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The Effect of In-Field Rain Water Harvesting on Orange-Fleshed Sweet Potato Biomass and Yield

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Abstract

Water scarcity affects both food security and human nutrition. In-field rain water harvesting (IRWH) combines the advantages of rainwater harvesting, no-till, basin tillage and mulching on high drought risk clay soils. In this study, the IRWH system was customized to fit the cropping system of orange-fleshed sweet potato (OFSP). Field trials were conducted over two seasons to compare cultivation of OFSP using IRWH versus conventional tillage (CON). Data collection included plant survival, root initiation, marketable root yield, unmarketable root yield classes and biomass. Planting OFSP using the IRWH system resulted in significantly higher total biomass, higher marketable and total root yield per plant, as well as larger number of roots per plant compared to CON. Despite the relatively higher yield, total production (t/ha) was only significantly higher in season two at 4.6 t/ha vs 2.7 t/ha for CON. Subsistence farmers and households in semi-arid areas may grow small plots of orange-fleshed sweet potato in IRWH opposed to only growing maize and in that way add vitamin A to the diet. This is the first study on the application of IRWH to produce OFSP under rainfed conditions, and more research can be conducted to expand the knowledge on application and benefits of IRWH for OFSP production.

Keywords: moisture stress, nutrition, sweetpotatoes, in-field rainwater

1. Introduction

Sweet potato is a deeply-rooted crop and therefore has the capability to withstand moderate water-stressed conditions (Lebot, 2009). It is a major staple crop in developing countries, a popular traditional crop in Africa and also important for food security (FAO, 2014; Fetuga et al., 2013; Laurie, Faber, Adebola, & Belete, 2015). When addressing issues of human nutritional insecurity, it is important to encourage the cultivation of sweet potato by small-holder farmers and subsistence farmers or home gardeners (Low, 2011). Orange-fleshed sweet potato (OFSP) is rich in β-carotene, a major precursor of vitamin A thus considered as an affordable remedy for vitamin A deficiency (Burri, 2011). Sweet potato is an excellent source of calories, and further contains dietary fibre, vitamin C, vitamin B6 and minerals (Burri, 2011; Laurie, Van Jaarsveld, Faber, Philpott, & Labuschagne, 2012). There is an estimated two billion people, mostly found in the rural parts of developing countries, who suffer from one or more micronutrient deficiencies (FAO/IFAD/WFP, 2012). Women of child-bearing age and children are especially vulnerable because of greater needs for micronutrients (Darnton-Hill et al., 2005). In South Africa, 43.6% of preschool children are vitamin A deficient (Shisana et al., 2013). Also, based on a hunger score index, 28.3% of the South African population is at risk of hunger and 26% experience hunger and therefore are food insecure (Shisana et al., 2013). Sweet potato features prominently in smallholder cropping systems and is an important food security crop (Motsa, Modi, & Mabhaudhi, 2015).

Moisure deficit has an effect on physiological and biochemical processes in the plants. This includes photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism, and growth promoters (Farooq, Wahid, Kobayashi, Fujita, & Basra, 2008). Several authors indicated the magnitude of yield reduction in sweet potato caused by moisture deficit (Saraswati, Johnston, Coventry, & Holtum, 2004; Lewthwaite &

Triggs, 2012; Andrade et al., 2015). For example, Andrade et al. (2015) in evaluating 58 lines observed on average 27% yield reduction between plots under irrigation versus plots without irrigation. Others researched the cause of the yield reduction (Van Heerden & Laurie, 2008; Kivuva, 2014; Gajanayake, Reddya, Shankleb, & Arancibiab, 2014). In this regard measurement of chlorophyll *a* fluorescence, and the relationship between stomatal conductance, intercellular CO_2 concentration and CO_2 assimilation rate, showed that during moisture stress photosynthesis is inhibited primarily through stomatal closure (Van Heerden & Laurie, 2008; Gajanayake et al., 2014).

