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Ridge–furrow–ridge Rainwater Harvesting System with Mulches and Supplemental Irrigation

Borut Gosar[1] and Dea Baričevič

Department of Agronomy, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, 1000 Ljubljana, Slovenia

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***Abstract*. New ridge–furrow–ridge rainwater-harvesting (RFRRH) system with mulches has been promoted in agricultural production to improve economic potential for high-value plant production. In this system, plastic mulch covers two ridges and the furrow between them, which serves as the rainwater-harvesting zone. To test this system more effectively, a field study using purple coneflower (*Echinacea purpurea* Moench) as an indicator crop was conducted to determine the effect of the RFRRH system with or without a covering of two different types of polyethylene mulches and with or without supplemental irrigation on soil water content, crop yield, and time dedicated to weed control during the growing seasons of 2007 and 2008. In the non-irrigated plots, the results showed significantly higher soil water content during dry periods at the beginning of plant growth in the mulch-covered RFRRH system in comparison with the control (uncovered ridges). In comparison with the control, the mulch-covered RFRRH system significantly increased yield and reduced time dedicated to weed control. In the event of a rainfall deficiency, the mulch-covered RFRRH system enabled simple supplemental irrigation, using an agricultural vacuum tanker, by flooding the polyethylene mulch-covered furrow with hardly any ridge erosion. However, in only 1 year did supplemental irrigation significantly increase yield.**

Purple coneflower (*Echinacea purpurea* Moench.) is a perennial plant used as a natural immunostimulant. It increases the non-specific resistance of a body against virus, bacterial, and fungal infections. Preparations made from purple coneflower are made from freshly pressed above-ground parts of the plant. Purple coneflower is cultivated in Slovenia on ≈20 ha for the pharmaceutical company Lek, which purchases and processes fresh above-ground plant parts and sells its preparations on domestic and international markets.

Ridge and furrow rainwater-harvesting (RFRH) systems with mulches were first researched in the flat, lowland, semiarid conditions of northwest China (Li et al., 2000, 2001) to improve water availability and to increase crop production. In this RFRH system, the plastic-covered ridges serve as rainwater harvesting zones, and bare or mulched furrows serve as planting zones. Although the RFRH system improves water availability and increases yield, it still has many deficiencies that prevent practical application of this system. The first is relatively high soil compaction in the cultivated plant rhizosphere, because planting in the furrow at the base of a ridge increases soil compaction (Mundy et al., 1999). The second is relatively high soil erosion (Kornecki et al., 2005) and leaching of fertilizers (Marr, 1993; Romić et al., 2003) in the cultivated plant rizosphere, especially with heavy rainfall. Another type of RFRH system with mulches, a RFRRH system, was first investigated in flat, lowland humid regions of central Europe (Gosar et al., 2010). In this RFRRH system, polyethylene mulch covers two ridges (which serve as planting zones) and the furrow between them, which serves as the rainwater-harvesting zone. The RFRRH system with mulches manages plant cultivation even under impermeable mulch without using an irrigation system, which was novel in plant production systems. The results of this 1-year study (Gosar et al., 2010) showed that the RFRRH system did not significantly increase yield but significantly increased soil water content in dry periods at the beginning of plant growth. Unlike the RFRH system, the RFRRH system with mulches does not have a negative effect on soil compaction, soil erosion, and when using impermeable mulch leaching of fertilizers (Marr, 1993; Romić et al., 2003) in the cultivated plant rhizosphere because the planting zone is on top of the ridges.

The aim of this study was to determine if RFRRH system with two different types of mulches enable simple and efficient supplemental irrigation and how supplemental irrigation affects soil water content, yield, and time dedicated to weed control in growing purple coneflower.

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[1]To whom reprint requests should be addressed; e-mail borut.gosar@bf.uni-lj.si.

