Farmers' perceptions on mechanical weeders for rice production in sub-Saharan Africa

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Summary

Competition from weeds is one of major biophysical constraints to rice (*Oryza* spp.) production in sub-Saharan Africa. Smallholder rice farmers require efficient, affordable and labor-saving weed management technologies. Mechanical weeders have shown to fit this profile. Several mechanical weeder types exist but little is known about locally specific differences in performance and farmer preference between these types. Three to six different weeder types were evaluated at 10 different sites across seven countries — i.e. Benin, Burkina Faso, Côte d'Ivoire, Ghana, Nigeria, Rwanda, and Togo. A total of 310 farmers (173 male, 137 female) tested the weeders, scored them for their preference, and compared them with their own weed management practices. In a follow-up study, 186 farmers from Benin and Nigeria received the ring hoe, which was the most preferred in these two countries, to use it during the entire crop growing season. Famers were surveyed on their experiences. The probability of the ring hoe having the highest score among the tested weeders is 71%. The probability of farmers' preference of the ring hoe over their usual practices —i.e. herbicide, traditional hoe, and hand weeding— is 52%, 95%, and 91% respectively. The preference of this weeder was not related to gender, years of experience with rice cultivation, rice field size, weed infestation level, water status, or soil texture. In the follow-up study, 80% of farmers who used the ring hoe indicated that weeding time was reduced by at least 31%. Of the farmers testing the ring hoe in the follow-up study, 35% used it also for other crops such as vegetables, maize, sorghum, cassava and millet. These results suggest that the ring hoe offers a gender-neutral solution for reducing labor for weeding in rice as well as other crops and that it is compatible with a wide range of environments. The implications of our findings and challenges for out-scaling of mechanical weeders are discussed.

Introduction

Limited use of mechanization has been considered as one of the major obstacles for enhancing agricultural productivity in sub-Saharan Africa (SSA) (Sims and Kienzle, 2016). This is also the case for rice cultivation in this region. Agricultural intensification and area expansion in SSA can be obtained by increasing amounts of inorganic fertilizer use and the introduction of labor-saving technologies such as herbicides and mechanization (Saito et al., 2013; Rickman et al., 2013; Ollenburger et al., 2016). However, rice farmers in this region are predominantly smallholders (Diagne et al., 2013), and this type of farmers has limited financial resources or access to credits and can therefore often not afford such technologies (Rodenburg and Johnson, 2009; Rickman et al., 2013). Even in case herbicides are accessible by farmers, they might have limited knowledge of effective and safe application procedures (Rodenburg and Johnson, 2009). If such procedures are not observed, herbicide use might result in environmental hazards (e.g. water contamination, herbicide resistant weeds) and turn detrimental to human health. Research and development should therefore focus on developing, testing and promoting safe and efficient labor-saving technologies that can be easily used and afforded by smallholder farmers (e.g. Ogwuike et al., 2014).

Smallholder farmers frequently indicate that weeds are one of the major constraints to rice cultivation (Niang et al., 2017). In smallholder rice production systems, weeding is the activity with the highest seasonal labor requirement (Lodin-Bergman et al., 2012; Ogwuike et al., 2014). The reason for this high labor requirement is that weeding is mainly conducted manually, i.e. by hand or traditional hoe (Rodenburg and Johnson, 2009). Due to its labor-intensive nature, weed control is often delayed or otherwise suboptimal, resulting in substantial yield reduction or crop failure (e.g. Becker et al., 2003). Improving competitiveness of rice against weeds through genetic improvement was considered as one of the potential options for reducing the weeding labor input (Dingukhn et al., 1998). However, these breeding efforts did not generate rice varieties as competitive as expected as varieties combining superior strong weed competitiveness with adaptation to the environmental conditions of sub-Saharan Africa are scarce (e.g. Rodenburg et al., 2009; Saito et al., 2012; Saito and Futakuchi, 2014).

An alternative approach to reduce the burden of weeding is through the introduction of mechanical weeders. The use of these implements could reduce labor requirements for weeding as well as the use of herbicides and therefore be instrumental in downsizing overall production costs. Use of such weeders, however, requires uniform transplanting/dibbling or drilling of the crop.

Mechanical weeders are not yet commonly used by farmers in SSA, apart from Madagascar. Recent studies reported results of effectiveness and farmers' perceptions of such weeders for rice cultivation (Krupnik et al., 2012; Gongotchame et al., 2014; Rodenburg et al., 2015). Participatory weeder selection in Benin showed that farmers' choice of weeders depends on water regimes (Gongotchame et al., 2014), and results from a trial in Tanzania indicated that their efficacy depends on water management and weeder types (Rodenburg et al., 2015). In Benin, the ring hoe was identified as the most suitable weeder in rain-fed lowland rice, because of its ease of operation and high efficiency (Gongotchame et al., 2014). However, farmers' preference for this weeder can be different across countries, rice growing environments, and water management regimes. Data from participatory testing across diverse countries in sub-Saharan Africa could provide the necessary information on target domains for out-scaling of this technology.