In South Africa, where water is a scarce commodity (Bennie & Hensley, 2001), optimizing utilization of rain water during production is of great importance. The majority of subsistence farmers in South Africa are growing crops under rainfed conditions where the periods of water stress is often unpredictable. In-field rain water harvesting (IRWH) is a relatively recent developed technique for *in-situ* water harvesting in South Africa (Hensley, Botha, Anderson, van Staden, & du Toit, 2000). IRWH was mainly designed for these subsistence farmers and has improved yield of a number of crops when compared to results obtained under conventional tillage (CON) (Hensley, Bennie, van Rensburg, & Botha, 2011). Maize and sunflower yields increased by between 30% and 50%, respectively, compared to the yield obtained with CON. Other results with IRWH on clay soils indicated that crop yield was improved by between 50% and 185% in comparison with CON (Hensley, Botha, Anderson, van Staden, & du Toit, 2000; Botha et al., 2003; Botha, 2006, Mzezewa, Gwata, & van Rensburg, 2011; Botha et al., 2012). The IRWH technique was also recently tested on maize by Welderufael, le Roux, and Hensley (2012) finding an increase of 10 mm/hr vs 5 mm/hr infiltration rate for IRWH as compared to CON, and surface storage of 2 mm vs 0.4 mm.

The IRWH technique combines the advantages of rainwater harvesting, no-till, basin tillage and mulching on high drought risk clay soils. This water conservation technique has the potential to reduce total runoff to zero and evaporation (Es), resulting in increased yields due to increased plant available water. The water harvesting from the no till, crusted soil on the 2 m wide inter-crop row area serves to concentrate runoff water in the basin, and by so doing promotes infiltration of water beyond the zone of evaporation in clay soils and thus minimizing water loss due to Es. Applying mulch in the draining basin further minimizes Es (Figure 1).

IRWH needs to be tested as a possible method of improving yield of OFSP in semi-arid regions. The crop especially needs adequate water during establishment and during storage root initiation (±40-60 days after planting). Fluctuating soil moisture levels during the root initiation stage reduces yield (Indira & Kabeerathumma, 1988; Gajanayake et al., 2014). The production of OFSP using the IRWH technique had not been done before, hence the study aim was to develop the technology for using sweet potato in IRWH and test the performance of OFSP with the IRWH technique.

2. Materials and Methods

2.1 Adapting IRWH System to Sweet Potato

The in-field rainwater harvesting (IRWH) technique developed by Hensley et al. (2000), for maize (Figures 1 and 2) was adapted to be applied in sweet potato production. The normal practice is to plant sweet potato on ridges (Niederwieser, 2004). For the IRWH system the sweet potato was established on top of the main ridge (adjacent to the basin) (Figure 3a). A second smaller ridge was prepared 90 cm inwards, but not continuous so as to allow run-off from the no till area to the basin (Figure 3b). The vines were spaced 30 cm apart as per normal recommendation (Niederwieser, 2004). Figure 3c shows the sweet potato at full canopy cover.

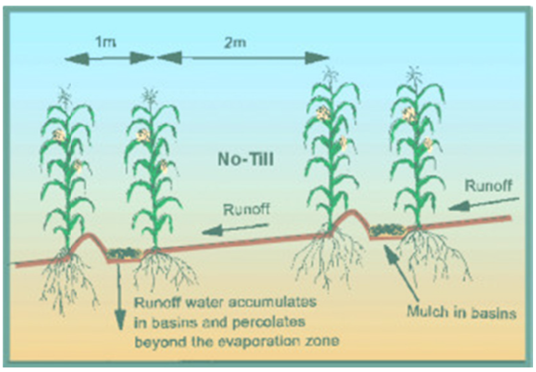

Figure 1. Diagram of the in-field rainwater harvesting (IRWH) technique as used for maize (Hensley et al., 2000)

Figure 2. Collection of runoff water in the basin of IRWH after rains in maize cropping system at Glen Agricultural Institute (28º57′ S, 26º20′ E)

Figure 3. In-field rainwater harvesting (IRWH) system adjusted for planting sweet potato at Glen Agricultural Institute (28º57′ S, 26º20′ E): a) Main ridge after planting; b) Main ridge and second ridge into the run-off area. The second ridge is not continuous to allow run-off (blue arrows) to the basin area; c) Sweet potato in IRWH after vines covered the area and control plot at the back. This was during a dry period, hence leaves are wilted

