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The Nature of Rainfall at a Typical Semi-Arid Tropical Ecotope in Southern Africa and Options for Sustainable Crop Production

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1. Introduction

Climate plays an important role in crop biomass production. Extreme climatic conditions and high seasonal variability of climatic parameters could adversely affect productivity (Li et al., 2006) since rainfall determines the crop yields and the choice of the crops that can be grown. The pattern and amount of rainfall are among the most important factors that affect cropping systems. The analysis of rainfall records for long periods provides information about rainfall patterns and variability (Lazaro et al., 2001). Drought mitigation can be planned by understanding daily rainfall behaviour (Aghajani, 2007). Dry spell analysis assists in estimating the probability of intra-season drought in order to adjust water management practices (Tesfaye and Walker, 2004; Kumar and Rao, 2005).

It is important to know the likely durations and probability of wet spells particularly at critical times during the growing season (Dennet, 1987; Sivakumar, 1992). Probability distributions are used widely in understanding the rainfall pattern (Abdullah and Al-Mazroui, 1998). The normal distribution is one of the most important and widely used parameter in rainfall analysis (Kwaku and Duke, 2007). Despite the wide applicability of the normal distribution, there are many instances when observed rainfall distributions are neither normal nor symmetrical. Rainfall can be abnormally distributed (Stephens, 1974) except in wet regions (Edwards et al., 1983). Jackson (1977) observed that annual rainfall distributions are markedly skewed in semi-arid areas and the assumption of normal frequency distribution for such areas is inappropriate. Rainfall can also be described by other distributions such as Gamma distribution (Abdullah and Al-Mazroui, 1998; Aksoy, 2000; Garcia et al., 2007), the log-Pearson type III distribution (Chin-Yu, 2005), the Weibull and Gumbel distributions (Tilahun, 2006).

In semi-arid areas, marginal and erratic rainfall, exacerbated by high runoff and evaporation losses, constrain crop production. The ecotope at Thohoyandou experiences these conditions. By definition, an ecotope is a homogenous piece of land with a unique combination of climate, topographic and soil characteristics (Hensley et al. 2000). In order to understand the feasibility of using a water harvesting system at the ecotope, rainfall analysis and the identification of prevailing rainfall patterns is required (Dennet, 1987; Rappold, 2005). The major objectives of this chapter are to outline (i) an analysis of long-term (1983-

2005) rainfall data recorded for the ecotope at Thohoyandou in the Limpopo River basin (LRB) (South Africa) in order to provide a basis for future management of crop production and (ii) viable options for sustainable crop production at the location and similar agro-ecological areas.

2. Analyses of rainfall distribution patterns

Rainfall distribution patterns can change over a given period. This is expected particularly when taking into account the global climate change. This climate change impacts negatively on agricultural activities (Rosenweig and Parry, 1994; Rosenberg 1992). The nature of the changes in rainfall distribution patterns may also depend on the geographical location of the area of interest.

2.1 Geographical location of the ecotpe

The ecotope used in this study is located at the University of Venda (21^{o} 58′ S, 30^{o} 26′ E; 596 m above sea level) at Thohoyandou in the LRB. The location falls in the lowveld of the greater LRB which is situated in the southern part of southern Africa between about 20^{o} and 26^{o} S latitude and 25 and 35^{o} E longitude. The greater LRB encroaches over the national borders of four different countries namely Botswana, Mozambique, South Africa and Zimbabwe. According to the Koppen Classification, the basin is predominantly semi-arid.

The daily temperatures at Thohoyandou vary from about 25˚C to 40^{o} C in summer and between approximately 12˚C and 26^{o} C in winter. Rainfall is highly seasonal with 95% occurring between October and March, often with a mid-season dry spell during critical periods of crop growth (FAO, 2009). Mid-season drought often leads to crop failure and low yields (Beukes et al., 1999). The average rainfall is about 800 mm but varies temporarily. The soils at the ecotope are predominantly deep (>150 cm), red and well drained clays with an apedal structure. Clay content is generally high (60 %) and soil reaction is acidic (pH 5.0). The soils are formed *in situ* and classified locally as Hutton form (Soil Classification Working Group, 1991) equivalent to Rhodic Ferralsol (WRB, 2006).

2.2 Statistical analysis of rainfall data

The records of daily rainfall data and reference potential evapotranspiration records were obtained from local institutions (the National Weather Service and Research Council) and used for determining annual and monthly totals. The years or consecutive months with missing data were not included in the calculations of averages. This was so for 1982, 2006 and 2007. Consequently, a 23 year rainfall data set (1983-2005) was analyzed following the standard procedure for analysing rainfall data for agricultural purposes which involves summarising the daily data to obtain monthly totals and then annual totals (Abeyasekera et al., 1983). This was done partly to reduce the volume of data in subsequent analyses. The approaches used in data analysis were similar to those used by Belachew (2002) and Tilahun (2006).

