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Comparison of Yields of Paddy Rice Under System of Rice Intensification in Mwea, Kenya

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Abstract: Rice (*Oryza sativa L.*) is the world's most important food crop and a major food grain for about half its population. It is also the greatest consumer of water among all crops and uses about 80% of the total irrigated freshwater resources in some countries. The conventional paddy system of rice production depends on a continuous supply of water for irrigation. With rapid population growth, and a change in eating habits due to urbanization, annual demand for rice continues to grow, and it presently exceeds the Kenya national annual production by about 200%. To meet the demand for rice with the limited water resources in a sustainable way, new innovative ways of rice crop production are needed. System of Rice Intensification (SRI) is an innovation that offers farmers an opportunity to reduce their water demand while increasing rice yield. Field experiments were conducted in 2010 and 2011 seasons at the Mwea Irrigation Agricultural Development (MIAD) centre located in the Mwea Irrigation Scheme (MIS), Kenya to compare yields of three rice varieties (Basmati 370, BW 196, and IR 2793-80-1) grown under SRI management with reduced water applications versus conventional practices of continuous flooding (CF). SRI gave the highest yields and water savings for all three rice varieties, on average increasing yield 1.7 t ha^{-1}, 3.4 t ha^{-1} and 3.3 t ha^{-1} for the Basmati 370, BW 196, and IR 2793-80-1 varieties, respectively, while the water savings were 2,983 m^3 ha^{-1} 3,714 m^3 ha^{-1} and 3,791 m^3 ha^{-1}. Similarly, water productivity for the three varieties averaged 140% higher under SRI management (1.2 kg m^{-3} vs. 0.5 kg m^{-3}). These findings are consistent with similar evaluations in other countries.

Keywords: System of Rice Intensification (SRI), Rice, Varieties, Yield, Mwea, Water Productivity

1. Introduction

The world population continues to grow fast, leading to an increased need for more food production. With the growing scarcity in water resources, there is an ever-greater challenge of sustainably producing more food to meet the food demand [7]. Rice is the foremost staple food for about 50% of the world's population and is currently the food crop that requires the most water for its production [14]. There is an upward shift in demand for rice worldwide due to urbanization, as people change their eating habits [28].

In Kenya, rice is the third most important cereal after maize and wheat. With the continuing population growth, and change in eating habits due to urbanization, current demand for rice in Kenya is estimated at 325,000 tons per year against the national production of 110,000 tons per year [33]. The deficit, about two-thirds of consumption, has to be imported at a heavy cost. Moreover, the annual consumption of rice is increasing at a rate of 12% as compared to 4% for wheat and 1% for maize [10; 33]. Thus the deficit will grow considerably unless local production is accelerated. Due to the shortage of supply and high cost of current local production, the price of rice in Kenya is very high, with a kilogram retailing between 2-2.5 US Dollars.

Rice production in Kenya is now based mostly on the conventional practice of continuously flooding paddy fields [32]. This method is not sustainable due to the already-existing competition for water among farmers within and outside the Mwea irrigation Scheme [25]. Thus, innovative ways for improving the efficiency of water use are imperative for sustainable rice production [6; 24; 28]. Mwea Irrigation Scheme, where the research was conducted, is situated between longitudes 37°13'E and 37°30'E and latitudes 0°32'S and 0°46'S. The region is classified as tropical with a semi-arid climate, having an annual mean air temperature of 23-25°C with about 10°C difference between the minimum temperatures in June/July and the maximum temperatures in October/March. Annual rainfall ranges from 356mm to 1626mm with an average of 950mm, and annual sunshine of 2485h. The Scheme covers an area of 9,000ha, with a potential for 4,000ha expansion [10]. The soils here are classified as Vertisols [38]. Currently, the Scheme accounts for 80% of the country's rice production [32]. The scheme is divided into 5 sections covering 60 units in total. Two rice crops are grown annually, the main season occurring between August and December during the short rains, with a long-rains crop grown between January and June. Mwea producers suffer from water shortages during the main growing season and often from blast attack during the long rains season, factors that lead to reduced rice yields in both seasons. Other benefits of rice beside income generation for farmers include employment both on farms and in the market. Rice is very important to the livelihoods of Mwea people, with wider economic and food-security implications for Kenyans.

The System of Rice Intensification (SRI), developed in Madagascar over 25 years ago [21], offers an opportunity to improve food security through increased rice productivity by changing the management of plants, soil, water and nutrients while reducing external inputs like fertilizers and herbicides [3; 43; 44; 47]. The system recommends the use of single, very young seedlings with wider spacing, intermittent wetting and drying, use of a mechanical weeder which also aerates the soil, and enhanced soil organic matter-SRI recommends addition of organic manure, thus boosts organic content of the soil [46]. All these practices are aimed at improving the productivity of rice plants grown in paddies through healthier, more productive soil systems and plants that are supported by greater root growth and by nurturing the abundance and diversity of soil organisms [50; 39]. Previous research has shown yield increases of between 50-100% while irrigation water inputs can be reduced by between 25% and 50% with SRI [2; 3; 14; 26; 34; 50].

However, little is known about the effectiveness of SRI practices, and the impact of their adoption on yields and water savings, under Kenyan conditions. This study investigated within the Mwea irrigation Scheme, which has the most concentrated production of rice in Kenya, whether SRI practices -- particularly transplanting quickly one young seedling per hill, alternate wetting and drying, and wider spacing -- could have significant effects on plant growth and subsequently on grain yield and water productivity.

For such an assessment, the study compared yields under SRI management with its reductions in water application, with those resulting from conventional practices under continuous flooding for three selected and representative varieties of paddy rice. Soil and climatic conditions, and fertilization were the same for both sets of trials.

