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Impact of ridge–furrow water harvesting system on faba bean (*Vicia faba* L.) production under rainfed conditions in Matrouh, Egypt

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Abstract In the North Western Coastal Zone (NWCZ) of Egypt, low rainfall results in poor crop production. Different techniques should be examined to enhance the crop yield productivity and increase the water use efficiency. The ridge–furrow water harvesting system (RFWHS) is examined under the rainfed conditions in the NWCZ of Egypt over the two growing seasons of 2012/2013 and 2013/2014. Two ridge:furrow ratios of 120:60 and 60:60 cm ridge:furrow were used and compared to the conventional cultivation in a flat plot. The RFWHS was combined with different plant densities produced from three different row spacing (i.e., 20, 30, 60 cm). The faba bean yield was highly influenced by the ridge:furrow ratio, the seed yield was increased by 47% and 128.2% when the 60:60 cm ridge:furrow ratio was used as compared to the conventional cultivation in the first and second seasons, respectively. The row spacing of 30 cm apart produced the highest seed yield of 491.1 kg/ha in the first season and 261.3 kg/ha in the second season as compared to 20 cm and 60 cm row spacing. The water use efficiency followed the same pattern as that of seed yield; it was the highest for the 60:60 cm ridge:furrow ratio and the highest for the 30 cm row spacing. It is concluded that the RFWHS can be used effectively in increasing faba bean production and maximizing water use efficiency in limited rainfall areas.

Introduction

Egypt is facing many challenges related to its water resources that are intensified by a rapidly growing population. The River Nile represents 97% of the total water supply in Egypt, while rainfall and flash floods represent another source of water which is estimated at about 1.0 BCM (MWRI, 2005); however, the limitation of rainfall is related to the quantity and the spatial and temporal distribution throughout the year. The North Western Coastal Zone (NWCZ) of Egypt, which extends from west of Alexandria by 500 km to El-Salloum on the Egyptian–Libyan border in the west, represents a good choice for population and agriculture expansion. This area has a unique hydrological cycle with low annual precipitation (from 130 to 150 mm). The rainfall in winter months is highly

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variable and less than crop water need; consequently, water conservation is essential to stabilize production and increase yields.

The principal measures to alleviate the shortage of water and irregular rainfall comprise: region specific research on supplementary irrigation; water harvesting techniques; alternative crops; and training, extension, and demonstration. Prinz and Singh (2000) reported that rainfall based agricultural lands occupy almost 75% of the total world cultivated land which still supplies some 60% of world food. Moreover, efficient water harvesting increases the crop yields in rainfed areas and depends strongly on the rainfall pattern and its distribution.

Water harvesting is the process of collecting and storing water for later beneficial use from an area that has been modified or treated to increase precipitation runoff (Frasier, 1994). The collected water can be used for most purposes such as domestic uses and for growing plants. Water harvesting systems are mainly practiced in arid and semi-arid areas with annual rainfall ranging from 100 to 600 mm (Oweis et al., 1999).

Two main systems of water harvesting techniques have been widely implemented. The macro-catchment water harvesting system, in which the surface runoff is collected from a large area (called the catchment or the contributing area). The collected water is then either stored in reservoir for further use as a supplemental irrigation or directly applied to the soil for use by the crops (Oweis et al., 2005). The system was evaluated by Singh (1976) who found that each hectare of cropped area receives 23–108 mm of runoff as irrigated water from the catchments in addition to 117–528 mm from direct rain. This may lead to the maximization of crop yield with lower risk of crop failure. Hassan et al. (1998) found that soil moisture content increasing with increasing catchment area to cultivated area ratios up to 3:1 as compared to 2:1 and 1:1 grain yield, biological yield and harvest index were significantly increased with increasing ratio of catchments area to cultivated area as compared to the control.

Micro-catchment water harvesting systems have been reported in many studies and found to be very effective in arid and semiarid regions where irrigation water is not available or costly (Ben-Asher et al., 1985; Boars et al., 1986). Micro-catchment water harvesting can improve soil moisture storage, prolong the period of moisture availability, and enhance growth of field horticultural and forest crops. Examples of these techniques are contour ridges and semi-circular and trapezoidal bunds. Li et al. (2000) stated that using the micro-catchment system accompanied with mulch increased the corn grain yield by 46.29% as compared to the cultivation in flat bare soil.

