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A screening protocol for developing high-yielding upland rice varieties with superior weed-suppressive ability

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ABSTRACT

In West Africa, upland rice (*Oryza* spp.) is mainly grown in low-input systems by resource-poor farmers. Weeds are one of the major constraints to rice production. Ideal rice varieties are high-yielding with strong weed-suppressive ability (WSA). WSA is the ability to suppress weed growth and reduce weed seed production and is determined by assessing weed biomass under weedy conditions. Development of such varieties requires simple screening protocols based on highly heritable traits, which can be evaluated in small plots under weed-free conditions. Then, in later stages of the breeding program, selected breeding lines could be evaluated with substitute weeds instead of natural weeds, as natural weed growth is heterogeneous. To develop such a protocol, I evaluated agronomic traits of 10 diverse rice varieties grown in plots with different numbers of rows (unbordered 1-row and 2-row, and self-bordered 4-row, in which the middle 2-rows were sampled) without weed competition and evaluated weed biomass of these varieties under competition with rice and cowpea as substitute weeds. I then examined whether agronomic traits in unbordered plots can predict yield and weed biomass in self-bordered plots. Broad-sense heritabilities of agronomic traits measured in weed-free conditions and weed biomass under weedy conditions were estimated. Among agronomic traits in unbordered plots, yield was positively correlated with yield in self-bordered plots ($r = 0.88$ and 0.96 in 1-row and 2-row plots, respectively, $P < 0.01$). Weed biomass estimated in competition with two rice varieties was more heritable than weed biomass in competition with cowpea. In 1-row plots, growth vigor at 63 days after sowing (DAS), total aboveground biomass at harvest, and yield were related to weed biomass in competition with cowpea and rice variety Aus 257. Growth vigor at 42 and 63 DAS was a reliable estimator for total aboveground biomass and number of panicles at harvest, as well as integrated information on height and number of stems (height multiplied by number of stems). I suggest that growth vigor at 42–63 DAS in unbordered, 1-row plots appears to be a useful selection criterion for developing high-yielding varieties with superior WSA, and WSA of selected varieties can be validated using rice varieties as substitute weeds. Future research is needed to validate this protocol with breeding populations, a wide range of genetic materials, and other important weed species in West Africa before it can be implemented in breeding programs.

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1. Introduction

In West Africa, upland rice is typically grown by resource-poor farmers as a subsistence crop in low-input production systems. It accounts for around 32% of the total rice area, yielding 0.6–3 t/ha (Diagne et al., 2013a). Weeds are one of the major constraints to rice production (Diagne et al., 2013b), mainly due to the fact that weeding is mainly done by hand or traditional hoe as herbicides are expensive for resource-poor farmers (Rodenburg and Johnson, 2009). An attractive and cost-effective approach would be to develop rice varieties that are high-yielding with superior weed-suppressive ability (WSA) (Saito, 2010; Saito et al., 2010a; Zhao et al., 2006a). Weed-suppressive ability is defined in this study as the ability to suppress weed growth and reduce weed seed production and is determined by assessing weed biomass under weedy conditions (Saito, 2010).

In the 1990s, scientists in the then West Africa Rice Development Association [WARDA, now Africa Rice Center (AfricaRice)] initiated an approach to increase the yield of upland rice through the

Abbreviations: ANOVA, analysis of variance; cv., cultivar; DAS, days after sowing; exp., Experiment; H, broad-sense heritability; LAI, leaf area index; LSD, least significant difference; WSA, weed-suppressive ability.

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development of interspecific varieties from the wide cross between Asian *O. sativa* (improved tropical *japonica*) and African *O. glaberrima*. The idea was to combine specific assets of *O. glaberrima*, such as WSA and tolerance to diseases, with the yield potential of tropical *japonica* (Dingkuhn et al., 1999; Futakuchi et al., 2012; Jones et al., 1997). The varieties derived from these crosses that performed well were named New Rice for Africa (NERICA). To date, 18 interspecific varieties suitable for upland conditions have been named as NERICA 1 to 18 (Saito et al., 2012; Tollens et al., 2013). The upland NERICA varieties are broadly adapted to African rice-growing environments and met with great enthusiasm by farmers, who looked at not only at yield but also at other traits such as short growth duration, grain quality, and resistance to pests and diseases (Wopereis et al., 2008). However, many studies have reported that there is clear scope for improving the current family of upland NERICAs (e.g. Saito and Futakuchi, 2009; Saito et al., 2014; Touré et al., 2011). For example, poor tillering ability in these NERICA cultivars limits the full expression of WSA and yield under low soil-fertility conditions.

Development of high-yielding varieties with superior WSA requires a simple screening protocol based on highly heritable traits, which can be evaluated in small plots under weed-free conditions (Saito et al., 2010a; Zhao et al., 2006a,b). One approach for improving heritability could be to sow weeds or crops as substitute weeds to simulate natural weed infestation (Bastiaans et al., 1997; Dingkuhn et al., 1999; Kawano et al., 1974; Saito and Futakuchi, 2014; Saito et al., 2010b). Saito and Futakuchi (2014) examined WSA of upland rice varieties using substitute weeds, as natural weed growth is heterogeneous. They show that substitute weeds can be used for screening for WSA. However, indirect selection for WSA under weedy conditions using agronomic traits measured in weed-free conditions is also possible—if there is a strong relationship between the agronomic traits measured under weed-free conditions and WSA estimated under different weedy conditions including substitute weeds. The traits for indirect selection should be highly heritable under weed-free conditions (Zhao et al., 2006a,b). Saito and Futakuchi (2014) did not examine the relationship between WSA and agronomic traits under weed-free conditions. Previous studies on upland rice using self-bordered plots identified several agronomic traits related to WSA, including early vegetative vigor, height, and yield (Saito et al., 2010a; Zhao et al., 2006a,b).

