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RELATIVE TRANSPIRATION AS A DECISION TOOL IN CROP MANAGEMENT: A CASE FOR RAINFED MAIZE IN ZIMBABWE

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ABSTRACT

Water stress has been considered to be the primary constraint to yield in water-limited arid and semi-arid environments. This paper describes the characterisation of the rainfall season using relative transpiration (T_{rel}) of a maize crop at 13 climate stations in Zimbabwe. A soil water balance model was used to simulate relative crop transpiration for a maize crop over the duration of each rainfall season to assess its quality (severity of intra-seasonal dry spells). The T_{rel} and length of growing period (LGP) were subjected to frequency analyses and the results were interpolated (kriging) to form a GIS library of expected events in normal, wet and dry years. The normal LGP (50% PE) varied across the stations, with a range of 75 days, exposing opportunities for objective management of variety selection to match crop growth cycles to expected LGP. The time series of T_{rel} showed the time variation of quality of the season with periods of high T_{rel} identifying the high quality parts of the rainfall season suitable for crop production. Soil depth influenced quality of the season, with deeper soils improving quality. A simple tool that can be used to indicate whether or not to grow maize varieties of particular length of growth cycle in a specified region for typical wet, normal or dry rainfall seasons was developed.

Key Words: GIS, kriging, soil water balance

RÉSUMÉ

Le stress hydrique a été considéré comme contrainte majeure au rendement des cultures dans en régions arides et semi arides. Cet articles decrit la caractérisation de la saison pluviométrique par la transpiration relative (T_{rel}) de la culture de ma¿s dans 13 stations climatiques au Zimbabwe. Un modèle de balance sol-eau était utilisé pour simuler la transpiration relative pour la culture du ma¿s sur une durée de chaque saison de pluie pour évaluer sa qualité (séverité entre les saisons sèches). La T_{rel} et la longueur de la période de croissance étaient soumises aux analyses de fréquence et les résultats étaient interpollés (kriging) pour former une base des données GIS des événements attendus des années normales aussi bien que humides que sèches. Le LGP normal (50% PR) variait à travers les stations, avec environ 75 jours, révélant des opportunités pour une gestion objective de la sélection variétale, afin de correspondre les cycles de croissance au LGP attendu. Le temps de série de la T_{rel} a montré la variation dans le temps de la qualité de la saison des périodes de T_{rel} élevée identifiant les parties de haute qualité de la saison pluvieuse appropriées à la production des cultures. La profondeur du sol a influencée la qualité de la saison, avec des qualités améliorant les sols les plus profonds. Un simple outil qui peut être utilisé pour produire ou pas des variétés de ma¿s d'un cycle particulier de longueur de croissance dans une région spécifiée pour des saisons à précipitation typiquement humide, normale ou sèche était développé

Mots Clés: GIS, kriging, balance sol-eau

INTRODUCTION

Water stress is considered to be the primary constraint to yield in water-limited arid and semi-arid environments (Martin *et al.*, 2000). In Zimbabwe, agriculture is primarily rainfed (Raes *et al.*, 2004). The rainfall season is unimodal and spans the months of November to March. No rainfall of agricultural significance is received during the rest of the months covering the cold dry winter from April to July and hot dry spring from August to October. The prevailing climate is characterised by high inter-annual rainfall variability and drought on a seasonal time scale, with punctuations of within season dry spells a common feature (Manatsa *et al.*, 2011). When dry spells coincide with critical moisture sensitive stages of crop development, they may hamper crop transpiration resulting in a reduction of the biomass production and often in yield decline (Raes *et al.*, 2006a).

Various authors have reported different approaches to analysing dry spells in a rainfall season and their effects on agriculture. Examples include meteorological dry spell analysis by Markov chain process and agricultural dry spell analysis using a simple water balance model for east Africa (Barron *et al.*, 2003); dry spell frequency assessment to determine temporary rainfall patterns for southern Africa (Usman and Reason, 2004); examination of wet and dry synoptic spells in studying moisture transport within wet and dry austral summers for southern Africa (Cook *et al.*, 2004).

It can be noted that dry spells affect crop production through a reduction in available soil water in the crop's root zone, which below certain thresholds may cause mild or severe water stress and consequently reduce transpiration. The greater the water stress level, the greater the difference between observed crop transpiration and potential transpiration (when water is non-limiting). The ratio of actual crop transpiration to potential transpiration, called relative transpiration (T_{rel}), can therefore be a good indicator of occurrence and severity of intra-season dry spells in relation to their effect on the particular crop considered. Calculating T_{rel} by a water balance approach also involves considering the soil water retention characteristics together with crop, rainfall and climate (atmospheric demand for water measured by reference evapotranspiration (ET_o)) characteristics. The main advantage of using T_{rel} in comparison with other techniques is in conditioning the rainfall climate assessment to particular crops in specific environments.