Therefore, the objectives of this study were to (i) investigate farmers' preferences among different weeder types, (ii) compare the use of mechanical weeders with current farmers' weed management practices in a wide range of countries in sub-Saharan Africa, and to (iii) test whether the preference was related to rice growing environments, water management regimes, and other biophysical parameters, as well as socio-demographic conditions.

Material and Methods

Description of study sites and mechanical weeders

This study was conducted at 28 fields divided over 10 sites in Benin, Burkina Faso, Côte d'Ivoire, Ghana, Nigeria, Rwanda, and Togo (Table 1). The sites were selected by national agricultural research institutes and their partners as priority intervention areas for rice sector development in their countries. The sites represent a wide range of rice growing environments in sub-Saharan Africa, ranging from irrigated rice systems with full water control to upland rice systems entirely depending on rainfall for water inputs.

On each site, 3 to 5 weeder types were tested —(1) the ring hoe, (2) the twisted-spike floating weeder, (3) the curved spike floating weeder, (4) the straight-spike floating weeder, (5) the straight spike weeder and (6) the simple rotary weeder— all with different characteristics (Table 1 and Supplementary material Fig. S1). As technical characteristics and drawings were described in a previous study (Gongotchame et al., 2014) and on a website (http://www.ricehub.org/RT/weeds/weeders/), here we only briefly describe differences among them. The ring hoe does not have any rotating parts, like other weeders. The simple rotary weeder has a single rotating weeding drum with a ring hoe in front. Weeders 2, 3, and 4 have two rotating weeding drums and a floater in front, and the difference between them primarily concerns the shape and curvature of the spikes. Weeder 5 does not have a floater, as it was originally developed for upland crops (Gongotchame et al., 2014). All the tested weeders were fabricated locally or acquired from Africa Rice Center, Cotonou, Benin. The number of tested weeder types differed among sites, according to their availability, but the ring hoe was included in all the sites. A follow-up study was conducted at the sites Glazoue (Benin) and Lafia (Nigeria).

Participatory testing of mechanical weeders

The on-farm testing of weeders followed a farmer participatory approach similar to methods used by Gongotchame et al. (2014). At each site, one to five fields were selected in consultation with farmers. We purposely selected fields, in which rice was sown or planted in rows or grids by farmers, which is a requirement for the use of these weeders. Water status and weed infestation (weed cover ≤ 10%; weed cover >10% and ≤ 30%; weed cover > 30%) were visually scored in a similar way as done by Gongotchame et al. (2014). Soil texture was roughly determined in each field following Defoer et al. (2009). Information on production system and crop management practices in selected fields was collected by interviewing the farmers concerned.

In each test field, eight to twelve participating farmers were conducting the tests. The total number of participants was 310 (173 male; 137 female) (Tables 1 and 2). Socio-demographic information (gender, years of experience in rice cultivation, rice cultivation area) was collected from each participant (Table 2). We explained to the participants how to use the mechanical weeders one by one, and then asked all the participants to test each weeder in the field and to evaluate its effectiveness and ease of operation. Once all the weeders had been tested by each of the participants, they were free to try any of the weeders again for any further assessment if they deemed this necessary.

After the participants tested the weeders, they were asked to provide scores for each weeder. There were five possible scores: 1= very bad; 2= bad; 3= fairly good; 4= good; 5=very good. The participants were also asked to compare each mechanical weeder with their own weed management practices (i.e. herbicide application, traditional hoe weeding, hand weeding) using a structured survey form. Key statistics of participants are shown in Table 2.

Follow-up study

A follow-up study was conducted in Benin and Nigeria to assess farmers' appreciation of their most preferred weeder when they used it during an entire cropping season on their own farm. Additionally, it was tested whether their appreciation was related to biophysical or socio-demographic factors. For this follow-up study, we used the ring hoe, which was identified as the most preferred one in the first study (participatory testing of mechanical weeders) both in Benin and in Nigeria. In total, 186 farmers received the ring hoe in the two countries. Villages and farmers for the follow-up study were randomly selected in each target sites. In total, 8 and 7 villages were selected in Benin and Nigeria (with rain-fed upland and rain-fed lowland fields), respectively. In each village, 1 to 29 farmers received a ring hoe. Among the farmers who received a ring hoe, 101 were male and 85 were female farmers and all received training on how to use it. After the rice cropping season, farmers were asked the following questions:

1. Was the weeder used during this rice growing season? 1. yes, 2. no
2. How many people (number of persons) used the weeder you received?
3. Who used the weeder mainly? 1. male, 2. female farmer
4. What was the rice cultivation area (in ha) for which the weeder was used?
5. How much was weeding time reduced by using the weeder compared to the usual weeding method? 1. less than 30%, 2. more than 30% but less than 50%, 3. more than 50% but less than 80%, 4. no difference, 5. use of the weeder took more time than required previously (Only one answer can be selected here.)
6. In which other crops was the weeder used?
7. Is there an intention to use the weeder in the following season? If yes, why? Compared to the usual weeding method the use of the weeder 1. is easier, 2. results in better weed control, 3. is labor- or time-saving, 4. Increases rice yield, 5. has other advantages. (More than one reason can be selected here.)
8. What should the weeder cost (costs in local currency)?