2. Materials and Methods

2.1. Experimental Site and Soils

This field experiment was conducted in 2010 and 2011 main growing seasons at the Mwea Irrigation Scheme in Kenya. To determine the types and amounts of fertilizers to use, sampling and analysis of the soil was done as explained in [36].

The topsoil contained 0.014% available N, 29ppm available P, and 0.042meq/100g available K, 1.13% organic carbon, and had a pH of 6.3 at the start of the experiment in the first season. In the second season, available N, P and K were 0.021%, 32ppm and 0.041meq/100g respectively; organic carbon was 0.96% while pH was 6.2.

2.2. Land Preparation, Experimental Design, and Treatments

Land preparation for both CF and SRI was standard wet tillage and harrowing. This was done by first flooding the fields for three days, then puddling them to soften and mix the mud [48].

The experimental design was a two way factorial in a complete randomized block design with three replications. The plot sizes were 3m x 3m and 5m x 5m in the first and second seasons, respectively. In the first season, land available for the research was limited. In the second season however, plot sizes were increased as land became available. The spatial allocation of treatments, done using random numbers, is shown in Figures 1 and 2. Rice trials were grown under the two alternative crop management systems (treatments) of SRI and CF. Three rice varieties (Basmati 370, BW 196, and IR 2793-80-1) were grown on the plots, with three replications each. Basmati 370 is an aromatic, low tillering, and short-duration, 130-day variety; BW 196 is a long-duration variety of 160 days and is considered high tillering, while IR 2793-80-1 has medium-long duration of 145 days and is medium yielding, close to BW 196.

Each plot was surrounded by consolidated bunds and lined with plastic sheets installed to 0.3m depth to prevent seepage and nutrient diffusion between the plots, followed by 1m wide channels for irrigation. The hill spacing for SRI practice was 20cm by 20cm, while that under CF was 10cm x 10cm. These spacing gave a plant population of 25 and 100 plants per square meter under SRI and CF practices respectively.

2.3. Crop Management and Irrigation

The nursery was adjacent to the main field so that transplanting could be performed quickly to minimize injury to the young plants [39; 50]. For SRI practice, 8-day-old seedlings were transplanted at a rate of one seedling per hill. At 8 days, seedlings were still in their second phyllochron of growth as recommended for SRI practice [39]. For the CF practice, 28-day-old seedlings were transplanted on the same day at a rate of three seedlings per hill. This is the conventional way of growing rice in the Scheme.

Both sets of treatments received the same basal fertilizer supply of 125kg ha^{-1} di-ammonium phosphate (DAP) and 62 kg ha^{-1} muriate of potash (MoP) 1 day before transplanting. All plots received an additional 125kg ha^{-1} of sulphate of ammonia (SA) 10, 30 and 60 days after transplanting (DAT) as recommended for Mwea soils [48]. No herbicide, insecticide or chemical disease control measures were used.

SRI plots were weeded four times, while CF plots were weeded three times during the growing seasons. Manual weeding, where weeds were uprooted, was used in both practices, since the rotary weeder recommended for SRI practice was not available at the time of the first trial. However, rotary weeders were used with SRI practice in the second season, thus SRI plots received the prescribed active soil aeration in the trial.

The CF treatments were kept continuously flooded with water to a depth of 5cm except at the end of the tillering stage when the depth was reduced to 3cm. The SRI plots were kept saturated at the first week after transplanting. After that, and up to panicle initiation stage, plots were maintained with a thin layer (2cm) of standing water for 2 days and then without standing water for 5 days before being re-irrigated with river water. At this stage, the cracks on the soil surface ranged between 1-1.5cm wide.

2.4. Climate Data and Water Measurements

Data on daily rainfall, daily relative humidity, daily minimum (Tmin), and maximum temperature (Tmax) were collected from the weather station at the research farm located 500m from experimental plots. In the first season, the total rainfall, average temperature, and average relative humidity were 238.9mm, 23.2°C and 78.6%, respectively. In the second season, total rainfall was considerably higher, 556.2mm, while average temperature was 23.4°C and average relative humidity was 76.2%, neither much different from the year before.

Water was supplied from its river source through a concrete channel to a plot channel and subsequently to the plots. A trapezoidal Parshall flume was installed at the gate provided for each plot during the construction of bunds for the purpose of supplying and measuring water for both practices. For the SRI plots, water measurement was made during periods of irrigation and when draining off excess water, especially on rainy days so as to achieve the 2-3cm layer of water as recommended. Water measurement for the CF plots was made only during irrigation. The amount of water applied was estimated by reading both water height and the time taken for the water to flow through the Parshall flume and into the plot to the required level. This information was then converted to the volume of water applied for the cropping season [12]. Each plot was irrigated separately. All plots were drained at 14 days before harvest to promote ripening. Water productivity, calculated as the grain yield in kilograms divided by the total of volume of water supplied to the plot (rainfall and irrigation) [5], was expressed as kg m^{-3}.

2.5. Assessing Root Dry Weight

Three hills from each replicate were randomly selected at the early-ripening stage of each variety for collection of root samples. This was done using an auger of 10cm diameter to remove soil down to 20cm deep along the hill [17]. A uniform soil volume (1571cm^3) was excavated to collect root samples from all the plots. Roots were carefully washed, dried under a shade for two weeks, and then dry weight was measured [51].

