The role of water conservation strategies and benchmark ecotopes for increasing yields in South Africa's semi-arid croplands

Malcolm Hensley[1], Pieter AL le Roux[1], J Jacobus Botha[2]* and Leon D van Rensburg[1]

[1]*Department of Soil, Crop and Climate Sciences, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa*

[2]*Agricultural Research Council - Institute for Soil, Climate and Water, Private Bag X01, Glen, 9360, South Africa*

ABSTRACT

Recently published results regarding South Africa's cropping potential show that about one third of the arable land is of low potential, located mainly in semi-arid areas, with the main problem being water shortage. This is therefore an appropriate time to review priorities and procedures, for selecting benchmark ecotopes to represent marginal areas, and for research needs with regard to water conservation strategies to mitigate the problems of low yields. Relevant international principles encapsulated in the words agro-ecology, sustainability and socio-economic conditions, are discussed. Relevant new technologies are described, namely: digital soil mapping that will facilitate the identification of benchmark ecotopes; a stochastic procedure to predict rainfall intensity data from daily rainfall that will facilitate runoff predictions; a crop yield cumulative probability procedure that enables sustainability to be described quantitatively. As a case study, results from a successful field experiment using the infield rainwater harvesting production technique on benchmark ecotopes in a semi-arid area, inhabited by subsistence farmers, are presented. The objectives of the study, procedures used and the method of expressing the results are recommended as guidelines for contributing towards mitigating the problem of low crop productivity across a large portion of the arable area in South Africa.

Keywords: water conservation, benchmark ecotopes, semi-arid areas, subsistence farmers, infield rainwater harvesting

INTRODUCTION

The recently published results regarding the cropping potential of South Africa (Le Roux et al., 2016) show that at least one third of the arable land is of low potential. This land is located mainly in semi-arid areas where the main cropping problem is a water shortage due to a low and erratic rainfall pattern, high evaporation rates and often with soils having some unsatisfactory characteristics. The available estimates also indicate that in the case of a serious drought, such as in 1983/84, the production of maize, the staple food of a large fraction of the population, could easily be less than required. With regard to land evaluation in the general sense, for example, compared to grazing or forestry potential, these results dictate that land evaluation for crop production needs to have the highest priority. Le Roux et al. (2016 p. 83) also recommend that 'detailed assessment of the 15 m ha occupied by subsistence farmers needs to receive the highest priority'. This priority is also intimated in the following statement by Paterson et al. (2015 p. 6): 'The challenges begin with the need for recognition of the future central role to be played by the Natural Agricultural Resource Information System towards food security, environmental sustainability and ultimately the nation's social well-being.'

Considering the current land evaluation needs in South Africa leads to the logical conclusion that the most important current objective needs to be the identification and evaluation of ecotopes that are representative of the cropping areas of low potential, and especially those in areas occupied by subsistence farmers. These ecotopes will be described as benchmark ecotopes, equivalent to the term 'benchmark sites' used by Uehara and Tsuji (1990) for their international project titled 'International Benchmark Sites Network for Agro-technology Transfer (IBSNAT)', and as used in the following Water Research Commission reports that appear in the reference list: Bennie et al. (1998); Hensley et al. (1997); Hensley et al. (2000).

Considerable advances have been made internationally in recent years regarding the principles of land evaluation. The following, accentuated by Bouma et al. (2012 p. 34.1–34.2), are relevant, especially the title of their paper, i.e. land evaluation for landscape units:

- 'In all cases land use is the core issue to be studied, while socio-economic considerations often play a crucial role as well'
- The focus needs to be on 'agro-ecology as related to sustainable development'
- Defining land qualities in terms of land characteristics is unsatisfactory; details in this regard are presented in Le Roux et al. (2016)
- Ongoing consultation with all stakeholders is necessary

Agro-ecology is described by Altieri (1989 p. 37–38) as a 'new research and development paradigm for world agriculture' and also states that, 'solving the sustainability problem of agriculture is the primary aim of agro-ecology'. Three aspects are emphasized: '(i) the need for a systems framework analysis; (ii) the need to focus on both biophysical and socio-economic constraints on production; (iii) the need for a suitable land unit for the analysis'. Regarding the last need, the ecotope concept of MacVicar et al. (1974) is appropriate.

The recent FAO publication on land evaluation (FAO, 2007) is a revised version of its predecessor (FAO, 1976). In FAO (2007), among the eight proposed principles of land evaluation, the three following ones are particularly relevant to the current prevailing conditions in South Africa, and accentuate similar principles to those of Bouma et al. (2012) that:

- Land evaluation requires a multi-disciplinary and cross-sectoral approach.
- Suitability refers to use or services on a sustained basis; sustainability should incorporate productivity, social equity and environmental concerns.
- Land evaluation needs to consider all stakeholders.

