CROP MODELS AS TOOLS TO SIMULATE IN-FIELD WATER HARVESTING UNDER DIFFERENT SOI SCENARIOS

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INTRODUCTION

In semi-arid regions limited rainfall is received and so the water use in crop production needs to be optimised. One method of achieving this is by using rainwater harvesting. Even though insufficient rain may be received to produce a crop, runoff can be concentrated into a smaller area and thus crop production is possible. Water harvesting is one of the practises that could be recommended together with an unfavourable seasonal rainfall forecast. However an assessment of the implications over the long-term and the probabilities of increased crop yields under this type of option needs to be made. Many types of water harvesting techniques have been reported (e.g., Boers and Ben-Asher, 1982; Cater and Miller, 1991; Hensley et al., 2000; Wiyo et al., 2000), however, field experiments for assessing those systems are very expensive and laborious. As a result, several models of water harvesting and comprehensive models of rainfall-runoff-yield systems have been developed (Gould and Nissen-Petersen, 1999; Young et al., 2002, Walker and Tsubo, 2003). Therefore, it is now possible to assess risk of crop production with water harvesting techniques using a rainfall-runoff-crop yield model (Sanchez et al., 1995).

Hensley et al. (2000) reported on a water harvesting technique using a combination of a no-till type of micro-catchment, and basin tillage covered by mulch (WHBM), as shown in Fig. 1, and the WHBM production technique has been demonstrated to be advantageous in field experiments (on-station and on-farm experiments) in a semi-arid region of South Africa, compared with a conventional total soil tillage (CT) production technique. In order to quantify risk for different production techniques, crop growth modelling, normally run on a daily basis, can be used as an analytical tool. However, an estimation of daily runoff may be a prerequisite for the analysis. In general, subtracting runoff from rainfall gives effective rainfall water available for conventional crop production, while adding water from a runoff area to rainfall gives additional water which can be used by crops in water harvesting crop production. Thus, for the WHBM technique, the effective rainfall is made up of the measured rainfall plus twice the runoff. This is to try and simulate the runoff from the 2 m no-till section which will infiltrate into the soil in the 1 m wide basin section. For the CT technique, the effective rainfall is taken as the measured rainfall minus the runoff. Modelled comparisons of long-term crop production with these different production techniques have seldom been carried out because of lack of reliable runoff information. Therefore, in order to quantify risk for different production techniques using crop growth models, an estimation of runoff is a prerequisite to calculating the effective rainfall under different systems.

In a deterministic model of rainfall-runoff processes, the amount of rainfall per unit time (generally an hour or a minute), termed rainfall intensity, is often needed to run the model (e.g., Morin and Cluff, 1980) together with soil texture and conditions of soil surfaces. As long-term data of rainfall intensity is not available a stochastic model to disaggregate daily rainfall into rainfall intensity (e.g., Woolhiser and Osborn, 1985) can be acceptable for rainfall intensity-runoff modelling in quantifying risk for long-term crop production systems.

The objective of this paper is to compare the predicted maize (*Zea mays* L.) yield produced under a conventional tillage production technique with that produced under in-field water harvesting for El Niño and La Niña years on a clay soil in a semi-arid area of South Africa.