2.6. Measurement of Plant Dry Weight, Yield, and Yield Components

To determine the number of tillers, ten hills in each plot were randomly marked at the time of planting for counting tiller number periodically at intervals of 7 days up to panicle initiation stage. All plants in an area of 2.5m by 2.5m (first season) and 4.9m x 4.9m (second season) for each replicate were harvested for determination of yield per unit area. Dry weight of plant samples was determined at harvest after drying under shade for a period of two weeks to reach a constant weight. The grain yield was adjusted to 14% seed moisture content using equation (1) below [18, 48]:

$$\text{Grain yield (kg/ha) at 14\% moisture} = \left(\frac{(100-MC)*GW(kg)*10000\ (m^2)}{(100-14)*Net\ plot\ area\ (m^2)}\right) \quad (1)$$

Where; MC= moisture content after drying, GW= grain weight per plot area

Harvest Index (HI) was calculated by dividing dry grain yield by the total dry weight of aboveground parts [43]. Average tiller number and panicle number were determined from the crop harvested from 1m^2 area from each plot. Panicle length, number of grains per panicle, and number of filled grains were measured for each panicle individually harvested from the sample area. The per cent of ripened grains was calculated by dividing the number of filled grains by the number of total grains on a panicle.

2.7. Statistical Analysis

Yield data were analyzed statistically using analysis of variance (ANOVA) technique. The ANOVA was conducted using the mixed procedure in SAS 9.1.3 (SAS Institute, 2004). To determine the significance of any difference between two treatment means, least significant difference (LSD) was estimated at performance of rice at 5% probability level as shown in the equation below. If the LSD was less than the difference in means between two treatments, then the two treatments were significantly different [11; 22].

3. Results

3.1. Dry matter Accumulation, Grain Yield and Yield Components

3.1.1. Continuous Flooding Versus System of Rice Intensification

The dry weights of aboveground parts per unit area were significantly greater (P= 0.0002) in SRI than in CF plants for all three varieties (Table 1). There was no significant difference (P=0.36), however, in straw weight per unit area between Basmati 370 and BW 196 varieties under SRI and between BW 196 and IR 2793-80-1 varieties under CF practices across the seasons. However, we note that higher straw weight was observed in the mid-to-long duration variety (IR 2793-80-1) than in the short- or long-duration varieties (Basmati 370 and BW 196) in season one for both practices (Table 1). During the second season, the results shifted completely, with the long- duration variety recording higher straw weight than the mid-duration variety under SRI practice.

Table 1. *Dry matter accumulation, grain yield and Harvest Index for different varieties under SRI and CF practices.*

		1000-grain wt (g)		Straw dry weight (g/m²)		Grain yield (g/m²)		Harvest Index (HI)	
Practice	**Variety**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**
SRI	Basmati 370	23.05[d]	23.10 [c]	1,036.67 [b]	828.33 [b]	593[c]	707[d]	0.36[c]	0.45[c]
	BW 196	27.85[a]	28.93 [a]	1,286.67 [a]	1025.67 [a]	590[c]	1373 [b]	0.3[d]	0.57[b]
	IR 2793-80-1	26.27[b]	26.04 [b]	1,340.0 [a]	748.67 [c]	1086 [a]	1482 [a]	0.45[b]	0.67[a]
CF	Basmati 370	21.57[e]	20.7 [d]	633.33 [d]	728.33 [d]	527[d]	513[e]	0.46[b]	0.42[cd]
	BW 196	24.39[c]	28.23 [a]	686.67 [d]	704.33 [d]	387[e]	913[c]	0.36[c]	0.57 [b]
	IR 2793-80-1	26.08 [b]	26.60 [b]	976.67 [c]	737.00 [c]	943[b]	953[c]	0.49[a]	0.56 [b]

Values with the same letters in a column under the respective seasons are not significantly different by LSD at the 0.05 level across both practices.

The System of Rice Intensification plots produced significantly (P=0.026) larger grain yield for all varieties (26% more in the first season and 47% more in the second season on average) than from CF plots. The interaction effects of practice and variety on grain yield were not significant (P=0.533). Between SRI and CF practices, the Harvest Index (HI) was significantly different (P=0.034) with variations in both variety and practice. Panicle length was significantly higher (P=0.018) with SRI practice than with CF practices (Table 2).

Among the yield components, grains per panicle, grain-filling percentage, and 1000-grain weight were significantly (P < 0.05) affected by practice and variety (Table 2). SRI panicles had a significantly lower number of filled grains (P=0.0085) than CF panicles in the first season, but significantly higher 1000-grain weight than CF (0.006) during both seasons. Thus, most of the increase in grain yield was a result of higher 1000-grain weight in the first season. Both grain filling and 1000-grain weight contributed to the increase in grain yield during the second season. Overall, SRI plots had significant improvement in various yield components compared with CF plots.

Table 2. *Interaction effect due to season, practice and variety on grain yield and its components during the two seasons.*

	df	Tiller no.	Productive tillers (%)	Panicle length (cm)	Grain no/panicle	Filled grains (%)	1000-grain weight (g)	Grain yield (g/m²)	Straw dry weight (g/m²)	Harvest Index	Root dry weight (g/m²)
Season (S)	1	**	**	Ns	**	ns	ns	**	**	**	*
Rep (R)	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Practice (P)	1	**	**	**	**	*	*	**	**	ns	*
S*P	1	*	ns	ns	ns	**	ns	**	**	**	ns
Variety (V)	2	**	**	**	**	**	**	**	ns	**	**
S*V	2	*	*	ns	**	**	*	**	ns	*	ns
V*P	2	**	**	**	*	*	*	ns	ns	ns	ns
S*V*P	2	*	*	ns	Ns	*	ns	ns	ns	ns	ns

*Values are significantly different by LSD at the 0.05, ** Values are significantly different by LSD at the 0.01.

3.1.2. Comparison Among Varieties

It normally takes 130, 160, and 145 days for the Basmati 370, BW 196, and IR 2793-80-1 varieties to mature. There was an average difference of 6, 21 and 21 days between harvesting dates for SRI and CF plots for the three varieties, respectively, representing a shortening of the varieties' crop cycle. In these trials, SRI plants matured in about 4% less time, and the CF plants about 7% longer time, than is usually expected from these varieties. Under SRI management, the plants considered short (130-day) and medium (145-day) duration matured at the same time (135 days) in the first season, but differed by 16 days in the second season.