Materials and Methods

Description of study site. Field experiments were carried out in Vodice, near Ljubljana, Slovenia, in the Biotechnical Faculty laboratory field (lat. 46°09′40.51″ N; long. 14°30′41.09″ E; elev. 320 m a.s.l.) during the growing seasons of 2007 and 2008. The climate of the region was humid. The 1999–2008 average minimum and maximum air temperatures ranged from 0.8 °C (January) to 21.0 °C (July). The 1999–2008 average precipitation for the period from April to September was 705 mm. Precipitation during the months from April to September was 670 mm in 2007 and 703 mm in 2008. The measured pan evaporation from April to September was 624 mm in 2007 and 606 mm in 2008 (Fig. 1). Precipitation and pan evaporation were measured at the experimental site. The weather conditions in the growing seasons of 2007 and 2008 were similar to the 10-year average. The slope in the experimental field was from 0.05% to 0.2%. The soil in the experimental field was a deep dystric cambisol. The soil in the upper 30 cm was silty clay loam/silty loam. The average groundwater depth in this area from April to September ranged from 2 to 4 m and is rarely less than 1 m. The soil wilting point was 17.2 vol%, the soil field capacity was 38.8 vol%, and the soil bulk density was 1.11 $g \cdot cm^{-3}$. The water infiltration rate, using an FAO infiltration test (using ring infiltrometer), was 17 $mm \cdot h^{-1}$ and was achieved after 80 min. However, the first 20 mm of water infiltration lasted ≈20 min.

Experimental design and management. The experimental field was fertilized with stable manure (20 $t \cdot ha^{-1}$) in fall and deeply (25 cm) ploughed in both years. Each spring fields were fertilized with mineral fertilizers (60 kg N/ha, 60 kg P_2O_5/ha, and 60 kg K_2O/ha). After fertilization, the soil was tilled with a cultivator.

The field experiment consisted of two factors: use or not of irrigation for the main plots and the RFRRH system with different mulches as subplots in a split-plot design with four repetitions that were arranged in a randomized complete block design. There were two levels of irrigation: non-irrigated and irrigated. Three levels of the RFRRH system were covered with different mulches: RFRRH system with impermeable mulch [1.2 m wide and 0.02 mm thick black ultraviolet stabilized polyethylene (PE) mulch], an RFRRH system with permeable mulch (1.2 m wide and 0.02 mm thick black woven ultraviolet stabilized PE mulch), and uncovered ridges (control). Split plots, each with a length of 30 m, consisted of three different RFRRH sub-plots. Each sub-plot measured 14 m^2 and consisted of two rows (ridges) with a length of 10 m. In the RFRRH system with mulches, the mulch was placed over two ridges (the ridge height was in average 11 cm and the ridge maximum slop was 70%) and the furrow between them, which serves as the rainwater-harvesting zone. The interrow width between the mulched ridges was 60 cm. The interrow width of the unmulched furrow between mulched ridges was 120 cm (in practice can be reduced to ≈80 cm) and served as a driving path (Figs. 2 and 3). Wide driving paths also replaced border rows and prevented rain or irrigation moving between split plots. The edges of the mulch were dug into a shallow side ditch. On the top of the ridges, the mulch was cut at intervals of 25 cm to create space for the seedlings. Only when using impermeable PE mulch was the mulch cut transversely at 50-cm intervals between the ridges (in the furrow) to allow rainwater to reach the space under the mulch and to prevent lengthways flow. Purple coneflower seedlings (*Echinacea purpurea* Moench; Johnny' Selected Seeds, Lot No. 16697) were obtained from the Biotechnical Faculty in Ljubljana, Slovenia. Seedlings were planted in May (in 2007 and 2008), after rainfall, and watered once more after 3 d. The purple coneflowers were regularly cleared of weeds. No plant protection products were used during the growing period. This system allowed the cultivation of purple coneflower using impermeable mulch without a trickle irrigation system beneath the mulch by enabling the rainwater to drain beneath the mulch. No mulch was used with the control, whereas soil preparation before planting, interrow width between ridges, interrow spacing between plants, and supplemental irrigation were the same as in other treatments.