2.2 Experimental Conditions

An on-station field experiment was conducted at the Glen Agricultural Institute (28º57′ S, 26º20′ E), 25 km north east of Bloemfontein, South Africa. Based on soil (red; 11% clay), climate and topography, the site is of the Glen/Bonheim ecotype. The institute is located in a semi-arid zone receiving a mean annual rainfall of 567 mm. OFSP cultivar W-119 (an US cultivar) was chosen for the experiment as the cultivar was recommended for cultivation in South Africa following cultivar evaluation trials (Laurie & Magoro, 2008). The trials were planted in the summer season of 2007/8 and 2008/9 in the IRWH system and in a conventional tillage system (CON) and replicated three times. The experimental design was a randomized complete block design. The first trial was established 27-29 November 2007 and harvested on 12-15 May 2008. The follow-up trial was planted 1-4 December 2008 and harvested on 11-15 May 2009. The same plots were used during the two planting seasons.

The IRWH plots of sweet potato vines were planted at plant spacing 30 cm × 90 cm; 2 rows per block, where the first row was on the ridge (18 plants per row) and for the second at 90 cm; 4 small curved ridges were made (12 plants per row). Each replicate consisted of 4 IRWH blocks (area 6 m × 12 m; 120 plants). The CON consisted of 11 rows spaced 100 cm apart; plants spaced 30 cm (area 6 m × 12 m; 198 plants). The planting material consisted of 30 cm top vine cuttings sourced from the ARC-VOP in Pretoria, South Africa. The cuttings were planted with 2-4 nodes in the soil and were watered using watering cans only for establishment (14 days). Pre-plant fertilizer was applied as per standard recommendation based on soil analysis (Allemann, 2004). Rainfall during this period amounted to 352.6 mm in 2007/8-season and 351.5 mm in the 2008/9-season (Table 1). The mean minimum maximum temperature range was 12-34 °C for both seasons for the period December till March, largely within the minimum for growth of sweet potato, since the basal temperature for accumulation of heat units is 10 °C for this crop. April to May had low temperatures at night as expected from this temperate climate zone receiving frost during winter. Rainfall distribution was more even during the season during 2007/8 than during 2008/9, and the mean monthly temperatures lower over all five months than in 2008/9 (Figure 4).

2.3 Data Collection

Plant survival was recorded before harvesting approximately 150 days after planting. The mass of top growth (vines and leaves) were measured from all plants per plot. The storage roots were harvested with garden forks and graded as marketable and unmarketable. Marketable roots were considered as good quality between 100 to 1200 g) and subsequently divided into size classes extra large (between 0.8-1.2 kg), large (between 0.5-0.8 kg), medium (between 0.25-0.5 kg) and small (between 0.1-0.25 kg). Unmarketable roots were graded as extra small (< 100 g), cracked, damaged, mice damaged, rotten, long curved and extra large (> 1.2 kg). The number of plants not producing storage roots (sweet potatoes) were recorded.

Table 1. Weather data at Glen Agricultural Station during 2007/8 and 2008/9 growing seasons of the sweet potato trials

Season	Month	Tx	Range	Tn	Range	Rain	Range
2007/8	Dec	30.2	22.5-36.4	14.0	10.5-18.1	55.9	0-28.6
	Jan	31.0	25.2-36.0	15.5	8.4-18.3	55.9	0-22.4
	Feb	30.9	23.3-36.7	15.3	9.6-18.4	73.0	0-28.0
	Mar	27.5	12.7-27.5	12.6	5.8-17.3	98.0	0-38.3
	Apr	25.2	16.4-29.5	5.3	-3.0-11.9	9.9	0-5.6
	May	16.1	7.5-24.8	0.7	3.3-9.4	58.9	0-23.2
	Total	-	-	-	-	351.6	-
2008/9	Dec	34.1	29.5-37.9	15.9	8.9-21.4	26.7	0-9.9
	Jan	32.4	20.6-38.2	16.2	10.8-21.3	130.3	0-52.3
	Feb	28.9	17.0-33.0	16.1	10.8-18.5	126.7	0-39.4
	Mar	29.4	25.6-31.8	12.3	5.4-15.8	18.0	0-8.6
	Apr	27.5	18.9-31.6	9.3	3.4-13.4	19.6	0-13.2
	May	22.3	13.7-24.1	5.5	-0.9 - 10.9	31.2	0-17.5
	Total	-	-	-	-	352.6	-

