Research Article

Evaluation of Sunflower, Soybeans, and Maize Cropping Systems under In-field Rainwater Harvesting on a Glen/Bonheim Ecotope

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Abstract

To achieve the specific objectives, data from a research project (funded by the Agricultural Research Council) on two tillage practices (conventional and in-field rainwater harvesting) and three crop rotation systems, which included maize, sunflower, and soybean, were utilized [1]. The research was done at the Glen Agricultural Institute, on a Glen/Bonheim ecotope (28°57` S, 26°20` E), 25 km northeast of Bloemfontein. The selected ecotope encompasses numerous thousands of hectares of land in the Free State Province, where numerous rural households are situated. The term ecotope can be defined as an area of land on which homogeneous natural resources (climate, topography, and soil) influence crop yields [2].

Keywords: Conventional; In-field rainwater harvesting; Crop rotation systems; Rural households

Introduction

By 2050, extreme water shortages are projected to affect 47% of the global population. This can significantly impact food production, which will need to double over the next 20-30 years, especially in sub-Saharan Africa, where malnutrition and food demand growth are highest [3]. Hence, in the quest to sustain productivity, rain-fed production systems will be vital, especially considering that 73% of the freshwater consumed globally for food production is used in rain-fed production systems [4,5].

This is also true for South Africa as crop production (field crops and horticultural products) contributes approximately 60% towards total agricultural production and uses approximately 12% of the rainfall; 62% of the rainfall is used for animal production and forestry (maintenance of natural veld and forestry) and 2% for producing crops under irrigation [6]. However, sustaining rain-fed crop production under low and irregular rainfall and high drought risks requires the implementation of best soil cultivation practices and effective cropping systems. This is also true for most subsistence (communal) and small-scale farmers in South Africa, who are generally located in these peripheral regions that are not conducive to crop production.

Ensuring sustained food security in rural communities is a major challenge [7], which requires effective use of soil and rainfall

by improving soil cultivation practices and cropping systems. The Agricultural Research Council (ARC) introduced a water management soil cultivation practice titled in-field rainwater harvesting (IRWH). The simple construction of the IRWH system includes a 2-meter runoff strip laterally to the slope of the field (catchment area) and a 1-meter dish (storage or basin) zone crosswise to the angle of the field. In this method, runoff is sent and kept in the basin area (Figure 1).
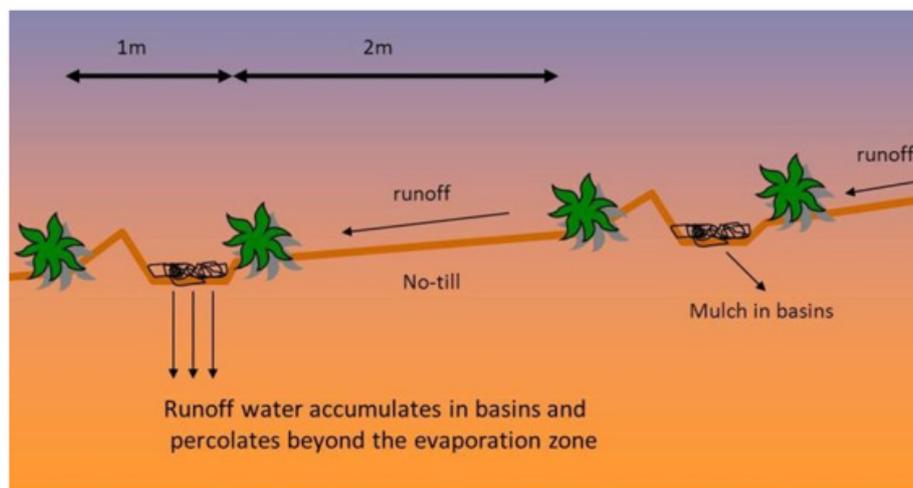

Figure 1: A diagrammatic illustration of the IRWH technique.

The benefits of water harvesting, basin tillage, no-till, and mulching are all combined in this practice. Botha et al. [8] found that, using the IRWH technique, total runoff can be reduced to zero, and evaporation from the surface can be significantly decreased, especially on clay soils located in dry areas. Some of the additional benefits of the system include:

• improvement in soil structure because of organic mulches used to cover the runoff area.