*Corresponding author, email: BothaC@arc.agric.za
Received 29 June 2018; accepted in revised form 19 June 2019

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019

Addressing sustainability of agricultural production, FAO (2007) accentuates the need for information regarding risk assessment and the environmental impact of production strategies on different classes of land. Addressing social equity, it is also stated (p. 1) that 'most current rural development is directed at areas where people face economic and social problems, in particular hunger and poverty'. The importance of reliable land evaluation procedures is accentuated, especially in developing countries due to the increasing pressure on land resources largely due to rapid increases in population.

Altieri and Nicholls (2005 p. 99) present a convincing motivation for international attention to the needs of subsistence farmers with these words: 'Throughout the developing world, resource-poor farmers (about 1.4 billion people) located in risk-prone, marginal environments, remain untouched by modern agricultural technology'. Equivalent estimates for South Africa in 1985 were reported by Fényes (1985 p. 15) as follows: 'The predominantly subsistence-orientated African agricultural sector in South Africa presently occupies 15.1 million ha of land, 14% of which is cultivated and employs 1.1 million (1970) people'. Van der Merwe (1985) also reported a similar area of land occupied by subsistence farmers, and that it was, at that stage, relatively underutilized in terms of its potential. Cousins (2015) estimates that the number of market-orientated smallholder farmers in communal areas in South Africa and in land reform context amount to between 200 000 and 250 000; and, in addition, that subsistence-oriented smallholder farmers growing food for themselves, and selling occasionally, amount to between 2 and 2.5 million. Data about the arable area of land used by these two groups of farmers is not currently available.

NEW LAND EVALUATION TECHNOLOGIES

Identifying benchmark crop ecotopes and improving the procedure for estimating areas

This is a subject of ongoing importance in South Africa because of the lack of permanent food security for all its people. Reliable information about the area of marginal crop ecotopes, and what can be done to mitigate the problems, is needed by decision makers. The provisional procedure for identifying ecotopes using land type survey (LTS) data in the form of climate-soil-slope units, described by Schoeman and MacVicar (1978), was a valuable first approximation that served a useful purpose. Because it did not involve actual measurements, it was subjective in nature and could therefore have resulted in considerable errors. Van Zijl (2013) has developed a procedure using modern technology in the form of digital soil mapping (DSM) that could greatly facilitate and improve the efficiency of this step. An example is presented by Van Zijl et al. (2013) of their procedure, and termed 'disaggregation of land types using terrain analysis, expert knowledge and GIS methodology'. It is recommended that this procedure, developed further with careful testing, be used for the urgently needed identification of important benchmark ecotopes.

Runoff prediction models

Although the semi-arid areas of South Africa have the disadvantage of low rainfall, they nevertheless have the advantage that a significant portion of the rain is in the form of storms of reasonably high intensity (Pi). Therefore, by harvesting as much as possible of the runoff water from these events, i.e., those with Pi > the final infiltration rate of the soil (Pf), maximum use can be made of the limited rainfall. In a Water Research Commission (WRC) project aimed at contributing to infield rainwater harvesting (IRWH) studies, Walker and Tsubo (2003) describe a stochastic procedure developed in the USA that enables the prediction of Pi data for rainfall stations with long-term daily rainfall (Pd) data and relatively short-term Pi data. They used measured rainfall intensity data for 30 years for Bloemfontein (20 km from Glen) to develop and successfully calibrate the model. Both Zere et al. (2005) and Anderson (2007) used the model, together with carefully selected input parameters for the Morin and Cluff (1980) mechanistic runoff model, to simulate the results of a long-term (18 years) runoff experiment by Du Plessis and Mostert (1965) at Glen on a soil of Tukulu form. Their objective was to test with what degree of reliability the combination of the two models could predict the measured runoff results obtained by Du Plessis and Mostert (1965). Willmot (1982) statistics were used to determine the reliability of the predictions and found by both researchers to be satisfactory. These results were only obtained after the field experiments on the two benchmark ecotopes at Glen (Botha, 2006) had been completed. Anderson (2007) showed, however, that the original runoff procedure used in the crop model titled 'crop yield prediction for semi-arid areas' CYP-SA (Botha, 2006) gave similar yield prediction results to those that could be obtained using the Morin and Cluff model together with predicted Pi data. Useful results were also obtained using Pi data and the Morin and Cluff (1980) runoff model for three benchmark ecotopes in Ethiopia by Welderufael (2006) and Welderufael et al. (2008; 2009).

Considering the future need to evaluate the productivity of many marginal benchmark ecotopes in semi-arid areas, if the use of the combination of the two models described above proves to be consistently reliable, this strategy offers a useful means of estimating the yield benefits obtainable with the in-field rainwater harvesting (IRWH) production technique before conducting expensive field experiments on an unnecessary number of benchmark ecotopes.

Appropriate procedures for expressing crop productivity

The importance of sustainability is relevant, as stressed by Bouma et al. (2012) and FAO (2007). For marginal ecotopes in semi-arid areas this consideration is of particular importance because of the low and variable rainfall coupled with high evaporation rates. Reliable recent contributions in this regard are the use of appropriate kinds of crop models to predict long-term yields with different production techniques, coupled with results expressed in the form of cumulative probability functions (CPF's). The basic procedure is described in detail by Uehara and Tsuji (1990), and has been widely and effectively used, e.g., Monteith and Virmani (1990) in India; Muchow et al. (1990) in Australia; Bouma and Droogers (1998) in The Netherlands; Hensley et al. (2000) in South Africa; Botha (2006) in South Africa.

