Trade-offs between rice yield, weed competition and water use in the Senegal River Valley

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Abstract
This study explores trade-offs between yield, water use and weed-inflicted relative yield losses (RYL) by comparing conventional management practices (CMP) with a water-saving system based on the System of Rice Intensification (SRI). SRI was evaluated in two experiments in the Senegal River Valley. Eight cultivars, including *Oryza sativa* and *O. glaberrima* species and their interspecific crosses, were screened. In Experiment 1, mechanical and manual weeding was practised in SRI, while herbicides (propanil mixed with 2,4-D) and manual weeding were used in CMP. In Experiment 2, we standardized weeding regimes — weedy (one hand weeding) and weed-free (regular hand weeding) treatments — to study the effects of the remaining system components on weed competition. In Experiment 1, SRI used 15–19% less water than CMP, depending on cultivar. Yields under SRI were between 4% less and 45% greater than under CMP (mean 11% more with SRI). Good weed control was achieved in SRI, but weeding was more laborious than in CMP. Both weed-free and weed-affected yields in Experiment 2 were variable. Without weed interference, SRI yielded on average 3% less than CMP, but used 17–40% less water than required for continuous flooding. Relative yield losses due to weeds were on average 48% more under SRI than under CMP. Jaya and Sahel 202 were identified as promising weed-competitive cultivars, but each has an intermediate-length cycle and required more irrigation water than shorter-duration cultivars. Good yields and significant water savings can be achieved with SRI if weeds are carefully controlled. Weed-competitive cultivars could contribute to reducing elevated weed-inflicted yield losses associated with such water-saving systems.

Introduction
In the Senegal River valley (SRV), where rice is the staple grain and food security concerns have increased reliance on irrigated crop production, water can comprise the largest cost in many farm budgets. Reducing irrigation requirements could consequently present economic advantages, especially in northern Senegal, where future water scarcity is anticipated (de Vries *et al.*, 2010). While numerous water-saving cultivation systems have been proposed, the System of Rice Intensification (SRI) has received the most attention. Water savings of up to 50% with concomitant yield increases have been reported (Uphoff, 2003). System components include transplanting single, young rice seedlings at wide spacing, intermittent irrigation, mechanical weed control using a push-weeder, and the application of organic matter, preferably compost. SRI is currently reported to be practised in 14 sub-Saharan African countries (CIIFAD, 2011), and about 1000 farmers in the SRV have experimented with SRI in Farmer Field School programs backed by the Food and Agriculture Organization of the United Nations (FAO). Despite its growing popularity, however, SRI has been the subject of considerable debate. Citing decades of research that have culminated in high-yielding, conventional management practices reliant on continuous flood irrigation, critics have called for rigorous evaluation of SRI, with emphasis on the risks that the system might entail (Doberman, 2004).

Weed pressure is among the leading constraints to rice production in the Sahel (Diallo and Johnson, 1997). Haden *et al.* (2007) note that several components could render SRI more weed-prone than conventional management. Globally, rice farmers have practised flood irrigation for millennia to suppress weeds, and even temporary elimination of standing water could increase weed growth. Other components of SRI that could foster weed competition include transplanting at wide plant spacing, which may enhance growth per hill, but also increases the surface area available to weeds in the early growth stages. Given these constraints, the potential risk of yield losses, where farmers lack sufficient labor or appropriate weed control options, could reduce the system's benefits.

This study compared the performance of eight rice cultivars grown using a locally modified form of SRI. Intermittent irrigation, wider plant spacing and the transplanting of single, young seedlings, mechanical and/or manual weeding were combined with one locally adapted component (combined rice straw and fertilizer application replacing compost). In two locations in the SRV, we tested whether SRI could reduce water use without yield loss. We further investigated the impact of such practices on rice–weed competition. Compared to CMP, we hypothesized that SRI would save significant amounts of water while maintaining similar yields, but

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only when weeds were controlled completely. Where this was not the case, we expected greater weed-inflicted relative yield losses (RYL) in SRI than CMP, except for the most weed-competitive cultivars.