• storage of soil water in the root zone during the growing season and subsequent

• increases in crop yield [8,9].

The IRWH system also indirectly decreases production risk and utilizes capital more effectively, as the technique employs equipment that small-scale farmers can afford. Ultimately, increasing revenue [10] and contributing to household food safety and poverty mitigation [11].

Growing the same crop on the same piece of land each year, however, leads to various problems, namely depletion of soil nutrients, increased weed expression, and outbreaks of diseases and pests. Subsequently, this leads to a dependency on pesticides and fertilizers. The nutrient balance under monocropping without fertilizers or manure becomes negative for each nutrient; the soil nutrient pool must counterbalance this negative balance. Consequently, the system mines the soil nutrients and is unsustainable [12]. Conversely, the benefits of a crop rotation system include a reduction in pathogens, pests, weeds, and soil erosion, as well as the risk of weather damage, the storage of soil water, reliance on agricultural chemicals, improvement in soil structure and fertility, and increases in yield [13-16].

Unfortunately, research on different cropping systems under IRWH on marginal soils in dry areas is limited, especially where oil-rich crops like sunflowers and legumes like soybeans are included in the rotation system. Under conventional tillage (CON), Botha et al. [9] found that the yields of maize and sunflower grown under these conditions were higher when continuously cultivated, as opposed to when they were rotated, except when sunflower followed dry beans. None of these differences, however, were significant. It is argued that no significant increase in yield was found under CON tillage due to a water shortage in marginal clay soil. Research is therefore required to investigate whether the opposite will be true under IRWH, where more water is available.

Our paper compares the growth of maize, sunflower, and soybean in monoculture under conventional tillage and in-field rainwater harvesting (IRWH), and examines the different crop rotations of maize, sunflower, and soybean under IRWH.

Methodology

Climate

Rainfall and temperature data for Glen have been reported by Botha et al. [9], and the monthly mean values are listed in Table 1. The mean annual rainfall at Glen is approximately 544 mm, and

the atmospheric evaporative demand (expressed as a reference evapotranspiration of a short-clipped cool-season grass) is 1482 mm, i.e., a semi-arid region. Conditions for crop production are particularly marginal during December and January because rainfall during these months is erratic, as much of it falls in high-intensity showers. During January, rainfall is the highest of all the months, with a long-term mean of 84 mm. March, therefore, has the highest aridity index (AI) with a value of 0.63.

Table 1: Long-term mean monthly and annual rainfall (R, mm), atmospheric evaporative demand, expressed as reference evapotranspiration of a short clipped cool season grass (ETo, mm), daily maximum (RHx, %), and minimum (RHn, %) relative humidity, and daily maximum (Tx, °C) and minimum temperature (Tn, °C) from the Glen meteorological station [9].

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
R	84.2	79	80.3	49.7	19.9	8.5	7.5	11.4	19	49.1	69.9	65.7	544.4
ET$_0$	168.6	132.7	128.3	98.1	74.7	66	74.7	98.7	130.2	155.9	170.7	183.2	1482
RHx	79.1	83.6	86.2	87.6	84.5	82.7	77.1	69.5	68.4	76	78.3	79.2	79.4
RHn	24.9	29.4	31.7	28.5	25.6	25	21.6	18.8	18.3	21	22	22.4	24.1
Tx	30.7	29.5	27.4	24	20.6	18	17.9	20.7	24.5	25.6	28.5	30.3	24.8
Tn	15.4	15.1	13	8	2.8	-0.9	-1.4	1	5.3	9.6	12	14.1	7.8

This feature of the local climate can be exploited by planting crops with a short growing season early in January. The long-term mean AI for the January to April growing season is 0.50. Although the mean annual rainfall (MAR) may appear to be adequate to produce cash crops, the rainfall intensities and distribution are of such a nature that the water available during the crop growth cycle is generally inadequate to support stress-free growth.