The choice of the type of crop model to use for the CPF procedure is important. Passioura (1996) differentiates between 'scientific' and 'engineering' crop models, and provides detailed evidence why he favours the latter for solving practical problems and providing sound management advice. He states furthermore (p. 690) that 'the best engineering models are based on robust empirical relations between plant behaviour

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019

and the main environmental variables'. In support of the views of Passioura (1996), Penning de Vries and Spitters (1990 p. 123) state that, 'Summary models and regression models derived from simulation results, are ultimately ideal tools for application and predictive purposes'. These authors also indicate that for water-limiting environments, adherence to these criteria is of additional importance. A local example in support of this contention is available in the improvement made by Botha (1997) with regard to the crop-stress algorithm used for maize in the PUTU crop model (De Jager, 1990). Although a specific algorithm was used in PUTU before 1997 for a specific crop, soil differences in different ecotopes were not taken into account. Careful and detailed measurements in a maize crop, growing in a Glen/Sepane ecotope as the soil dried out and stress increased, showed that an improved crop-stress algorithm was needed on this type of ecotope, i.e., high clay duplex soil with a semi-arid climate. With the improved algorithm the performance of the model improved significantly.

The crop model SWAMP (soil water management programme; Bennie et al., 1998) and CYP-SA (Botha 2006) are of the type described by Passioura as 'engineering models'.

BENCHMARK ECOTOPES

The ecotope concept

The ecotope concept is described in detail by MacVicar et al. (1974). The main part of the definition is described as: An ecotope is a class of land defined in terms of its macro-climate (including where necessary, aspect), soil and soil surface characteristics (mainly slope) such that, in terms of the farming enterprises that can be carried out on it, the potential yield class for each enterprise, or the production techniques needed for each enterprise, there is a significant difference between one ecotope and any other. The original agro-ecological nature of the ecotope concept is revealed by the second part of this definition, and also by the initial procedure used by Schoeman and MacVicar (1978) for identifying ecotopes using LTS data in the form of climate-soil-slope units and obtaining crop yield estimates for each unit by consulting with knowledgeable and experienced local people.

Currently the most important ecotopes in South Africa are the benchmark ones representing cropping areas of low potential, and especially those in areas occupied by subsistence farmers. The benchmark ecotope concept is not new in South African literature associated with land evaluation. It played a prominent role in the following publications: Hensley et al. (1997); Bennie et al. (1998); Hensley et al. (2000).

Selecting benchmark crop ecotopes

Important sources of information for this process are the supporting database of around 2 500 modal soil profiles described and analysed for the LTS (Paterson et al., 2015), together with the detailed soil knowledge gained by all those intensively involved over a long period with the survey. This knowledge is expressed in the numerous LTS memoirs and in the following publications by soil scientists involved: Verster (1974); Schoeman and MacVicar (1978); Eloff (1984); Ellis (1984); Turner (2000); Schoeman et al. (2002); Turner et al. (2014). The tacit knowledge of these people is also valuable as most of them are fortunately still available for consultation purposes.

Information from the LTS will indicate in which particular land types, or group of land types, such as the relatively homogenous farming areas defined by Scheepers et al. (1984) for the Highveld Region, and the bio-resource units defined by Camp (1999) for KwaZulu-Natal, the sought-after benchmark ecotopes will be located. For these areas, it is important that diligent consultation with relevant expert knowledge and local farmers be carried out to obtain reliable information about potential yields and their sustainability. This procedure was employed by Turner et al. (2014) for the survey of Eastern Cape Province. It yielded valuable information with regard to proposed suitability class maize yields for subsistence farmers, considerably lower than those normally adopted for commercial farming. The importance of the fact that the socio-economic parameters for subsistence farming are very different from those for commercial farming, as explained by Kundhlande et al. (2004), is accentuated.

CASE STUDY

Land type Dc17, with an area of 239 080 ha (Eloff, 1984), is located east of Bloemfontein. It is a semi-arid area characterized by a low and variable rainfall, high evaporative demand, and predominantly duplex soils or soils with margalitic A horizons, both being unfavourable for crop production with the prevailing climate. Eloff (1984) estimated the fraction of arable land in Dc17 as 10%, all with low cropping potential. As Dc17 is occupied mainly by subsistence farmers who often experience a lack of food security, it was considered a suitable area for identifying benchmark crop ecotopes and appropriate research to attempt to find solutions to the problem of low productivity. Two ecotopes similar to those in Dc17 were identified on the Glen Research Station, a suitable site for long-term field experiments. The soils of these ecotopes are (Soil Classification Working Group, 1991): Swartland form/Rouxville family (Glen/Sw); and Bonheim form/Onrus family (Glen/Bo). Detailed profile descriptions and analytical data for these soils are presented in Hensley et al. (2000).