The long-duration and high-yielding BW 196 variety had the highest percentage increase in yield (51% and 53%), followed by the mid-duration IR 2793-80-1 at 16% and 56%, and finally the short-duration Basmati 370 at 11% and 33% in the first and second seasons, respectively, under SRI. HI was also considerably higher in the IR 2793-80-1 variety than in Basmati 370 and BW 196 varieties.

Panicle length was highest in the short-duration Basmati 370 variety and lowest in the long-duration BW 196 variety.

IR 2793-80-1 had the highest number of grains per panicle, followed by Basmati 370, and lastly BW 196 during the first season; but this changed in the second season when Basmati 370 recorded the highest number of grains per panicle.

3.2. Tillers and Panicles Number

The number of tillers and panicles m^{-2} was highly significant with SRI practice (P < 0.0001) compared with CF practice (Table 3) in both seasons. With SRI practice, both tiller and productive tiller number m^{-2} were significantly increased for the IR 2793-80-1 and BW 196 varieties compared with Basmati 370 variety. In SRI plots, panicles per hill ranged, respectively, between 53-56, 62-70 and 62-79, for the Basmati 370, IR 2793-80-1, and BW 196 varieties in the first season. In the second season, however, the range was slightly lower for all the varieties. The percentage of tiller-bearing panicles, i.e., effective tillers, was considerably higher (P< 0.0001) in the SRI plots (averaging 94% for all varieties). The CF plots, on the other hand, had somewhat lower percentages of effective tillers (87%). The highest percentage of effective tillers with CF management was still lower than the lowest effective tillering rate under SRI management (Table 3). In spite of having more number of tillers in each hill and more panicles m^{-2} in SRI, the grain-percentage was higher in CF than SRI during the first season.

Among the varieties, Basmati 370 had the lowest number of tillers or panicles m^{-2}, while IR 2793-80-1 and BW 196 had the highest numbers in the first and second season, respectively. Across the three varieties, the percentage of effective tillers was significantly enhanced with SRI, by 7% compared with CF.

Table 3. *Panicle length and yield components for the three rice varieties under SRI and CF.*

		Tiller no./m^2		*Productive tillers/m^2		Panicle length (cm)		Grain no./panicle		Grain filling (%)	
Practice	**Variety**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**
SRI	Basmati 370	831^{bc}	711^{d}	788.3^{c} (94.3)	692de (97.4)	25.2^{a}	25.51^{a}	115^{a}	98^{a}	67.67^{bc}	84.3^{bc}
	BW 196	1,136 ^{a}	1,216^{a}	1044. ^{b} (94.2)	1040 ^{a} (85.5)	21.3^{d}	24.93^{a}	70^{cd}	74^{bc}	45.67^{e}	84.6^{b}
	IR 2793-80-1	1,300 ^{a}	894^{bc}	1235.9 ^{a} (94.8)	850^{b} (95.1)	22.3^{bc}	21.88^{c}	119 ^{a}	77^{b}	71.67^{b}	89.1^{a}
CF	Basmati 370	775^{bcd}	656^{ed}	667.5^{de} (86.3)	492^{f} (75)	22.4^{bc}	23.2^{b}	92^{b}	72^{bcd}	81.67^{a}	79.6^{de}
	BW 196	847 ^{b}	943 ^{b}	726.4^{cd} (87.1)	794^{bc} (84.2)	19.7^{ef}	20.4^{d}	43^{e}	51^{f}	53.67^{d}	80.2^{d}
	IR 2793-80-1	744^{cd}	816^{cd}	693.0 ^{d} (88.2)	768^{cd} (94.1)	20.4^{e}	20.3^{de}	76^{c}	67de	85.33^{a}	87.3^{a}

Productive tillers/m^2=number of panicles/m^2 (one tiller=one panicle). Values with the same letters in a column under the respective seasons are not significantly different by LSD at the 0.05 level across both practices *Values in parenthesis are percentage of effective tillers

3.3. Root Dry Weight

The results of root dry weight showed a significant improvement in root growth in the SRI plants (P= 0.042) for all varieties (Table 4). For Basmati 370 and BW 196, root dry weight gm^{-2} under SRI practice was almost double that with CF practices in both seasons.

Table 4. *Root dry weight for different varieties under SRI and CF practices.*

Root dry weight (g/m^2)			
Practice	**Variety**	**Season 1**	**Season 2**
SRI	Basmati 370	80.3^{bc}	74.99 ^{d}
	BW 196	105.6 ^{b}	129.94 ^{b}
	IR 2793-80-1	128.3^{a}	152.62 ^{a}
CF	Basmati 370	50.0 ^{d}	47.65 ^{e}
	BW 196	74.4 ^{c}	90.20 ^{c}
	IR 2793-80-1	97.1 ^{b}	132.82 ^{b}

Values with the same letters in a column under the respective seasons are not significantly different by LSD at the 0.05 level across both practices.

3.4. Water Productivity and Water Savings

Rainfall received was 285.7mm and 556.2mm during the first and second cropping seasons, respectively. However, the SRI plots were drained, so this left 61.3mm, 69.6mm and 61.3mm for the respective varieties in the first season, and in the second season, 139.0mm for the Basmati 370, BW 196, and IR 2793-80-1, respectively.

The amount of rainfall utilized by the respective varieties was different: 246.2mm, 285.7mm, and 228.7mm under CF practice for Basmati 370, BW 196, and IR 2793-80-1 in the first season. During the second season, all the rainfall was utilized under CF practice (Table 5). The irrigation amounts for the three rice varieties under both practices are also shown in Table 5.