Materials and methods

Sites

Two experiments were conducted between 2007 and 2009 at the Africa Rice Center's (AfricaRice) Sahel stations in the delta (Ndiaye: 16°11′ N, 16°15′ W) and middle SRV (Fanaye: 16°32′ N, 15°11′ W). The region receives limited rainfall, has high temperatures and high evaporative demand (Table 1). The soil at Fanaye is a Eutric Vertisol (FAO, 2006; Table 2). Ndiaye is a former back-swamp, with an Orihithionic Gleysol soil (FAO, 2006; Table 2), and represents the typical geomorphic position of most delta-area irrigated perimeters. Ndiaye was under continuous rice cropping for 3 years before our experiments. At Fanaye, double cropping had been practised for 3 years, although the year prior to experimentation, fields were fallow.

Table 1. Meteorological conditions during experiments

Year and season	Parameter	Ndiaye	Fanaye
2007 WS	Mean pan evaporation (mm/day)	–	6.8
	Total rainfall (mm)	–	176.5
	Mean temperature (°C)	–	28.2
2008 DS	Mean pan evaporation (mm/day)	7.3	9.0
	Total rainfall (mm)	4.0	85.9
	Mean temperature (°C)	26.4	30.1
2008 WS	Mean pan evaporation (mm/day)	5.04	–
	Total rainfall (mm)	277.2	–
	Mean temperature (°C)	27.9	–
2009 WS	Mean pan evaporation (mm/day)	–	4.4
	Total rainfall (mm)	–	288.2
	Mean temperature (°C)	–	26.9

Dashes indicate that no trial was conducted at this site/season. Due to equipment malfunction, some of Fanaye's temperature data were sourced from Richard Toll, 30 km away.

Table 2. Soil chemical, physical and hydrological characteristics for Ndiaye and Fanaye (0–15 cm depth)

Soil characteristic	Method	Units	Ndiaye	Fanaye
N total	Dry combustion	%	0.05	0.11
C total	Dry combustion	%	0.8	0.6
P	Bray-1 (colormetric analysis)	mg/kg	5.9	7.3
K	Atomic absorption spectroscopy	cmol/kg	0.46	0.36
pH	1:2.5 H_20 saturated paste		5.9	6.5
EC[a]	1:5 H_20 saturated paste	dS/m	0.38	0.09
Texture (Sand–Silt–Clay)	Measured by Haefele *et al.* (2004)	%	16–44–40	8–28–64

[a] EC, electrical conductivity (regularly monitored in both experiments, remained consistently below 2 dS/m).

Experimental design

Experiment 1 was conducted during the 2007 wet season (WS) at Fanaye only, in a split-plot design with four replicates. Plots measured 251 m^2. CMP and SRI comprised main treatments. Weed management was practised as recommended for each system (Table 3). Seven cultivars were screened, including the locally popular Sahel 108 (S108, short duration) and 202 (S202, intermediate duration), two interspecific short-duration cultivars (WAS-161-B-9-2 and the upland cultivar of New Rice for Africa, NERICA 1), and the common genetic parents of the lowland cultivars of NERICA, TOG 5681 (*O. glaberrima*) and IR64 (*O. sativa*). The intermediate-duration Jaya was used as a weed-competitive check. Cultivars were grown in completely randomized areas (36 m^2) within main plots separated by 0.5 m alleys. A 4 m space was maintained between blocks, and plastic sheeting was installed over bunds to a depth of 0.4 m to restrict water movement across blocks. Twelve- and 24-day old SRI and CMP seedlings, respectively, were transplanted on 28 August 2007.

Experiment 2 was conducted in the 2008 dry season (DS: Ndiaye and Fanaye) and WS (Ndiaye), and the 2009 WS (Fanaye). In these trials, we experimentally manipulated weed management, which was standardized across systems to isolate and study the effects of the remaining system components (transplant age, number of plants per hill, crop density, fertility and water management) on rice–weed competition. Cultivars were consequently grown under weedy (one hand weeding 15 days after transplanting, DAT) and weed-free (hand