Note. Tx = Mean Daily Maximum Temperature; **Tn = Mean Daily Minimum Temperature.

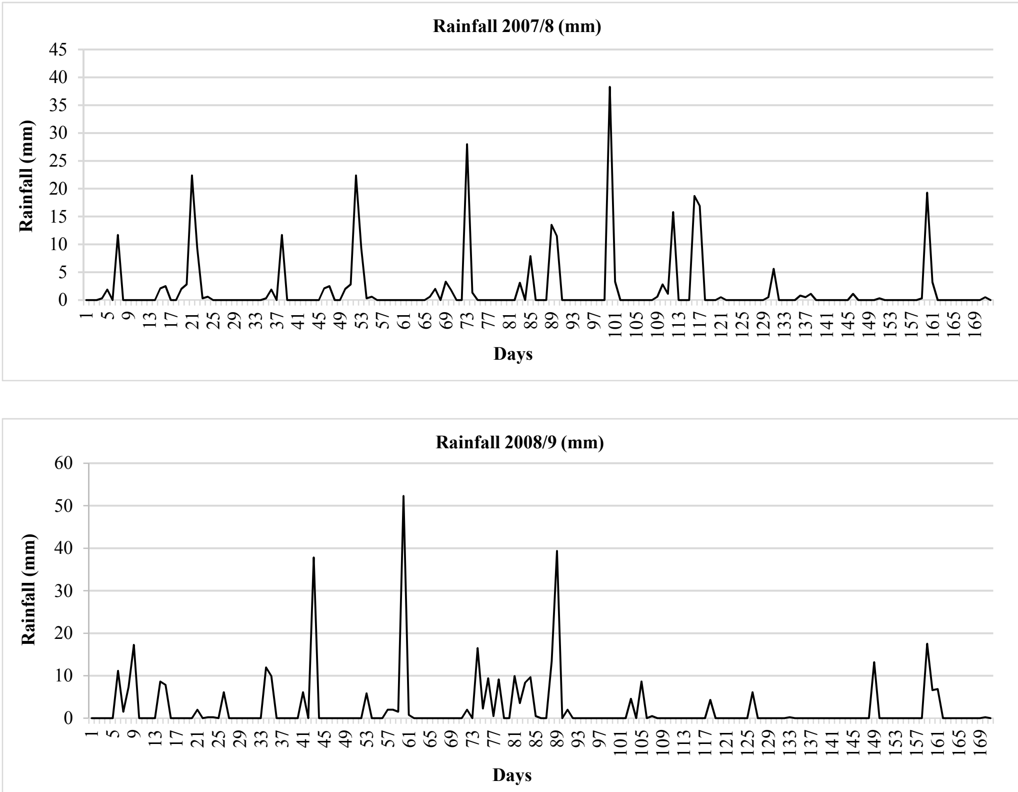

Figure 4. Rainfall per day at Glen Agricultural Station over the growing period for 2007/8 and 2008/9 when the sweet potato trials were conducted

2.4 Statistical Analysis

Biomass was calculated as the total of top growth and root yield. All parameters were calculated on per plot and per plant basis. Analysis of variance with year as subplot factor was performed using Gen Stat 64-bit Release 15.1 (PC/Windows 7) (VSN International Ltd., Hemel, Hempstead) to separate the means and the Student's protected t-Least Significant Difference (LSD) test was calculated at the 10% significance level to compare treatment means.