Table 5. *Water use and water productivity for the three rice varieties under SRI and CF.*

		Rainfall (m^3/ha)		Irrigation water (m^3/ha)		Water use (m^3/ha)		Water Productivity (kg/m^3)	
Practice	**Variety**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**	**Season 1**	**Season 2**
SRI	Bas 370	613	1390	8422	5332	9035	6122	0.7	1.1
	BW196	696	1390	11573	6830	12269	7280	0.5	1.7
	IR 2793-80-1	613	1390	10420	5890	11033	8220	1.0	2.0
CF	Bas	2452	5562	11610	8109	14062	13291	0.4	0.4
	BW196	2784	5562	15691	10139	18475	11701	0.2	0.8
	IR 2793-80-1	2452	5562	15096	8796	17548	11358	0.5	0.8

This resulted in significant water savings of up to 34% with SRI practice (Table 6). BW 196, the long-duration variety, had the least water saving, followed by IR 2793-80-1, which was close to that for Basmati 370. On average, IR 2793-80-1 had the highest water savings in both seasons, reflecting that the savings were almost equal for this variety in both seasons.

SRI demonstrated significantly higher water productivity -- 0.7kg m^{-3}, 0.5kg m^{-3} and 1.0kg m^{-3} in the first season, and 1.1kg m^{-3}, 1.7kg m^{-3} and 2.0kg m^{-3} in the second season for Basmati 370, BW 196 and IR 2793-80-1. Simultaneously, the water productivity with CF was 0.4kg m^{-3}, 0.2kg m^{-3} and 0.5kg m^{-3} first season, and 0.4kg m^{-3}, 0.6kg m^{-3} and 0.7kg m^{-3} the second season for the respective varieties. Average water productivity during the two seasons for the three varieties under SRI management was 1.2kg m^{-3}, 140% more than the 0.5kg m^{-3} average under conventional management.

Table 6. *Savings on irrigation water (%) for the three rice varieties during the growing seasons.*

Variety	Savings on irrigation water (%)		Average savings on irrigation water (%)
	Season 1	Season 2	
Basmati 370	27.5	34.2	30.9
BW 196	26.2	32.6	29.4
IR 2793-80-1	31.0	33.0	32.0

4. Discussion

4.1. Yield and Yield Components

Yields for Basmati 370, IR 2793-80-1 and BW 196 varieties are normally with conventional practices, including continuous flooding, 3-5t ha^{-1}, 7-9t ha^{-1} and 9-11t ha^{-1}, respectively [48]. The somewhat higher yields achieved with conventional methods in this study compared to the usual averages in Mwea may have been due to the size of plots, which are much smaller than farmers' farm sizes. Also, farmers getting higher yields than usual with their regular practices have been reported by other researchers such as [39], [13]. Availability of rotary weeders in the second season may have contributed to the higher rice yields harvested in the second year of the trials, though there was also a difference in levels of rainfall.

The difference in time taken for the crop to mature among the varieties and between season could be explained by the low temperatures during the ripening phase during the first season (Figure 1) and high rainfall during the second season (Figure 2). High rainfall towards the end of second season delayed harvesting since the plots were soaked with water.

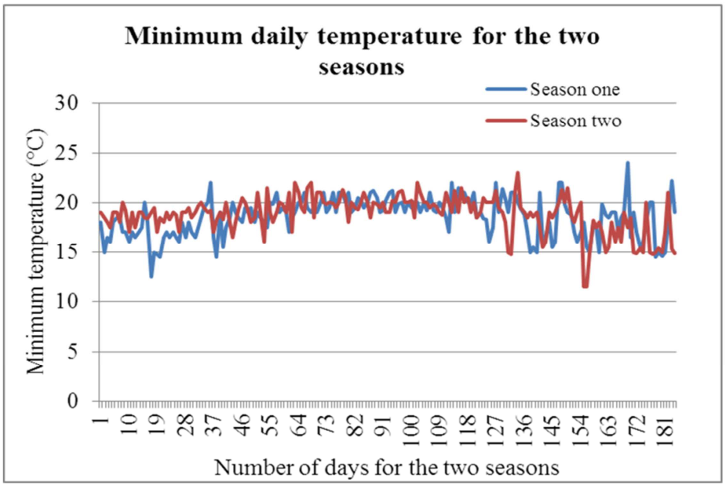

Figure 1. *Daily minimum temperature during entire growth cycle for both seasons.*

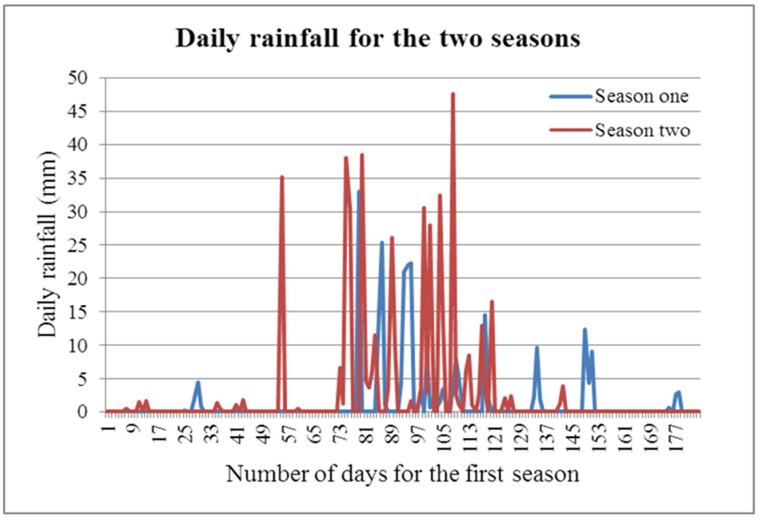

Figure 2. *Daily rainfall events during entire growth cycle for both seasons.*

The results showed that for all varieties, using SRI methods increased components of yield and final grain yield. The associated yield components that contributed to yield increase were more productive tillers, longer panicle length with greater number of grains, and enhanced 1000-grain weight with SRI practice. The increased weight of dry matter per meter square with SRI was a result of high tillering numbers (Table 3). This indicates that differences in grain yield for various varieties were attributable to differences in dry matter production and Harvest Index.