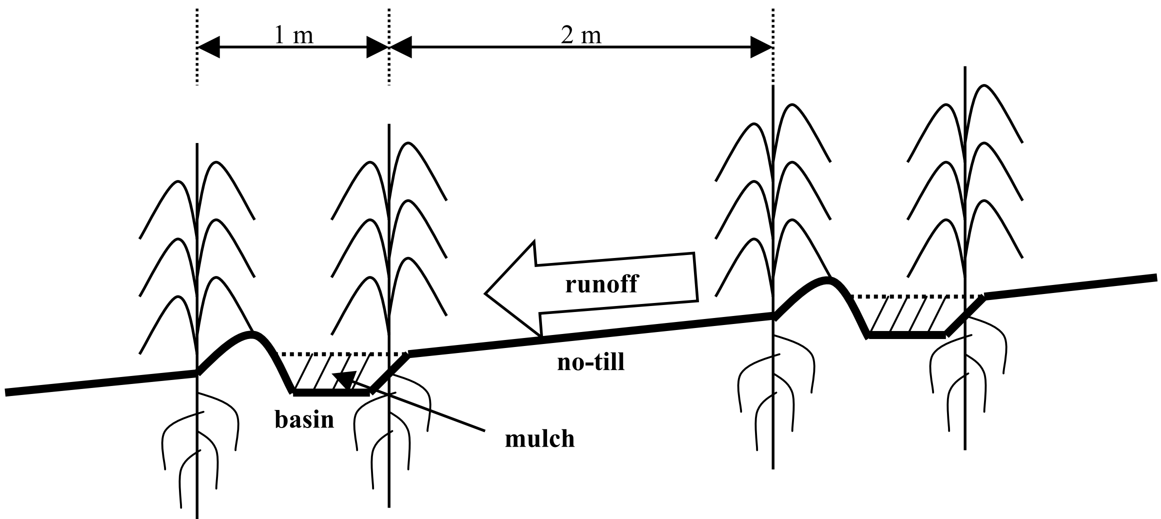

Fig. 1. A diagrammatic representation of the water harvesting / basin tillage / no-till / mulching (WHBM) production technique (after Hensley et al., 2000).

MATERIALS AND METHODS

A combination of models was used with long-term daily weather data as the input and the maize crop yield as output. Firstly, rainfall intensity is generated using a stochastic rainfall intensity model, i.e. Woolhiser and Osborn (1985) type model. Secondly, runoff is estimated using a deterministic runoff model, i.e., Morin and Cluff (1980) model. Thirdly, crop yield is predicted using a climate-crop growth model, i.e., Putu crop growth model (de Jager et al., 2001). Thus, crop production risk for different production techniques was quantified using these comprehensive modelling techniques. Many crop growth models have been developed and tested worldwide: e.g., BEANGRO (Hoogenboom et al., 1991) for dry beans, CERES-Maize (Jones and Kiniry, 1986), SOYGRO (Wilkerson et al., 1985) for soybeans. In this study, the crop growth model "Putu", which means maize porridge in Zulu, developed by de Jager et al. (2001) was employed to assess risk of maize yield. The Putu crop growth model was developed under South African semi-arid conditions and has demonstrated an acceptable degree of reliability in simulating crop yields. The Putu crop growth model describes the proportionate limitation on growth due to each of the climatic variables for each day of the growing season. A major advantage of the model is its subroutine structure, and each of the operations is undertaken in an independent subroutine, so modellers may alter any subroutines and introduce routines from other models. The model is written in Quick Basic and a version in C-language is also available. The deterministic rainfall intensity-runoff model by the Morin and Cluff (1980) (one of the most appropriate models of rainfall intensity-runoff processes for semi-arid regions) was combined with the stochastic rainfall intensity model based on Woolhiser and Osborn (1985) (WOMC). For this combination model (WOMC), the generated data of rainfall intensity using the hyetograph method (Walker and Tsubo, 2003) was used to estimate runoff by the Morin and Cluff (1980) runoff model with an exponential relationship between the infiltration and rainfall intensity.

