Chapter

Risk Assessment of Sunflower Production Using In-Field Rainwater Harvesting on Semi-Arid Ecotope in South Africa

Jestinos Mzezewa and Leon Daniel van Rensburg

Abstract

Risk assessment of sunflower production was carried out using an empirical model. The crop yield prediction for semi-arid areas (CYP-SA) was used to simulate sunflower yield using 26 years (1984–2010) climatic data. Scenarios of crop yield simulation included production techniques associated with in-field rainwater harvesting (IRWH), and conventional tillage (CT). IRWH is a no-till (NT) crop production practice that promotes runoff from a crusted runoff strip into basins where water infiltrates beyond evaporation. The study focused on the effect of initial soil water content at planting *viz*. empty profile (water content near the lower limit of plant available water (LL)); half profile (water content between LL and the drained upper limit (DUL)); full profile (water content near DUL) and planting dates (November, December and January). Yield difference at 80% probability was 74% higher under IRWH compared to CT with empty initial soil water content at planting. Results indicated that IRWH is more sustainable compared to the CT.

Keywords: ecotope, crop yield simulation, empirical model, production risk, rainwater harvesting

1. Introduction

Water scarcity is a major constraint in semi-arid areas, leading to a natural focus on in-field rainwater conservation [1]. However, field experiments to assess water harvesting techniques are very expensive and laborious [2]. As a result several models of water harvesting have been developed in order to quantify risk for different production techniques. Models can be used as research tools to conduct research faster and cost-effectively [3]. In addition, a valuable property of models is their ability to utilize long-term climate data to provide long-term yield simulations, which can serve to quantify risk [4–6]. The modeling in this study simulate the in-field rainwater harvesting (IRWH) production technique (**Figure 1**) that was implemented during the field experiments [7]. This modeling approach has been described previously [2–4, 8]. By constructing cumulative probability functions (CPFs), risk associated with various production systems can be quantified [2, 4, 5, 8–11].

Crop Yield Predictor for Semi-Arid Areas (CYP-SA) model was developed to simulate crop yield on a semi-arid ecotope in South Africa [3, 4]. An ecotope is defined as a

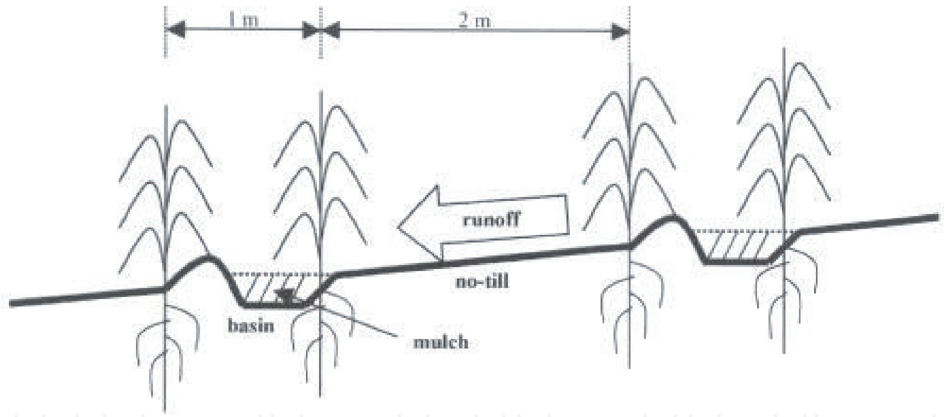

Figure 1.
A diagrammatic representation of the in-field rainwater harvesting (IRWH) production technique.

homogenous piece of land with a unique combination of climate, topographic and soil characteristics [4]. The CYP-SA model has potential to be applied for assessing risk for crop production in other ecotopes and therefore was chosen for this study to assist in decision making. The IRWH was introduced on this ecotope during the 2007/08 and 2008/09 growing seasons. The objective of this study was to simulate long-term (26 years) sunflower yield to quantify risk for two production techniques (IRWH versus CT) on a semi-arid ecotope in the Limpopo Province of South Africa: University of Venda, Thohoyandou (22° 58′ S; 30° 26′ E, 596 m) whose 23-year average rainfall is 781 mm with coefficient of variation (CV) of 315% [12]. The daily temperatures at the University of Venda vary from 25 to 40°C in summer and between approximately 12 and 26°C in winter. Soil at the University of Venda was classified as a Hutton form [13], equivalent to a Rhodic Ferralsol [14]. The soil is deep (>1500 mm) with clay concentration of 60% [7].