Statistical analysis

To examine variation in farmers' scores for each tested weeder, we used a three-level multinomial linear model including two random intercepts after taking into account (i) variation across fields and among farmers within the same fields, (ii) variation across production system and site combination (referred to as 'environment') and among fields within the same environment. We started with an unconditional model for each tested weeder, i.e. a model containing no predictors. In the participatory testing of mechanical weeders (first study), there were in total 28 test fields within 12 distinct environments (i.e. rice production system × geographical site; 2 out of 10 geographical sites comprised two rice production systems, resulting in 12). The field factor includes effects of individual farmer' crop management practices, soil type and water condition, and considers that each field was different, whereas the environment factor considers that fields in the same production system within a given site are similar and they are grouped. The estimate of the intercepts in the unconditional model represents the log odds of scores of a tested weeder at a typical field or environment. Predicted probabilities (PP) at a typical field from our sample are calculated as below.

$$PP = \frac{e^{\eta_{ij}}}{1 + e^{\eta_{ij}}}$$

where $e^{\eta_{ij}}$ is the odds of rating a tested weeder for farmer i in field j

The unconditional model provides information on the degree of clustering (dependence) in the data which can be summarized by the intraclass correlation coefficient (ICC). The ICC at field-level measures the expected correlation between two farmers in the same field and the ICC at the environment-level measures the expected correlation between two fields from the same environment. The ICCs are calculated as follows:

$$ICC_{Field} = \frac{\tau_f + \tau_e}{\tau_f + \tau_e + 3.29}$$

$$ICC_{environment} = \frac{\tau_e}{\tau_f + \tau_e + 3.29}$$

Where τ_f is the variance for the field-level, τ_e the variance for the environment-level and 3.29 the farmer-level error variance, which is $\pi/3$ (Snijders and Bosker, 1999).

As in a previous study by Gongotchame et al. (2014) the ring hoe was the most preferred weeder, we computed a binary response variable indicating whether the ring hoe received a higher score than any other weeder in this study. With this binary variable, we performed again an unconditional model. Then, we estimated a full model by including both farmer-level predictors (socio-demographic information: gender and experience) and field-level predictors (water status, weed infestation below the canopy, and soil texture) as fixed effects to identify predictors that could explain farmers' preference for the ring hoe over the other weeders. We also examined the relationship between farmers' socio-demographic characteristics, the field size and their likelihood of preferring the ring hoe compared to their own weed management practices (i.e. herbicide application, traditional short-handled hoe weeding, hand weeding). For each of these management practices, we also ran unconditional and full models. For the unconditional model, we did not consider field size, as we assumed that it does not affect farmers' scoring for each weeder. In the follow-up study, we used multiple regression analysis to identify factors affecting the farmers' willingness to purchase the ring hoe. We included different socio-economic parameters (country, production system, use of herbicide, number of persons who used the weeder in a farm household, gender and age of the main person using the weeder, average rice field size, weeding time difference in comparison with the conventional weeding method, use for other crops) as predictors and computed the Akaike's Information Criteria (AIC) (Akaike, 1973) for all possible subsets of multiple regression models. The model with the best subset of variables that minimizes the AIC among all possible subsets is considered as the best model. SAS GLIMMIX procedure was used (SAS 9.2, SAS Institute Inc., Cary, NC, USA) for these computations.

Results

Participatory testing of mechanical weeders

Among 28 fields, 9 were irrigated lowland, 11 were rain-fed lowland, and 8 were rain-fed upland (Table 1). With respect to soil texture, 13 fields had a clay soil, 6 fields had soils with a dominant percentage of silt and soils of the remaining 9 fields were characterized as predominantly sandy. At the time of the weeder testing, 36% of the fields were flooded and 64% were not flooded. Fields were dominated by either sedges (dominant weed category in 54% of the fields) or broad-leaf weed species (46%). Weed infestation below the rice canopy varied between less than or equal to 10% (32% of the fields), between 11 and 30% (39% of the fields) and more or equal to 31% (29%). Of the farmers, 44% were female (Table 2).

While weed control by hand was the dominant farmer practice (66%), more than half of the farmers (54%) indicated to use herbicides, and a substantial share of the farmers (37%) use the traditional short-handled hoe at some point in time (Table 2). A substantial number of farmers used combinations of any of those three methods.

Results from the unconditional model using field as random effect showed that 38% of the variability in the score for the ring hoe was accounted for by the field in our study, leaving 62% of the variability to be accounted for by the environment (production system and site combination), the farmers or other unknown factors (Table 3). Similarly, 37, 79, 64, 36, and 54% of the variability in the scores for the twisted-spike floating weeder, the curved-spike floating weeder, the straight-spike floating weeder, the straight spike weeder, and the simple rotary weeder, respectively, was accounted for by the field. However, when environment was used as random effect, less than 22% of variation was explained by environment, and for none of the weeders the environmental effect was significant. This suggests that scores might be largely affected by non-environmental conditions of the field, and hence that scores of weeders are relatively consistent across environments.