2.3 Rainfall distribution pattern and probability distribution models

The identification of the probability distributions of annual and monthly rainfall data was also important. The observed distributions were fitted to theoretical probability distributions by comparing the frequencies (Tilahun, 2006). Data normality was tested using skewness and kurtosis coefficients and probability distributions were evaluated with the aid of probability plots and curve fitting using Minitab 14 statistical software (Minitab Inc., 2004)). The goodness-of-fit tests were based on the Anderson-Darling (AD) test (Stephens, 1974) which measures how well the data follow a particular distribution pattern. The p-value with the greatest magnitude was considered to be the best fit. Where the p-values were equal, the smallest AD value was then used to decide the best fit. Rainfall data from October to March (which is the cropping season at the ecotope) were considered in fitting distributions. In addition, four probability distribution models namely the normal, lognormal, Gamma and Weibull distributions were tested (Table 1).

Distribution	Probability density function	Parameter description
Normal	$f_{(x)} = n(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\Pi}}$ $\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] for -\infty \le x \le \infty$	μ= mean of the population x σ= standard deviation of the population x
Lognormal	$f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2\right)}{x\sigma\sqrt{2\pi}}$	σ = the standard deviation of ln x μ = the mean of ln x
Gamma	for 0 ≤x≤∞ $f_{(x)} = \frac{1}{\beta^{\alpha}\Gamma_{(\alpha)}}\alpha^{x-1}e^{-x/\beta}$	α is the scale parameter β is the shape parameter of the distribution $\Gamma_{(\alpha)}$ = the normalising factor
Weibull	for 0≤x≤∞ $f_{(x)} = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left[\frac{x}{\beta}\right]^{\alpha}\right)$	α = the scale parameter β = the shape parameter of the distribution

Table 1. Probability distribution models used for testing the rainfall distribution patterns at the ecotope.

The results of the analysis showed that there was variation among the AD values depending on the distribution model applied (Table 2). Based on the AD goodness-of-fit and p-values, the normal distribution model was the best in describing the annual rainfall at the ecotope. This was in agreement with the observation reported previously for a semi-arid environment in Kenya at which the annual rainfall approximated a normal distribution (Rowntree, 1989). In contrast, 50% of the monthly rainfall patterns during the cropping season (October to March) were described best by the lognormal theoretical distribution model (Table 3). This suggested that for a given ecotope, the distribution model that best describes the annual rainfall pattern is not necessarily identical to that describing the monthly rainfall pattern. In addition, the results also suggested that there is no constant best distribution function for rainfall distribution for all the months at an ecotope. In a similar study in Ethiopia, Tilahun (2006) found that most of the monthly rainfall data sets were best described by the lognormal distribution while annual rainfall distribution patterns fitted either the Weibull or the Gumbel or the Gamma distribution models.

	Normal				Lognormal				Gamma				Weibull			
	AD	**μ**	**σ**	**The *p*-values**	**AD**	**μ**	**σ**	**p-value**	**AD**	**α**	**β**	***p*-value**	**AD**	**α**	**β**	**The *p*-values**
Oct	1.168	64.38	56.41	<0.005	0.308	3.775	0.9904	0.533	0.250	45.14	1.420	>0.250	0.269	68.86	1.216	>250
Nov	1.529	97.89	77.14	<0.005	0.370	4.292	0.8297	0.397	0.466	52.59	1.861	>0.250	0.555	107.80	1.385	0.154
Dec	0.912	140.00	89.59	0.017	0.289	4.735	0.6718	0.584	0.419	54.17	2.583	>0.250	0.474	157.80	1.695	0.232
Jan	0.595	135.00	100.20	0.109	0.489	4.578	0.9126	0.200	0.341	80.48	1.677	>0.250	0.316	147.90	1.384	>250
Feb	0.905	133.90	117.10	0.017	0.539	4.375	1.2060	0.149	0.389	122.30	1.094	>0.250	0.404	137.70	1.078	>0.250
Mar	0.958	91.63	79.50	0.013	0.995	4.086	1.0910	0.010	0.519	70.57	1.298	0.218	0.478	97.06	1.185	0.228
Annual	0.339	781.50	248.10	0.468	0.818	6.603	0.3711	0.029	0.586	89.43	8.738	0.144	0.361	867.30	3.634	>0.250

AD = Anderson-Darling statistic

Table 2. Goodness-of-fit values and parameters of theoretical probability distributions fitted to annual and monthly rainfall data

Rainfall Month	**Best DistributionModel**
October	Lognormal
November	Lognormal
December	Lognormal
January	Weibull
February	Weibull
March	Gamma

Table 3. The best-fit distribution models for the respective monthly rainfall patterns at the semi-arid ecotope in the Limpopo River basin.

2.4 The exceedance probability of annual and monthly rainfall

Apart from establishing the rainfall distribution pattern, the exceedance probability of annual and monthly rainfall, was calculated. By definition, it is the probability that a given amount of rainfall is exceeded in a specific unit period. The probability of exceedance of annual and monthly rainfall was calculated from the respective rainfall distribution parameters as obtained from testing the probability distribution models described in section 2.3. This information is useful in selecting crops since each crop has a specific water requirement to take it through the growth cycle (Rappold, 2005). The information may also be critical in designing appropriate water storage facilities for supplementary irrigation in future. In order for such facilities to be efficient, they need to be constructed in proportion to the amount of water that can be expected during a rainfall event (Schiettecatte, 2005). However, the chances of implementing such strategies in many parts of Africa inhabited by smallholder farmers remain remote and highly unlikely.

