbicide formulations as well as other labor-saving weed management strategies that stimulate farmers to diversify their approaches, and (3) both innovations and investments that benefit agricultural service provision and communications with farmers specifically concerning the correct choice and timing of herbicides.

Acknowledgements This is an output of the CGIAR Research program Global Rice Science Partnership. Financial support for this study was provided by the African Development Bank as part of the project “Support to Agricultural Research for Development of Strategic Crops in Africa”. Survey work in Tanzania, Uganda and Rwanda was financially supported by the German Federal Ministry for Economic Cooperation and Development, commissioned by the Deutsche Gesellschaft für Internationale Zusammenarbeit, through the project “East African Wetlands: Optimizing sustainable production for future food security (WETLANDS)”.

We thank Justin Djagba of AfricaRice for generating Fig. 1. We thank all farmers and extension personnel for their participation in the surveys.

Compliance with ethical standards

Conflict of interest statement The authors declared that they have no conflict of interest.

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Jonne Rodenburg has a PhD in Production Ecology and Resource Management from Wageningen University (2005). He worked for 13 years as an Agronomist at the Africa Rice Center of the CGIAR. Since January 2018 he has been working as a Senior Lecturer/Researcher in Agroecology at the Natural Resources Institute (NRI) of the University of Greenwich. His expertise is in agronomy, weeds and parasitic weeds in cereal cropping systems, primarily rain-fed rice production in Africa.

Jean-Martial Johnson (MSc) is an agricultural engineer with 9 years of professional experience of which 6 years were as a research assistant and soil laboratory manager at the Africa Rice Center. His expertise is in agronomy, soil science and mycorrhizas. His main research tasks are (1) implementation of research protocols (on-farm and on-station trials) and participatory surveys in rural areas, (2) management of data and (3) analytical assessment of soil, plant and water chemical content.

Ibnou Dieng (PhD) is a Biometrician with 10 years of professional experience at post-doctoral level in Africa. His expertise is on biometrics and data management. He is experienced in analyzing complex data structure – e.g. (generalized) mixed models, multivariate analysis, stochastic frontier analysis, multilevel modeling, machine learning techniques — as well as in the design and implementation of automated data collection using smartphones and in household surveys.

Kalimuthu Senthilkumar (PhD), completed his BSc in Agriculture (1995-99) and MSc in Agronomy (2001-02) with distinction from Tamil Nadu Agricultural University (TNAU), India. He did his PhD (2003-2008) on water-saving rice production technologies at Wageningen University, The Netherlands. As a post-doctoral researcher, he worked at PRI, Wageningen, Netherlands, INRA-Bordeaux sciences agro and INRA, Toulouse, France. Since October, 2012 he has been working as an agronomist at AfricaRice.

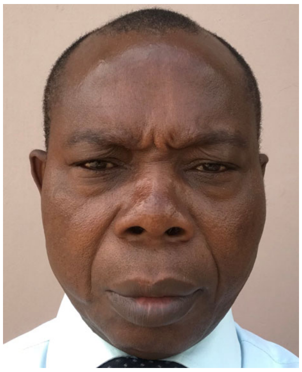
Elke Vandamme (PhD) is an agronomist with 10 years experience in agricultural research for development in Africa. She has worked as an MSc and PhD student with CIAT in Central Africa and Kenya and as a post-doctoral fellow and scientist at the Africa Rice Center in Benin and Tanzania. She is currently working as Food Systems Agronomist at CIP in Rwanda. Her work focuses on integrated soil fertility management, integrated crop management and cropping and farming systems research.

Cyriaque Akakpo is an Agronomist with 30 years experience. He worked at the Institut National des Recherches Agricoles du Bénin (INRAB) where he coordinated the national rice research program for 15 years. He was the national focal point for the Africa-wide Agronomy Task Force, founded by AfricaRice. He retired in 2015 and works as an independent consultant residing in Benin.

Moundibaye Dastre Allarangaye (PhD) is a principal researcher at the Institut Tchadien de Recherche Agronomique pour le Développement (ITRAD), in Chad. His focus is on agronomy and selection of varieties with resistance against biotic stresses such as virus diseases. He is also the coordinator of research activities in Chad's so-called Rice Sector Development Hubs.

Idriss Baggie (PhD) is an Agronomist/Soil Scientist with 20 years professional experience in Africa, of which 13 years were post-doctoral. His expertise is soil fertility, agronomy and yield gap studies, mainly in lowland rice-based cropping system. His research focus is on sustainable soil fertility management, chemical characterization of lowland rice soils and cereal cropping systems.