With respect to the ring hoe (Table 3), the predicted probability (PP) of score 1 to 5 for the ring hoe was 3%, 4%, 7%, 27%, and 59%, respectively, making it the most preferred weeder type. The PPs of the other weeders were calculated in the same manner whereby the twisted-spike floating weeder was ranked second-best and the straight spike weeder third (Table 3). The ring hoe had the highest PPs in scores 4 (i.e. 'good') and 5 (i.e. 'very good') among the weeders, with 86% probability of scores 4 or 5. For other weeders, the probability was less than 24% for scores 4 or 5. The ring hoe also had the lowest PPs in scores 1 (i.e. 'very bad') and 2 (i.e. 'bad') compared to other weeders.

Comparing the preference of the ring hoe and other tested weeders with that of farmers' own weed management practices, no significant effect of environment on preference was observed except for the comparison ring hoe vs. hand weeding (Table S1). When field was used as random effect, the probability of the ring hoe receiving the highest score among weeders was 71%, and the probability of farmers' preference of the ring hoe over herbicide application and the use of the traditional short-handled hoe was 52% and 95%, respectively. Farmers' preference for the ring hoe over hand weeding was consistent across fields. When the factor 'environment' was considered as random, the probability of farmers' preference of the ring hoe over hand weeding was 91%.

As farmers' preference for the ring hoe against the other weeders was affected by field (Table 3), it was hypothesized that socio-demographic condition (Table 2) and field-level predictors (Table 1) could explain variation in their preference. However, the results from the two-level multinomial linear model revealed that the preference of this weeder was not related to field water status, weed infestation level, level, or soil texture ($P>0.05$, Table 4). Similarly, no farmer-level predictors like gender, year of experience in rice cultivation, were identified for explaining the variation in preference for the ring hoe compared to farmers' weed management practices.

Follow-up study

Of the 186 farmers surveyed in the follow-up study, 39 farmers (21%) did not actually use the ring hoe, despite having received one (Table 4). The number of farmers who did not use the ring hoe was the highest in the dry season in 2016 in Lafia (Nigeria), when 15 of the farmers did not grow rice. A total of 10 farmers in Lafia indicated that a lack of uniformity in planting was the reason why they did not use the ring hoe. Six upland rice farmers in Glazoue (Benin) did not use the ring hoe because of disturbing events (i.e. drought or bush fire) which destroyed their rice fields. Other minor reasons were shown in Table S2.

The farmers, who actually used the ring hoe, shared the tool with on average 4 other persons (Table S3). A small majority (52%) of farmers indicated that the ring hoe was mainly used by women. In the dry season in Lafia, when there was an overall lower demand for labor due to a limited number of crops, fewer women used the ring hoe for weeding. In Lafia, average rice field size on which the ring hoe was used (1.14 ha) was much larger than in Glazoué (0.18 ha).

Around 80% of the farmers indicated that the ring hoe reduced weeding time by at least 31%. Apart from rice, 35% of the farmers used the ring hoe in other crops as well. Nearly all (99%) farmers who actually used the ring hoe during the follow-up study indicated they want to use it for next season as well. Farmers' expected to pay between US $1 and $8 per ring hoe, with the average price ranging from US $3.2 in Glazoue (Benin) to $2.6 in Lafia (Nigeria). In Benin, the expected, and presumed acceptable, price for the ring hoe was much higher among upland rice farmers than among lowland rice farmers.

A multiple regression analysis was conducted to identify factors affecting the farmers' willingness to purchase the ring hoe. This analysis revealed that the best-fitted model (R^2=0.29; AIC=469.1; $P < 0.001$) comprised 4 predictors: (1) rice production system, (2) use of herbicides, (3) number of persons who used the weeder and (4) gender of the main person using the weeder. In the model, rice production system, use of herbicides, and number of persons who used the weeder are the predictors which showed significant effects on the willingness to pay. Upland rice farmers were willing to pay more than lowland rice farmers. Farmers who used to buy and apply herbicides were more eager to purchase the ring hoe than others. The higher the number of ring hoe users in a farm household, the more willing the head of the household was to purchase the ring hoe (Table S4).

Discussion

This study presents the first report on test results of various types of mechanical weeders with a large sample of farmers in a wide range of rice growing conditions in sub-Saharan Africa, revealing farmers' preferences. The ring hoe was identified as the most preferred mechanical weeder, confirming a previous study conducted in Benin (Gongotchame et al., 2014), followed by the twisted-spike floating weeder. The ring hoe was adapted to a wide range of conditions as scoring was consistent across 12 environments (rice production system × geographical site). The ring hoe proved to be gender and age neutral, as women and elderly also preferred this weeder. This contrasts with results from Senthilkumar et al. (2008) who observed in India that farmers' perception of weeders was related to gender. Since the weeders tested by Senthilkumar (2008) were all rotary or cono-weeders, which are heavier and more expensive than the ring hoe, this result could imply that the ring hoe is specifically gender neutral because of its light weight and low price. However, the effect of cultural aspects cannot be ruled out in comparisons between India and Africa.