Topography and Soil

The experimental plots were located on an upper foot slope terrain unit with a 1% slope and a westerly aspect. A detailed profile description and analytical data are presented in the report of Hensley et al. [17]. Important features are summarized in Table 2. The soil is classified, according to the Soil Classification Working Group (1991), as belonging to the Onrus Family of the Bonheim Form. It forms part of the Land Type Ea39c. It is a dark brown clay soil overlying CaCO3-enriched sandstone saprolite at a depth of 800 mm. The parent material of the solum is a mixture of dolerite and sandstone colluvium, with dolerite dominating. The underlying saprolite is sufficiently weathered to a depth of at least 1200 mm, i.e. the effective root zone. The soil has a high clay content (45%) and strong structure with a high portion of smectite clay minerals, resulting in a high CEC (24-25 cmol kg-1 soil). Dry spells cause large cracks to form that penetrate deep into the soil. Additionally, the surface soil has a high plasticity index, ranging from 21 to 33, and self-mulching properties, which promote erosion during high-intensity rain events. In the surface soil, the exchangeable Na content is low (0.7 cmol kg-1 soil), and it cannot therefore be blamed for exacerbating the swell-shrink properties. However, the relatively high exchangeable Mg content (11-12 cmol kg-1 soil) may promote cracking.

Table 2 [8] provides the drained upper limit (DUL), also known as the upper limit of plant-available water, which is the highest field-measured water content of the soil after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible. The lower limit of plant-available water (LL) is also defined, specifically, as the lowest field-measured water content of the soil after plants have stopped extracting water and are at or near premature death or have become dormant due to water stress [18]. Since LL depends on soil, crop, and climate characteristics, it is not meaningful to speak of the LL value of soil on its own. LL needs to be related to a specific crop ecotope. LL was taken as the lowest neutron water meter (NWM) reading for each soil layer measured during this study (soybeans) or previous studies conducted on this ecotope with maize and sunflower.

Table 2: Soil horizons (Melanic A, ml; Pedocutanic B, vp; rock weathering, so), clay content (%), bulk density (BD, g cm-3), drained upper limit (DUL, mm), lower limit (LL, mm) and plant available water (PAW, mm) for the effective root zone of the Glen/Bonheim ecotope.

Soil properties					Soybean		Maize		Sunflower	
Horizon	Clay (%)	BD (g cm-3)	Depth (mm)	DUL (mm)	LL (mm)	PAW (mm)	LL (mm)	PAW (mm)	LL (mm)	PAW (mm)
ml	45	1.3	300	122	40	82	39	83	45	77
vp	43	1.45	600	123	74	49	74	49	67	56
vp	40	1.45	900	106	70	36	74	32	67	39
so	38	1.45	1200	105	65	40	76	29	61	44
Total				456	249	207	263	193	240	216

Experimental Layout

A randomized block design with three crops (sunflower, maize, and soybean), two tillage treatments (IRWH and CON), and three replications were used. The three crops were grown in monoculture (maize-maize, soybeans-soybeans, sunflower-sunflower) under CON and IRWH and in rotation (maize-sunflower, maize-soybeans, sunflower-soybeans) under IRWH. Each of the crops was planted in the first season to ensure five yields for each treatment over the experimental period.

The total area of the experimental site is 3,672 m² (72 m x 51 m). Two neutron water meter access tubes were installed to a depth of 1300 mm, i.e., to a greater depth than that of the root zone, in each experimental plot. Access tubes were installed in the runoff and basin area. For the CON treatment, access tubes were installed at the same position as the IRWH treatment.

Agronomic Practices

All crops were planted by hand, and soybean seeds were inoculated with Soyflo® and Mollyflo®. The amount of fertilizer applied was based on the analyses of soil samples taken before the growing season. All the fertilizer was applied at the time of planting. In general, the soil potassium status was high and, hence, potassium application was ignored. Before planting and after harvesting, weeds were controlled with herbicides. During the growing season, weeds were manually controlled by pulling them from the soil. Insect control was performed using insecticides as needed.

Measurements

Daily weather data (rainfall, temperature, humidity, and radiation) were recorded with an automatic weather station that was installed next to the experimental plots. Soil water content measurements of the root zone were conducted before planting, at planting, and on a weekly basis during the growing season, at 300 mm depth intervals starting at a depth of 150 mm. A Campbell Pacific 503 DR NWM was used. This procedure ensures that the various pedological layers in the soil are adequately represented. In the event of rain, the soil water content was measured where possible after the rainfall event. The NWM was calibrated for every soil layer as discussed by Hensley et al. [17].