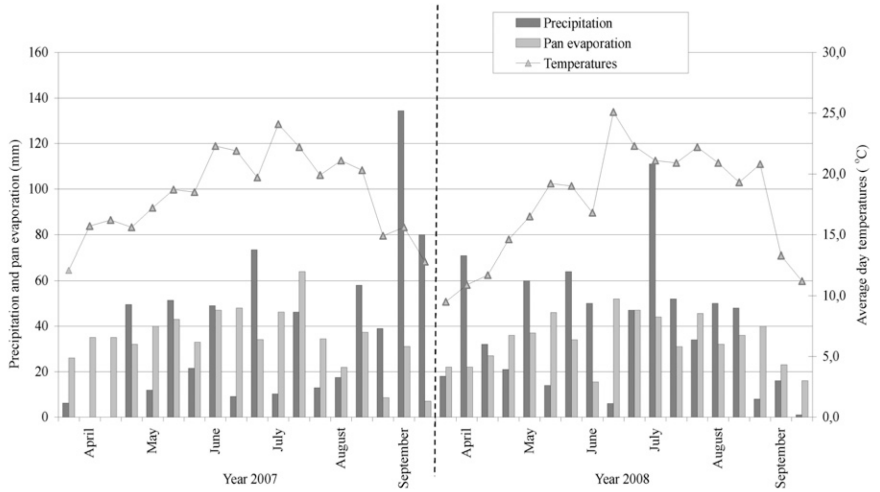

Fig. 1. Precipitation, pan evaporation, and average minimum–maximum temperatures in °C by 10-d average (ARSO, 2008) from the 2007 and 2008 growing seasons.

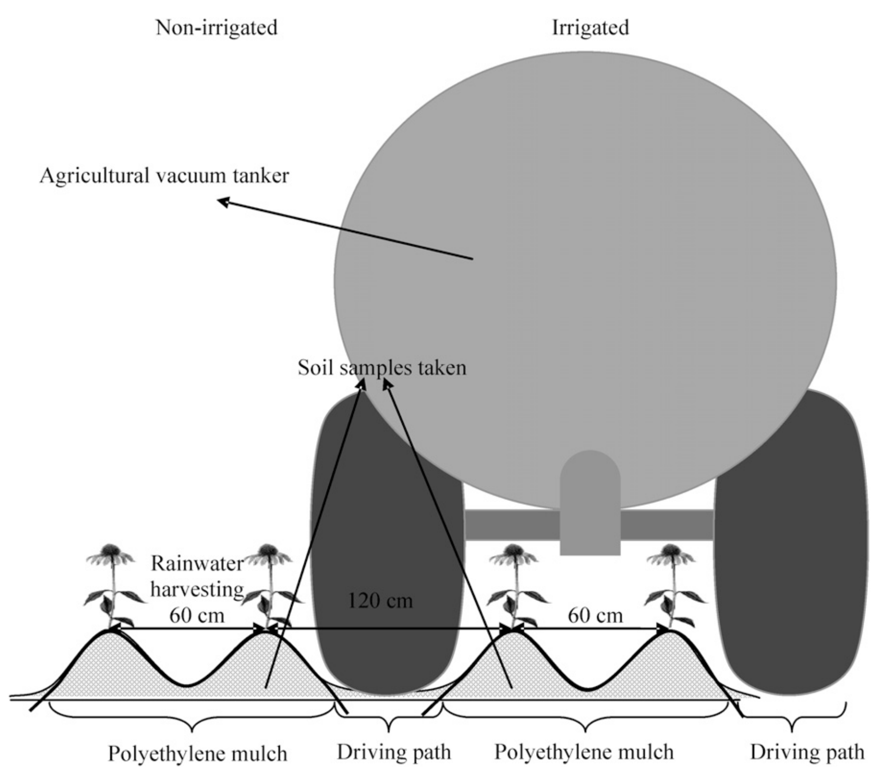

Fig. 2. Ridge setting, placement of mulch (sectional view), and presentation of additional irrigation by flooding the polyethylene mulch-covered furrow in a ridge–furrow–ridge rainwater-harvesting system.