Table 3. Management parameters for the main treatments

	Recommended practices (CMP)	Adapted System of Rice Intensification (SRI)
Nursery management	Wet seedbed (1–3 cm H_20). 40 kg seeds/ha.	Damp seedbed (no standing water). 12 kg seeds/ha.
Transplant age	23–24 days (WS), 27–28 days (DS).	12–13 days (WS), 14–15 days (DS).
Crop density	20 × 20 cm, 3 plants/hill.	25 × 25 cm, 1 plant/hill.
Fertility management	120.5 kg N/ha. Urea: three splits (40%, 40%, 20%) at 20, 40, 60 DAT (WS) and 20, 45, 65 DAT (DS) + 19.3 kg P/ha (diammonium phosphate, 10 DAT).	5 t/ha rice straw[a] incorporated 14 days before transplanting + fertilizer as in CMP.
Water management	Continuous flooding. In Experiment 1, drainage was performed prior to herbicide application.	Intermittent irrigation until the reproductive stage. Shallow flooding thereafter.
Weed management	Experiment 1: Propanil (8 L/ha) + 2,4-D (1 L/ha) applied 15 DAT + hand weeding at 30 DAT. Experiment 2: hand weeding every 10 days, 15–55 DAT (weed-free); one hand weeding (15 DAT, weedy treatment).	Experiment 1: mechanical 'cono' weeding with rotary hoe + hand weeding (15 and 30 DAT). Experiment 2: hand weeding every 10 days, 15–55 DAT (weed-free); one hand weeding (15 DAT, weedy treatment).

[a] Mean nutrient concentrations in rice straw (all sites and seasons): 0.64% N, 33.9% C, 0.08% P and 1.14% K.

weeding every 10 days from 15 to 55 DAT) conditions in both systems. Main plot design and replicates were the same as in Experiment 1. Split-split plots measured 18 m^2. In experiment 2, because of its poor adaptation to lowland conditions, even under intermittent irrigation, NERICA 1 was replaced with the short-duration lowland NERICA-L 55. Dry-season transplanting was done on 10 and 26 March 2008 at Fanaye and Ndiaye, respectively (Table 3). Wet-season transplanting at the same seedling ages as Experiment 1, took place on 22 August 2008 (Ndiaye) and 24 August 2009 (Fanaye).

Water, weed and crop measurements

Field water heights, rainfall and irrigation were measured from land preparation until harvest following de Vries *et al.* (2010), but using a constant of 13.8 $cm^{0.5}$ water/s for V-notched weirs. Irrigation was combined with rainfall and summed to provide the water volume applied to each cultivar. In experiment 1, weed biomass (dry weight) was used as a measure of weed pressure. Weed biomass was obtained at 15, 30 and 63 DAT from two randomly placed 0.25 m^2 quadrats per sub-plot, after oven drying (70°C for 72 h). Grain yields in each experiment (14% moisture content) were determined at maturity from a 4 m^2 area.

Data analysis

Data from Experiment 1 were analyzed by analyses of variance (ANOVA) for a two-factor split-plot design using JMP 8.0.2 (SAS Institute, San Francisco, CA). Weed data were square-root transformed prior to analysis. System, cultivar and their interactions were treated as fixed effects. Block was treated as a random factor. Experiment 2 was analyzed as a three-factor split-plot design. Seasons and sites were analyzed separately. System, weeding treatment, cultivar and their interactions were treated as fixed, while block was again random. Rice yields under weed pressure and RYL were used as measures of a cultivar's competitiveness following Rodenburg *et al.* (2009). During the Ndiaye DS, the photoperiod-sensitive TOG 5681 did not flower, and was consequently excluded from analyses.

Results and discussion

Experiment 1

There were highly significant cultivar (P<0.001) and system × cultivar effects (P<0.001) on yield in Experiment 1. Mean yields under SRI were 11% greater than under CMP (P=0.002). Five of seven varieties tested with SRI yielded more than 7 t/ha, each higher than under CMP. The best CMP yields achieved were with S202, while the best SRI yields came from IR64 (Table 4). NERICA 1 gave the lowest yields for each system, indicating poor adaptation to lowland conditions.