Indirect selection might be possible using small plots such as unbordered 1- or 2-row plots. The use of such small plots could dramatically reduce the resources needed for screening and the number of breeding lines to be tested could be increased. However, it is not known for rice whether agronomic traits measured in such unbordered plots can predict performance in self-bordered plots. Jearakongman et al. (2003) report that unbordered 2-row plots cannot estimate grain yields of rainfed lowland rice in self-bordered plots, unless the grain yield is adjusted using plant height. To the best of my knowledge, there was no similar study for upland rice. If scientists ignore the importance of number of rows, the possible confounding effects of inter-plot competition are likely to result in biased selection of germplasm and the identification of genomic regions that are not relevant to the target trait and target environment (Rebetzke et al., 2013). Likely, such bias is high under both high-yielding conditions, where neighboring plants compete for light, and low-yielding conditions, where neighboring plants compete for resources (nutrients, water).

Therefore, the objectives of this study were to: (1) examine whether agronomic traits in weed-free, unbordered plots are highly heritable; and (2) assess whether the traits are correlated with yield in self-bordered plots, and WSA under weedy conditions in upland rice production systems. On the basis of the results, I propose a screening protocol for developing high-yielding varieties with superior WSA.

2. Materials and methods

Fourteen varieties, selected from different germplasm groups and for their variation in agronomic traits (days to heading, plant height, and number of panicles) were grown in 2008–2011 at the Africa Rice Center (AfricaRice) experimental farm in Cotonou, Benin (2°20′E, 6°25′N) (Saito and Futakuchi, 2014). However, in this study, I analyzed data from only 10 varieties due to the fact that there were missing data on WSA in some of experiments (Saito and Futakuchi, 2014). Entries comprised one *O. glaberrima* variety, two tropical *japonica* varieties, two NERICA varieties (Saito and Futakuchi, 2009; Saito et al., 2012), and five *indica* varieties (Asai et al., 2009; Atlin et al., 2006; Saito et al., 2007) (Table 1). CG14 and Aus 257 are traditional varieties, while all the others are improved ones.

2.1. Weed-free trial with unbordered and self-bordered treatments

Four experiments were designed with number of rows (unbordered 1-row; unbordered 2-row; self-bordered 4-row) as the main-plot factor and variety as the sub-plot factor in a split-plot design with three replications. Table 2 shows the crop management practices, weather data, and soil properties in the four experiments. I assumed that self-bordered treatments provided a control treatment that revealed true varietal performance free from the effects of competition. The length of each sub-plot was 3 m, resulting in sub-plot sizes of 0.2 m × 3 m for the 1-row plots, 0.4 m × 3 m for the 2-row plots, and 0.8 m × 3 m for the 4-row plots. Rice was then sown by placing about four seeds into 1–2 cm deep holes in hills within rows, with 0.2 m between hills and 0.2 m between rows. After emergence, plants were thinned to two plants per hill. In two out of the four experiments, the crop was not limited by moisture as supplemental irrigation was applied. Basal fertilizer at a rate of 3 g N, 1.3 g P, and 2.5 g K/m^2 was applied at sowing, and a further 3 g N/m^2 at 30 days after sowing (DAS), except for exp. 2 (Table 2).

Growth vigor, leaf area index (LAI), plant height, and number of stems were determined in each plot in weed-free, unbordered treatments (1-row or 2-row) at 21, 42, and 63 DAS. Growth vigor (total aboveground biomass) was visually rated, following Zhao et al. (2006b) and Saito et al. (2010a). The rating for growth vigor was expressed on a 1–9 scale, where 9 was equivalent to most vigorous growth and 1 was least vigorous growth. LAI was determined nondestructively in 2-row plots only with the Delta-T Devices SunScan (Delta-T Devices, Cambridge, UK; Potter et al., 1996), following Sone et al. (2009). A sequence of readings, one above and four below the rice canopy, was taken in each plot to estimate the LAI. Plant height was measured from the aboveground stem base to the tip of the top leaf on four randomly selected hills. Number of stems (main stem plus tillers) per hill was counted on the same hills. At maturity, plant height and number of panicles were determined on six hills in each plot. Height was measured from the aboveground stem base to the tip of the tallest panicle in a hill.In both unbordered and self-bordered treatments, grain yield (hereafter referred to as 'yield') and straw dry weight were measured for all hills (grain yields are reported at 14% moisture content), excluding 1 hill on the end of each row. In the self-bordered 4-row plots, yield measurements were carried out only for the two central rows. All plant samples were separated into straw, filled grains, unfilled grains, and rachis. Dry weights of straw, unfilled grains, and rachis were determined after oven-drying at 75 °C to constant weight.

2.2. Weedy trial

The field conditions and management for the weedy trial are described in detail by Saito and Futakuchi (2014). Each of the four experiments consisted of three or four weed treatments including

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