Supplemental irrigation was supplied by means of an agricultural vacuum tanker in such a way that the furrow between the ridges was flooded (Fig. 2). The amount of applied water for each application was 20 mm. Supplemental irrigation was supplied when at least one of the RFRRH treatments with impermeable mulch or the RFRRH treatment with permeable mulch had a soil water content under 30 vol.% (which is ≈60% of the maximum plant-available water the soil can provide at field capacity). If the 2-d weather report forecasted an abundance of precipitation, supplemental irrigation was not applied. Supplemental irrigation was applied four times in 2007 (20 July, 24 July, 9 Aug., and 18 Aug.) and five times in 2008 (3 July, 5 Aug., 4 Sept., 8 Sept., and 19 Sept.). The soil water content dynamic with rainwater and supplemental irrigation is shown in Figure 4.

Measurements and data analysis. The purple coneflower yield, soil water content, and number of hours required for manual weed control were measured for four replicates in all treatments.

Plant weight was determined by weighing the fresh, above-ground parts of the plant cut ≈10 cm above the ground. Soil water content was measured gravimetrically for the period from 28 June to 25 Sept. in 2007 and from 27 May to 27 Sept. in 2008. Because purple coneflower fully developed plants have ≈91% of the roots in the 30 cm upper layer of the soil (Gosar et al., 2010), soil samples were taken 15 to 25 cm beneath the ridge (Fig. 2) at every treatment plot. Soil samples were taken at 3- to 5-d intervals at the same time of day and at least 12 h after rainfall. Weeds were controlled on 3 June, 20 July, and 1 Sept. in 2007 and on 25 June, 25 July, and 19 Aug. in 2008 and weeding time was measured and summed for each plot individually.

Because soil water content was meaningful to analyze for non-irrigated RFRRH treatments only, analysis of variance (ANOVA) test and Duncan's multiple range tests were used to assess the significance of the treatments. In cases in which the ANOVA test showed significant differences among treatments ($P < 0.05$), comparisons of means were undertaken using the Duncan's multiple range test ($P < 0.05$). Yield and weed control time were examined using a split-plot ANOVA test. In cases in which the split-plot ANOVA test showed significant differences among treatments ($P < 0.05$), comparisons of means were undertaken using the Duncan's multiple range test ($P < 0.05$). The statistical analysis was carried out by using STATGRAPHICS Plus 4.0 software (STATPOINT TECHNOLOGIES, INC., Warrenton, VA).

Results and Discussion

In the non-irrigated plots, the soil water content in dry periods at the beginning of the trial (from 17 to 28 July in 2007 and from 27

Fig. 3. A photograph showing the ridge–furrow–ridge rainwater harvesting (RFRRH) system with mulches. In the bottom of the photograph is a RFRRH system cowered with water-impermeable polyethylene mulch fallowed by the RFRRH system cowered with water-permeable (woven) polyethylene mulch.

June to 12 July in 2008) was mostly significantly higher in the RFRRH system with mulches in comparison with the control. However, in later dry periods (from 8 to 11 Aug. in 2007 and from 3 to 6 Aug., 19 to 22 Aug., and from 29 Aug. to 27 Sept. in 2008), the soil water content was consistently not significantly different among treatments in both years (Fig. 5). These findings are in agreement with the results of a similar trial (Gosar et al., 2010; Gosar and Baričevič, 2010). This soil water content dynamic can be explained by the finding that black mulches can decrease evaporation by 50% to 80% but increase transpiration by 10% to 30% (Battikhi and Hill, 1986; Ghavwi amd Battikhi, 1986; Haddadin and Ghawi, 1983; Hegazi, 2000). The RFRRH system with mulches therefore had a significantly higher soil water content in dry periods at the beginning of the trial because of relatively high evaporation and low transpiration (as a result of smaller plants) and did not show different soil water content in dry periods in the last part of the trial because of relatively high transpiration and low evaporation (as a result of larger plants). As a result, only when the plants are small can the RFRRH system covered with mulches contribute much to reducing evapotranspiration.