Maize crop simulation runs were carried out for Glen (28º57´S, 26º20´E, 1304 m) for a period of 52 years from 1950/1951 to 2001/2002 for the summer growing seasons. In order to run the long-term crop simulation, it was assumed that the soil of the location was a highly clayey soil (35–45 %) situated on a gentle slope (1–5 %). As mentioned by Walker and Tsubo (2003), a problem which arises when making long-term simulations is that the soil water content at planting in each of the growing seasons in unknown. Another problem is that the models generally do not simulate the water balance well during fallow seasons. The result is that if one makes an uninterrupted long-term simulation including fallow periods, and starting with some assumed initial water content in the first year, the water content at planting in any particular years could be incorrect by a significant amount. This gives invalid results especially for semi-arid regions where the initial water content in very important. In this study, an alternative strategy was employed. Long-term crop model simulations were run with a range of different initial root zone water content at planting each year. In the present study a medium duration cultivar was planted on 1 December each year at an optimal plant population of 12000 plants/ha. The simulations were run at three initial soil water contents. This simulation study has supporting results from a field experiment conducted at Glen by Hensley et al. (2000), they reported that WHBM (4678 kg ha^{-1}) had 1.5 times greater yield than CT (3133 kg ha^{-1}) during a growing season (450 mm of rainfall during the season). The simulation result (with the scenario of half initial soil water / medium maturity cultivar / December sowing date / optimum plant density for the same growing season) was 4382 kg ha^{-1} for WHBM and 3400 kg ha^{-1} for CT, showing that the simulation had the similar yield ratio to the field experiment.

EFFECTS OF EL NIÑO / LA NIÑA ON MAIZE YIELDS

One of the indicators normally used to identify El Niño / La Niña episodes is the Southern Oscillation Index (SOI). The SOI is negative during El Niño episodes while the SOI is positive during La Niña episodes (Glantz, 1996). This index has been used to investigate the influences of El Niño / La Niña on crop yields. Hammer and Muchow (1991) showed that there were remarkable differences in simulated sorghum (*Sorghum bicolor*) yield in Australia between years with SOI < -5 and SOI $> +5$ (SOI was averaged over three month prior to planting). They reported that with SOI < -5 the yield was lower at any cumulative probability level, compared with SOI $> +5$.

In the present simulation study, the 3-month (September, October and November) average of the SOI was used to separate the simulated medium maturity maize yield with the optimum plant density (planting on 1st December; harvest in March/April of the following year) into three categories: SOI < -5, $-5 \leq$ SOI $\leq +5$, and SOI $> +5$. The cumulative probability curves for the simulated yield with these SOI ranges are presented in Fig. 2. With full initial soil water at planting, not much difference was found on cumulative probability curves among SOI classes in both CT and WHBM production techniques. This indicates that if there is adequate soil water initially, there is little effect of SOI on final yield. With empty and half-full initial soil water, at higher probability (yield) levels, the El Niño tendency years (SOI < −5) had lower yield potential than the La Niña tendency years (SOI > +5) in both production techniques. However, using the Kolmogorov-Smirnov Test, it was found that there was not a statistically significant difference in the yield between the El Niño tendency years and the La Niña tendency years (D statistics < 0.27 and P values > 0.58).

Concerning an advantage of in-field water harvesting, Table 1 shows the ratio of the yield for the WHBM production technique to the CT production technique for the El Niño and La Niña tendency years. On average (for three probability levels), the yield for years with SOI < −5 with the WHBM production technique was 45, 33 and 15 % higher than the yields with the CT production technique for empty, half and full initial soil water at planting, respectively. This clearly shows the advantage of water harvesting during the drier El Niño years. For years with SOI > +5, the WHBM production technique had 44, 11 and 12 % higher yield than the CT production technique. Thus, the superiority of the WHBM production technique is clearly demonstrated in both El Niño and La Niña years, particularly with little initial soil water at planting.

Table 1. The ratio of simulated maize yields for the water harvesting (WHBM) to the conventional tillage (CT) production technique for the El Niño tendency years (SOI < −5) and the La Niña tendency years (SOI >+5) at the 25, 50 and 75% cumulative probability level.