1.1 Model description

CYPA-SA runs on daily time-step [8, 15]. The inputs required by the model are crop modified upper limit (CMUL) of plant available water (PAW); drained upper limit (DUL) of PAW; lower limit (LL) of PAW; rainfall (P); evaporative demand (ET_o) and soil water content at planting (θ_p) (**Figure 2**). More symbols are explained in **Table 1**. It was assumed that runoff (R) would be zero if the precipitation was less than 8 mm. Runoff from rainfall events of more than 8 mm can be calculated using Eqs. (1) and (2).

CT :

$$P < 8: \ Pe = P$$

$$P > 8: \ P = P - [\{0.473 \times P) - 2.168\} \times 0.4] \quad \mathrm{R}^2 = 0.60 \tag{1}$$

(after [4])

where P is the rainfall for a day (mm) and P_e is the effective rainfall for a particular day (mm)

IRWH :

$$P < 8: \ P_e = P$$

$$P > 8: \ P_e = P + [(0.474 \times) - 0.8791] \quad \mathrm{R}^2 = 0.64 \tag{2}$$

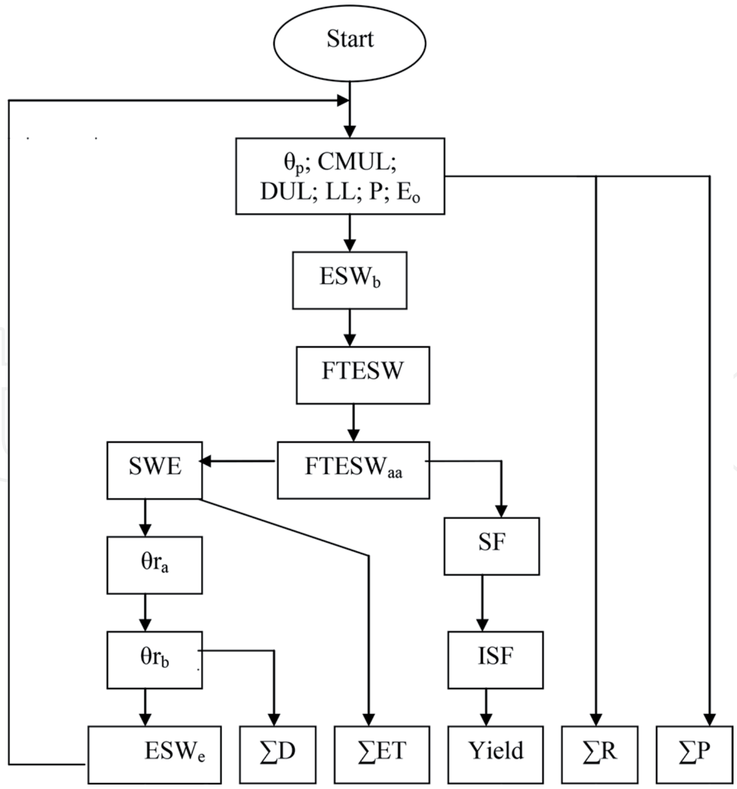

Figure 2.
Flow diagram of the CYP-SA model.

Symbol	Explanation
ESW_b	Extractable soil water at the beginning of a day
FTESW	Fraction of total extractable soil water
$FTESW_{aa}$	Adapted fraction of total extractable soil water
SWE	Soil water extraction
θr_a	Water content of rootzone, not adapted to cater for values above CMUL
θr_b	Adapted water content of rootzone, to cater for values not to exceed CMUL
ESW_e	Extractable soil water at the end of a day
SF	Stress factor
ISF	Integrated stress factor and the stress weighting factor (λ)
D	Deep drainage
ET	Evapotranspiration
R	Runoff

Table 1.
CYP-SA model flow diagram symbols.