The critical growth stages of maize, sunflower, and soybean were recorded throughout the growing season through visual inspection. Visual symptoms were used to identify plant water stress, as described by Turner [19] and Laker et al. [20]. Wilted leaves and whitish colorization of plants were also used as indicators of plant water stress.

For sunflower and maize, 6 rows, each 1 m long, and 9 rows, each 1 m long, were harvested for soybeans to determine the final above-ground biomass from each replicate. The biomass was weighed, oven-dried, and adjusted to a 13% moisture content, then expressed as oven-dry material in kilograms per hectare.

The grain and seed yield for maize and sunflower were determined by harvesting 6 rows, each 4 m in length, and for the soybeans, 9 rows, each 4 m long, from each replicate. The grain and seeds were weighed, oven-dried, and adjusted to a 13% moisture content, expressed as kilograms per hectare.

Statistical analysis

Yield data were subjected to regression analyses using the NCSS 2000 Statistical System for Windows [21] to determine significant differences between the various treatments with the LSD Fisher method.

Results and Discussions

Soil tillage

Three of the five years were wet, i.e., the mean rainfall over these three years during the growing season and followed period were 42 and 47% more than the long-term mean, respectively. In contrast, however, when compared to the long-term mean, the first season can be classified as dry, i.e., the mean rainfall over this period was 58 and 66% less than the long-term mean. During the second dry year, the rainfall was 35 and 18% less than the long-term mean during the growing season and fallow period, respectively.

The seed yield for mono-culture maize, soybean, and sunflower grown under CON and IRWH tillage was measured. The above-ground biomass and soil water content were also measured for the different seasons. On average, over the five years when maize grew continuously, IRWH produced 140% and 114% higher seed yields and biomass, respectively, compared to CON tillage. For continuous soybeans, this amounted to 252 and 194%, respectively, and for sunflowers, 115 and 149%, respectively. During the three wet years, mono-culture maize and soybean seed yields under IRWH tillage were significantly higher compared to CON tillage, which was also true for biomass. This can be attributed to the more efficient storage of rainwater under IRWH tillage [17] during both the fallow period and the growing season. Under CON tillage during the three wet growing seasons, the soil water content was lower when compared to IRWH. Only during the driest year (2006/2007), no significant difference between the seed yield of maize and soybean grown under CON and IRWH tillage was observed.

This is, however, not conclusive evidence of no significant yield increase of maize and soybean during dry years because yields under IRWH tillage during the second dry year were significantly higher compared to CON tillage. It should be noted, however, that the second dry year was not as dry as the first. For mono-culture sunflower grown under IRWH, a similar trend of significantly higher seed yield was also observed when compared to CON tillage, except during the last wet season. It could be argued that this can be attributed to the aggressive root system of the sunflower, which extracts more water compared to maize and soybeans. The soil water content should then be at its lowest during the last season; hence, there should be no significant effect of IRWH tillage when compared to CON tillage.