Samuel Oladele Bakare (PhD) is an Agronomist/Weed Scientist at the National Cereals Research Institute, Badeggi, Nigeria. His research interest is in the improvement of best agronomic practices for rice production. He has about 26 years of professional experience in rice husbandry. Administratively, he is the Acting Head of Research Operations Department in his work-organization.



Ralph Kwame Bam has worked as a Rice Agronomist at the CSIR-Crops Research Institute, Ghana for the past 22 years. His current research is focused on the impact of farmers' postharvest practices on (1) mechanical and structural properties of rice and how these affect seed storage longevity, seedling establishment, and vigour and (2) weed competitiveness of rice seedlings during seedling establishment.

Ibrahim Bassoro obtained his degree as Ingenieur in Agronomy from the Université de Dschang of Cameroon in 2001. He is currently working as agronomist at the Institut de Recherche Agricole pour le Développement (IRAD) in the Cereals programme. He is based in Garoua and has been the Agronomy Task Force focal point for Cameroon since 2013.

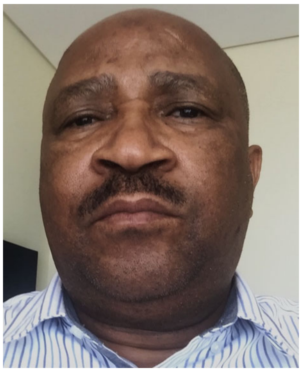
Bayuh Belay Abera is a researcher at the Ethiopian Institute of Agricultural Research and a PhD candidate at Hohenheim University, Institute of Agricultural Science in the Tropics in Germany. He contributed to the newly established National Rice Research and Training Center in Fogera, Ethiopia and served as the first director (resigned December 2015). He was the leader of the National Rice Research Program in Ethiopia and the country's focal point for the Africa-wide Agronomy Task Force.

Madiama Cisse , has a PhD from Goettingen University, Germany (2000). He is an agronomist and "Maître de Recherches" at ISRA, Saint-Louis, Senegal, and coordinator of the program "Production systems and natural resource management in the Senegal River Valley". He has conducted several studies in the fields of crop and irrigated systems management, and participatory evaluation approaches of agricultural technologies.

Wilson Dogbe (PhD) is a cropping Systems Agronomist with 30 years professional experience in Rice Research and Development in Ghana and West Africa. He has led the Rice R & D at CSIR-Savanna agricultural research institute for more than 25 years and is currently the Manager of the USAID – Direct Support Project to the CSIR-Savanna Agricultural Research Institute.

Henri Gbakatchétché is a Systems Agronomist at the National Center for Agricultural Research (CNRA), with 28 years professional experience in research in Côte d'Ivoire. His experience is in rice-based cropping systems. He is also the country's focal point of the Africa-wide Agronomy Task Force.

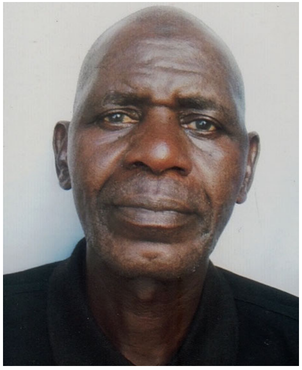
Famara Jaiteh studied Agronomy and Plant Breeding at Kwame Nkrumah University of science and technology. Famara works as a Research Officer at the cereals program of the National Agricultural Research Institute. He is specialized in cropping systems and other agronomic practices.



Geophrey Jasper Kajiru (PhD) is a Soil Scientist with 15 years experience in the Department of Research and Development in the Ministry of Agriculture, Tanzania. In the last 10 years, he has planned and coordinated the implementation (in collaboration with Sokoine University of Agriculture) of major action-oriented research for development projects in Tanzania.

Alain Kalisa (MSc), is an Agronomist with 8 years professional experience in the Rwandan Agriculture and Animal resources development Board under the ministry of Agriculture. His expertise is in crop protection. He has worked with the Africa Rice Center as the focal person in different Agronomy related projects, funded by BMZ/GIZ. His research also focuses on the rice pathogenic fungus (*Magnaporthe oryzae*).

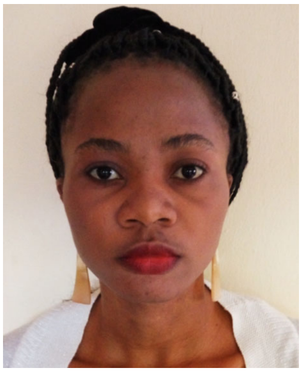
Nianankoro Kamissoko has a PhD from the Université de Bamako in Sustainable Natural Resource Management. He is the head of agronomy within the Programme Riz Irrigué at CRRA in Niono, Mali. He also leads a WAAPP-2 project on nutrient management in legume-rice rotations in agricultural enterprises in the Office du Niger.