1.2 Calibration and verification of the CYP-SA model

The calibration process can provide important insight into both local conditions and model performance [16]. The original model algorithms rules were evaluated by combining available data for ecotopes in the Free State Province [4, 8]. Modifications of the model were necessary to adapt to the soil and climatic conditions of this ecotope. Model calibration was achieved by inputting soil and climate data as detailed in Section 2.1. The original model runoff Eqs. (1) and (2) were replaced with Eqs. (3) and (4) which were developed for this ecotope [17].

CT :

$$R = 0.421 \times P{-}3.008 \quad R^2 = 0.769 \tag{3}$$

IRWH :

$$R = 0.59 \times P{-}2.203 \quad R^2 = 0.947 \tag{4}$$

The predicted yield was compared with the measured sunflower yield for that season. The model parameters were adjusted stepwise until the predicted yield matched with the measured yield. This was repeated for all replications for that season. The averaged correction factors were then used for model verification. Separate calibrations were done for CT and IRWH treatments. Model verification test were designed to evaluate the model performance. After calibration of the model, it was verified using another set of field data from 2008/08 growing season. The verified model was then used for simulation of long-term sunflower yield.

1.3 Statistical analyses for model verification

Model reliability tests were performed following the procedures proposed by Wilmott [18] who recommended use of the index of agreement (D-index), root mean square error systematic ($RMSE_s$), root mean square error unsystematic ($RMSU_u$) and root mean square error (RMSE) for model evaluation. The mean absolute error (MAE) and RMSE are among the best overall measures of model performance.

1.4 Model application

Meteorological data for both Thohoyandou and University of Venda were used for long-term (26 years) sunflower yield simulation. Rainfall and class A-pan evaporation data have been recorded for Thohoyandou meteorological station in the period 1984–2004. Calculated E_o values. For University of Venda meteorological records were used. The data was obtained from Agricultural Research Council-Institute for Soil, Climate and Water- Pretoria. Long-term evaluation of production techniques was achieved by comparing cumulative probability functions (CPFs) of yield using the CYP-SA model and long-term climate data.

The following θ_p were used in the simulations: 0% (soil water content of the profile near empty, but enough in the top soil for germination of seeds, defined as the difference between DUL and LL), 50% (half full) and 100% (full). Total DUL and LL of the soil profile are 448 and 250 mm, respectively. The amount of plant-extractable soil water at planting in the effective rooting zone is 0 mm for empty profile, 99 mm for half full profile and 198 for full profile. The simulations were run for 26 seasons from 1984 to 2010 with different production techniques (CT and IRWH) and three planting dates: 1 November (early planting), 1 December (intermediate) and 1 January (late planting).

All statistical tests on cumulative probability functions were carried out using the Kolmogorov–Smirnov test for two samples ($P < 0.05$). This test is about the agreement between two empirical cumulative distributions [11]. The null hypothesis is that the two groups are the same, and the test statistic D for two data sets x (the maximum distance between the two distributions) is defined as:

$$D = \max|S_{1(x)} - S_{2(x)}|, \tag{5}$$

where $S_{1(x)}$, $S_{2(x)}$ are the cumulative distributions, $S(x)$, for the two samples.

2. Results and discussion

2.1 Evaluation of the model performance

Results of model verification test using the procedure of [18] are presented in **Table 2**. The prediction performance was reasonable. The D-indices for both CT and IRWH were high (>0.80), indicating good model performance. Furthermore, crop yield was correctly predicted ($R^2 > 0.8$) for IRWH and reasonably predicted for CT ($R^2 = 0.68$; **Table 2**), confirming a positive association and good agreement between measured and simulated yield. On the whole crop yield was underestimated by less than 25% in the CT whilst the model overestimated crop yield by less than 15% in the IRWH treatment (**Table 2**). The models for both CT and IRWH showed low $RMSE_u$/RMSE values (<0.5), indicating that a high level of bias was associated with the models. The bias was also indicated by the large $RMSE_s$ relative to RMSE. Poor prediction of runoff could account for less satisfactory statistical indices in the model [19].