The ridge–furrow water harvesting system (RFWHS) is one type of micro-catchment harvesting technique in which the rainfall water is harvested through the mulched ridges and the crop is planted in the furrows between the ridges (Li and Gong, 2002). The planting zone can be covered in order to prevent the evaporation from the soil as illustrated by Li and Gong (2002), Li et al. (2013, 2000), Zhou et al. (2009), and Xiaili et al. (2012) or by using supplemental irrigation (Xiao et al., 2007; Gosar and Baricevic, 2011) during different periods of plant growth; or using both practices (Wang et al., 2009, 2011).

There are few studies on the implementation of this water harvesting technique in dry areas; therefore, an experiment was designed and conducted in the field with the following objectives: (a) to understand the factors contributing to the yield of faba been cultivated under different ratio of ridges and furrows as compared to the conventional method in a flat plot (b) to assess the effect of different plant densities on faba bean productivity under the rainfed conditions of Marsa Matrouh in the North Western Coastal Zone of Egypt.

Materials and methods

Site description

This study was conducted during the two growing seasons of 2012/2013 and 2013/2014 at the agricultural research station, Sustainable Development Center of Matrouh Resources, Desert Research Center that is located in the North Western Coastal Zone of Egypt (31.35° N, 27.18 E) and is at 9 m in altitude. Mean annual precipitation is 126 mm, with considerable year to year variation ranging from 76 mm to over 225 mm and the mean annual temperature is 20.47 °C. The soil is sandy clay loam, which is strongly calcareous (17.7% CaCo3), with an EC of 0.224 dS/m and pH of 8.3.

Treatments and experimental design

Seeds of faba bean (cultivar, Nubaria 1) were sown in Nov. 14, 2012 for the first season and in Nov. 17, 2013 for the second season, with about 20 cm apart, weeding was carried out by hand. The experiment was laid out in a split plot design with three replications, ridge:furrow ratios were allocated in the main plots, while the plant densities were assigned to the sub-plots. The three treatments of the RFWHS were: (1) conventional cultivation in a flat plot, (2) plastic mulched ridges of 120 cm wide and 60 cm wide furrows (2:1 ratio), and (3) plastic mulched ridge with both ridge and furrow 60 cm wide (1:1 ratio). Whereas, Plant density included planting in 2 rows (60 cm apart), three rows (30 cm apart), and four rows (20 cm apart).

The plants were harvested from an area of 3.6 m^2 (plot area) which obtained from 0.6 m width and 6 m length of cultivated furrow. Seed, straw and biological yields/ha were based on the land area including ridge and furrow. No fertilizer applications were applied to the plants as is practiced by the local farmers in the region. The plants were harvested in March 20, 2013 for the first season and in March 10, 2014 for the second season.

Sampling and measurements

During the two growing seasons, soil moisture content was determined gravimetrically to a depth of 20 cm. Before sowing, the average bulk density was measured to be 1.41 g/cm^3 and the porosity is 46.7%. Sampling plot area i.e. 3.6 m^2 was chosen randomly from every treatment to record the following criteria; plant height (cm), plant dry weight (g), weight of seeds/plot (g), 100 seed weight (g), seed yield (kg/ha), straw yield (kg/ha) and biological yield (kg/ha). The harvest index (%) and crop index (%) were calculated as the percentage ratio of seed yield to the biological yield and the straw yield, respectively. The water use efficiency (seed yield kg/ha mm) was calculated as the ratio of the unit area faba bean yield to the sum of the total rainfall during the growing season, assuming that the soil was dry at the beginning and the end of the growing season.

Statistical methods

All data were analyzed using analysis of variance (ANOVA) to determine the significance of the main effects and their interaction. Least significance difference (LSD) tests were performed to determine the significant differences between individual means. All statistical analyses were performed using the Cropstat version 7.2 statistical software (Cropstat, 2009).