The hypothesis for the proposed experiment was that with conventional tillage (CON), an unnecessary loss of water occurs by runoff (R) and evaporation (Es) from the rough soil surface. Therefore, if R could be reduced to zero and Es also significantly reduced, crop yield would be significantly increased (Hensley et al. 2000; van Rensburg et al. 2010). Regarding Es, detailed quantitative measurements by Schwartz et al. (2010), comparing losses with tilled and untilled surfaces in a semi-arid area, showed that the former were significantly greater than the latter throughout a season. The instrumentation used was time-domain reflectometry and a neutron water meter.

To test our hypothesis at Glen, the IRWH production technique depicted in Fig. 1 was proposed. The plan was that the only mechanical cultivation on the land would be that needed to establish the basins shown in Fig. 1. The cultivation consisted of one deep ploughing on the contour with soil deposited onto the downslope side. Cross walls were made in the furrows at 3 m intervals to form basins. Maize rows were located as shown in Fig. 1. No-till was maintained on the smooth crusted runoff strips and weeds were controlled with chemical sprays. CON started with ploughing, followed by disking for seedbed preparation, and about 1 month after germination a shallow cultivation was given for weed control. Plant populations, planting dates and fertilisation were always the same as on the IRWH plots.

The first IRWH vs. CON experiments with maize and sunflower on both ecotopes were conducted over 3 growing

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019

seasons (1996–1999). They were followed by similar experiments on Glen/Bo over 4 seasons. Measured results for critical parameters needed for the experiments are presented in Fig. 2 and Table 1, with measured maize yields and other relevant data in Tables 2 and 3. Statistical results show that out of 10 comparisons made, IRWH gives significantly better yields than CON in 9 cases. The failure for the 1996/97 season on the Glen/Bo IRWH plots was logical because it had not been possible for the first year to complete the construction of basins on that treatment before the start of the spring rains. The crop was therefore denied the benefit of the additional runoff water during the spring rains.

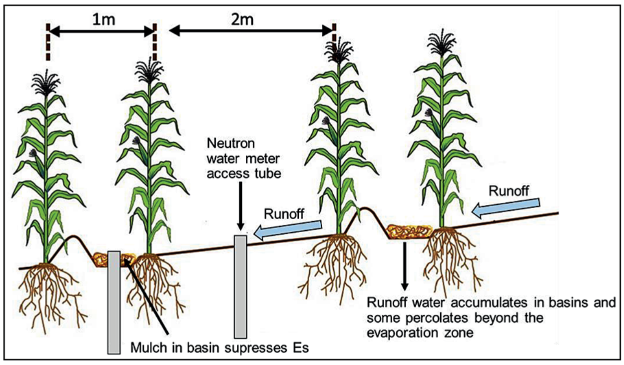

Figure 1. A diagrammatic representation of the in-field rainwater harvesting technique (modified from Botha, 2006)

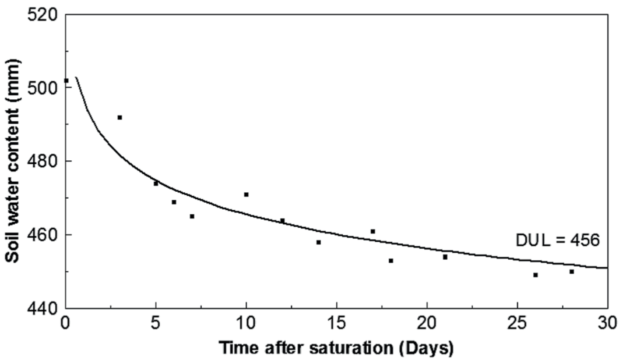

Figure 2. Drainage curve for Glen/Bo (data from Botha; 2006)

Soil water content measurements were by neutron water meter access tubes, replicated many times, as shown in Fig. 1. The measured effective root zone for maize and sunflower on both ecotopes was 1 200 mm.

Equation 1 provides a mathematical description of the curve and enables the drainage rate at any time after field saturation (F_{Sat}) to be calculated, and to estimate deep drainage after periods of heavy rain. The value given for F_{Sat} is the measured value at field saturation, and not the intercept on the vertical axis by the curve's equation.

$$\text{Glen/Bo } (F_{Sat} = 512 \text{ mm}): \quad Y = 512 - 8.92 (\ln t) \quad r^2 = 0.91 \quad (1)$$

where:
Y = water content of the root zone (mm)
t = time (h) after drainage starts at a root zone water content of F_{Sat}

The drainage curve for the Glen/Sw has a similar shape to that of Glen/Bo, with the resultant curve described by the following equation (Van Staden, 2000):

$$\text{Glen/Sw } (F_{Sat} = 433 \text{ mm}): Y = 433 - 11.43 (\ln t) \quad r^2 = 0.80 \quad (2)$$