2.2 Effects of initial soil water at planting

Yield variation over 26 years predicted under CT and IRWH management practices were compared using cumulative probability curves (**Figure 3**). The curves were constructed by averaging across all scenario factors. The curves were compared with for each scenario factor using the Kolmogorov–Smirnov test ($P \leq 0.05$). Sunflower yield was significantly higher in full initial water than in the other two water contents in the CT. Similarly, empty profile water gave the lowest yield compared to both half and full water contents in the IRWH (**Table 3**). At 80% probability the yield in the empty, half and full profile was 355, 691 and 1088 kg ha^{-1} for the CT, respectively. In the IRWH the yield was 1357, 1984 and 2601 kg ha^{-1} in the empty, half and full profile, respectively (**Figure 3**). In general, the full profile gave the greatest yield, followed by half profile and then the empty profile, illustrating the importance of adequate profile water content at planting in semi-arid environment. This is akin to the observation made in the Free State Province South Africa [2, 4, 8, 11]. They reported that sufficient soil water content at planting is important for a good harvest. In addition, water stored between DUL and LL before planting contributes mainly to transpiration [8]. Recently Garcia-Lopez et al. [20] reported that sunflower yield ranged between 1333 and 2622 kg ha^{-1} corresponding to irrigation water that ranged from 146 to 326 mm, respectively. The lowest yield was obtained under deficit irrigation volume, emphasizing the importance of adequate soil water content on sunflower yield. More recently, sunflower yield reduction was observed under four levels of irrigation with the lowest level of water availability accounting for the lowest yield loss [21]. They reported sunflower seed yield of 2371, 2173, 2018 and 1764 kg ha^{-1} corresponding to 100 potential evapotranspiration (PET), 80 PET, 60 PET and 40% PET, respectively. Similar results were obtained when the seed yield of different sunflower inbred lines were compared under limited and full irrigation [22]. There were no effects of planting dates on yield in

Treatment	MAE	RMSE	$RMSE_s$	$RMSE_u$	D-index	R^2	Measured mean yield	Predicted mean yield
CT	405	415	405	91	0.993	0.68	1685	1280
IRWH	370	403	384	121	0.994	0.96	1844	2062

Table 2.
Statistical analysis of CYP-SA model performance predicting yields produced with conventional tillage (CT) and in-field rainwater harvesting (IRWH) (kg ha^{-1}).