Results and discussion

Rainfall data

The total rainfall was 102.25 mm and 96.05 mm during the 2012/2013 and 2013/2014 growing seasons, respectively. Rainfall started early in the first season (Oct. 24) with 5.9 mm, and the first effective rainfall of 13.57 mm fell on Nov., 8. While during the second season, the first effective rainfall of 10.71 mm was recorded on Dec., 12. The distribution of the precipitation during the two growing seasons consisted of 9 rainfall events (72.72% of the total first growing season) and only 5 rainfall events (85.2% of the total second season) over 5 mm per event. Cumulative precipitation, as determined from the Tropical Rainfall Measuring Mission (TRMM; http://trmm.gsfc.nasa.gov), during the two growing seasons is presented in Fig. 1.

Effect of different ridge/furrow ratios on faba bean seed yield, yield components and WUE

The ridge:furrow ratio had a significant effect on seed yield and its components in the two growing seasons (Table 1). The treated ratio of 120:60 cm produced the highest plant height (43.76 and 34.16 cm), plant dry weight (17.33 and 10.86 g), weight of seeds/plot (813.3 and 489.9 g) and 100-seed weight (87.05 and 62.86 g) for the 2012/2013 and 2013/2014 seasons, respectively (Table 1). These results suggest that the increase in ridge:furrow ratio can improve the individual plant parameters as a result of increasing the concentrated rain water in the furrows between the ridges. Li et al. (2000) showed that plastic cover over the ridges increases the efficiency of runoff generation which reaches 87% in average; however, the runoff efficiency of bare ridges is very low (7%).

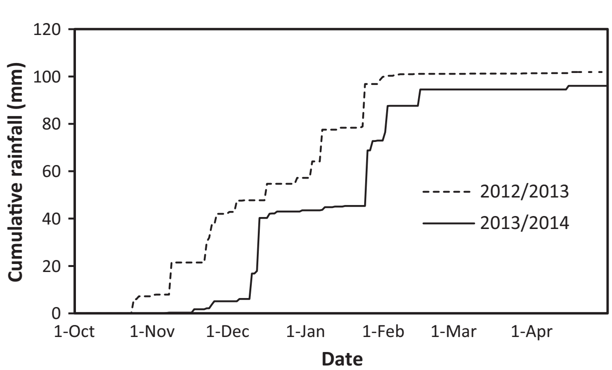

Fig. 1 Cumulative rainfall during the two growing seasons.

On the other hand, seed, straw and biological yields responded differently to the ridge:furrow ratio. For the treated ratio of 60:60 cm, the seed yield increased by 47% in the first season and 128% in the second season as compared to the conventional cultivation in a flat plot. However, straw and biological yields reached their maximum values in the flat plot cultivation. At this point, we should mention that seed, straw and biological yields were estimated from plants entire plot; therefore, it is expected that flat plot which has plot area of 3.6 m^2 will produce the highest yields/ha. Similar results were obtained by Li and Gong (2002) who reported that the 120:60 ridge:furrow ratio plots had increased the grain yield of corn by 27.9% based on the area harvested of the cropped furrow as compared to that from the 60:60 ridge/furrow ratio. However, the crop from the 120:60 ratio had a decreased seed yield measured from the individual plots including ridge and furrow by 16.2% in comparison with the 60:60 ratio. Also, Jia et al. (2006) reported that mulched ridges with both ridges and furrows 60 cm wide increased the total alfalfa forage yield in three years by about 40.3% higher than the conventional cultivation in a flat plot.

There are no significant differences between the 120:60 ratio system and 60:60 ratio for the crop index and harvest index in the first season, however, in the second season the 60:60 ratio system produced the highest crop index (92.62%) and harvest index (48.33%). The water use efficiency was increased by 47% and 42.7% in the first season, and by 128.2% and 18.15% in the second season, when the plants were cultivated in the 60:60 furrow:ridge ratio plots as compared to the conventional cultivation and the 120:60 furrow:ridge ratio, respectively.