The data in Table 1 shows that the pedocutanic horizons in both ecotopes have not impaired root distribution to a significant extent. For maize on Glen/Sw the fraction of TESW from the 0–600 mm layer (A, B1 and B2 horizons) is 57%, and for the 600–1 200 mm layers (B3, B4 and C horizons) is 43%; and the equivalent results for the Glen/Bo are 68% and 32%, respectively. The considerably higher TESW values for Glen/Bo are due to the higher content of clay and silt compared to Glen/Sw. It is expected that the maintenance of a relatively higher soil water content in the IRWH plots, compared to CON plots, will have had a beneficial effect throughout each season on TESW, and therefore on yield. The wide variation in seasonal rainfall, a characteristic of semi-arid areas in South Africa, and hence its influence on yield, is clearly shown by the data in Tables 2 and 3. This factor accentuates the importance with regard to

Table 1. The soil water extraction properties of the Glen/Sw (data from Hensley et al., 2000) and Glen/Bo (data from Botha; 2006)

Ecotope	Profile detail								Maize		Sunflower	
	Diagnostic horizon[*1]	Colour	Clay (%)	Silt (%)	Bd[*2] (Mg m^{-3})	Lower depth (mm)	DUL (mm)		LL (mm)	TESW[*3] (mm)	LL (mm)	TESW (mm)
Glen/Sw	ot	DkBr	38	7	1.50	300	82		33	49	23	59
	vp	DkBr	40	7	1.66	600	96		67	29	62	34
	vp	DkBr	44	9	1.51	900	96		62	34	62	34
	vp & so[*1]	DkBr & mottled[*4]	35	7	1.46	1 200	84		60	24	60	24
						Total	358		222	136	207	151
Glen/Bo	ml	DkBr	45	10	1.30	300	122		39	83	45	77
	vp	DkBr	43	12	1.45	600	123		74	49	67	56
	vp	DkBr	40	14	1.45	900	106		74	32	67	39
	so	mottled[*4]	38	20	1.45	1 200	105		76	29	61	44
						Total	456		263	193	240	216

*1 *Abbreviations from Soil Classification Working Group (1991): ot = orthic; vp = pedocutanic so = saprolite; ml = melanic*
*2 *Bulk density*
*3 *Total extractable soil water, calculated as the measured drained upper limit of available water (DUL) minus the measured lower limit of plant available water (LL)*
*4 *Due to $CaCO_3$ concretions*

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019

the sustainability of any new production technique that is being tested in an attempt to ameliorate socio-economic conditions where food security is a problem. Hence, the value of a reliable crop model and the CPF procedure for expressing long-term yields (Fig. 3).

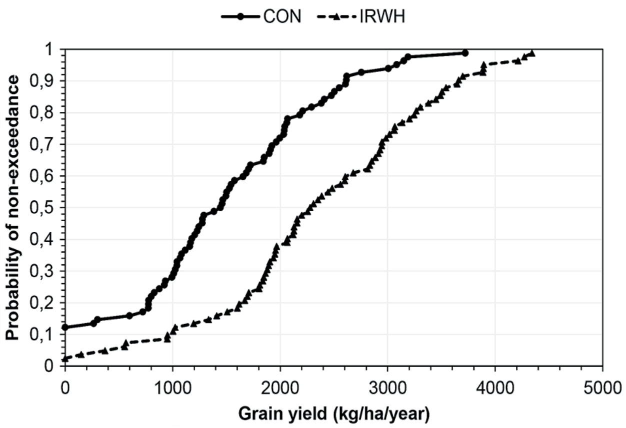

Figure 3. CPF graphs of long-term maize yields simulated with CYP-SA (80 seasons, 1922–2003), on the Glen/Bo ecotope with CON and IRWH (Botha, 2006)

The final condensed results of the experiment to test the hypothesis IRWH vs CON, are presented in the crop yield CPF in Fig. 3, and the yields and statistical results in Tables 2 and 3. The long-term superiority of IRWH is clearly demonstrated, indicating that there is generally a 50% probability on the Glen/Bo ecotope of achieving sustainable maize grain yields of approximately 1 300 kg·ha^{-1} and 2 300 kg·ha^{-1} with the CON and IRWH tillage treatments, respectively. For maize on the Glen/Sw the equivalent figures are very similar. The hypothesis for the ecotopes is therefore proved to be valid, and IRWH shown to be a suitable production technique for subsistence farmers in the Thaba Nchu area. Soils of the Bonheim, Sepane, Swartland and Valsrivier forms in this area with rooting depth at least 900 mm, should be considered as arable using IRWH where the aridity index (AI) value is at least 0.25, and the slope approximately 5%.