At the ecotope, the probability of exceeding various amounts of annual rainfall diminished as the threshold rainfall amount increased. For example, there was 94 % chance of receiving annual rainfall >400 mm whilst the chance of having >1 500 mm of rainfall was zero (Table 4). There was 47 % probability of exceeding 800 mm of annual rainfall. During February, there was a 72% chance of receiving rainfall ≥ 5.0 mm yet the probability of receiving rainfall > 500.0 mm diminished to 2.0% (Table 5). The mean annual rainfall for the site was about 781.0 mm (Table 6).

Annual rainfall (mm)	**Probability of Exceedance (%)**
>400.0	94.0
>600.0	77.0
>800.0	47.0
>1 000.0	19.0
>1 200.0	5.0
>1 500.0	0.0

Table 4. The probability of receiving annual rainfall exceeding specific amounts ranging from 400.0 mm to 1 500.0 mm.

Month	**Monthly Rainfall (mm)**					
	5.0	**50.0**	**100.0**	**200.0**	**500.0**	**600.0**
	Probability of exceedance (%)					
Oct	99.0	44.0	20.0	6.0	1.0	0.0
Nov	100.0	68.0	35.0	11.0	1.0	1.0
Dec	100.0	89.0	58.0	20.0	1.0	1.0
Jan	99.0	80.0	56.0	22.0	0.0	0.0
Feb	72.0	71.0	49.0	22.0	2.0	0.0
Mar	97.0	63.0	35.0	9.0	0.0	0.0

Table 5. The probability of receiving monthly rainfall exceeding specific amounts ranging from 5.0 mm to 600.0 mm

Parameter	**Mean**	**SD**	**CV**	**Min**	**Max**	**SC**	**KC**
Oct	64.38	56.41	1.14	3.5	243.8	1.64	3.31
Nov	97.89	77.14	1.27	7.3	296.5	1.40	1.20
Dec	139.95	89.59	1.56	31.3	331.7	0.78	-0.68
Jan	134.96	100.24	1.35	12.0	420.0	1.02	1.29
Feb	133.87	117.07	1.14	5.3	420.7	0.87	-0.02
Mar	91.63	79.50	1.15	5.7	361.2	1.87	5.15
Apr	39.87	53.94	0.74	0.1	249.2	2.57	8.55
May	17.74	35.35	0.50	0.0	162.7	3.53	13.74
Jun	12.41	14.10	0.88	0.0	45.9	1.00	-0.16
Jul	8.00	15.29	0.52	0.0	67.3	3.01	10.37
Aug	7.87	10.87	0.72	0.0	48.5	2.67	8.60
Sept	25.29	38.11	0.66	0.0	162.5	2.58	7.35
Annual	781.47	248.07	3.15	281.2	1239.3	-0.15	-0.14

CV = Coefficient of variation; SD = Standard deviation; SC = Skewness coefficient; KC = Kurtosis coefficient.

Table 6. Statistical parameters for mean monthly and annual rainfall data (1983-2005).

2.5 The probability of dry spells

Equally important was determining the probability of dry spells. A dry day was defined as a day receiving less than 1.0 mm of rainfall. A dry spell was a sequence of dry days bracketed by wet days on both sides (Kumar and Rao, 2005). The analysis of the frequency of dry spells was adapted from the method of Belachew (2002). In this approach, a period of Y years of records, the number of times i that a dry spell of duration t days occurs, was counted on a monthly basis; then the number of times I that a dry spell of duration longer than or equal to t occurs was computed through accumulation. The consecutive dry days (1d, 2d, 3d …) were prepared from historical data. The probabilities of occurrence of consecutive dry days were estimated by taking into account the number of days in a given month n. The total possible number of days, N, for each month over the analysis period was computed as, $N = n*Y$, hence the probability p that a dry spell equal or longer than t days was computed as:

$$p = \frac{I}{N}$$

The distribution of daily rainfall totals by amount and frequency was obtained by using frequency analysis of historic daily rainfall data. The statistical parameters (namely the mean, standard deviation, coefficient of variation, coefficient of skewness and coefficient of kurtosis) for both the annual and monthly rainfall were also determined (Table 6). For a normal distribution, the skewness and kurtosis coefficients should be zero or near zero. This approach can be confirmed further by determining the p-values using the AD test.