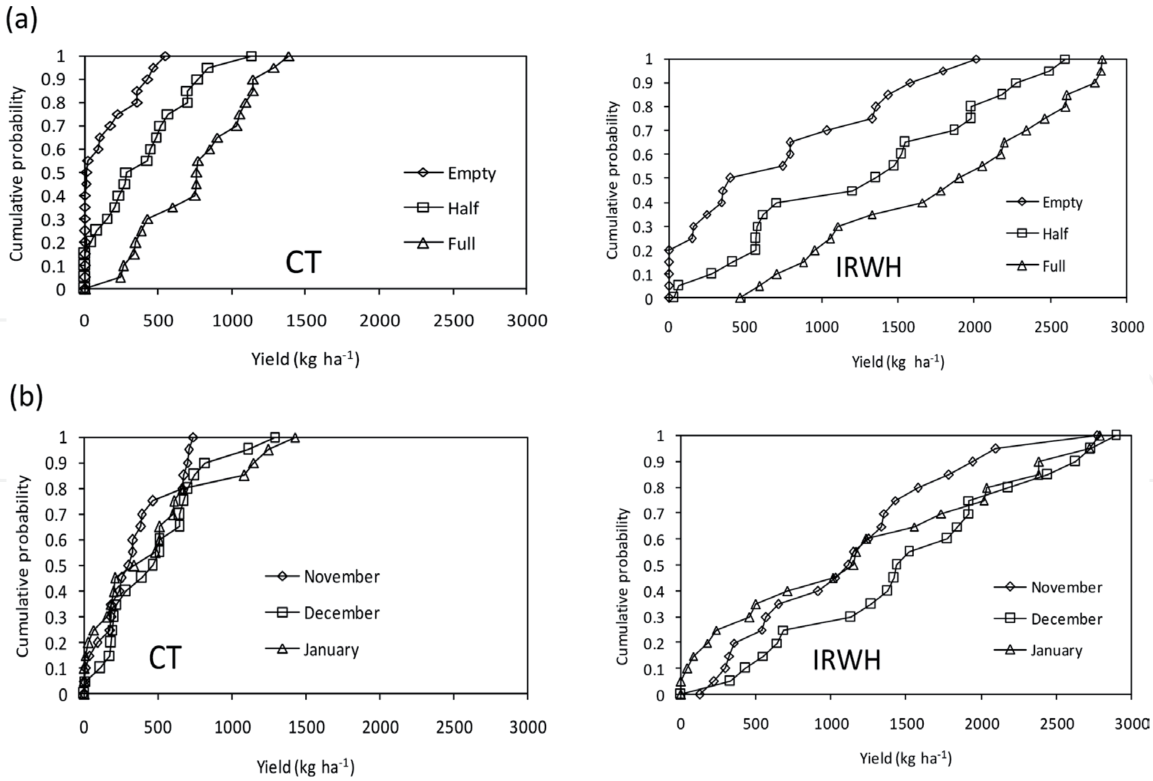

Figure 3.
Cumulative probability of simulated long-term (1984–2010) sunflower for conventional (CT) and in-field rainwater harvesting (IRWH): (a) different profiles of initial soil water content (averaged over three planting dates) and (b) different planting dates.

Initial soil water	Tillage treatments		Planting date	Tillage treatments	
	CT	IRWH		CT	IRWH
Empty	a	a	November	a	a
Half	a	ab	December	a	a
Full	b	b	January	a	a

The same letter within columns indicates not significant difference at $P \leq 0.05$.

Table 3.
The Kolmogorov–Smirnov (KS) test comparing tillage treatments (CT and IRWH) at different initial soil water levels and planting dates.

either production technique although differences were noted between techniques (**Table 3** and **Figure 3**). This may be attributed to high variability of rainfall on the ecotope. In another study [12] reported that the coefficient of variation (CV) for November, December and January were 1.27, 1.56 and 1.35, Using the CYP-SA model [8] reported that late planting (January) was significantly better ($P \leq 0.01$) than December planting in the semi-arid Free State Province. He attributed this to the fact that when the sunflower crop is planted in November its flowering period may coincide with favorable rainfall conditions in December. **Figure 3** also shows that at 80% probability farmers are likely to harvest about 700 kg ha^{-1} of sunflower in CT regardless of the planting date. However, in the Mediterranean region it is reported that earlier planting date resulted in higher seed yield in all the 4 years of the study [23]. The graphs also show that farmers planting sunflower using IRWH in December, are likely to expect a 50% chance of getting higher yields (1432 kg ha^{-1}) than planting either in November (1118 kg ha^{-1}) or January (1148 kg ha^{-1}). The results show that IRWH has a yield advantage in sunflower productivity, as reported

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Initial soil water	Statistics		Planting date	Statistics	
	D-statistic	Probability level		D-statistic	Probability level
Empty	0.48	0.011	November	0.62	0.000
Half	0.57	0.001	December	0.67	0.000
Full	0.62	0.000	January	0.43	0.029

Table 4.
The Kolmogorov–Smirnov (KS) test for cumulated sunflower yield with CT and IRWH production techniques produced at different initial soil water levels and planting dates.