3. Results and Discussion

3.1 Plant Survival

The mean plant stand for 2007/8 was 162 (82% survival) for CON and 101 (84% survival) for IRWH from the 198 and 120, which were planted, respectively (Table 2). In the 2008/9 season, the CON on average only had 80 plants left (40%) by harvesting and IRWH 105 plants (87%). The lower rainfall during December 2008 (26.7 mm), as compared to December 2007 (55.9 mm), coupled with higher temperatures, might be the cause of the seasonal differences in plant survival.

As indicated by Welderufael, le Roux and Hensley (2012), IRWH leads to better collection of water in the basin as seen in the increase in infiltration rate for IRWH (10 mm/hr vs 5 mm/hr), as well as increased surface storage of 2 mm vs 0.4 mm. This might have led to the better survival of plants in IRWH.

3.2 Marketable Root Yield

Table 2 presents the results for the root yield components of OFSP for IRWH compared to CON for the individual seasons and mean over two seasons. The mean marketable yield per plant was significantly higher for IRWH (0.307 kg/plant), as compared to CON (0.195 kg/plant) over two seasons, however, marketable yield per area was not improved significantly. The marketable yield (kg/ha) achieved was relatively low at 3.53 t/ha for CON and 4.27 t/ha for IRWH, indicative of the moisture stress at rainfall around 350 mm during the season. Restricted water supply has been shown to decrease relative water content of leaves in sweet potato, having a negative effect on stomatal conductance, thus leading to inhibition of CO_2 assimilation resulting in reduced root yield (van Heerden & Laurie, 2008).

Table 2. Sweet potato root yield using in-field-rain water harvesting (IRWH) and conventional tillage (CON) over two seasons

Variable		2007/8-season			2008/9-season			Combined		
		CON	IRWH	F Prob	CON	IRWH	F Prob	CON	IRWH	F Prob
Plant stand	nr plants	162.3	101.3	**	80	105	*	121.15	103.15	ns
	% survival	82.0	84.4	ns	40.4	87.5	*	61.2	86	*
Top growth	Tops kg/plot	29.1	29.2	ns	41.4	73.9	**	35.2	51.6	*
	Tops kg/plant	0.18	0.29	**	0.53	0.71	ns	0.354	0.5	*
Root initiation	% plants no sweet potatoes	25.6	13.0	**	36.8	52.4	ns	31.2	32.7	ns
Unmarketable roots	XXL (> 1.2 kg) (t/ha)	0.0	0.1	ns	0	0		0	0.03	ns
	XXS (< 0.1 kg) (t/ha)	1.1	0.7	ns	0.20	0.53	ns	0.66	0.61	ns
	Cracked (t/ha)	0.0	0.0		0	0.0		0.0	0.0	
	Rotten (t/ha)	0.0	0.0		0	0.0		0.0	0.0	
	Insect (t/ha)	0.0	0.0		0	0.0		0.0	0.0	
	Damaged(t/ha)	0.5	1.0	ns	0.42	0.88	ns	0.47	0.94	ns
	Long curved (t/ha)	0.0	0.1	*	0.1037	0.143	ns	0.07	0.12	*
	Mice (t/ha)	0.0	0.0		0.26	0.23	ns	0.13	0.12	ns
	Unmarketable nr/plot	257.0	179.0	ns	99	184.0	*	178.2	181.80	ns
	Unmarketable nr/plant	1.6	1.8	ns	1.26	1.74	ns	1.42	1.75	ns
	Unmarketable kg/plant	0.1	0.1	ns	0.091	0.126	ns	0.08	0.13	**
	Unmarketable kg/plot	12.0	13.4	ns	7.1	13.1	ns	9.55	13.27	ns
Marketable roots	Marketable yield t/ha	5.4	5.8	ns	1.72	2.74	ns	3.53	4.27	ns
	marketable nr/plot	219.0	160.0	ns	66	171.00	*	142.5	165.8	ns
	marketable nr/plant	1.3	1.6	ns	0.83	1.6	ns	1.086	1.604	ns
	Marketable avg (g)	179.8	258.9	**	186.4	117.2	ns	183	188	ns
	Marketable kg/plant	0.24	0.43	*	0.153	0.2	ns	0.195	0.307	*
	Marketable kg/plot	38.5	41.7	ns	12.4	19.8	ns	25.5	30.8	ns
	XL% (0.8-1.2 kg)	3.2	2.7	ns	0	0.0		1.6	1.3	ns
	L% (0.5-0.8 kg)	13.5	30.4	ns	0	0.0		6.7	15.2	ns
	M% (0.25-0.5 kg)	41.2	43.4	ns	62.2	64.2	ns	51.7	53.8	ns
	S% (0.1-0.25 kg)	42.2	23.5	*	37.8	35.8	ns	40	29.7	**
Total root yield	Total yield t/ha	7.0	7.7	ns	2.7	4.6	**	4.86	6.11	ns
	total roots nr/plot	476.0	340.0	ns	166	356	*	321	348	ns
	total roots nr/plant	2.9	3.4	ns	2.1	3.4	ns	2.51	3.36	**
	total avg (g)	107.0	162.4	*	117.23	95.4	**	112	129	ns
	Total kg/plot	50.5	55.1	ns	19.5	32.8	**	35	44	ns
	Total kg/plant	0.3	0.5	*	0.2	0.3	ns	0.28	0.43	*
Biomass	Biomass t/ha	11.1	11.7	ns	8.5	14.9	**	9.78	13.32	*
	Biomass kg/plot	79.6	84.3	ns	60.87	106.8	ns	70.2	95.5	**
	Biomass kg/plant	0.49	0.83	ns	0.774	1.028	**	0.633	0.93	**