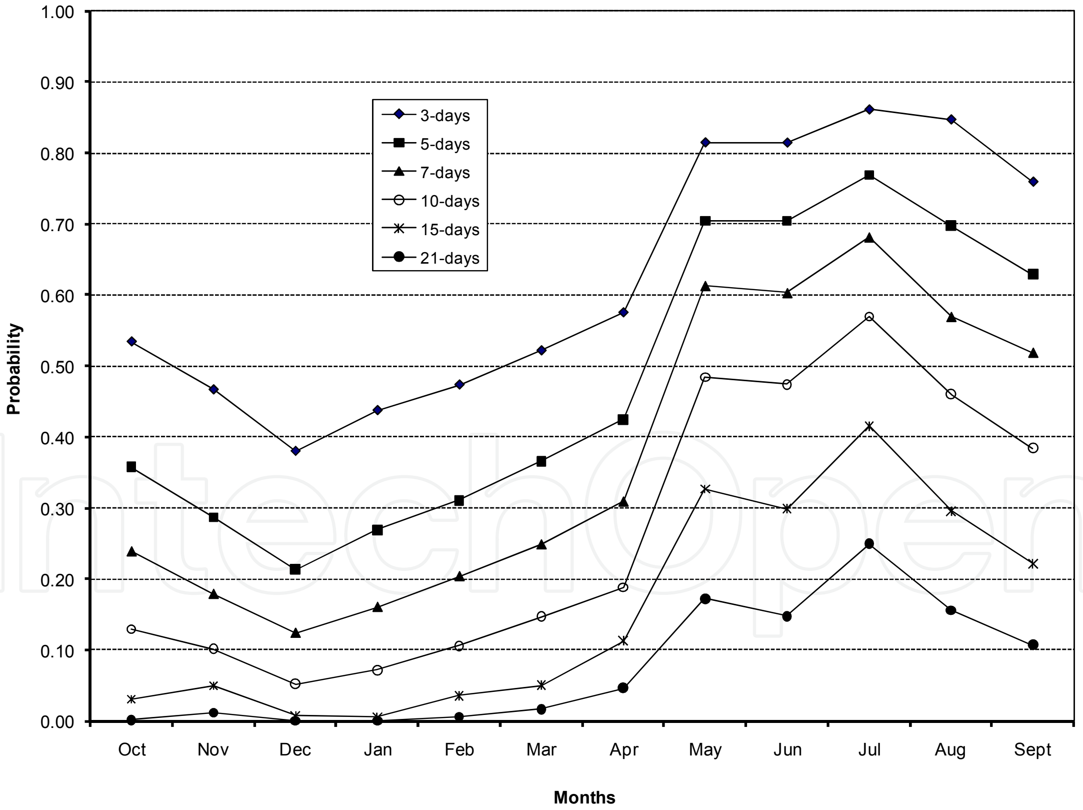

Fig. 1. Probability of a dry spell lasting ≥n days in each month estimated using the raw data from 1983-2005 at the semi-arid ecotope. (n=3, 5, 7, 15, 21).

The occurrence of dry spells has particular relevance to rain-fed agriculture, as rainfall water is one of the major requirements for plant life in rain-fed agriculture (Belachew, 2002; Rockstrom et al., 2002). The probability of occurrence of dry spells of various durations varied from month to month (Fig. 1). December had the lowest probabilities of occurrence of dry spells of all durations. Generally the occurrence of dry spells of all durations decreased between October and March. This period coincides with the rainy season in the region (Lynch et al., 2001). The probability of having a dry spell increased with the reduction in the duration of the dry spell. In other words, there were more chances of having a 3d dry spell than a 10 or 21d dry spell. For instance, in December, there was 20% probability of having a dry spell lasting five days but 0% probability of having a dry spell lasting 21d (Fig. 1). This trend was in agreement with observations reported in literature (Sivakumar, 1992; Aghajani , 2007).

2.6 The variability of rainfall

The rainfall data for the ecotope indicated that monthly rainfall was strongly skewed to the right (high positive values of skewness coefficients) and highly leptokurtic, a phenomenon common in semi-arid regions. The yearly rainfall analysis indicated that the mean annual rainfall (781.0 mm) at the ecotope was accompanied by a high (248.0 mm) standard deviation. In addition, the coefficient of variation of the annual rainfall was high (315 %) indicating high variability of rainfall from year to year. The monthly rainfall analysis indicated that the site receives about 80% of annual rainfall during the period October to March (Fig. 2). This was in agreement with the observation that most of the rainfall amount in the region occurs between October and March (Landman and Klopper, 1998). However, this rainfall amount received at the the ecotope should be approached with caution partly because of the relatively high potential evapotranspiration. The effective rainfall is low. The coefficient of variation for the monthly rainfall was high (156 %) confirming the high variability in the monthly rainfall at the location. This result was consistent with the findings by Tyson (1986) who reported a similar rainfall pattern in the interior regions of South Africa.