Weeding is mostly done by women and this task negatively affects the well-being of those farmers (Bergman Lodin et al. 2012). Gender neutral weeders, such as the ring hoe, could therefore alleviate the burden of women farmers and consequently improve their well-being. One of the reasons why most farmers preferred the ring hoe to the other weeders might be related to the fact that puddling is not a common practice even in irrigated lowland rice fields in SSA. Puddling in combination with transplanting is a common practice in irrigated rice in Asia and an effective method to reduce weed infestation (Chauhan et al., 2015). Puddling may also contribute to a better performance of the rotary weeders such as the twisted-spike floating weeder, the curved spike floating weeder and the straight spike weeder. The ring hoe on the other hand does not require puddling. Furthermore, as the ring hoe was originally developed for upland crops in Japan (Gongotchame et al., 2014), it is not surprising that farmers used it for other crops than rice as well and this probably raises its attractiveness as a tool. African (rice-based) smallholder farming systems hardly ever comprise only one crop species (Kuivanen et al., 2016) and in such systems technologies that serve more than one crop are likely to be favored over technologies that serve just one.

Around 50% of the farmers who used herbicides actually preferred herbicide application over the use of the ring hoe. This contrasts with the high preference for the ring hoe over manual weeding practices by hand or using traditional equipment (short-handled hoe). This can be attributed to the ease and speed of application of herbicides compared with using mechanical weeders (Rodenburg et al., 2015). This does not mean that farmers who use herbicides are not interested in mechanical weeders. On the contrary, the regression analyses showed that farmers using herbicides were more eager to purchase the ring hoe than farmers who were not using herbicides. This is probably because farmers purchasing and applying herbicides inherently have more financial means. In addition, the follow-up study showed that almost 100% of farmers, including the ones using herbicides, indicated they want to continue using this weeder. The ring hoe may therefore be used complementary to other weed management practices. This actually provides an attractive outlook for farmers that are already using herbicides, as integrated weed management approaches can both reduce the cost and increase the efficacy of weed control (Swanton and Weise, 1991). Mechanical weeders, in general, are very compatible with other weed management practices —e.g. transplanting, continuous flooding, the use of weed competitive varieties, herbicide application— and can therefore be a valuable component in an integrated crop and weed management approach (Rodenburg et al., 2015).

The ring hoe reduced weeding time by at least 31% compared with the farmer's conventional weeding method. The evaluation of the weeding time by farmer is subjective and we acknowledge that farmers might not be able to precisely indicate their time saving in percentages. However, we believe that this indicator could be used to show how much farmers appreciate the weeder for its labor saving. Furthermore, labor-saving time of the ring hoe reported in this study was similar to what was obtained in a researcher-managed trial with other types of mechanical weeders in Tanzania, i.e. the twisted-spike and the straight-spike floating weeder (Rodenburg et al., 2015). It confirms the high weeding efficiency of the ring hoe.

About 20% of the farmers (39 farmers) did not use the ring hoe in the follow-up study. However, looking at the underlying reasons for this, it becomes clear that this can hardly be explained by a lack of appreciation for the ring hoe as a weeding tool itself. Only 2% of the famers (4 farmers) were not using the ring hoe due to its perceived poor performance under prevailing (soil and water) conditions.

Our results indicate that mechanical weeders, in particular the ring hoe, work well in a wide range of conditions and can be promoted to smallholder rice farmers in Africa to save weeding labor. As Rickman et al. (2013) indicated, there are various bottlenecks for the effective introduction of mechanization tools in sub-Saharan Africa. Such tools are often abandoned for many different, partly concomitant and overlapping reasons: (1) the technology is not adapted to the specific field conditions of smallholder farms in sub-Saharan Africa, (2) the technology does not have an appropriate design, (3) there is a lack of spare parts for the tool to be repaired after break-down, and (4) maintenance is costly. A lack of initial adoption of machineries in SSA can often be explained by the high costs of such technologies, in particular if they are fuel-powered (Guthiga et al., 2007). The initial investment cost for purchasing the machinery is often too high for smallholder farmers. However, none of the above reasons for lack of adoption, or for the high rate of dis-adoption, seems to be applicable for any of the mechanical weeders tested in the current study. These weeders are well adapted and can be made locally. The design is simple (Supplementary material Fig. S1), and could also be adapted according to local conditions. Spare parts can be locally made and maintenance should therefore be affordable. In addition, in contrast with fuel-powered tools, the use of the weeders is not associated with any additional costs.