According to a split-plot ANOVA analysis, interaction of irrigation × RFRRH system was never significant (Table 1); therefore, only mean values of main effects for irrigation and RFRRH system are presented further in Table 2. The RFRRH system as a factor had a significant impact on yield (P = 0.028 in 2007 and P < 0.001 in 2008) and weed control time (P < 0.001 in 2007 and P < 0.001 in 2008). Irrigation as a factor had a significant impact on yield (P = 0.043) in 2007 and not significant impact on yield (P = 0.46) in 2008 (Table 1).

The RFRRH system with mulches showed a significant yield increase in both years. In comparison with the control, there was a significant yield increase of 14% and 20% in the RFRRH system with impermeable mulch and permeable mulch, respectively, in 2007 and a significant yield increase of 85% and 79% in the RFRRH system with impermeable mulch and permeable mulch, respectively, in 2008 (Table 2). The higher yields using the RFRRH system with mulches can be explained by the higher soil water content in dry periods at the beginning of plant growth in the RFRRH system with mulches as well as by the higher soil temperature (not measured) under black mulch (Tanner, 1974) and the lower nitrogen leaching (not measured) under the impermeable mulch (Marr, 1993; Romić et al., 2003). Yields in 2008 were lower than yields in 2007. There are two possible explanations. First, it might be because of the first dry period in 2008, which arrived ≈3 weeks earlier than the first dry period in 2007. The earlier drought in 2008 may have had more effect on younger plants, especially in the control plots, which at that time had the lowest soil water contents among all treatments (Fig. 5). Moreover, supplemental irrigation did not have much effect on plant growth in that dry period because it was carried out only 3 d before abundant precipitation (Fig. 4). A second explanation might be that the first weeding was carried out 22 d later in 2008 than in 2007. This had a significant effect on young non-mulched plants in control plots in 2008, which were more affected by the weeds.

Supplemental irrigation by flooding the PE mulched furrow with the help of an agriculture vacuum tanker was a simple task and caused almost no ridge erosion. Supplemental irrigation had a significant effect (P = 0.043) (Table 1) of 11% (Table 2) higher yield in comparison with non-irrigated plots in 2007. Irrigation was applied twice in the first dry period, when juvenile plants needed moisture. Supplemental irrigation in 2008 had no significant effect on yield and may be explained by the relatively humid climatic conditions through the juvenile plant stage. Moreover, supplemental irrigation applied in Sept. 2008 was ineffective because of the plant's well-developed root systems, which can absorb water from deeper soil layers as well as because of the low temperatures that appear at that time (Fig. 1), which consequently reduced plant growth.

Within the growing period, the RFRRH system had a significant (P < 0.001) effect on reducing work hours that were devoted to weed control in both years (Table 1). Compared with the control, the impermeable mulch reduced weed control time by 87% in 2007 and 95% in 2008; permeable mulch reduced weed control time by 82% in 2007 and 87% in 2008 (Table 2). The results of this study show that mulches assist in weed control, which was consistent with other studies (Gosar et al., 2010; Gosar and Baričevič, 2010; Hegazi, 2000; Johnson and Fennimore, 2005).

Supplemental irrigation, however, had no significant effect on time dedicated to weed control, which suggests that weeds had enough water for their normal growth in both years.