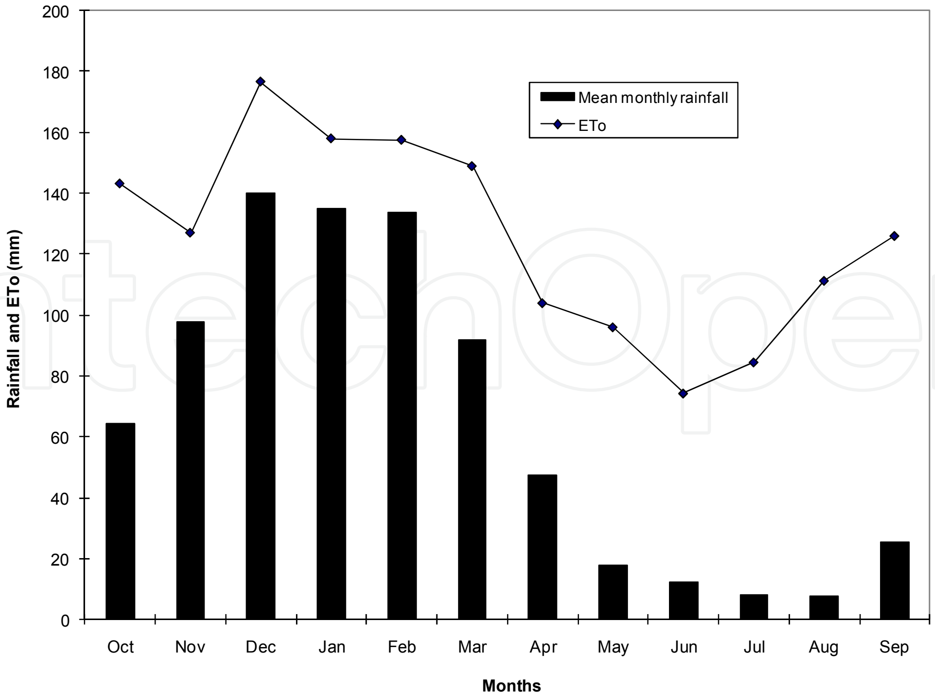

Fig. 2. Mean monthly rainfall and potential evapotranspiration (ETo) over a 23-year period at the semi-arid ecotope.

2.7 Agro-climatic zonation

An aridity index represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of the crop (Tsiros et al., 2008). Mzezewa et al. (2010) reported that the aridity index for the study area was 0.52. Based on the UNESCO (1979) classification criteria, the study area is on the borderline case between semi-arid and sub-humid since it receives low rainfall and experiences high evapotranspiration. At the semi-arid ecotope at Thohoyandou, the potential evapotranspiration was consistently higher than the mean monthly rainfall throughout the year (Fig. 2) indicating that rainfall was not effective at the study site. Moreover, research conducted elsewhere in semi-arid regions showed that approximately 70 % of annual rainfall is lost due to evaporation from the soil (Hoffman, 1990; Jalota and Prihar, 1990; Botha et al., 2003). Therefore, the adoption of effective practices that maximise the utilization of rainfall and minimize water loss is imperative so as to achieve sustainable crop production at the ecotope.

3. Options for crop production

Information on rainfall amount and variability is important in deciding on the choice of crops and cultivars to produce at the ecotope. The rainfall threshold under rain-fed conditions varies from one crop species to the other and depends on a combination of several environmental factors such as soil type and diurnal temperatures. For instance, the water retention properties of sandy soils would be considerably different from those of clay soils while high day temperatures encourage evapotranspiration. Although the mean annual rainfall at the ecotope was in excess of 700 mm, there was high variability (315%) in the quantity of rainfall received. Nonetheless, the high evaporative demand as indicated by the Aridity Index (0.52) of the ecotope means that most of the rain is not available for crop use. On the other hand, the optimum rainfall for a staple cereal such as corn (Zea mays) is considered to range between 500 and 800 mm (Ovuka and Linqvist, 2000) but in crop production, the distribution of the rainfall is critical.

This spatial and temporal variability in annual rainfall experienced in the area imposes several major challenges for crop growers particularly small-holder farmers. Therefore, their crop choices must take into consideration the challenges imposed by moisture stress during the cropping season. In this regard, the use of drought tolerant crop technologies as a means for achieving sustainable crop production in the area is merited. Such crops include specific legumes and small-grain cereals.

3.1 Cropping systems

The ecotope is an agro-ecological representation of the prevailing conditions in the Limpopo basin. The crop production at the ecotope is dependent on the agricultural systems in the area. The systems consist of either the large-scale sector or small-scale sector (also called the small-holder sector). The latter is more prevalent and is characterized by resource-poor farmers in possession of small land holdings averaging approximately 0.4 ha per household. The pressure of limited land for cultivating crops, insufficient production inputs as well as the subsistence form of crop production practiced by typical smallholder farmers largely influence the types of crops they grow. The cropping systems typically consist of rain-fed cereals such as corn grown either in a monocrop or intercropped with a variety of minor crops such as peanut (*Arachis hypogeae*), common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*). Corn is the staple cereal. In some sub-regions of the LRB such as the dry-land area of Sekhukhune district, the farmers grow small grain cereals (especially millets) intercropped with tapery bean (*Phaseolus acutifolius*). In contrast, crop production in the large-scale sector is more intensive, highly mechanized and commercially oriented.

3.2 Drought tolerant legumes

The specific legume species recommended for production under these frequent moisture deficit conditions include chickpea (*Cicer arietinum*), cowpea (*Vigna unguiculata*) pigeonpea (*Cajanus cajan*) and tapery bean (*Phaseolus acutifolius*). These legumes offer to the farmers numerous advantages ranging from promiscuous (non-specific or tropical) type of nodulation to high potential for income generation (Table 7). Their ability to form effective nodules with soil rhizobia ubiquitous in African soils enables them to be sown without treating the seed with commercial inoculants. The legumes improve soil fertility through biological nitrogen fixation (Mapfumo et al., 1999; Serraj et al.,1999; Shisanya 2002) and provide food for human consumption.