Depending on cultivar, SRI used 15–19% less water than CMP, a consequence of the system's intermittent irrigation regime (Fig. 1). Short-duration cultivars generally require less irrigation, and the lowest water use under SRI was with NERICA 1 (783 mm), followed closely by S108 (785 mm). In CMP, these cultivars also had the lowest water use, though they received 170 and 195 mm more water, respectively, than in SRI. Before

Table 4. Grain yield, weed biomass, water use and input for seven varieties grown in CMP and SRI (Experiment 1)

System	Cultivar	Grain yield (t/ha)	Weed biomass (g/m^2)			Water input (mm)[b]
			15 DAT	30 DAT	63 DAT	
CMP	IR64	6.06	2.89	95.61	22.23	53 (55)
	Jaya	6.35	2.69	105.40	18.28	962 (58)
	NERICA 1	2.38	1.56	61.32	23.31	953 (108)
	S108	5.43	6.66	23.95	26.02	953 (108)
	S202	8.35	3.56	33.91	17.42	1108 (119)
	TOG5681	3.11	3.92	59.22	2.48	891 (77)
	WAS 161-B-9-2	6.47	0.17	35.41	12.97	1108 (119)
SRI	IR64	8.01	19.50	89.16	18.33	860 (82)
	Jaya	7.67	14.9	39.20	21.81	926 (70)
	NERICA 1	2.28	9.22	47.95	15.15	783 (55)
	S108	7.86	10.30	169.10	29.92	785 (78)
	S202	7.45	11.50	35.50	63.91	926 (70)
	TOG5681	2.59	11.80	72.70	15.61	891 (77)
	WAS 161-B-9-2	7.19	7.87	68.33	60.67	847 (68)
SED[a]						
	System	0.20	0.34	1.10	0.88	–
	Cultivar	0.39	0.65	2.06	1.66	–
	System × cultivar	0.55	0.92	2.91	2.34	–

[a] Standard error of the difference. Parentheses show standard error of the mean (SEM). [b] Sum of irrigation and rainfall for land preparation and crop field growth until harvest.