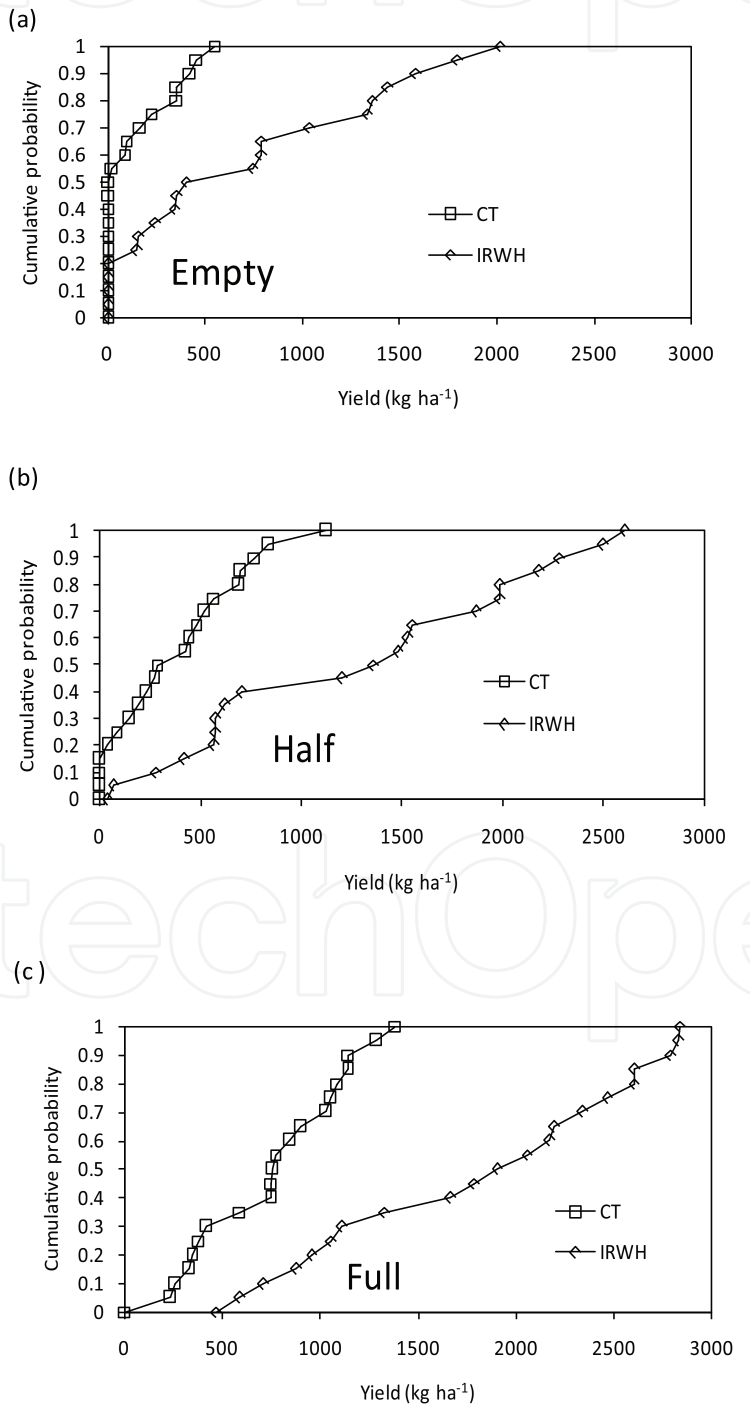

Figure 4.
Cumulative probabilities of simulated long-term (1984–2010) sunflower yield with conventional (CT) and in-field rainwater harvesting (IRWH) for three water contents (averaged over three planting dates); (a) empty, (b) half and (c) full.

earlier [2–4]. It was clear that the most important factor is initial soil water content when IRWH was compared with CT, a result as also obtained by Walker et al. [2].

Further comparison of cumulative probability curves for each scenario across different techniques was carried using the Kolmogorov–Smirnov test. There was significant yield difference between CT and IRWH production at all levels of initial profile water content and planting dates, confirming the advantages of IRWH over CT (**Table 4** and **Figures 4** and **5**). At 80% probability the yield difference between CT and IRWH was 74, 65 and 58% in empty, half and full profile, respectively (**Figure 4**). This finding confirms the finding of [2] who reported that the lower the initial water content at planting, the greater the yield difference between the IRWH and CT. Similar results were reported by [24]. From **Figure 5** it could be deduced that the yield difference between CT and IRWH was the same (68%) for the months of December and January, whilst the difference was 58% for the months of November, further confirming that planting dates may play a less important role than profile water content on this ecotope. The results strongly suggest that a farmer