CONCLUSION AND RECOMMENDATIONS

Considering the current land evaluation needs in South Africa it is logical that the highest priority should now be given to the identification of the most important benchmark crop ecotopes that require research attention in order to seek possible remedial actions. Also important is the identification of arable regions in land types where crop ecotopes occur that are

Table 2. Maize grain yields on the Glen/Sw and Glen/Bo ecotopes for three seasons comparing results for the CON and IRWH treatments. Data from Hensley et al. (2000)

Season	Ecotope	Treatment*1	P*2 (mm)	Maize grain yield (kg·ha^{-1})	Stat. test*3	R*4 (mm)
96/97	G/Sw	CON	297	1 138	*	28
		IRWH		1 917		0
	G/Bo	CON	297	2 282	NS	14
		IRWH		2 274		0
97/98	G/Sw	CON	451	3 187	*	41
		IRWH		5 308		0
	G/Bo	CON	451	3 133	*	33
		IRWH		4 678		0
98/99	G/Sw	CON	208	41	*	0
		IRWH		234		0
	G/Bo	CON	208	0	*	0
		IRWH		132		0

*1 *CON = conventional tillage; IRWH = infield rainwater harvesting*
*2 *Precipitation during the crop growing period*
*3 *Statistical significance at the 5% level indicated by **
*4 *Runoff during the crop growing period*

Table 3. Maize grain yields on the Glen/Bo ecotope for 4 seasons 1999–2003; comparing results for the CON and IRWH treatments. Data from Botha (2006).

Season	Treatment	P*1 (mm)			Maize grain yield (kg·ha^{-1})	Stat. test*2	R*3 (mm)
		F	G	T			
99/00	CON	157	228	385	3 093	*	31
	IRWH				3 455		0
00/01	CON	233	281	514	1 489	*	56
	IRWH				2 543		0
01/02	CON	360	247	607	1 521	*	64
	IRWH				3 281		0
02/03	CON	315	215	530	459	*	52
	IRWH				2 401		0

*1 *Precipitation for: F = fallow period; G = crop growing period; T = overall production period*
*2 *Statistical significance at the 5% level indicated by **
*3 *Runoff during the overall production period, i.e. crop growing season + preceding fallow period*

similar to the selected benchmark crop ecotopes.

We propose that in order for a benchmark ecotope to become a registered 'habitat pigeon hole' in the South African crop potential database in which 'production yield data can be stored' (MacVicar et al., 1974; Paterson et al., 2015), the requirements listed below need to be met.

1. A name for the benchmark ecotope consisting of 4 words in the following order: a place name indicating the approximate geographical location; soil form; soil family; soil series
2. Detailed profile description as in the modal profiles of the LTS, and in accordance with the format proposed by Turner (1991); plus analytical data for each horizon of the solum, as in modal profiles for the LTS
3. Drainage curve of the root zone (as in Fig. 2)
4. Soil water extraction properties of the root zone for each main crop expected to be grown on the benchmark ecotope (as in Table 1)
5. Detailed long-term daily climate data, including as much rainfall intensity data as possible
6. Expected long-term yield potential with specific crop/crops, using specified production techniques. The yield potential should be expressed in terms of a CPF of long-term yields so that the risk is quantified. The latter is of particular importance for marginal crop ecotopes in semi-arid areas. To obtain the necessary data for this, a field experiment over at least three seasons with at least two of the main crops for the region, using the most appropriate production techniques available at the time, will be needed.
7. To enable long-term yield predictions obtained with a crop model to be determined, measured values for all the parameters required by the selected crop model need to be provided for each benchmark crop ecotope.

ACKNOWLEDGEMENTS

Appreciation is expressed for funding provided for many IRWH projects by the Water Research Commission (Sanewe and Backeberg, 2012) and for assistance from the Free State Department of Agriculture for providing suitable land at Glen for the experiments and for the loan of farm equipment for field experimentation at Glen over many years.

REFERENCES

ALTIERI MA (1989) Agro-ecology: A new research paradigm for world agriculture. *Agric. Ecosyst. Environ.* **27** 37–41.

ALTIERI MA and NICHOLLS CI (2005) *Agro-Ecology and the Search for a Truly Sustainable Agriculture.* Basic Textbooks for Environmental Training. University of California, Berkeley, USA.

ANDERSON JJ (2007) Rainfall-runoff relationships and yield responses of maize and dry beans on the Glen/Bonheim ecotope using conventional tillage and in-field rainwater harvesting. PhD Agric. Thesis, University of the Free State, Bloemfontein.

BENNIE ATP, STRYDOM MG and VREY HS (1998) The application of computer models for agricultural water management at ecotope level [in Afrikaans, with English abstract]. WRC Report No. 625/1/98. Water Research Commission, Pretoria.

BOTHA JJ (1997) Quantifying of the stress curve for selected crop ecotopes [in Afrikaans]. MSc. Agric. thesis, University of the Free State, Bloemfontein.

BOTHA JJ (2006) Evaluation of maize and sunflower in a semi-arid area using in-field rainwater harvesting. PhD Agric. thesis, University of the Free State, Bloemfontein.

BOUMA J and DROOGERS P (1998). A procedure to derive land quality indicators for sustainable agricultural production. *Geoderma* **85** 103–110. https://doi.org/10.1016/s0016-7061(98)00031-7

BOUMA J, STOORVOGEL JJ and SONNEVELD MPW (2012) Land evaluation for landscape units. In: Huang PM, Li Y and Sumner ME (eds) *Handbook of Soil Sciences: Properties and Processes* (2nd edn). CRC Press, Boca Raton. 34-1–34-22.

CAMP KGT (1999) A bio-resource classification for KwaZulu-Natal, South Africa. MSc. Agric. thesis, University of KwaZulu-Natal, Pietermaritzburg.