SOI	Probability	Initial soil water		
		Empty	Half	Full
< −5	25 %	1.80	1.55	1.34
	50 %	1.37	1.25	1.06
	75 %	1.18	1.20	1.04
> +5	25 %	1.52	1.19	1.27
	50 %	1.38	1.07	1.04
	75 %	1.42	1.07	1.04

CONCLUSIONS

If there is adequate soil water initially, then there is little effect of SOI on final yields. For the other starting water conditions, which more often occur in practice, the El Niño tended to give lower yields than the La Niña years, although they were not significantly different. The water harvesting technique gave 33 to 45% more yield in El Niño years than the conventional tillage technique when beginning with half or empty soil profile respectively. This endorses the fact that in-field water harvesting can be recommended with unfavourable rainfall outlooks. The advantages of the in-field water harvesting production technique were clearly demonstrated through the crop simulation outputs.

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REFERENCES

Boers, T.M., Ben-Asher, J., 1982. A review of rainwater harvesting. Agric. Water Manage. 5, 145-158.

Cater, D.C., Miller, S., 1991. Three years experience with an on-farm macro-catchment water harvesting system in Botswana. Agric. Water Manage. 19, 191-203.

De Jager, J.M, Mottram, R., Kennedy, J.A., 2001. Research on a compuerised weather-based irrigation water management system. WRC Report No. 581/1/01. Water Research Commission, Pretoria

Glantz, M.H., 1996. Currents of Change: El Niño's Impact on Climate and Society. Cambridge University P:ress, Cambridge UK.

Gould, J., Nissen-Petersen, E., 1999. Rainwater Catchment Systems for Domestic Supply: Design, Construction and Implementation. Intermediate Technology, London.

Hammer, G.L., Muchow, R.C., 1991. Quantifying climatic risk to sorghum in Australia's semiarid tropics and subtropics: Model development and simulation. In: Muchow, R.C., Bellamy, J.R. (Eds.), Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. CAB International, Wallingford, pp. 205-232.

Hensley, M., Anderson, J.J., Botha, J.J., van Staden, P.P. 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria.

Hoogenboom, G.J., Jones, W., White, J.W., Boote, K.J. 1991. BEANGRO 1.01. Dry bean crop growth and simulation model. User's guide. Universities of Florida and Georgia. Florida Agric. Exp. Station J. No. N00379.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A simulation model of maize growth and development. Texas A&M University Press, College Station.

Linsley, Jr., R.K., Kohler, M.A., Paulhus, J.L.H., 1982. Hydrology for Engineers, 3rd Edition. McGraw-Hill, New York.

Morin, J., Cluff, C.B., 1980. Runoff calculation on semi-arid watersheds using a rotadisk rainulator. Water Resour. Res. 16, 1085-1093.

Sanchez, C.I., Lopes, V.L., Slack, D.C. and Yañez, C.H., 1995. Assessing risk for water harvesting systems in arid environments. J. Soil and Water Cons. 50, 446-449.

Walker, S., Tsubo, M., 2003. Estimation of rainfall intensity for potential crop production on clay soil with in-field water harvesting practices in a semi-arid area. WRC Report No. 1049/1/02. Water Research Commission, Pretoria.

Wilkerson, G.G., Jones, J.W., Boothe, K.J., Mishoe, J.W., 1985. SOYGRO V5.0: Sojabean crop growth and yield model. Technical memo. Agric. Eng. Dept., University of Florida, Gainsville.

Wiyo, K.A., Kasomekera, Z.M., Feyen, J., 2000. Effect of tied-ridging on soil water status of a maize crop under Malawi conditions. Agric. Water Manage. 45, 101-125.

Woolhiser, D.A., Osborn, H.B., 1985. A stochastic model of dimensionless thunderstorm rainfall. Water Resour. Res. 21, 511-522.

Young, M.D.B., Gowing, J.W., Wyseure, G.C.L., Hatibu, N., 2002. Parched–Thirst: development and validation of a process-based model of rainwater harvesting. Agric. Water Manage. 55, 121-140.