The relatively low seed yield in both growing seasons is mainly caused by the long dry spells during the two seasons, for example in the first season the last significant rain was on Jan. 24 with 17.91 mm; however, in the second season, it was on Feb. 15 with 6.86 mm. Water stress during the critical periods of plant growth; i.e. flowering and seed filling, resulted in a dramatic loss in seed yield. Supplemental irrigation during these critical periods is necessary to improve the seed yield. Oweis et al. (2005) showed that full supplemental irrigation based on the crop water requirements increased the average faba bean seed yield and WUE to 1.89 t/ha and 0.61 kg/m^3 as compared to only relying on rainfall (1.13 t/ha and 0.50 kg/m^3, respectively). Moreover, some research has shown that different types of mulch can improve the crop yield (Li and Gong, 2002; Wang et al., 2009; Xie et al., 2005).

Effect of row spacing on faba bean yield, its components and WUE

The data presented in Table 2 show that there were significant differences between row spacing in all of the studied characteristics in the first season, however, in the second season only plant dry weight, weight of seeds/plot, 100-seed weight, crop yield and water use efficiency, showed significant differences.

The results indicate that the traits of weight of seeds/plot, seed yield and water use efficiency in the two growing seasons and plant height, straw yield and biological yield in the first season increased at the plant population density of 30 cm

Table 1 Effect of furrow ridge ratios on faba bean seed yield, its components and water use efficiency in the 2012/2013 and 2013/2014 growing seasons.

Ridge:furrow ratio	Plant height (cm)	Plant dry weight (g)	Weight of seeds/plot (g)	100 – seed weight (g)	Seed Yield (kg/ha)	Straw yield (kg/ha)	Biological yield (kg/ha)	CI (%)	HI (%)	WUE (kg/ha mm)
2012/2013 season										
S1	43.78	17.33	813.3	87.05	410.1	642.5	1052.6	64.36	38.12	4.011
S2	34.09	12.64	641.5	75.05	511.6	832.6	1344.2	64.11	38.78	5.003
S3	27.10	6.088	253.4	39.79	348.0	1135.9	1483.8	29.96	22.78	3.403
LSD	5.50	2.22	135.73	3.11	52.52	173.3	173.3	9.81	3.55	0.513
2013/2014 season										
S1	34.16	10.86	489.6	62.86	272.0	393.4	665.5	71.94	41.45	2.660
S2	25.44	6.185	347.1	47.72	321.4	388.72	710.1	90.62	48.33	3.143
S3	17.77	2.627	50.70	33.31	140.8	516.9	657.7	29.14	22.25	1.377
LSD	4.41	1.64	12.59	3.27	18.87	158.2	168.79	17.86	6.47	0.184

Note: S1 is 120:60 ridge/furrow, S2 is 60:60 ridge/furrow, S3 is the conventional cultivation on a flat plot, CI is crop index, HI is harvest index and WUE is water use efficiency, LSD is Least Significant Difference.

Table 2 Effect of row spacing on faba bean seed yield, its components and water use efficiency in the 2012/2013 and 2013/2014 growing seasons.

Row spacing	Plant height (Cm)	Plant dry weight (g)	Weight of seeds/Plot (g)	100 – seed weight (g)	Seed yield (kg/ha)	Straw yield (kg/ha)	Biological yield (kg/ha)	CI (%)	HI (%)	WUE (kg/ha mm)
2012/2013 season										
D1	33.15	14.64	470.8	74.02	424.1	739.9	1164.0	64.71	37.21	4.148
D2	38.30	12.27	642.3	65.70	491.1	963.2	1454.3	54.20	34.75	4.803
D3	37.52	9.140	595.1	62.18	354.5	907.7	1262.2	39.52	27.73	3.467
LSD	1.81	1.12	80.41	2.43	42.66	86.85	105.53	5.29	2.59	0.417
2013/2014 season										
D1	25.97	8.792	295.6	54.16	234.1	383.3	617.5	61.07	36.76	2.290
D2	25.53	6.353	319.6	46.51	263.8	441.7	705.6	69.48	37.78	2.580
D3	25.86	4.528	272.2	43.22	236.2	474.0	710.3	61.14	35.48	2.310
LSD	NS	1.65	19.02	3.05	20.69	NS	NS	NS	NS	0.202