Note. *F Prob = Probability significant at p = 0.10, and **p = 0.05, ns = not significant; XXL = Unmarketable large, XXS = Unmarketable small, XL = Extra large, L = Large, M = Medium, S = Small.

With regards to size of marketable roots produced, IRWH was advantageous in the 2007/8 season with significantly larger mean marketable root mass of 258.9 g vs 179.8 g. The percentage in size class small (100-250 g) was significantly less, with a trend of higher percentage in the large size (500-800 g). In the 2008/9 season, no large roots were produced in any of the treatments, again related to the harshness of this season. The root size was reduced due to the water stress during root bulking in February to April.

3.3 Total Root Yield

Total root production (t/ha) was not significantly improved by IRWH as per mean over two seasons (Table 2). However, in 2008/9 a significantly higher total yield of 4.6 t/ha for IRWH was accomplished compared to 2.7 t/ha for CON (Table 2, Figure 5). A higher number of roots per plant, 3.3 vs 2.5, and higher mass per plant, 0.43 vs 0.28 kg/plant, were obtained from IRWH (Table 2). In addition to the higher availability of moisture in IRWH, the smaller plant population for IRWH and consequent lower plant competition could have caused this. Using a quick screening method in boxes in a glass house, W-119 was indicated as drought tolerant (Omotobora, Adebola, Modise, Laurie & Gerrano, 2014). In subsequent field testing at severe water stress by the same authors, W-119 achieved marketable and total root yield of 1.83 t/ha and 3.23 t/ha, respectively (Omotobora, Adebola, Modise, Laurie & Gerrano, 2014). Drought tolerance of W-119 was also shown by Laurie, du Plooy and Laurie (2009), and Kivuva (2014), which conducted research for the Kenyan program using South African lines. This author further indicated that sensitivity moisture stress was related to producing more pencil roots rather than storage roots (sweet potatoes), and that water stress during the first 90 days after planting significantly affected the total root yield and should be considered as a critical period when moisture stress will affect root yield.