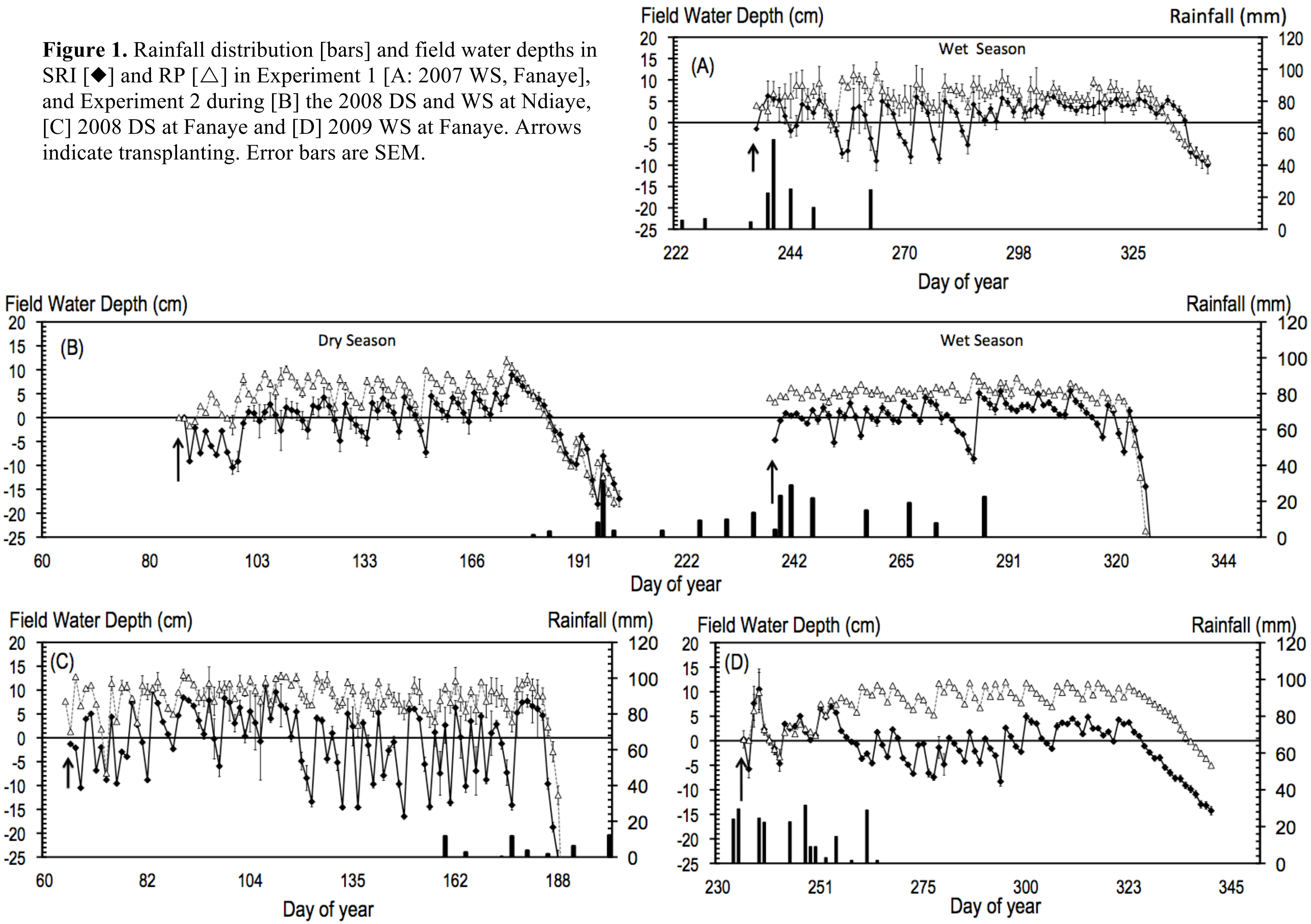

Figure 1. Rainfall distribution [bars] and field water depths in SRI [◆] and RP [△] in Experiment 1 [A: 2007 WS, Fanaye], and Experiment 2 during [B] the 2008 DS and WS at Ndiaye, [C] 2008 DS at Fanaye and [D] 2009 WS at Fanaye. Arrows indicate transplanting. Error bars are SEM.

control was initiated at 15 DAT, average weed biomass across cultivars was approximately four times higher with SRI as compared to CMP (*P*<0.001; Table 4). For both systems, weed pressure declined over the course of the season. Analyzing each system independently, significantly less weed biomass was found at 63 DAT compared to 30 DAT (SRI: *P*=0.004; CMP: *P*=0.043), indicating that good weed control was achieved (Table 4). Nonetheless, weed management in SRI was more laborious than in CMP. This led us to further investigate the integration of weed-competitive cultivars in SRI.

Experiment 2

Weed-free rice grain yields

Average weed-free yields were not significantly different between systems, and ranged from 36% less to 32% more with SRI than CMP across seasons, sites and cultivars (on average SRI yielded 3% less than CMP). While some of the SRI yields observed in the current study approached the region's yield potential (Dingkuhn and Sow, 1997), they remained less than the very high SRI yields reported elsewhere (Uphoff, 2003), and were rarely much higher than those achieved under CMP (Table 5 and 6). Our results were probably influenced by fertility management. While SRI proponents advise the application of compost or manure (Uphoff, 2003), sizeable amounts of organic amendments are scarce in the SRV. Because SRI should be adapted to site-specific circumstances, we consequently applied a lower-quality, yet readily available amendment (rice straw) 14 days before transplanting. While we are fairly certain that early incorporation into moist soil reduced the risk of nutrient immobilization after transplanting, the mineralizable-N in the straw (25–31.5 kg N/ha) was probably too small to stimulate drastically higher yield gains during this relatively short experiment. Consistent straw applications over multiple seasons could prove more promising, as could larger amounts of materials with low C:N ratios, though some authors cite the difficulty of sustaining large applications of organic amendments as reason for caution (e.g. Doberman, 2004).

Rice grain yields under weed pressure and relative yield losses

The highest weed-affected CMP yields obtained at Ndiaye were over 1 t/ha greater than the highest weed-affected SRI yield. These CMP yields were achieved with Jaya in the DS (4.86 t/ha) and NERICA-L 55 in the WS (4.95 t/ha). In SRI, S202 was the best-yielding cultivar in both seasons when grown under weedy conditions (3.64 and 3.57 t/ha in DS and WS, respectively). At Fanaye, Jaya yielded the highest in both weedy CMP (DS: 5.22 t/ha; WS: 7.08 t/ha) and weedy SRI (DS: 6.12 t/ha; WS: 5.19 t/ha), confirming earlier reports of its competitiveness (Haefele *et al.*, 2004; Rodenburg *et al.*, 2009). NERICA-L 55 was somewhat less competitive in SRI than in CMP (Tables 5 and 6).