In areas with no nearby water, the RFRRH system with mulches offers now an alternative in producing plants under impermeable mulch where under the mulch, expensive tubing for a drip irrigation system is needed. To choose which mulch production system (mulch drip irrigation system or mulch RFRRH system) is more cost-efficient, each producer should calculate between higher investment costs (costs for tubing and water source) when using mulch drip irrigation system and expected supplemental irrigation costs when using a mulch RFRRH system. One irrigation (20 mm) costs ≈300 EUR/ha and mostly depends on remoteness of the water source and on the volume of the agricultural vacuum tanker. A mulch RFRRH system is expected to be economically more efficient than

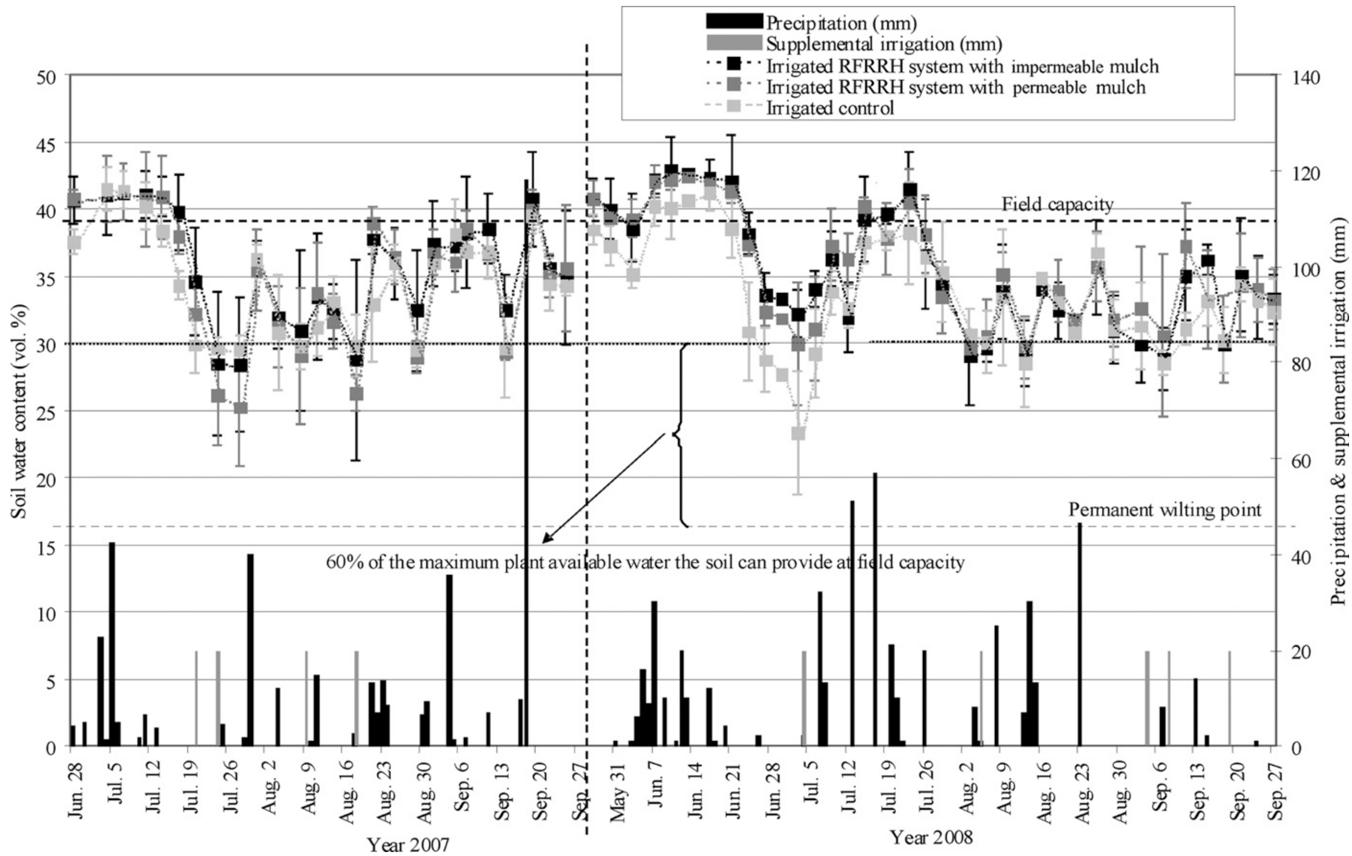

Fig. 4. Precipitation (in millimeters) and soil water content dynamic (vol. %) with an irrigated ridge–furrow–ridge rainwater-harvesting (RFRRH) system with impermeable, permeable mulch, and a control at a depth of ≈0.2 m measured in 3- to 5-d intervals between 28 June and 25 Sept. in 2007 and 27 May and 27 Sept. in 2008.