Note: D1 is 60 cm row spacing, D2 is 30 cm row spacing, D3 is 20 cm row spacing, CI is crop index, HI is harvest index, WUE is water use efficiency, LSD is Least Significant Difference, NS; Non-Significant.

row spacing in comparison with the other densities; i.e., 20 and 60 cm row spacing. However, plant dry weight and 100 seed weight in both seasons were increased by increasing the row spacing up to 60 cm. Although the higher row spacing of 60 cm produced the heaviest 100-seed weight of 74.02 and 54.16 g in the two growing seasons, respectively. The highest seed yield at 30 cm apart may have resulted from higher number of seeds per plot produced from this treatment. Low 100-seed weight produced from the higher density might be due to the high plant competition during the water stress period at the end of the growing season which coincides with the seed filling period.

Both crop index and harvest index responded differently in both seasons. For example, in the first season, the 60 cm row spacing produced the highest harvest index (37.21%) and crop index (64.71%); however, in the second season these two measurements were the highest for the 30 cm row spacing with no significant differences among the three populations. Some studies have shown that wide row spacing (i.e., 60 cm (Bakry et al., 2011), from 50 to 70 cm (Thalji, 2006) produced the highest faba bean seed yield; however, others have shown that narrower row spacing (between 10 and 12 cm (Yucel, 2013), and 15 cm (Kondra, 1975) is optimal for maximum seed yield.

Determining the optimum plant density under the conditions of rainfed agriculture is an important task. Increasing plant density increases the competition among plants for light, nutrients, water and all other growth resources; however, it might produce a higher yield per unit area and a lower yield and growth per plant because the lower plant attributes are compensated through higher plant population per hectare. That was noticeable from our results: the highest plant density (20 cm row spacing) produced a relatively higher straw and biological yield in the two seasons and seed yield in the second season as compared to the lowest plant density used (60 cm row spacing). However, the narrow row spacing reduces the inter-row evaporation with a little impact on seed yield (Chen et al., 2010).

Table 3 Effect of furrow ridge ratios and row spacing interaction on faba bean seed yield, its components and water use efficiency in the 2012/2013 and 2013/2014 growing seasons.

Treatments		Plant height (cm)	Plant dry weight (g)	Weight of Seeds/Plot (g)	100 – seed weight (g)	Seed yield (kg/ha)	Straw yield (kg/ha)	Biological yield (kg/ha)	CI (%)	HI (%)	WUE (kg/ha mm)
2012/2013 season											
S1	D1	46.16	23.48	878.9	95.93	563.96	626.2	1190.1	89.91	47.30	5.51
	D2	49.95	16.47	1065	86.10	413.27	658.9	1072.2	63.66	38.75	4.04
	D3	35.25	12.04	496.1	79.13	253.22	642.2	895.5	39.53	28.31	2.47
S2	D1	27.13	12.76	299.0	83.33	444.43	567.0	1011.5	78.51	43.96	4.35
	D2	36.65	13.81	517.1	68.00	543.98	920.8	1464.9	59.56	37.26	5.32
	D3	38.50	11.36	1108.	73.83	546.35	1009.	1556.1	54.25	35.14	5.34
S3	D1	26.16	7.699	234.6	42.80	263.90	1026.	1290.4	25.73	20.37	2.58
	D2	28.30	6.550	344.8	43.00	515.98	1309.	1825.9	39.38	28.25	5.05
	D3	26.83	4.016	180.8	33.58	264.03	1071.	1335.1	24.77	19.74	2.58
LSD		3.14	1.94	139.3	4.21	73.891	150.4	182.77	9.16	4.49	0.723
2013/2014 season											
S1	D1	36.11	15.13	535.4	74.36	297.46	403.5	701.00	73.82	42.41	2.909
	D2	32.00	11.53	507.1	58.70	281.75	461.2	742.94	64.58	38.65	2.755
	D3	34.37	5.920	426.3	55.51	236.85	315.7	552.57	77.40	43.29	2.316
S2	D1	24.66	8.966	308.3	53.53	285.50	376.3	661.79	76.13	43.16	2.792
	D2	25.84	4.813	402.6	46.60	372.79	320.9	693.67	116.7	53.78	3.645
	D3	25.84	5.276	330.4	43.03	306.00	469.0	775.03	78.95	42.03	2.992
S3	D1	17.15	2.776	43.05	34.58	119.58	370.2	489.80	33.25	24.70	1.169
	D2	18.76	2.716	49.29	34.23	136.93	543.3	680.25	27.10	20.93	1.339
	D3	17.39	2.390	59.76	31.12	166.00	637.3	803.32	27.06	21.13	1.623
LSD		4.37	2.86	32.95	5.28	35.85	215.2	202.07	35.42	12.18	0.351