	Agronomic Aspect	**Chickpea**	**Cowpea**	**Pigeonpea**	**Tapery bean**
(i)	Requirement for commercial inoculants for seed at planting time	None	None	None	None
(ii)	Requirement for production inputs	Minimal	Minimal	Minimal	Minimal
(iii)	Tolerance to drought	High	Very High	Very High	High
(iv)	Yield potential (approx.)	Very High (5.0 t ha^{-1})	High (4.0 t ha^{-1})	High (3.0 t ha^{-1})	Medium to High (2.0 t ha^{-1})
(v)	Amount of N_2-fixed (approx.)	High (124 kg ha^{-1})	Medium (120 kg ha^{-1})	Very High (166 kg ha^{-1})	Not Available
(vi)	Ability to ratoon and produce another harvest	None	None	Yes	None
(vii)	Requirement for expertise in seed production	None to Very Low	None to Very Low	None to Very Low	None to Very Low
(viii)	Household utilization	Yes	Yes	Yes	Yes
(ix)	Storability	High	Low	High	Medium
(x)	Use as stock feed	Yes	Yes	Yes	Yes
(xi)	Demand in domestic or regional or international markets	Very High	Very High	Very High	Very High

Table 7. Summary of important agronomic traits of four tropical legumes suitable for production by small-holder farmers at the ecotope.

3.2.1 Mechanisms of drought tolerance in the legumes

The legumes employ a variety of mechanisms to avoid the effects of moisture stress. One of such mechanisms is drought avoidance in which the legume plant maintains a relatively high tissue water potential despite a soil moisture deficit. The legume plant can also escape the effect of drought stress by completing its life cycle before the occurrence of soil and plant water deficit. In drought tolerance, the plants are able to withstand water deficit periods with low tissue water potential (Mitra 2001). According to Turner (1986), plants that utilize the drought tolerance mechanism are able to maintain turgor by accumulating compatible solutes in the cell environment (osmotic adjustment), increased cell elasticity, decreased cell volume and resistance to desiccation through protoplasmic resistance. Indeterminate legume types with sequential flowering are capable of recovering from drought spells producing a compensatory flush of pods when soil moisture is restored. In addition, the long tapered root associated with most leguminous species facilitates moisture acquisition from deep layers of the soil.

Chickpea is unique partly because it is a post-rainy season (planted in April/May at the ecotope) crop which thrives on the residual moisture after other field crops are harvested. Under receding soil moisture conditions, the chickpea deep root system directly contributes to the grain yield (Kashiwagi et al., 2006). Because of the lack of competition for space with other crops in the field then, it is advantageous for the small-holder farmers who have limited land for cultivation and no irrigation facilities for producing off-season crops during the dry season (May to October). Chickpea is also tolerant to drought, producing higher yields in winter than in summer (Saxena et al., 1993; Katerji, et al., 2001; Kumar et al., 2001; Sabaghpour et al., 2006). On the other hand, tolerance to drought in both cowpea (Elhers and Hall 1997; Singh et al., 1999; Singh and Matsui, 2002) and pigeonpea (Gwata and Siambi, 2009; Kumar et al. 2011; Sekhar et al. 2010) have been reported. Apart from its ability to develop deep roots, cowpea can have reduced leaf size with thick cuticles that reduce water loss (Graham and Vance 2003). The crop utilizes a combination of avoidance, escape and tolerance mechanisms. In tapery bean, the preliminary results obtained from a study aimed at evaluating the potential of the crop at the ecotope, showed that it matures early, within three months after planting. According to Beaver et al. (2003), selecting for early maturity, efficiency in nutrient partitioning to the reproductive structures as well as phenotypic plasticity in bean is useful in adapting the crop to drought conditions. In addition, tapery bean is grown widely in the dry-land area of the Sekhukhune district in Limpopo (Mariga *pers. comm.,* 2011) and the semi-arid areas in eastern Kenya (Shisanya, 2002) indicating its adaptation to drought prone areas.

3.2.2 Agronomic performance of the legumes

In a study designed to evaluate a typical drought tolerant legume, pigeonpea, for two seasons for both adaptation and yield potential at the ecotope under rainfed conditions, 60% of the twenty genotypes flowered early and matured within the cropping season indicating their adaptation to the area (Mogashoa and Gwata 2009). At least five of the cultivars obtained grain yields >1.5 t/ha over the two year period. The highest mean yield (1.9 t/ha) was four-fold higher than that attained by the check cultivar. In another study conducted under similar rain-fed conditions in a semi-arid environment in Malawi, pigeonpea attained considerably high yields (Gwata and Siambi, 2009). The authors reported a high grain yield (3.0 t/ha) for the genotype ICEAP 01480/32 (Table 8).This indicated the potential of the crop under the semi-arid conditions and a viable option for legume farmers in the semi-arid agro-ecological zones. Since biological nitrogen fixation is adversely affected by heat and depleted soil moisture conditions (Zahran 1999; Serraj et al., 1999), the relatively high grain yield observed for the grain legumes indicated that their nitrogen fixation mechanisms were not suppressed under the prevailing agro-ecological conditions. Therefore, these legumes were adapted to the agro-ecological conditions at the ecotope and similar environments in the region. However, the subsistence small-holder farmers in the area tend to prefer planting corn prior to any other crop at the beginning of the cropping season in spite of the high risks paused by either mid-season or end-of-season moisture stress every year (Fig. 3). The sustainable production of corn, by small-holder growers is constrained by highly unpredictable rainfall, high temperatures and low soil fertility among other factors. In our view, small grain cereals are more appropriate than corn for the predominantly arid conditions at the ecotope and similar agro-ecological areas in the region.