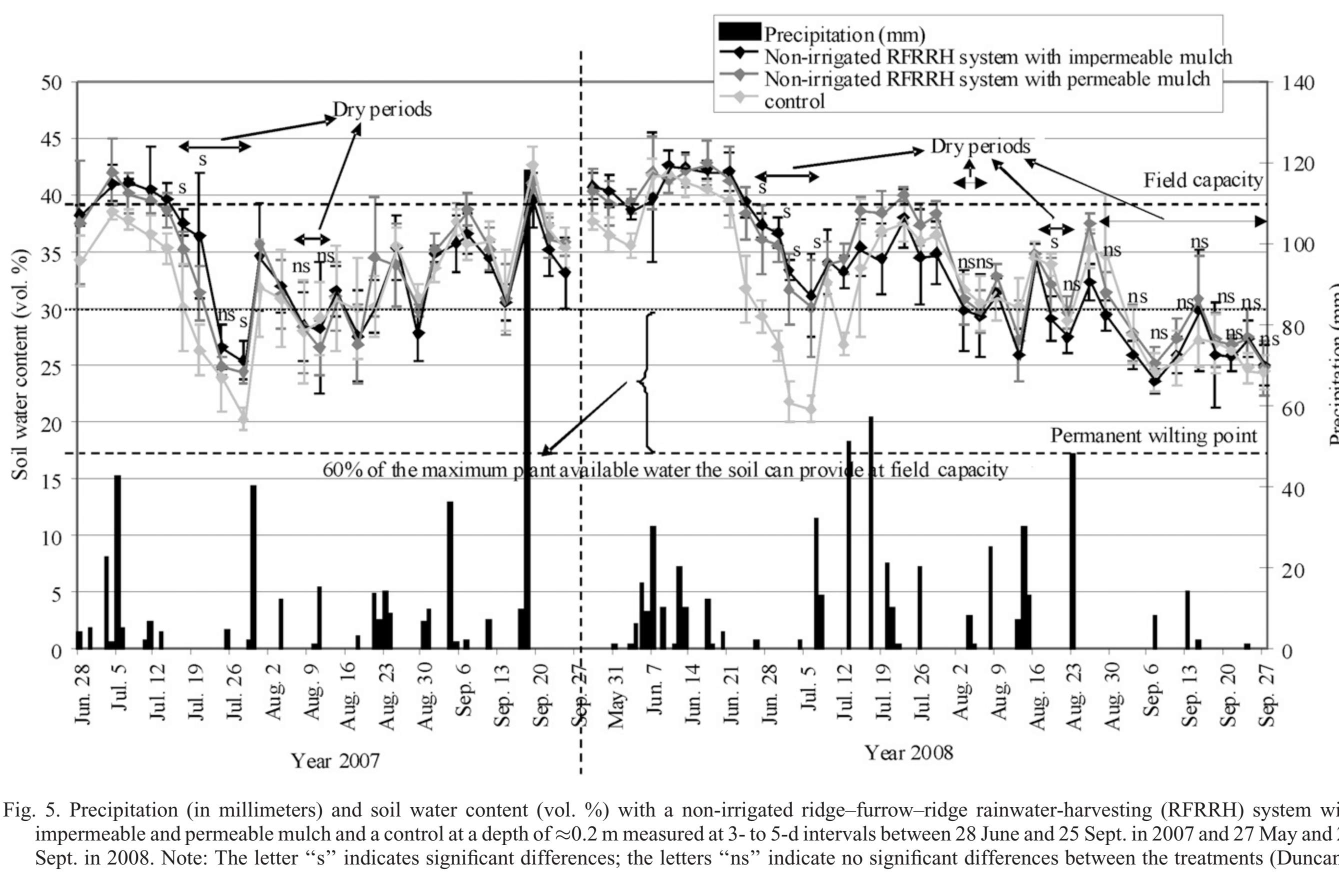

Fig. 5. Precipitation (in millimeters) and soil water content (vol. %) with a non-irrigated ridge–furrow–ridge rainwater-harvesting (RFRRH) system with impermeable and permeable mulch and a control at a depth of ≈0.2 m measured at 3- to 5-d intervals between 28 June and 25 Sept. in 2007 and 27 May and 27 Sept. in 2008. Note: The letter "s" indicates significant differences; the letters "ns" indicate no significant differences between the treatments (Duncan's multiple range test, $P < 0.05$).

Table 1. P values of the factors irrigation (on main plots), ridge–furrow–ridge rainwater harvesting (RFRRH) system (on subplots), and their interaction (irrigation × RFRRH system) on fresh weight yield and weed control time in 2007 and 2008.

Year 2007	Fresh wt yield	Weed control time
Factors		
Irrigation	$P = 0.043$	$P = 0.11$
RFRRH[z] system	$P = 0.028$	$P < 0.001$
Irrigation × RFRRH[z] system	$P = 0.82$	$P = 0.80$
Year 2008		
Factors		
Irrigation	$P = 0.46$	$P = 0.16$
RFRRH[z] system	$P < 0.001$	$P < 0.001$
Irrigation × RFRRH[z] system	$P = 0.45$	$P = 0.46$

[z]Ridge–furrow–ridge rainwater harvesting.

Table 2. Mean values for main effects of the factors irrigation (on main plots) and a ridge–furrow–ridge rainwater-harvesting system (on subplots) on fresh weight yield and weed control time in 2007 and 2008.

Mean values		Fresh weight yield		Weed control time	
Year 2007		($t \cdot ha^{-1}$)	SD	($h \cdot ha^{-1}$)	SD
Factors					
Irrigation	Non-irrigated	20.91 b	3.54	434 a	452
	Irrigated	23.30 a	2.87	487 a	437
RFRRH[z] system	Impermeable mulch	22.71 a	2.27	138 a	56
	Permeable mulch	23.75 a	2.73	192 a	104
	Control	19.87 b	3.97	1051 b	107
Year 2008					
Factors					
Irrigation	Non-irrigated	15.75 a	5.26	483 a	575