Keita Sékou is head of the national rice program of Guinea, at IRAG. He studied for 2 years in Cuba for his MSc in Agronomy (1989-1990) and 1 year in Japan (Tsukuba) for a certificate in rice cropping techniques.

Ahouanton Kokou is a research assistant of Agronomy at AfricaRice based in Bouaké, Côte de'Ivoire. He obtained his diploma "Ingenieur Agronome" in 1995 at the National University of Benin in Benin. He is in charge of on-station trials and also for capacity building of partners in different Africa countries.

Delphine Mapiemfu-Lamare has a PhD in Plant Biology/Biotechnology from the University of Yaounde. Her specific expertise is in plant production and post-harvest storage. She is a researcher in the Annual Crops Coordination group of the Institute of Agricultural Research for Development (IRAD, in Cameroon.



Fanny Mabone Lunze (Msc2) is an Agro Economist with 7 years of professional experience in agricultural research. Between 2010 and 2012, she served as research assistant with the Bureau of Socioeconomic Studies based at the University of Kinshasa. Afterwards in 2012, she joined the Rice program as research assistant at the National Agricultural Research Institute (INERA/DRC).

Jerome Mghase is a senior researcher at the Kilombero Agricultural Research and Training Institute (KATRIN) in Ifakara, Tanzania. He is a trained Agronomist with a PhD from Japan. He is also the coordinator of research activities in the Rice Sector Development Hub of Kilombero.

Illiassou Mossi Maïga (PhD), is a researcher from the Institut National de la Recherche Agronomique du Niger. He is specialized in agricultural water management. He has ample experience in technical and organization management of irrigation in Niger and other Sahelian countries. As focal point of the African-wide Agronomy Task Force, he has conducted collaborative work with partners across the continent.

David Nanfumba is an Agronomist & Seed Systems Specialist at the National Agricultural Research Organisation (NARO) in Uganda and a PhD candidate at Makerere University. He is also the country's focal point of the Africa-wide Agronomy Task Force of AfricaRice.

Abibou Niang (PhD candidate) is a chemist and soil scientist with 25 years of professional experience in different countries in Africa. His expertise is in soil chemistry, rice agronomy and crop modeling. His research is focused on the rice yield gap in West Africa. Abibou Niang is currently working on the implementation of an oil palm based research and development platform in Gabon.

Raymond Rabeson (PhD) is an Agronomist/Soil Scientist with 30 years experience in the Rice Research Department, in FOFIFA within the Ministry of Agriculture and Livestock and the Ministry of Higher Education and Scientific Research, Madagascar. He is the coordinator of rice research projects involving national and international institutions (AfricaRice, CIRAD, JIRCAS).

Zacharie Segda (Doctorat Unique) is a soil fertility agronomist with 23 years of professional experience in Burkina Faso, of which 11 years have been postdoctoral. His research focus is on (1) agronomy and rice cropping systems, and (2) sustainable agricultural and natural resource management of irrigated rice system. The main objective of his work is to develop integrated soil fertility and crop management strategies for rice farmers in Burkina Faso.

Fitta Silas Sillo is an agronomist with a Masters degree. He worked as an agricultural tutor and a rice farmers' trainer on Good Agricultural Practices (GAP) for 5 years. He has spent another 5 years researching nutrient management and drought tolerance in rice. He has also participated in various surveys, including the collection of herbicide information in Eastern and Southern Africa.

Atsuko Tanaka is an agronomist, with a PhD on the nutrient management of rice, obtained from the University of Tokyo, Japan. A key research interest has been to enhance sustainability and productivity of small-scale rice farmers in sub-Saharan Africa. She joined the Japan International Research Center for Agricultural Sciences in April 2017. She previously held a research position at the Africa Rice Center.

Kazuki Saito (PhD) is an agronomist of AfricaRice with more than 15 years experience in Asia and sub-Saharan Africa. He leads a multi-institutional Flagship Project: 'Sustainable farming systems' as part of the new RICE CRP led by IRRI. He works on yield gap assessment, integrated management practices including a decision support tool ('RiceAdvice'), farming systems research, and abiotic/biotic stress resistance in rice. He received the Louis Malassis International Scientific Prize for Young Promising Scientists in 2015.