Cropping systems

The seed yield of maize, soybean, and sunflower grown in monoculture and rotation under IRWH tillage is shown in Figure 2. The above-ground biomass and soil water content were also measured for the different seasons.
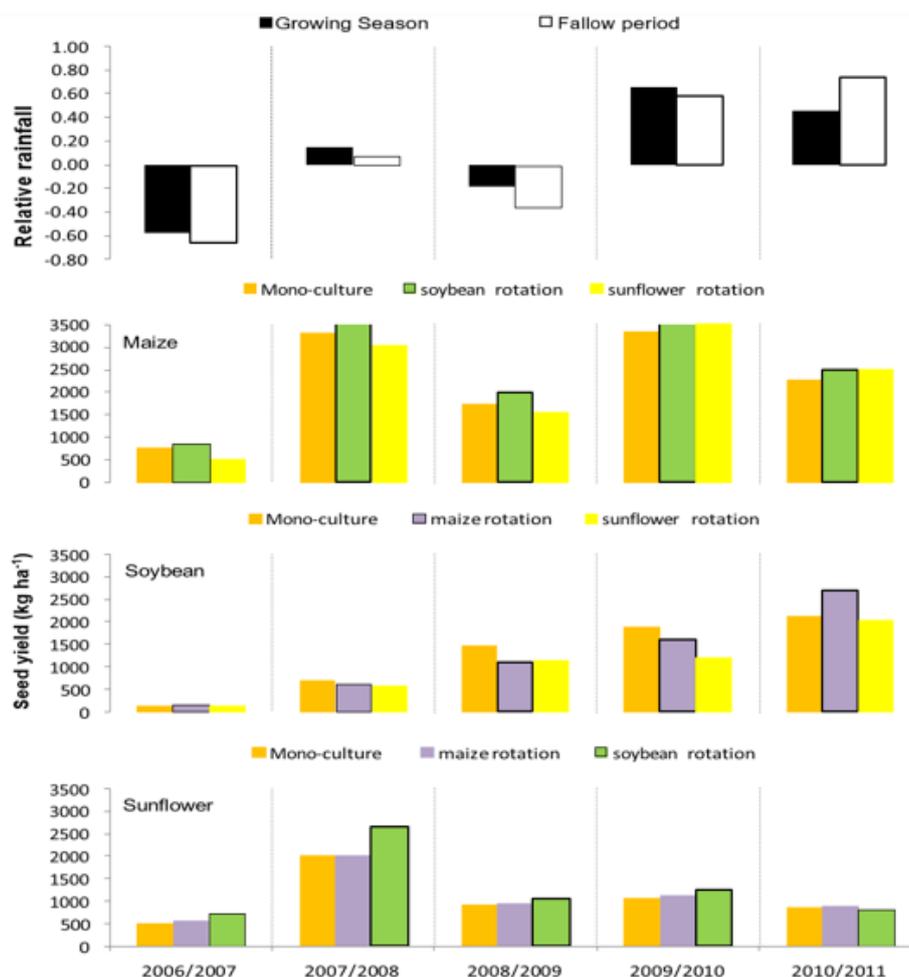

Figure 2: Measured rainfall (R) during the growing season and fallow period relative to the long-term mean (Rltm) during each of the five years (R - Rltm / Rltm). The seed yields of monoculture maize, soybean, and sunflower grown under IRWH and CON tillage are also included.

On average, over the five years when maize was rotated with soybean, the mean seed yield was 12% higher when compared to monoculture maize. However, when maize was rotated with sunflower, the mean seed yield was similar when compared to monoculture maize. For monoculture soybean, the mean seed yield was 2.3 and 25% higher when compared to the rotation with maize and sunflower, respectively. When sunflower was rotated with soybean, the seed yield was 17.2 and 20.5% higher than when rotated with maize and under monoculture, respectively. However, during none of the five years there was a significant difference in the seed yields of maize, soybean, and sunflower grown in monoculture and rotation. The beneficial nitrogen fixation capabilities of a legume crop, such as soybeans, in a crop rotation system [15], were therefore not observed.

Rainwater productivity

The mean rainwater productivity of monoculture maize, soybean, and sunflower grown under IRWH and CON tillage was measured over a five-year period. The mean rainwater productivity over the five years of the different crop rotations grown under IRWH tillage was also measured.

In general, for maize, soybean, and sunflower grown in monoculture, the rainwater productivity was significantly higher under IRWH tillage as opposed to CON tillage, irrespective of the season. The mean rainwater productivity of the three crops planted in monoculture over the five years was 1.13 kg ha^{-1} mm^{-1} under CON and 3.13 kg ha^{-1} mm^{-1} under IRWH tillage. Hence, in addition to a significant increase in seed yield, this substantial improvement

in rainwater productivity highlights the benefits of using IRWH over CON tillage. In contrast, however, no significant difference in rainwater productivity was found among maize, soybean, and sunflower grown in different rotations under IRWH, irrespective of the season.

The highest mean rainwater productivity over the five years was obtained for maize when rotated with soybean grown under IRWH, and the lowest for soybean grown in monoculture under CON tillage. The low rainwater productivity of soybeans grown under CON tillage proves that the nitrogen-fixing benefits were not obtained because of the poor interaction between nitrogen uptake and water supply, as not enough water is stored in the soil under CON tillage. However, under IRWH tillage, there is potential to enhance the rainwater productivity of maize due to the nitrogen-fixing capability of soybeans in the rotation. The "credit of nitrogen" for maize following soybean is due to the growing pool of simply mineralized organic nitrogen that the maize roots can easily take up in the presence of a sufficient water supply.