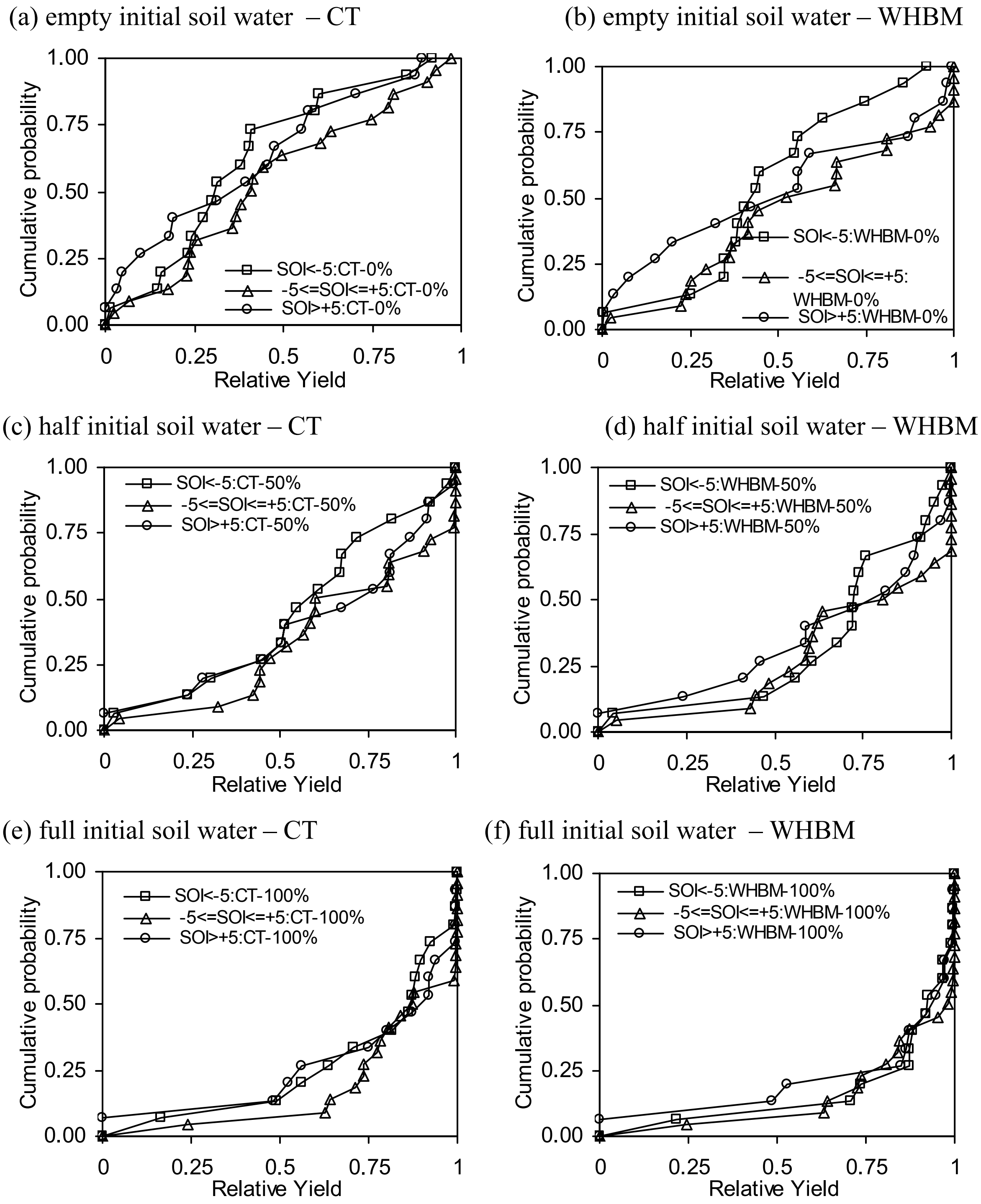

Fig. 2. Cumulative probabilities of simulated relative long-term (1951–2002) maize yields produced at Glen for SOI<−5, −5≤SOI≤+5 and SOI>+5, using the Putu crop growth model with the WOMC model and various initial soil water contents (0%=empty, 50% and full=100%; CT= conventional tillage; WHBM= in-field water harvesting).