Note: S1 is 120:60 ridge/furrow, S2 is 60:60 ridge/furrow, S3 is the conventional cultivation on a flat plot, D1 is 60 cm row spacing, D2 is 30 cm row spacing, D3 is 20 cm row spacing, CI is crop index, HI is harvest index and WUE is water use efficiency, LSD is Least Significant Difference, NS; Non-Significant.

Effect of furrow:ridge ratios and row spacing interaction on faba bean yield, its components and water use efficiency

A significant interaction between ridge:furrow ratios and the row spacing was observed in the results from the two growing seasons (Table 3). All studied characteristics showed a significant difference among the treatments. In the first season, using the ratio of 120:60 cm ridge:furrow with low plant density (60 cm row spacing) recorded the highest plant dry weight, 100-seed weight, seed yield, straw yield, crop index, harvest index and water use efficiency. However, the control (conventional cultivation) accompanied with the plant density of 30 cm row spacing produced the highest straw yield and biological yield for the unit area. This is probably caused by the high population of plants per hectare.

In the second season, again the 120:60 ridge/furrow ratio combined with the lowest plant density of 60 cm row spacing recorded the highest values of plant height, plant dry weight, 100-seed weight and weight of seeds/plot. The 60:60 ridge/furrow ratio with 30 cm row spacing produced the maximum seed yield, crop index, harvest index, and water use efficiency. As reported in the first season, the conventional cultivation in a flat plot showed the highest straw and biological yields, but with the highest plant density of 20 cm row spacing in this case.

Seed, straw and biological yields (kg/ha) were calculated based on the plot area including the ridges and furrows. The conventional cultivation does not contain any ridges; in this case it has the plot area of 3.6 m^2. It can be calculated from this investigation that the three yields based on only the cultivated area (3.6 m^2) had the highest seed and biological yields of 2818 and 5948 kg/ha were obtained at the 120:60 ridge/furrow ratio with the lowest plant density (60 cm row spacing), while the highest straw yield of 3293 kg/ha was at the 120:60 ratio with 30 cm row spacing. In the second season, the highest seed, straw and biological yields (1435, 2371 and 3752 kg/ha; respectively) were recorded at the system of ridge:furrow ratio of 120:60 cm with a row spacing of 30 cm.

Conclusion

The agriculture system in the North Western Coastal Zone of Egypt is mainly dependent on rainfall where its amount and distribution are the key factors of crop production in this area. The RFWHS is an effective system of the water harvesting and it is well known at the semi-arid Loess Plateau in China; however, it is unknown to the local farmers in the NWCZ of Egypt. Under the dry conditions of the NWCZ of Egypt, regardless of the ridge/furrow ratio, the RFWHS system increased the seed yield of faba bean yield, its components and the water use efficiency over the control (conventional cultivation in a flat plot). According to the obtained results, the most effective ridge size for faba bean production is 60 cm. Increasing the plant density is one way of compensating for the area consumed by the ridges; the row spacing of 30 cm produced the highest seed yield over the two growing seasons. We suggest that the system needs to be evaluated for other crops cultivated under the rainfed conditions in the study area; i.e., wheat, barley, medicinal, and aromatic plants.

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