Fig. 3. Contrast in sensitivity to mid-season moisture stress between corn (in the foreground) and pigeonpea (in the background).

	Cultivar	Grain Yield (t/ha)
(i)	ICEAP 01144/3	2.7 a
(ii)	ICEAP 01160/15	2.4 a
(iii)	ICEAP 01480/32	3.0 a
(iv)	ICEAP 01162/21	2.6 a
(v)	ICEAP 01167/11	2.2 a
(vi)	ICEAP 01514/15	2.9 a
(vii)	*Royes	1.0 b
(viii)	**Mutawa Juni	1.1 b

Table 8. Grain yield of pigeonpea germplasm evaluated under rain-fed conditions in Malawi. (*Source*: Adapted from Gwata and Siambi, 2009).

Means in the column followed by the same letter are not significantly different at the 0.05 probability level by Tukey's test. *Commercial cultivar in Malawi; **Unimproved traditional landrace popular in Malawi.

3.3 Drought tolerant small-grain cereals

In many parts of Africa, small grain cereals such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*) are useful for both human consumption and animal feed. For instance, sorghum is regarded as the major source of food in many countries in sub-Saharan Africa such as Chad, Sudan and Tanzania (Bucheyeki et al., 2010). In parts of southern Africa, sorghum grain is used for brewing commercial alcoholic and non-alcoholic beverages (Mushonga et al 1993). The stover is used for fodder, fencing, thatching as well as fuel purposes (Rai et al., 1999). Similarly, pearl millet is used for food and feed (Rai et al., 1999). On the other hand, finger millet is used widely for human consumption throughout southern Africa (Mushonga *et al.,* 1993; Mnyenyembe, 1993). In contrast to the other cereals, finger millet is rich in the protein fraction eleusinin and considerable amounts of cystine, methionine and tryptophan. It also contains a range of minerals such as calcium, copper and manganese. Partly because of its slow digestion, it is preferred by some end-users. The crop residue also provides readily digestible nutrients in livestock feeds.

3.3.1 Mechanisms of drought tolerance in the small grain cereals

These small grain cereals cope with moisture deficit in a variety of ways. For instance, pearl millet can withstand periods of moisture stress and still produce biomass and grain because of its high water use efficiency as opposed to increased water uptake efficiency by a deep root system (Zegada-Lizarazu and Lijima 2005). Similarly, the adaptive features of sorghum enable the crop to grow well in agro-ecological conditions where other staple cereals such as corn would not be suitable (Haussmann et al., 2000). These features include a highly branched rooting system, considerable amounts of silica in the root endodermis, ability to form tillers and capability of rolling the leaves to reduce water loss. In finger millet, drought tolerance was attributed to the ability to synthesize stress proteins (Umar et al., 1995).

3.3.2 Agronomic performance of the small-grain cereals

The performance of the small-grain cereals at the ecotope have not yet been investigated adequately. However, studies conducted elsewhere in marginal tropical zones in southern Africa reported moderately high grain yield potentials. For instance, in Zambia, finger millet attained 3.0 t/ha (Agrawal et al., 1993; Mnyenyembe 1993). In comparison, sorghum attained similar high yields in the African sub-continent (Table 9). According to Gari (2001), these small grain cereals, particularly pearl millet, have superior adaptation to drought and poor soils, providing a reliable harvest under such conditions, with minimal inputs. Moreover, rotating these cereals with the legumes enhances their productivity since they benefit from biological nitrogen fixation by the legumes (Batiano and Ntare 2000). Alternatively, the cereals can be intercropped with the legumes especially cowpea and pigeonpea. The benefits of cereal x legume intercrops in sub-Saharan Africa have been documented widely (Stoop and Staveren 1981; Ntare 1989; Klaij and Ntare 1995; Batiano and Ntare 2000).

Crop	Yield Potential (t/ha)	Country (Major Agro-ecological region)	Source
Finger millet	3.3	Malawi (southern Africa)	Mnyenyembe, 1993
	3.0	Zambia (southern Africa)	Agrawal et al., 1993
Sorghum	2.8	Chad (north/west Africa)	Yapi et al.,1998
	3.0	Mali (north Africa)	Shetty et al.,1991
	1.8	South Africa (southern Africa)	Olembo et al., 2010
	3.5	Tanzania (east Africa)	Bucheyeki et al.,1991
Pearl Millet	2.6	Mali (north Africa)	Wilson et al., 2008
	2.0	Mali (north Africa)	Shetty et al., 1991
	2.7	Zambia (southern Africa)	Wilson et al., 2008

Table 9. Potential yield of three small grain-cereals observed in various African countries.