COUSINS B (2015) Through a glass darkly: towards agrarian reform in South Africa. In: Ben Cousins and Cherryl Walker (eds.) *Land Divided, Land Restored, Land Reform in South Africa for the 21st Century.* Jacana, Auckland Park. 250–269.

DE JAGER JM (1990) Maize production risk in the RSA [in Afrikaans]. Report to the Department of Agricultural Development. Dept. Agrometeorology, University of the Free State. 85 pp.

DU PLESSIS MC and MOSTERT JWC (1965) Runoff and soil losses at the Agricultural Research Centre, Glen. [Afrikaans, with English summary]. *S. Afr. J. Agric. Sci.* **8** 1051–1061.

ELLIS F (1984) The soils of the Karoo [in Afrikaans]. PhD thesis, University of Stellenbosch, Stellenbosch.

ELOFF JF (1984) The soil resources of the Free State Province [in Afrikaans]. PhD thesis, University of Stellenbosch, Stellenbosch, South Africa.

FAO (Food and Agriculture Organization of the United Nations) (1976) A framework for land evaluation. *Soils Bulletin 32*. FAO, Rome.

FAO (Food and Agriculture Organization of the United Nations) (2007) Land evaluation. Towards a revised framework. Land and water discussion paper No. 6. FAO, Rome.

FÉNYES TI (1985) An assessment of the present situation of subsistence farmers in southern Africa: implications for the future. In: *Proceedings of the 23rd Annual Conference of the Agricultural Economics Association of South Africa*, 30 April–1 May 1985, Bloemfontein, South Africa.

HENSLEY M, ANDERSON JJ, BOTHA JJ, VAN STADEN PP, SINGELS A, PRINSLOO, M and DU TOIT A (1997) Modelling the water balance on benchmark ecotopes. WRC Report No. 508/1/97. Water Research Commission, Pretoria.

HENSLEY M, BOTHA JJ, ANDERSON JJ, VAN STADEN PP and DU TOIT A (2000) Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria.

KUNDHLANDE G, GROENEWALD DG, BAIPHETHI MN, VILJOEN MF, BOTHA JJ, VAN RENSBURG LD and ANDERSON JJ (2004) Socio-economic study on water conservation techniques in semi-arid areas. WRC Report No. 1267/1/04. Water Research Commission, Pretoria.

LE ROUX PAL, HENSLEY M, VAN RENSBURG LD and BOTHA JJ (2016) The cropping potential of South Africa: land evaluation results obtained during the last 50 years. *S. Afr. J. Plant Soil* **33** (2) 83–88. https://doi.org/10.1080/02571862.2014.981878

MACVICAR CN, SCOTNEY DM, SKINNER TE, NIEHAUS HS and LOUBSER JH (1974) A classification of land (climate, terrain form, soil) primarily for rain fed agriculture. *S. Afr. J. Agric. Ext.* **3** 21–24.

MONTEITH JL and VIRMANI SM (1990) Quantifying climatic risk in the semi-arid tropics: ICRISAT experience. In Muchow DC and Bellamy JA (eds.). *Proceedings of the International Symposium on Climatic Risk in Crop Production: Models and Management for the Semi-Arid Tropics and Subtropics*, Brisbane, Australia, July 1990.

MORIN J and CLUFF CB (1980) Runoff calculations on semi-arid watersheds using a rotadisk rain simulator. *Water Resour. Res.* **16** 1085–1093. https://doi.org/10.1029/wr016i006p01085

MUCHOW RC, HAMMER GL and CARBERRY PS (1990) Optimising crop and cultivar selection in response to climatic risk. In: Muchow DC and Bellamy JA (eds). *Proceedings of the International Symposium on Climatic Risk in Crop Production: Models and Management for the Semi-Arid Tropics and Subtropics*; Brisbane, Australia, July 1990.

PASSIOURA JB (1996) Simulation models: science, snake oil, education or engineering? *Agron. J.* **88** 690–694. https://doi.org/10.2134/agronj1996.00021962008800050002x