Maize had 93% and 88.3% higher rainwater productivity values than sunflower and soybean, respectively. This means maize can produce more food than sunflower and soybeans from the same rainfall. The rainwater productivity of sunflower grown in the soybean rotation IRWH had the highest RWP, and IRWH performed the best with soybean. This emphasizes the importance of incorporating a legume (e.g. soybean) into a crop rotation system due to its nitrogen fixation benefits.

Recommendations and Conclusion

Research on the effective use of soil and rainfall by improving soil cultivation and cropping systems can help sustain food security in rural communities. The primary objective of this study was to compare two tillage practices, namely IRWH and CON, when used to cultivate maize, soybeans, and sunflowers in monoculture. In addition, monoculture maize, soybean, and sunflower grown under IRWH were compared to rotations of these crops.

Data from an on-station field experiment conducted at the Glen Agricultural Institute, on a Glen/Bonheim ecotope (28057` S, 26020` E), 25 km north-east of Bloemfontein, was used to accomplish the objectives [1]. The experiment was conducted for five growing seasons (2006/07, 2007/08, 2008/09, 2009/10, and 2010/11). A randomized block design, with three replications, was employed, where the three crops were grown in monoculture under IRWH and CON tillage. Additionally, a maize-soybean, maize-sunflower, and sunflower-soybean crop rotation under IRWH tillage was also included. Nine experimental plots were added to repeat the rotations and alter the crop sequence. Hence, in doing so, each of the crops was planted in the first season to ensure five yields for each crop in the rotation system over the experimental period. Measurements included soil water content throughout the experimental period, as well as biomass and seed yield at harvest. Rainwater productivity was calculated for each crop under the various treatments [22].

The results showed that when maize, soybean, and sunflower were grown in monoculture under IRWH tillage, significantly higher biomass and seed yields at harvest, as well as rainwater productivity, were obtained compared to CON tillage during most seasons. IRWH tillage increased monoculture maize, soybean, and sunflower yields on average over the five years with 140%, 252%, and 114%, respectively, compared to CON tillage. Over the production period, which includes the fallow period, under IRWH tillage, 2.79, 1.20, and 2.01 kg more maize, soybean, and sunflower seed yields were harvested per hectare per mm of water, respectively, compared to CON tillage. The reasons for this were due to the ability of IRWH tillage to stop ex-field runoff completely, minimize evaporation, and store additional rainwater from the untilled 2 m runoff area. Another important advantage of IRWH tillage is the ability to distribute rainwater evenly over the land, compared to CON tillage, where runoff is high or surface water collects in ditches.

Where crops were planted in rotation under IRWH, it was expected to yield higher yields compared to monoculture. This, however, was not the case, as no significant difference in seed yields was observed. The soybean monoculture system produced the highest seed yield, followed by the soybean-maize and soybean-sunflower rotation. Where maize or sunflower was planted in rotation with soybean, the highest yields were obtained. This is due to the beneficial effect of nitrogen fixation on the soybean that was planted in the previous season. Low yields were obtained when maize or soybeans were planted in rotation with sunflowers. This can be attributed to the fact that the sunflower crop has an aggressive, deep-rooting system that extracts most of the available water in the soil profile, leaving little to no water for the next season.

With IRWH tillage, runoff water was effectively collected in the basin structures and stored in the soil profile, deeper than the layer from which evaporation takes place. In contrast, runoff losses occurred with CON tillage, leaving less water available for plant growth. The soil water content under IRWH tillage was higher during most of the five growing seasons than that of CON tillage. In an area where water is the most limiting resource, every drop of water must be converted into food as efficiently as possible. Maize proved to be the most productive crop on the Glen/Bonheim ecotope. The standard rainwater productivity for maize, soybean, and sunflower was 3.86-, 2.05-, and 2.01 kg ha^{-1} mm^{-1}, respectively.

Acknowledgement

Conflict of Interest

No conflict of interest.

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