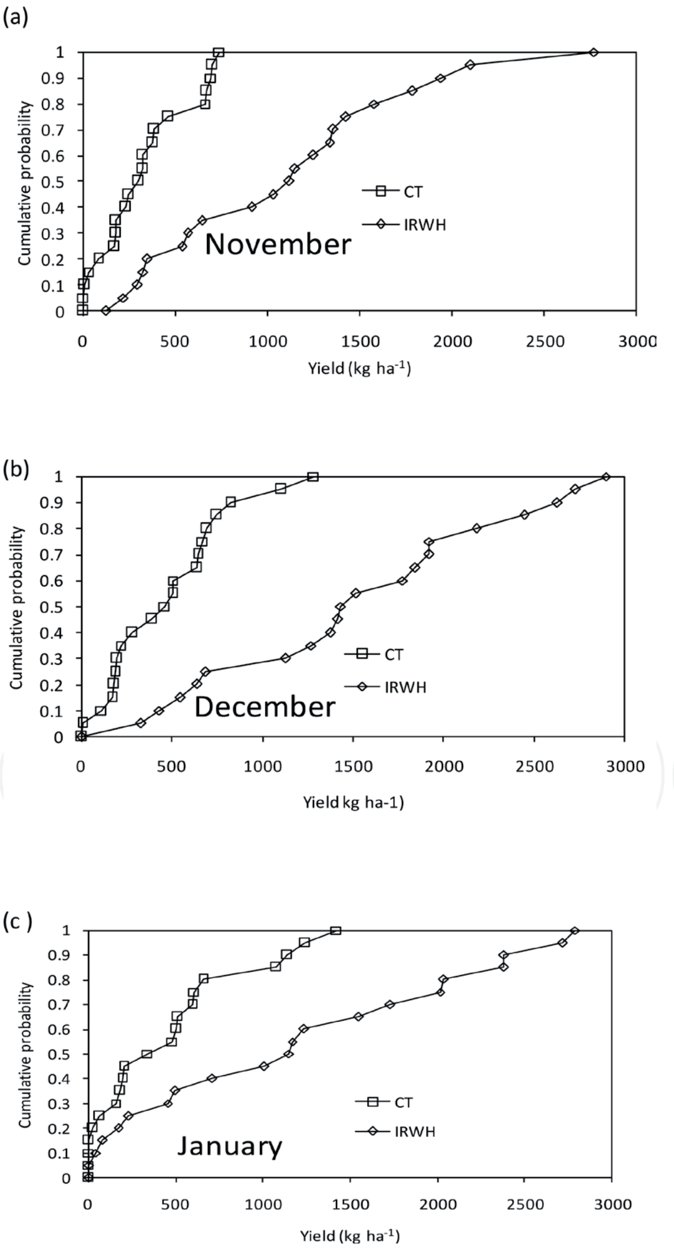

Figure 5.
Cumulative probabilities of simulated long-term (1984–2010) sunflower yield with conventional (CT) and infield rainwater harvesting (IRWH) for three planting dates (averaged over three water contents); (a) November, (b) December and (c) January.

who adopts IRWH and plants on empty profile water content is likely to get higher yields than who uses CT production technique. The findings could be important in semi-arid environments where water for agriculture is a constraint. Earlier [2] reported that for all scenarios with empty initial soil water, the curves for IRWH were significantly different from those for CT while the difference was not significant under half and full initial soil water when they simulated maize yield in the Free State Province. In his study [8] concluded that simulated sunflower production risk was significantly less under IRWH compared to CT when CYP-SA was run between three-fourth full and full profile water content.

3. Conclusions

In this study the CYP-SA model was applied to simulate long-term sunflower yields to quantify the risk of crop production at the ecotope. The conventional tillage (CT) was compared with the in-field rain water harvesting (IRWH) production technique. Results from this study indicated that farmers who choose to adopt the IRWH technique and plant when profile water content is empty can get higher yields compared to those who choose the CT technique. The IRWH technique consistently gave higher sunflower yield than the CT regardless of the planting date although sowing date was not significant within each crop production technique. Therefore, it could be concluded that the IRWH is a sustainable crop production technique compared to the CT.

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