Forty-eight days after transplanting, the plants had reached their maximum tillers under both practices. Plants under CF had an average of 31 tillers among the varieties, while the plants under SRI practice had an average of 68 tillers for the three varieties during the first season. This however changed significantly during the second season, especially for CF practice (Table 3). In this season, by the time that SRI plants had reached their 9^{th} phyllochron of growth, those under CF management had reached just their 5^{th} phyllochron. Phyllochrons are the time period required for the development of one or more sets of phytomers, i.e., units of tiller, leaf and root, emerging from the plant's apical meristem [30; 3]. This explains why SRI plants had more tillers than the CF plants as their rate of growth, reflecting different rates of cell division, elongation and differentiation, a subject not included in this study.

The dry weight of roots was also considerably higher with SRI practice compared to CF practice for all three varieties. There is a strong and necessary correlation between tiller number and root emergence as well as growth, with roots and canopies having a positive feedback relationship to one another and originate from the same vegetative growth centers, given the normal growth and production of phytomers.

Earlier reports have shown that younger seedlings raised according to SRI principles perform better in terms of various root characteristics (root length density, root health, and root weight) than do older seedlings [29]. The higher dry weight of roots seen in hills with SRI practice compared with CF practice (Table 6) could be responsible for more transportation of cytokinins, a phytohormone synthesized in the roots, through the xylem up to the shoot. SRI roots had a lighter colour compared to CF roots, an indication that SRI roots were healthier and more active than CF roots [39].

SRI's water management practices of intermittent irrigation also help in improving root systems [7]. CF, on the other hand, can cause degeneration (necrosis) of as much as three-fourths of a rice plant's roots by the flowering stage due to their hypoxia [16]. Lack of aeration of the soil affects not only root health and functioning, but also the populations of beneficial aerobic organisms (bacteria and fungi) that can contribute to plant nutrition and health.

4.2. Temperature Effects

For this particular study, the percentage of grain filling was not one of the main contributing characteristics to overall grain yield in the first season, perhaps due to low temperatures during the growing season. In Mwea, the optimum temperatures for rice plant growth range between 16°C and 31°C. Low temperatures (below 16-17°C) at the ripening stage adversely affect yields [48]. From Figures 1a, b; representation for all varieties, it was observed that the minimum temperature dropped as low as 14.5°C during the ripening stage of SRI plants in the first season. In the second season, minimum temperatures remained above the threshold of 16°C during this critical period (Figures 3, 4, 5 and 6).

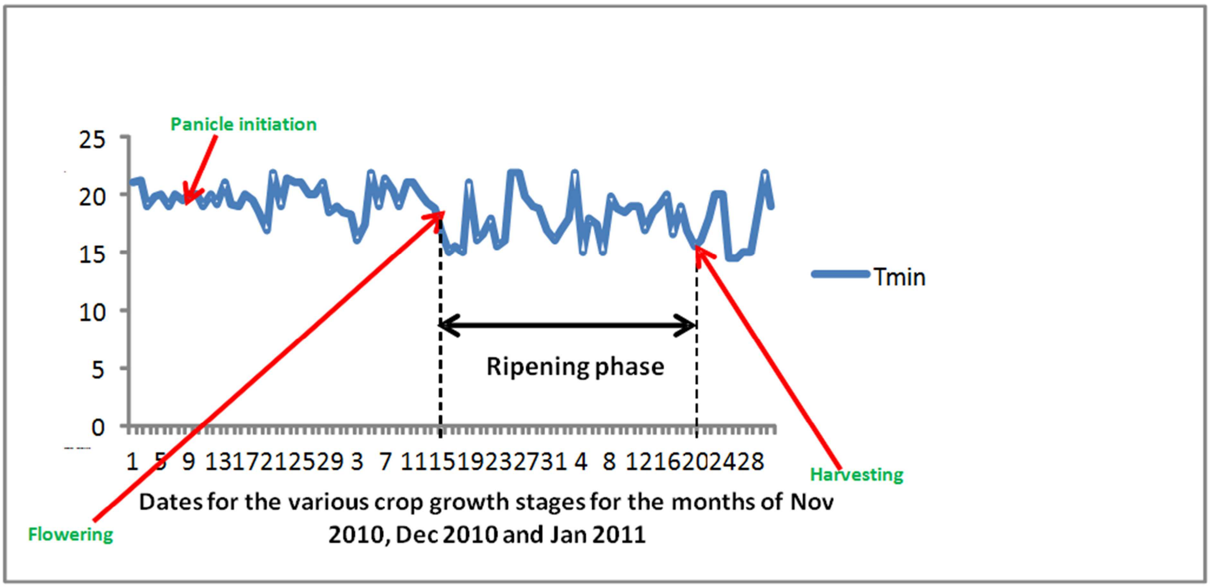

Figure 3. *Changes in minimum temperature during ripening stage of rice growth cycle for Basmati 370 variety under SRI, first season.*