3.4 Use of short-duration crops

Another sustainable option for the farmers in the region represented by the ecotope is to utilize short-duration (or short-season) crop technologies. The types are able to flower and mature before the on-set of mid-season moisture stress, thus escaping drought. Among tropical legumes, short-duration cultivars have been developed for cowpea (Gwathmey and Hall 1992; Hall and Patel 1992; Mligo and Singh 2006) and pigeonpea (Gwata and Siambi 2009; Silim and Omanga 2001). Short-duration cowpeas that can attain 2.0 t/ha within 60 to 70 d after planting have been reported (Ehlers and Hall 1997). In chickpea, extra-short duration genotypes were reported for the semi-arid tropics (Kumar et al., 2001). These genotypes require < 100 d from sowing to maturity and would be ideal for the limited moisture conditions during the post-rainy season at the ecotope.

3.5 Use of field water conservation and harvesting techniques

In-field water harvesting (IRWH) technique described by various researchers (Hensley et al., 2000; Li et al., 2000; Mzezewa et al., 2011) promotes rainfall runoff on a 2.0 m wide no-till strip between crop rows and collects the runoff water in basins where it infiltrates into the soil profile. The in-field runoff captured in the water basins, can result in increased crop yields. In 2003, Botha et al., demonstrated that the soil moisture captured in this way was responsible for increased crop yields on smallholder farms in Thaba Nchu, South Africa. In a similar study utilizing this water harvesting technique, both corn and sunflower attained up to 50% higher yields compared to conventional production systems on duplex soils in the Free State province in South Africa (Hensley et al., 2000). There has been increasing interest recently in South Africa of making crop production less risky and sustainable in semi-arid ecotopes through in-field rainwater water harvesting (Botha et al., 2003). In a study conducted at the ecotope, Mzezewa et al., (2011), observed that IRWH resulted in significantly higher water use, water use efficiency and precipitation use efficiency for both sunflower and cowpea in comparison with the conventional tillage system. However, despite the increase in crop yields, considerable losses of moisture through evaporation were observed. Li et al., (2000) successfully used gravel-mulched furrows to reduce evaporation and increase the grain yield of corn. Alternatively, living soil cover (that is using live or green mulches) between crop plants was proposed as a sustainable option for minimizing water loss from the soil surface. According to Aladesanwa and Adigun (2008), the living mulches can be integrated in an intercrop in order to derive some of the benefits associated with intercropping such as increased yield under conditions of moisture stress, weed suppression, reducing the risks of drought and pests as well as achieving adequate crop diversity. Nonetheless, the economic potential of adapting mulches depends on an array of factors such as the cost of the complementary changes (for example availability of mulch adapted field equipment) as well as land availability.

4. Concluding remarks

The statistical analysis of rainfall data at the ecotope revealed that the rainfall is low and highly unreliable, thus constraining crop production. Soil moisture which is available for crop growth only for limited periods at the location can be lost by evaporation. Sustainable production of cereals and legumes at the ecotope and similar agro-ecological environments hinges on adopting drought tolerant or short-duration cultivars as well as water conservation practices such as in-field rainwater harvesting. Information from the combination of climatic analysis and crop cultivar performance needs to be considered in selecting appropriate planting dates.

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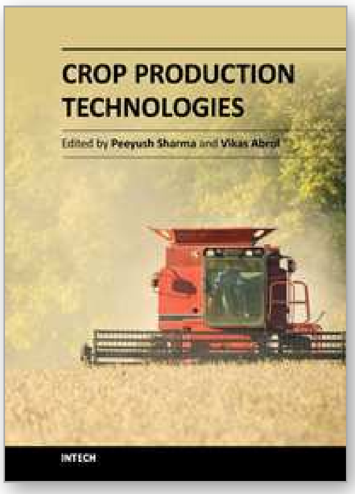

Crop Production Technologies

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Crop production depends on the successful implementation of the soil, water, and nutrient management technologies. Food production by the year 2020 needs to be increased by 50 percent more than the present levels to satisfy the needs of around 8 billion people. Much of the increase would have to come from intensification of agricultural production. Importance of wise usage of water, nutrient management, and tillage in the agricultural sector for sustaining agricultural growth and slowing down environmental degradation calls for urgent attention of researchers, planners, and policy makers. Crop models enable researchers to promptly speculate on the long-term consequences of changes in agricultural practices. In addition, cropping systems, under different conditions, are making it possible to identify the adaptations required to respond to changes. This book adopts an interdisciplinary approach and contributes to this new vision. Leading authors analyze topics related to crop production technologies. The efforts have been made to keep the language as simple as possible, keeping in mind the readers of different language origins. The emphasis has been on general descriptions and principles of each topic, technical details, original research work, and modeling aspects. However, the comprehensive journal references in each area should enable the reader to pursue further studies of special interest. The subject has been presented through fifteen chapters to clearly specify different topics for convenience of the readers.

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