PATERSON DG, TURNER DP, WIESE LD, VAN ZIJL GM, CLARKE

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019

CE and VAN TOL JJ (2015) Spatial soil information in South Africa: Situational analysis, limitations and challenges. *S. Afr. J. Sci.* **111** (516) Art # 2014-0178, 7 pp. http://dx.doi.org/10.17159/sajs.2015/20140178
PENNING DE VRIES FWT and SPITTERS CJT (1990) The potential for improvement in crop simulation. In: Muchow DC and Bellamy JA (eds) *Proceedings of the International Symposium on Climatic Risk in Crop Production: Models and Management for the Semi-Arid Tropics and Subtropics*; Brisbane, Australia, July 1990.
SANEWE AJ and BACKEBERG GR (2012) Overview of research on rainwater harvesting and conservation by the Water Research Commission. In: Van Rensburg LD (ed.) *Rainwater Harvesting and Conservation techniques for improving household food security. Irrigation and Drainage*: Volume 61, Suppl. 2 October 2012. 1–6. https://doi.org/10.1002/ird.1691
SCHEEPERS JJ, SMIT JA and LUDICK BP (1984) An evaluation of the agricultural potential of the Highveld region in terms of dryland cropping and livestock production. Technical Communication no. 185. Department of Agriculture, Pretoria.
SCHOEMAN JL and MACVICAR CN (1978) A method for evaluating and presenting the agricultural potential of land at regional scales. *Agrochemophysica* **10** 25–37.
SCHOEMAN JL, VAN DER WALT M, MONNIK KA, THACKRAH J, MALHERBE J and LE ROUX RE (2002) Development and application of a land capability classification system for South Africa. ARC-ISCW Report no. GW/A/2000/5T. ARC-Institute for Soil, Climate and Water, Pretoria.
SCHWARTZ RC, BAUMHARD RL and EVETT SR (2010) Tillage effects on soil water distribution and bare soil evaporation throughout a season. *Soil & Till. Res.* **110** 221–229. https://doi.org/10.1016/j.still.2010.07.015
SOIL CLASSIFICATION WORKING GROUP (1991) Soil classification – A taxonomic system for South Africa. *Mem. Agric. Natl. Resour. S. Afr. No. 15*. Department of Agricultural Development, Pretoria.
TURNER DP (Ed) (1991) A procedure for describing soil profiles. Soil and Irrigation Research Institute Report No. GB/A/91/67. Soil and Irrigation Research Institute, Pretoria.
TURNER DP (2000) Soils of KwaZulu-Natal and Mpumalanga. PhD thesis, University of Pretoria.
TURNER DP, CHIRIMA JG, PATERSON DG, CARSTENS JP, SEABI FT and MUSHIA N (2014) Integrated food and nutrition security initiative. Mapping of crop producing areas in the Eastern Cape Province. ARC-ISCW Report No: GW/A/2014/23. ARC Institute for Soil, Climate and Water, Pretoria.
UEHARA G and TSUJI GY (1990) Progress in crop modelling in the IBSNAT project. In: Muchow DC and Bellamy JA (eds). *Proceedings of the International Symposium on Climate Risk in Crop production: Models and management for Semi-Arid Tropics and Subtropics*, Brisbane, Australia, July 1990.
VAN DER MERWE FJ (1985) Food production in Southern Africa and the limiting factors [in Afrikaans]. Priorities up to the year 2000. Unpublished report. South African Academy for Science and Arts, Pretoria.
VAN RENSBURG LD, BOTHA JJ, ANDERSON JJ and HENSLEY M (2012) The nature and function of the in-field rainwater harvesting system to improve agronomic sustainability. In L.D. van Rensburg (Editor). *Rainwater Harvesting and Conservation techniques for improving household food security. Irrigation and Drainage*: Volume **61**, Suppl. 2, October 2012. 34–40. https://doi.org/10.1002/ird.1678
VAN STADEN PP (2000) The influence of runoff-water harvesting relationships on water use by maize on high-risk clay soils. [in Afrikaans]. MSc. Agric. thesis, University of the Free State, Bloemfontein.
VAN ZIJL GM (2013) Developing a digital soil mapping protocol for Southern Africa using case studies. PhD thesis, University of the Free State, Bloemfontein.
VAN ZIJL GM, LE ROUX PAL and TURNER DP (2013) Disaggregation of land types using terrain analysis, expert knowledge and GIS methods. *S. Afr. J. Plant Soil* **30** (3) 123–129. https://doi.org/10.1080/02571862.2013.806679
VERSTER E (1974) The soils of the Transvaal region [in Afrikaans]. PhD thesis, University of the Free State, Bloemfontein.
WALKER S and 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.
WELDERUFAEL WA (2006) Quantifying rainfall-runoff relationships on selected benchmark ecotopes in Ethiopia: a primary step in water harvesting research. PhD thesis, University of the Free State, Bloemfontein.
WELDERUFAEL WA, LE ROUX PAL and HENSLEY M (2008) Quantifying rainfall-runoff relationships on the Dera Calcic Fluvic Regosol ecotope in Ethiopia. *Agric. Water Manage.* **95** (11) 1223–1232. https://doi.org/10.1016/j.agwat.2008.04.007
WELDERUFAEL WA, LE ROUX PAL and HENSLEY M (2009) Quantifying rainfall-runoff relationships on the Melkassa Hypo Calcic Regosol ecotope in Ethiopia. *Water SA* **35** (5) 639–648. https://doi.org/10.4314/wsa.v35i5.49189
WILLMOTT CJ (1982) Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **63** 1309–1313.
ZERE TB, VAN HUYSSTEEN CW and HENSLEY M (2005) Estimation of runoff at Glen in the Free State Province of South Africa. *Water SA* **31** 17–21. https://doi.org/10.4314/wsa.v31i1.5116

https://doi.org/10.17159/wsa/2019.v45.i3.6736
Available at https://www.watersa.net
ISSN 1816-7950 (Online) = Water SA Vol. 45 No. 3 July 2019