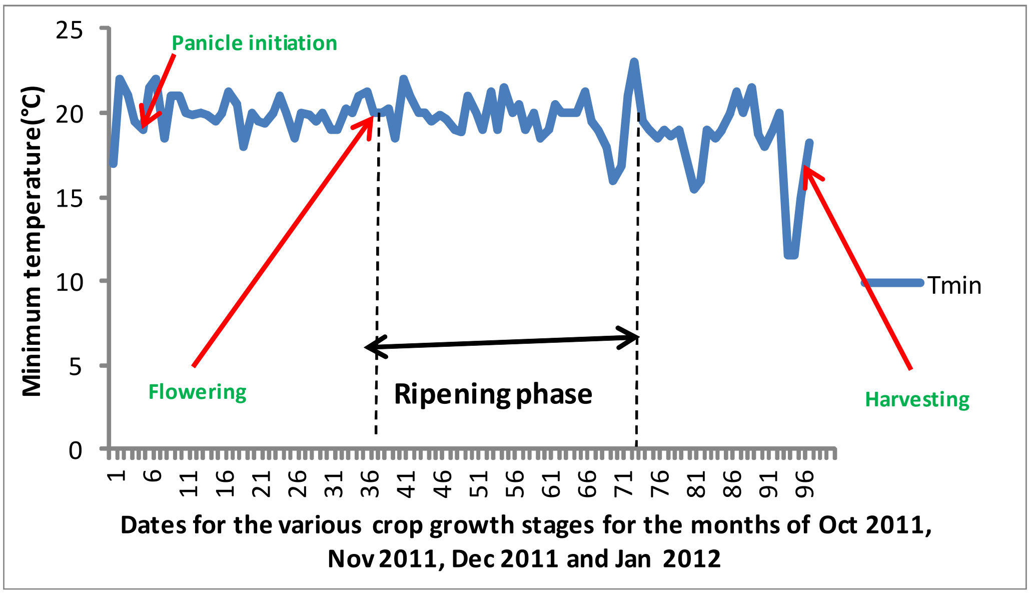

Figure 4. *Changes in minimum temperature during ripening stage of rice growth cycle for Basmati 370 variety under SRI, second season.*

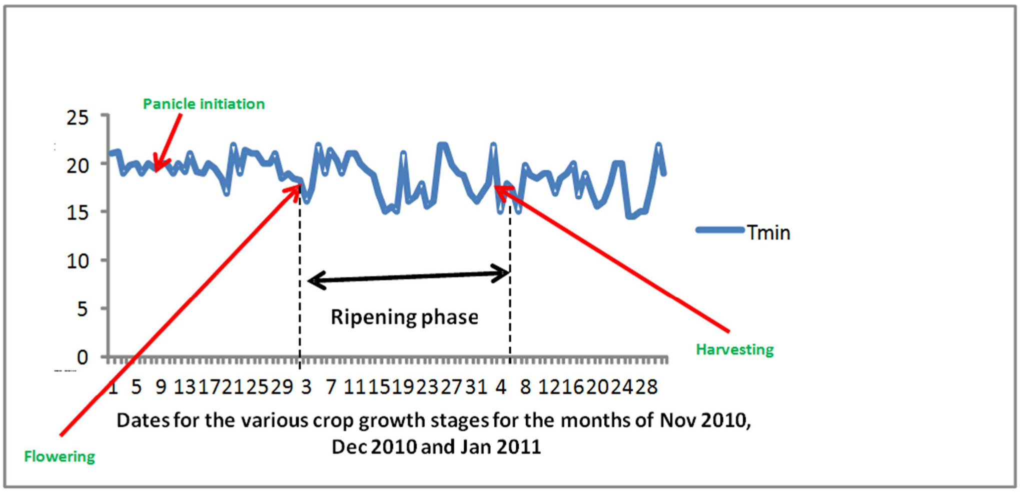

Figure 5. *Changes in minimum temperature during ripening stage of rice growth cycle for Basmati 370 variety under CF, first season.*

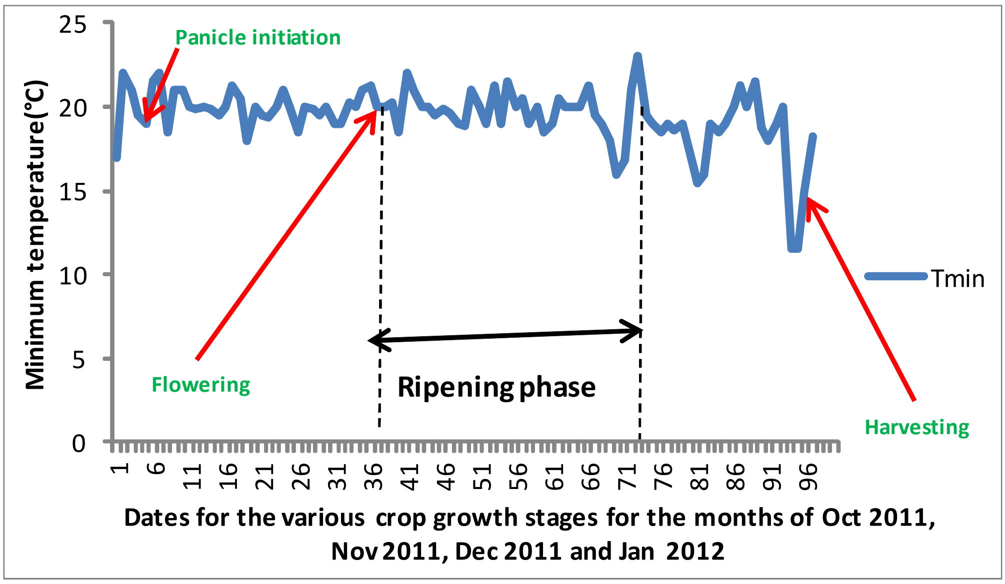

Figure 6. *Changes in minimum temperature during ripening stage of rice growth cycle for Basmati 370 variety under CF, second season.*

In this study, all varieties took longer than usual to mature under CF management, and especially the grain-filling stage was increased by one or two weeks depending on variety (Tables 7, 8 and 9). For CF practice, crop duration was increased by an average of 12 days across the varieties. This could be attributed to reduced respiration and endosperm cell size during the ripening phase [20].