In the follow-up study, three factors were identified as affecting the farmers' willingness to purchase the ring hoe. The trends showed that upland rice farmers, herbicide users and farmers who have many relatives with interests in using the ring hoe were more eager to purchase it. In Benin, the expected, and presumed acceptable price for the ring hoe was much higher among upland rice farmers than among lowland rice farmers. In these rice-growing environments there are fewer possibilities to control weeds compared to irrigated lowlands (Rodenburg and Johnson, 2009) which may explain the higher willingness to pay for such tools among upland rice farmers. Similarly, herbicide users tend to pay more for the ring hoe probably because they are more used to invest in weeding than others. Lastly, the higher the number of potential ring hoe users in a farm household, the more willing the head of the household is to purchase the ring hoe as it becomes evident that the ring hoe will be used. The price farmers are expected and willing to pay for the ring hoe is on average US $3 per unit. This is somehow lower than the price that local fabricators would like to sell it in Benin, which is around US $5 per unit (Azoma, B. *Personal communication*). It is, however, similar to what local fabricators in Nigeria like to fetch for it (Bakare, S.O., *Personal communication*). Interestingly, the weeder type that was most preferred by farmers in the current study, is also the cheapest solution, as price indications of the rotary weeders in Madagascar (US $23 per unit) are about five times higher (Rodenburg et al., 2015). It is not clear how the presumed price differences by the test farmers influenced — conscientiously or unconscientiously— their choices. Given the small difference between the willingness to pay indicated by the farmers and the required price indicated by local vendors, it is highly likely that there will be a viable market for ring hoes in rural Africa. Currently, apart from Madagascar, none of these weeders are yet widely available on rural markets in SSA (Ndiiri et al., 2013). It would probably require both the creation of incentives for their use —i.e. through the promotion of the technologies among end-users by farm radio or farmer-to-farmer instruction videos— and the necessary technical know-how for their production —i.e. the broad dissemination of technical drawings among artisans in rural Africa, followed by training— to create vibrant and reliable markets for weeders in Africa.

Conclusions

In this study, the mechanical weeders were introduced to farmers. The main objective of these technologies is to reduce labor inputs for weeding in rice cultivation. A farmer participatory approach was used to identify the most preferred ones. The ring hoe was identified as the best weeder by farmers. Other weeders that were appreciated by rice farmers were the twisted-spike floating weeder and the straight spike weeder. The most preferred weeder, the ring hoe, showed to be gender-neutral and broadly adapted to diverse environments and crops due to its simplicity and presumed affordability. For enhancing farmers' access to this weeder, agricultural research and development efforts should address improvements of local fabricators' technical skills, and challenges and opportunities for their business dealing with it. Wide-scale dissemination of technical drawings of these weeders and promotional materials such as videos could help to reach the right stakeholders and assist them in production, retail and use of these labor-saving technologies.

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Table 1. Tested weeders at each site, characteristics of a total of 28 fields in 10 sites in 7 countries in sub-Saharan Africa, and number of farmers participating in participatory weeder testing

Country	Site	Field code	Tested weeder [a]	Rice-growing environment [b]	Soil texture	Water status [c]	Dominant weed type [d]	Weed infestation (%) below rice canopy	No. of testing farmers
Benin	Glazoue	BG1	1, 2, 3, 4, 6	RL	Silt	NF	Bl	11-30	12
		BG2		RU	Silt	NF	Bl	11-30	12
		BG3		RL	Silt	NF	Bl	≤10	12
		BG4		RU	Silt	NF	Se	11-30	12
		BG5		RL	Silt	NF	Se	≤10	11
	Malanville	BM1	1, 3, 4	IL	Clay	FL	Se	≥31	11
		BM2		IL	Clay	FL	Se	11-30	12
		BM3		IL	Clay	FL	Se	≥31	12
Burkina Faso	Cascades	BC1	1, 3, 4, 5, 6	RL	Clay	FL	Se	≤10	9
	Hauts-bassins	BH1	1, 3, 4, 5, 6	RU	Clay	NF	Se	≥31	8
Côte d'Ivoire	Man	CM1	1, 4, 5	RU	Sand	NF	Bl	≤10	11
		CM2		RU	Sand	NF	Bl	11-30	12
		CM3		RU	Sand	NF	Se	11-30	12
		CM4		RU	Sand	NF	Bl	11-30	11
Ghana	Kumasi	GM1	1, 2, 3, 5, 6	RL	Clay	NF	Se	≤10	10
		GM2		RL	Sand	NF	Bl	≤10	10
		GM3		RL	Sand	NF	Bl	≤10	10
		GM4		RL	Sand	NF	Se	≥31	10
		GM5		RL	Sand	NF	Bl	≥31	10
Nigeria	Lafia	NL1	1, 3, 5	RL	Clay	NF	Se	11-30	10
Rwanda	Rwasave	RR1	1, 2, 4, 5	IL	Clay	FL	Bl	11-30	12
		RR2		IL	Clay	NF	Bl	≤10	12
		RR3		IL	Clay	FL	Bl	≤10	12
		RR4		IL	Clay	FL	Bl	≥31	11
Togo	Maritime	TM1	1, 2, 4, 5	IL	Clay	FL	Se	≥31	12
	Plateaux	TP1	1, 2, 4, 5	RL	Clay	NF	Se	11-30	12
		TP2		RL	Silt	FL	Se	11-30	11
		TP3		IL	Sand	FL	Se	≥31	11
7	**10**	**28**							**310**