Weed-affected SRI yields at Ndiaye were significantly lower than weed-affected CMP yields (DS: *P*<0.001, mean 43% less; WS: *P*=0.0003, mean 28% less). At Fanaye, DS weed-affected yields were not different between systems. Conversely, higher weed pressure in SRI during the WS resulted in significantly lower weed-affected yields (*P*<0.001; mean 30% less) than CMP (Table 6). In seven out of eight cases, IR64 produced consistently lower weed-affected grain yields than the weed–competitive check Jaya. This supports Haden *et al.* (2007) and Rodenburg *et al.* (2009), both of whom identified IR64 as weakly weed competitive. Relative yield loss was severe when SRI was compared to CMP. Jaya was a consistently competitive cultivar, having the least RYL at all sites and seasons under CMP. At Ndiaye, of the high-yielding weed-free cultivars (e.g. excluding TOG 5681 in the WS, which had the lowest weed-free yields), S202 had the lowest RYL under SRI. At Fanaye, Jaya had the lowest RYL under SRI for both seasons. These findings support Rodenburg *et al.* (2009), who suggest that Jaya could be a more valuable donor than IR64 for breeding efforts aimed at improving the weed competitiveness of lowland cultivars. Rodenburg *et al.* (2009) also identified NERICA-L 55 as weed competitive in the southern Guinea savanna. This cultivar performed relatively well in this experiment, with relatively low RLY under CMP, though its performance under SRI conditions was more variable. Specifically bred for Sahelian conditions, S202 also demonstrated high yields and weed competitiveness under SRI. This cultivar deserves further investigation in other Sahelian countries as a potentially promising source of genetic material.

Water use

Water use for land preparation and crop growth in CMP during the Ndiaye DS ranged from 1124 to 1172 mm (Table 5). Under SRI, 18–25% water savings were obtained compared to CMP. In the WS, rates were 820–925 mm under CMP and water savings were 12–18% with SRI (Table 6). Water use was high during the Fanaye DS for both CMP (1261–1780 mm) and SRI (1150–1358 mm), although the latter system still used 6–24% less water than CMP. Our results appear to support de Vries *et al.* (2010), who suggested that high percolation rates at Fanaye necessitated more frequent DS irrigation to avoid crop stress. Conversely, during the Fanaye WS, SRI used approximately 39–41% less water than CMP (Table 5). This was attributable to seasonally lower evaporative demand (Table 1) and raised ground-water levels after a series of heavy rainfall events caused temporary flooding at the experimental site (Fig. 1).

Table 5. Weed-free and weedy yields, relative yield loss (RYL) and water input in the dry season of Experiment 2

Season	System	Cultivar	Ndiaye				Fanaye			
			Grain yield (t/ha)		RYL	Water input	Grain yield (t/ha)		RYL	Water input
			Weed-free	Weedy	(%)	(mm)[b]	Weed-free	Weedy	(%)	(mm)[b]
Dry	CMP	IR64	6.99	3.75	46.4	1124 (33)	6.47	3.73	42.3	1586 (69)
		Jaya	6.32	4.86	23.1	1172 (31)	7.33	6.12	16.5	1780 (79)
		NERICA-L 55	7.93	3.86	51.3	1124 (33)	5.54	3.43	38.1	1462 (66)
		S108	7.83	2.72	65.3	1157 (42)	7.39	2.96	59.9	1261 (75)
		S202	7.25	3.78	47.9	1172 (31)	7.06	4.37	38.1	1462 (66)
		TOG5681	–	–	–	–	3.29	1.28	61.8	1339 (66)
		WAS 161-B-9-2	4.99	4.28	14.2	1124 (33)	8.40	2.96	64.8	1642 (71)
	SRI	IR64	6.40	2.59	59.5	918 (60)	6.83	2.98	56.4	1221 (39)
		Jaya	6.42	3.05	52.5	959 (60)	6.35	5.22	17.8	1358 (36)
		NERICA-L 55	6.18	2.12	65.7	918 (60)	5.95	2.40	59.7	1150 (29)
		S108	6.25	0.97	84.5	869 (58)	6.78	3.21	52.7	1150 (29)
		S202	6.85	3.64	46.9	959 (60)	8.17	2.91	64.4	1188 (29)
		TOG5681	–	–	–	–	2.71	1.07	60.5	1252 (35)
		WAS 161-B-9-2	7.36	1.14	87.1	869 (58)	6.18	3.81	38.3	1271 (37)
	SED[a]									
		System (S)	0.38	0.38	–	–	0.36	0.40	–	–
		Cultivar (C)	0.65	0.66	–	–	0.68	0.75	–	–
		S × C	0.76	0.93	–	–	0.97	1.06	–	–