Table 7. *Growth stages of Basmati 370 variety under SRI and CF.*

Activity	SRI		CF	
	Date	Duration of activity	Date	Duration of activity
Seeding	30/8/2010		11/8/2010	
Transplanting	8/9/2010		8/9/2010	
Max. tiller number	25/10/2010	50 days from seeding	25/10/2010	74 days from seeding
Panicle formation	5/11/2010	60 days from seeding	5/11/2010	82 days from seeding
Flowering	13/12/2010	35 days from panicle formation	30/11/2010	24 days from panicle formation
Harvest	20/1/2011	40 days from flowering	5/1/2011	35 days from flowering
Duration	135 days		141 days	

Table 8. *Growth stages of BW 196 variety under SRI and CF.*

Activity	SRI		CF	
	Date	Duration of activity	Date	Duration of activity
Seeding	30/8/2010		11/8/2010	
Transplanting	8/9/2010		8/9/2010	
Max. tiller number	25/10/2010	50 days from seeding	25/10/2010	74 days from seeding
Panicle formation	5/11/2010	60 days from seeding	5/11/2010	82 days from seeding
Flowering	15/12/2010	37 days from panicle formation	21/12/2010	43 days from panicle formation
Harvest	5/2/2011	54 days from flowering	5/2/2011	47 days from flowering
Duration	151 days		172 days	

Table 9. *Growth stages of IR 2793-80-1 variety under SRI and CF.*

Activity	SRI		CF	
	Date	Duration of activity	Date	Duration of activity
Seeding	30/8/2010		11/8/2010	
Transplanting	8/9/2010		8/9/2010	
Max. tiller number	25/10/2010	50 days from seeding	25/10/2010	74 days from seeding
Panicle formation	5/11/2010	60 days from seeding	5/11/2010	82 days from seeding
Flowering	13/12/2010	35 days from panicle formation	30/11/2010	24 days from panicle formation
Harvest	20/1/2011	40 days from flowering	20/1/2011	50 days from flowering
Duration	135 days		156 days	

Although the yield capacity of a rice crop is primarily determined during the pre-heading period, the actual yield is based on the amount of starch that fills spikelets, and this is largely determined at the post-heading stage (during the ripening phase) [49]. Low temperatures will cause damage to the rice crop at different stages of its development: at germination, seedling growth, panicle formation, flowering, and pollination. Low temperatures sometimes cause spikelet sterility with no grain produced [9]. The problem is worsened if cold irrigation water is used. In some countries, minimum air temperatures below 18°C will generally cause sterility, and sterility generally reaches 100% if the minimum air temperature drops below 16°C [41].

A similar study in the Philippines reported that the yield of irrigated rice decreased by 10% for each 1°C drop in T_{min} averaged over the growing season. Precisely, a 1°C change in T_{min} during the ripening phase reduced yield by 322.4kg ha^{-1} [49]. [40]; [42] and [20] have reported that T_{min} has a large, negative impact on yield. Recent extreme cold snaps in Europe and North America have also demonstrated how much trouble a temperature change can cause [9].

4.3. Rainfall Effects

From Figures 1a and 1b, it was observed that high rainfall events did not necessarily translate to low temperatures (which is the most critical parameter affecting the grain filling stage). Furthermore, the excess water from rainfall was drained from SRI plots hence, it was not possible to conclude what effect the excess rainfall water would have on yields for the crop under SRI. However, high rainfall in season 2 may have contributed to high water productivity since it was raining everyday almost all day and so the same level drainage could not be achieved as that in season 1. Water was only drained on a few days from the SRI plots and this was to achieve the 2-3cm layer of water as recommended. There was also a delay in drying of the crop and subsequently harvesting by two weeks for all varieties and in both systems during the second season.

4.4. Water Savings and Water Productivity

Water savings and water productivity were definitely higher under SRI practice. A 2cm layer of water was irrigated after every 5 days for the SRI practice. The water dried off usually by three days after irrigation, although this was quicker on some days when the temperatures were too high. Because the three rice varieties matured at different times, the amount of water used was different in the same season.

The higher water productivity observed in SRI than CF fields indicates that continuous flooding of rice plants into water is not essential for obtaining high rice yields [8]. Water savings of 28% and 33% were made in the first and second seasons, respectively during the study. [4] and [35] concluded after a series of research that about 40-45% of water normally used in irrigated rice can be saved by applying water in small quantities to keep the soil saturated throughout the growing season without sacrificing rice yield. [19], [36], and [52] have recorded a reduction in irrigation water by 40-70% and 20-50% and over 50%, respectively, while increasing yields under alternate wetting and drying compared to continuous flooding of rice crop.

Increased water productivity (1.74g l^{-1}) under SRI practice compared to (1.23g l^{-1}) for CF practice was reported by [8]. [43] and [52] also reported similar results. A meta-analysis by [14], which is based on 29 published studies and 251 comparison trials reported a water productivity of 1.24g l^{-1} and 0.52g l^{-1} under SRI and CF respectively across three varieties (short, medium and long term).

5. Conclusion

This study has shown that SRI water management practice is capable of producing considerably higher rice yields as well as saving on water usage compared to conventional continuous-flooding water management practice irrespective of rice variety. SRI practices can address some key constraints for rice production in Kenya and in many other countries. The improvement in grain yield under SRI practices was a combination of all the components of a rice plant, below and above the ground surface. SRI practices with alternate wetting and drying improve the growth of roots as explained by the higher dry root weight from SRI crops. There is presently and foreseeably a need to produce more food, and particularly rice, using more productively the limited land and water resources. More needs to be learned about how and why SRI methods raise productivity as much as they do, but the growing evidence from many countries indicates large agronomic and economic gains are available by modifying age-old cultivation practices, with benefits for the people. Governments and donor agencies which want to improve food security and conserve water resources would do well to make SRI knowledge more widely available to farmers in Kenya and elsewhere.

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