[a] 1=ring hoe; 2=twisted-spike floating weeder; 3=curved spike floating weeder; 4=straight-spike floating weeder; 5=straight spike weeder; 6=simple rotary weeder

[b] IL= irrigated lowland; RL=rain-fed lowland; RU=rain-fed upland; [c] Cl=clay; Si=silt; Sa=sand ; [d] FL=Flooded; NF=Non flooded; [e] Bl=broad-leaf weed species; Se=sedges

Table 2. Characteristics of the participating farmers (n=310)

Particulars	Number of farmers	%
Gender (n=310)		
Male	173	56
Female	137	44
Years of experience in rice cultivation (n=290)		
<4	43	15
≥4 to <10	98	34
≥10	149	51
Missing	20	-
Field size (ha, n=247)		
<0.2	57	23
≥0.2 to <0.5	64	26
≥0.5 to <1.0	46	19
≥1.0	80	32
Missing	63	-
Farmers' weeding method* (n=310)		
Herbicide application	167	54
Short-handled hoe weeding	114	37
Hand weeding	206	66

* Categories are non-exclusive, implying that individual farmers may combine two or three weeding methods

Table 3. P-values of random effects and estimates of intraclass correlation coefficient and predicted probabilities from a three-level multinomial linear model for assessing distribution of the scores given by farmers to the tested weeders (unconditional models)

	Ring hoe	Twisted spike floating weeder	Curve spike floating weeder	Straight spike floating weeder	Straight spike weeder	Simple rotary weeder
Number of samples	310	202	171	249	168	126
Random effects						
Intercept (field)	1.94***	0.83***	12.13***	4.13***	1.88***	3.94***
Intercept (environment)	0.10 ns	1.07 ns	<0.01 ns	1.64 ns	<0.01 ns	<0.01 ns
Intraclass correlation coefficient (ICC)						
Field	38%	37%	79%	64%	36%	54%
Environment	2%	21%	<1%	18%	<1%	<1%
Fixed effect						
Intercept (Score 1)	-3.47	-1.06	-0.12	-1.00	-1.24	0.53
Intercept (Score 2)	-2.53	0.30	1.99	0.60	0.77	1.43
Intercept (Score 3)	-1.79	1.19	2.83	2.12	1.71	1.99
Intercept (Score 4)	-0.36	2.93	4.79	4.03	3.21	2.97
Cumulative probabilities						
Intercept (Score 1)	0.03	0.26	0.47	0.27	0.23	0.63
Intercept (Score 2)	0.07	0.57	0.88	0.65	0.68	0.81
Intercept (Score 3)	0.14	0.77	0.94	0.89	0.85	0.88
Intercept (Score 4)	0.41	0.95	0.99	0.98	0.96	0.95
Predicted probabilities						
Intercept (Score 1)	0.03	0.26	0.47	0.27	0.23	0.63
Intercept (Score 2)	0.04	0.32	0.41	0.38	0.46	0.18
Intercept (Score 3)	0.07	0.19	0.06	0.25	0.16	0.07
Intercept (Score 4)	0.27	0.18	0.05	0.09	0.11	0.07
Intercept (Score 5)	0.59	0.05	0.01	0.02	0.04	0.05

*** P-value < 0.001; ** P-value < 0.01; * P-value < 0.05; ns = not significant at the 95% confidence interval.

Table 4. P-values of fixed effects and odds ratio estimates from a three-level multinomial linear model for the comparison between the ring hoe, and other tested weeders and farmers' own weed management practices for farmers' preference (full models)

	Ring hoe vs. other weeders (n=246)		Ring hoe vs. herbicide application (n=164)		Ring hoe vs. traditional hoe weeding (n=114)		Ring hoe vs. hand weeding (n=203)	
	P-value	Odds ratio [a]	P-value	Odds ratio	P-value	Odds ratio	P-value	Odds ratio
Gender								
Male vs. female	0.30	1.57	0.22	2.33	0.40	0.37	0.69	1.27
Year of experience								
<4 vs. ≥4 , <10	0.11	2.56	0.29	0.36	0.54	0.45	0.38	1.79
<4 vs. ≥10	0.70	1.25	0.19	0.27	0.48	0.39	0.35	1.88
Rice field size (ha)								
<0.2 vs. ≥0.2 , <0.5	nd[c]	nd	0.52	2.32	0.52	0.31	0.97	1.03
<0.2 vs ≥0.5 , <1.0	nd	nd	0.44	2.76	0.76	0.60	0.13	7.86
<0.2 vs. ≥1.0	nd	nd	0.48	2.67	0.23	0.13	0.58	0.57
Water status								
Non-flooded vs. flooded	0.66	0.65	nd	nd	nd	nd	nd	nd
Weed infestation below rice canopy								
Score[b] 1 vs. 2	0.36	0.42	nd	nd	nd	nd	nd	nd
Score 1 vs. 3	0.69	0.64	nd	nd	nd	nd	nd	nd
Soil texture								
Clay vs. sand	0.44	0.48	nd	nd	nd	nd	nd	nd
Clay vs. silt	0.77	0.73	nd	nd	nd	nd	nd	nd

[a] If the P-value is <0.05, the odds ratio estimate of <1 indicates that the ring hoe tends to be more preferred by farmers over other weeder in a specific reference condition.
[b] 1=weed cover less than or equal to 10% of ground cover; 2=weed cover more than 10% and less than or equal to 30% of ground cover; 3=weed cover more than 30%.
[c] 'nd' means 'not determined'.