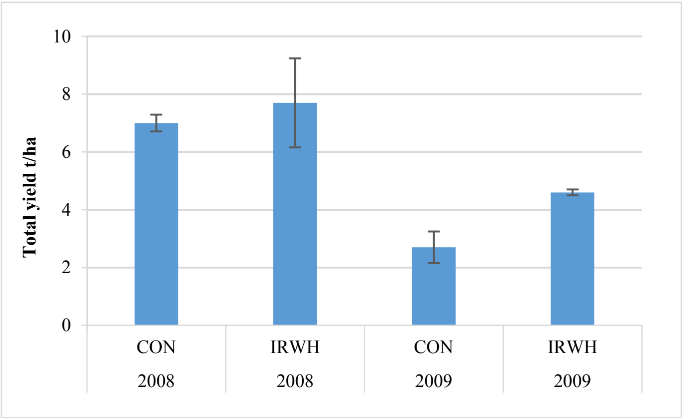

Figure 5. Mean total root yield obtained for orange-fleshed sweet potato in in-field-rain water harvesting (IRWH) and conventional tillage (CON) for 2007/8 and 2008/9 seasons

The most prevalent unmarketable root classes were unmarketable small (< 100 g) and mechanically damaged roots, but these did not differ significantly between treatments (Table 2). Mechanical damage can be related to suboptimal soil moisture (due to the water-stressed conditions) during harvesting which caused roots to be broken. No cracked roots were recorded. Higher unmarketable root mass per plant was obtained from IRWH, while higher number of unmarketable roots per plot were recorded in 2008/9 (Table 2).

3.4 Biomass

IRWH improved overall plant growth. A significantly higher biomass per plant was achieved from IRWH, while also being higher in terms of overall yield per area (kg/plot) for IRWH to CON (Table 2). Both top growth kg/plant and root kg/plant were significantly higher under IRWH as compared to CON.

Saraswati et al. (2004) in screening 15 clones of sweet potato for drought in the greenhouse found that plant biomass, main stem length, internode diameter, internode length, leaf number, leaf area and root weight decreased in response to water stress. Kivuva (2014) showed mechanisms such as reduced numbers and sizes of storage root, proliferation of pencil fibrous roots, reduced vine branching, prolonged fibrous roots, increased shoot, mature leaf pubescence and ability to retain chlorophyll content under moisture stress, were some of the drought tolerance mechanisms used by sweet potato clones. This may be explained by alteration of sink-source relationships, which affect assimilate production, translocation and partitioning, and thus influencing the size and number of roots and thus yield (Anjum et al., 2011).

The results show that the overall development of the sweet potato plants was better when planted in IRWH, which is an advantage over the CON. This is of importance as drought is a major abiotic stress in sub-Saharan Africa. Cropping environments which previously did not experience drought episodes are now encountering drought due to poor unreliable and erratic rainfall (B. V. S. Reddy, Ramesh, P. S. Reddy, & Kumar, 2009).

3.5 Nutritional Considerations

It was noted from a study by Rautenbach, Faber, S. Laurie, and R. Laurie (2010) that production under the drought stressed conditions increases β-carotene content of sweet potato roots. The latter is of importance in addressing malnutrition. These authors found that β-carotene content at a low irrigation treatment was higher than at intermediate and optimal irrigation treatment (Rautenbach, Faber, S. Laurie, & R. Laurie 2010). The raw roots contained 18.2 mg/100 g at dry conditions versus 14.3 mg/100 g at optimal irrigation. Water stress appeared to increase the β-carotene, as well as vitamin C, and chlorogenic acid contents and, consequently, the antioxidant capacity of OFSP cultivar W-119.

3.6 IRWH for OFSP

Planting of sweet potato on one main row and a second row, but not continues ridge allowing run-off from the no till area to the basin seems to work well (Figure 3). An interesting fact of using sweet potato in IRWH, is that the sweet potato vines covering the area serves as mulch, meaning that mulch does not have to be applied in the basin. Preparing IRWH plots initially requeres labour. However, thereafter the plots remain as is and a crop rotation system with preferred crops can be followed while only cultivating the basin area. For conventional production of sweet potato ridges will be prepared every season. Furthermore, in the light of climate change, IRWH can be a useful method to employ with OFSP.

Due to the nutritional advantages of OFSP above maize, the results can be a motivation to subsistence farmers and households in clay soils of semi-arid areas of South Africa to grow small plots of orange–fleshed sweet potato opposed to only growing maize and in that way add vitamin A to the diet.

This study is the first contribution, to our knowledge, on the application of IRWH to produce sweet potatoes under rainfed conditions. However, more research should be done to expand knowledge in this field.

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