[a] Standard error of the difference. Parentheses show standard error of the mean (SEM). [b] Sum of irrigation and rainfall for land preparation and crop field growth until harvest.

Table 6. Weed-free and weedy yields, relative yield loss (RYL) and water input in the wet season of Experiment 2

Season	System	Cultivar	Ndiaye				Fanaye			
			Grain yield (t/ha)		RYL	Water input	Grain yield (t/ha)		RYL	Water input
			Weed-free	Weedy	(%)	(mm)[b]	Weed-free	Weedy	(%)	(mm)[b]
Wet	CMP	IR64	6.23	3.45	44.6	925 (58)	5.92	4.97	16.0	853 (23)
		Jaya	6.30	4.80	23.8	925 (58)	6.61	7.08	–7.1	853 (23)
		NERICA-L 55	6.65	4.95	25.6	925 (58)	6.05	6.38	–5.5	837 (23)
		S108	5.87	2.83	51.8	884 (58)	6.41	5.28	17.6	762 (16)
		S202	6.00	4.18	30.3	917 (57)	6.21	6.37	–2.6	853 (23)
		TOG5681	2.58	1.47			3.77	3.80	0.8	716 (14)
		WAS 161-B-9-2	5.56	4.11	26.1	820 (56)	5.65	5.50	2.7	743 (15)
	SRI	IR64	6.24	2.02	67.6	755 (36)	6.54	3.9	40.4	502 (7)
		Jaya	5.70	1.79	68.6	755 (36)	5.78	5.19	10.2	502 (7)
		NERICA–L 55	5.94	2.27	61.8	755 (36)	6.58	4.44	32.5	502 (7)
		S108	6.12	1.67	72.7	755 (36)	6.25	4.64	25.8	467 (7)
		S202	6.17	3.57	42.1	755 (36)	6.12	4.85	20.8	502 (7)
		TOG5681	3.77	2.67			4.60	2.89	37.2	440 (4)
		WAS 161-B-9-2	6.11	1.39	77.3	723 (35)	5.56	4.37	21.4	455 (3)
	SED[a]									
		System (S)	0.19	0.33	–	–	0.27	0.26	–	–
		Cultivar (C)	0.36	0.55	–	–	0.49	0.48	–	–
		S × C	0.52	0.87	–	–	0.57	0.68	–	–

[a] Standard error of the difference. Parentheses show standard error of the mean (SEM). [b] Sum of irrigation and rainfall for land preparation and crop field growth until harvest.

Conclusions

This study examined the performance of eight cultivars grown under SRI compared to CMP, with different weeding regimes and weed pressures, in two experiments and locations in the SRV. Jaya and S202 were identified as promising weed-competitive cultivars under both management systems. Provided that farmers can plant on the recommended dates, these cultivars could be advised to maximize yield on fields prone to heavy weed infestation, in weed-prone water-saving systems, and/or where labor or tools for weeding are limiting. However, none of these cultivars are short duration, a key characteristic for meeting the twin goals of reduced water use and double cropping. Additional efforts are needed to develop new plant types that have high yield potential and low weed-inflicted RYL, and that are short duration to reduce the number of required irrigations. Finally, good yields and water savings were observed with SRI, although the system appears to be more susceptible to weed pressure than might be desirable for farmers managing fields with high weed infestations, or with limited resources to address weeds. Where farmers can assure careful transplanting, and effective weed and water management, SRI adds to the basket of water-saving technology options available in the SRV.

Acknowledgements

The IIE-Fulbright and STEPS Institute funded this research. We thank S. Stuerz, P. Ramondi, S. Martinson, M. de Vries and G. Manners for technical support and comments on this manuscript.

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