Table S1. P-values of random effects and estimates of intraclass correlation coefficient and predicted probabilities from a three-level multinomial linear model for assessing distribution of the preference for the ring hoe given by farmers compared to the other weeder types and farmers' own weed management practices (unconditional models).

	Ring hoe vs. other weeders [a]	Ring hoe vs. herbicide application	Ring hoe vs. traditional hoe weeding	Ring hoe vs. hand weeding
Number of samples	310	167	114	206
Random effect				
Intercept (field)	1.88***	3.7***	5.96***	0.55 ns
Intercept (environment)	0.94 ns	0.56 ns	<0.01 ns	1.47***
Intraclass correlation coefficient (ICC)				
Field	46%	56%	64%	38%
Environment	15%	7%	<1%	28%
Fixed effect				
Intercept (ring hoe was preferred)	0.87	0.10	3.03	2.32
Predicted probabilities				
Intercept (ring hoe was preferred)	0.71	0.52	0.95	0.91
Intercept (ring hoe was not preferred)	0.29	0.48	0.05	0.09

[a] We considered that farmers preferred the ring hoe when they gave higher scores to the ring hoe than to any other weeder or when the score for the ring hoe was among the highest.

Table S2. Reasons why farmers did not use the ring hoe in their farms in a follow-up study, in Glazoué, Benin in the wet season (WS) of 2015 and in Lafia, Nigeria in the wet season 2015 and the dry season (DS) of 2016.

Site and country	Glazoue, Benin	Glazoue, Benin	Lafia, Nigeria (WS, 2015)	Lafia, Nigeria (DS, 2016) [a]
Rice-growing environment	RU (n=30)	RL (n= 70)	RL (n=21)	RL (n=65)
Number of farmers who did not use ring hoe in their own rice fields	7	0	4	28
Reason		*Number of farmers*		
Farmers did not grow rice in dry season	0	0	0	15
Rice was not planted uniformly	0	0	4	6
Disturbing events (drought, bush fire)	6	0	0	0
Ring hoe was not adapted to soil and water conditions	1	0	0	3
Farmers received the ring hoe too late	0	0	0	3
Farmers did not know how to use the ring hoe	0	0	0	1

RU = Rain-fed upland, RL = Rain-fed lowland

[a] In Lafia, Nigeria, farmers grow rice during the dry season because the water table is high enough to support rice cultivation despite lack of rain during this period.

Table S3. Results from interviews with farmers who received the ring hoe and used it on their farms, in Glazoué, Benin (n=93) and Lafia, Nigeria (n=54).

Site and country	Glazoue, Benin (WS, 2015)	Glazoue, Benin (WS, 2015)	Lafia, Nigeria (WS, 2015)	Lafia, Nigeria (DS, 2016)
Rice-growing environment	RU	RL	RL	RL
Number of farmers using the ring hoe in their own rice fields	23	70	17	37
Percentage (%) of famers using herbicides	22	36	41	81
Number of persons using the ring hoe in addition to the farmer receiving it	6.5	4.0	4.6	2.8
Percentage (%) of farmers indicating that the ring hoe was mainly used by women	65	53	88	24
Average rice field size on which the ring hoe was used (ha)	0.38	0.12	1.2	1.1
Percentage (%) of farmers indicating that weeding time by the ring hoe was <30% less than their own weeding method	9	6	-	38
Percentage (%) of farmers indicating that weeding time by the ring hoe was 31-50% less than their own weeding method	70	64	53	30
% of farmers indicating that weeding time by the ring hoe was 51-80% less than their own weeding method	13	30	12	30
% of farmers who used the ring hoe for other crops	30	27	59	43
Major other crops	Vegetables	Sorghum, vegetables	Maize, sorghum, cassava, millet	Maize, vegetables, cassava, sorghum, sweet potato, yam, groundnut, sugarcane
% of farmers who are willing to use the ring hoe for next season	96	100	100	97
Average farmers' expected purchasing price per weeder (US $/unit)	4.9	2.7	2.7	2.6

RU = Rain-fed upland, RL = Rain-fed lowland

Table S4. Predictors' estimates and p-values of the multiple regression analysis to identify factors affecting the farmers' willingness to purchase the ring hoe

	Estimates	P-value	Lower 95% confidence limit	Upper 95% confidence limit
Intercept	1.51	<0.001	0.98	2.04
Production system: Rain-fed upland	2.09	<0.001	1.49	2.70
Herbicide: Yes	0.52	0.019	0.09	0.96
Number of persons who used the weeder	0.14	0.003	0.05	0.24
Gender: Male	0.43	0.053	-0.01	0.87