	Irrigated	16.59 a	4.95	592 a	700
RFRRH[z] system	Impermeable mulch	19.36 a	2.83	65 a	25
	Permeable mulch	18.71 a	3.65	174 a	92
	Control	10.44 b	2.14	1374 b	293

Note: Means within a subset column followed by the same letter are not significantly different at the 5% level (Duncan s multiple range test).
[z]Ridge–furrow–ridge rainwater harvesting.

a mulch drip irrigation system, especially in more humid regions because supplemental irrigation (using an agricultural vacuum tanker, by flooding the PE mulch-covered furrow) would not be necessary or would be applied just a few times in a growing season.

The disadvantages of the mulch-covered RFRRH system are that, as a result of the PE mulch cover, the planting zone cannot be easily cultivated and additionally fertilized without a drip irrigation system. Such a system requires investment in PE mulch, which reduces income per hectare, so can only be offset by growing cash crops that are usually grown under mulch such as strawberries, vegetables, and medicinal plants.

Conclusions

The RFRRH system with mulches offers many advantages. In comparison with the bare ground, RFRRH with mulches reduces weed competition and increases yield, which can be explained by the higher soil water content in dry periods at the beginning of the plant growth. The black PE mulch may also increase soil temperature (Tanner, 1974), reduce soil erosion (Kornecki et al., 2005), and reduce fertilizer leaching (Marr, 1993; Romić et al., 2003) from the root zone. Furthermore, in the event of inadequate rainfall, the RFRRH system with mulches enables simple supplemental irrigation using an agricultural vacuum tanker by flooding the PE mulch-covered furrow with hardly any ridge erosion.

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