Affiliations

Jonne Rodenburg[1,2] · **Jean-Martial Johnson**[2,3] · **Ibnou Dieng**[2] · **Kalimuthu Senthilkumar**[4] · **Elke Vandamme**[5] · **Cyriaque Akakpo**[6] · **Moundibaye Dastre Allarangaye**[7] · **Idriss Baggie**[8] · **Samuel Oladele Bakare**[9] · **Ralph Kwame Bam**[10] · **Ibrahim Bassoro**[11] · **Bayuh Belay Abera**[12] · **Madiama Cisse**[13] · **Wilson Dogbe**[14] · **Henri Gbakatchétché**[15] · **Famara Jaiteh**[16] · **Geophrey Jasper Kajiru**[17] · **Alain Kalisa**[18] · **Nianankoro Kamissoko**[19] · **Keita Sékou**[20] · **Ahouanton Kokou**[2] · **Delphine Mapiemfu-Lamare**[11] · **Fanny Mabone Lunze**[21] · **Jerome Mghase**[22] · **Illiassou Mossi Maïga**[23] · **David Nanfumba**[24] · **Abibou Niang**[25] · **Raymond Rabeson**[26] · **Zacharie Segda**[27,28] · **Fitta Silas Sillo**[29] · **Atsuko Tanaka**[30] · **Kazuki Saito**[2]

[1] Natural Resources Institute (NRI), University of Greenwich, Central Avenue, Chatham Maritime, Kent ME4 4TB, UK

[2] Africa Rice Center (AfricaRice), 01 B.P. 2551, Bouake 01, Côte d'Ivoire

[3] Institute of Crop Science and Resource Conservation (INRES), University of Bonn, 53115 Bonn, Germany

[4] Africa Rice Center (AfricaRice), P.O. Box 1690, Ampandrianomby, Antananarivo, Madagascar

[5] International Potato Center (CIP), P.O. Box 1269, Kigali, Rwanda

[6] Institut National des Recherches Agricoles du Bénin (INRAB), B.P. 143, Bohicon, Benin

[7] Institut Tchadien de Recherche Agronomique pour le Développement (ITRAD), B.P. 5400, N'Djaména, Chad

[8] Rokupr Agricultural Research Centre (RARC), Sierra Leone Agricultural Research Institute (SLARI), Tower HillP.M.B. 1313, Sierra Leone

[9] National Cereals Research Institute (NCRI), P.M.B. 8, Badeggi, Niger State, Nigeria

[10] CSIR-Crops Research Institute, P. O. Box 3785, Kumasi, Ghana

[11] Institut de Recherche Agricole pour le Développement (IRAD), B.P. 2123, Yaounde, Cameroon

[12] Ethiopian Institute of Agricultural Research (EIAR), P.O. Box 1745, Bahir Dar, Ethiopia

[13] Centre de Recherches Agricoles (CRA) de Saint-Louis, Institut Sénégalais de Recherches Agricoles (ISRA), B.P. 240, Saint-Louis, Senegal

[14] CSIR Savanna Agricultural Research Institute (SARI), P.O. Box 52, Tamale, Ghana

[15] Centre National de Recherche Agronomique (CNRA), B.P. 440, Man, Côte d'Ivoire

[16] National Agricultural Research Institute (NARI), P.M.B. 144, Brikama, Gambia

[17] Department of Research and Development, Ministry of Agriculture, P.O. Box 2066, Dar es Salaam, Tanzania

[18] Rwanda Agricultural Board (RAB), P.O Box 5016, Kigali, Rwanda

[19] Institute d'Economie Rurale (IER), CRRA, B.P. 258, Niono, Mali

[20] Institut de Recherche Agronomique de Guinée (IRAG), Kankan, B.P. 1523, Conakry, Guinea

[21] Institut National pour l'Etude et la Recherche Agronomiques (INERA), B.P. 2037, Kinshasa, Democratic Republic of Congo

[22] Kilombero Agricultural Research and Training Institute (KATRIN), Private Bag, Ifakara, Tanzania

[23] Institut National de la Recherche Agronomique du Niger (INRAN), B.P. 429, Niamey, Niger

[24] National Agricultural Research Organization (NARO), Mbale, Uganda

[25] Olam International Ltd. In Gabon, Galerie Tsika, BP 1024, Libreville, Gabon

[26] Centre National de Recherche Appliquée au Développement Rural (FOFIFA), Antananarivo, Madagascar

[27] Centre National de la Recherche Scientifique et Technologique, Institut de l'Environnement et de Recherches Agricoles (CNRST/INERA), Bobo Dioulasso, Burkina Faso

[28] Bureau National des Sols (BUNASOLS), 03 BP 7142, Ouagadougou 03, Burkina Faso

[29] Africa Rice Center (AfricaRice), East and Southern Africa, P.O. Box 33581, Dar es Salaam, Tanzania

[30] Japan International Cooperation Agency (JICA), Benin Office, Cotonou, Benin