In order to develop objective guidelines on crop selection, not only the length and quality of the growing periods need to be assessed (Mugalavai *et al.*, 2008). In Zimbabwe, rainfall is most reliable in agroecological zones IIa and IIb (Fig. 1), where rainfed maize production has the highest potential (Burt *et al.*, 2001; Philips *et al.*, 2002). This paper describes the characterisation of the length of growing period (LGP) and its quality (T_{rel}) in relation to maize production in Zimbabwe as a basis for developing simple guidelines applicable by farmers in actual decision making**.** The locations considered in this study are shown in Figure 1 and were grouped into the three categories, the maize belt (natural zone IIa and IIb), the maize belt border (natural zone III) and the region outside of the maize belt (natural zones IV and V).

MATERIALS AND METHODS

Description of climatic data. Thirteen meteorological stations, 7 within the maize belt, 3 at the border, and 3 outside the maize belt were considered in the study. Daily rainfall data for periods of 19 to 36 years were collected from the Zimbabwe Meteorological Services Department (Table 1).

Climatic data (temperature, humidity, wind speed and solar radiation) necessary for computing daily reference evapotranspiration (ET_o) with the FAO-Penman Monteith equation (Allen *et al.*, 1998), were obtained from the FAOClim database (FAO, 2001) as mean monthly averages. Three stations, namely, Chinhoyi, Chivhu and Kadoma, did not have adequate data in the database. ET_o data for these stations were derived from nearby stations with the help of the FAO New LocClim model (FAO, 2005). The quality of this approximation was evaluated by comparing computed ET_o with the ETo estimates of FAO New LocClim for two other stations (Belvedere and Rusape) in the same region. The

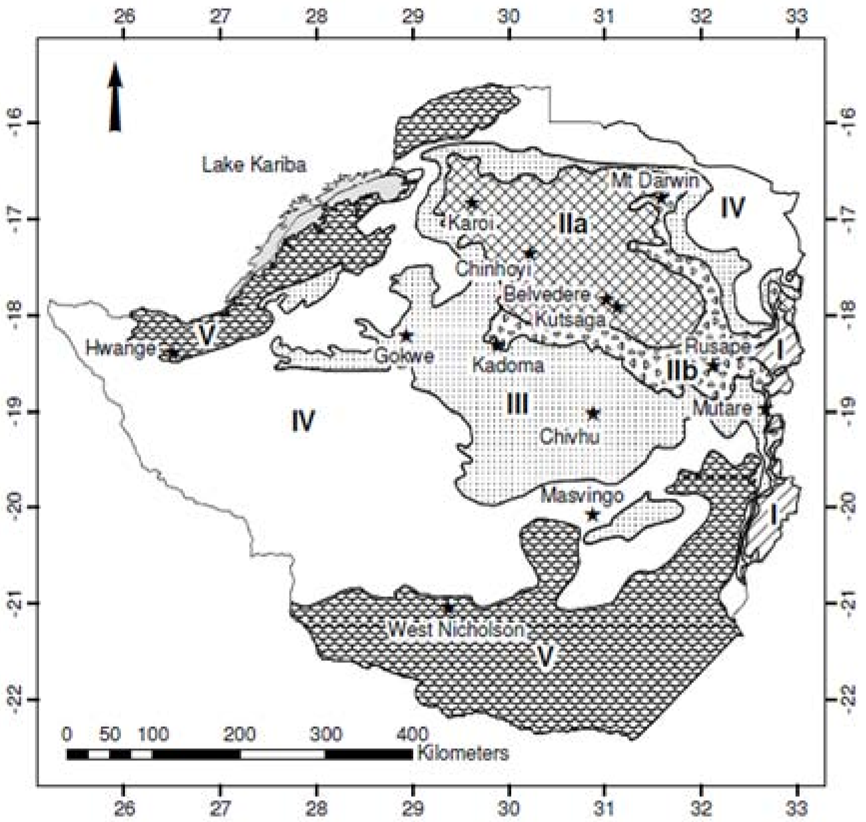

Figure 1. Natural or agro ecological zones of Zimbabwe as defined by Vincent and Thomas (1961) with indication of the meteorological stations used in the data-analysis.

TABLE 1. Locations of the 13 meteorological stations in (1 to 7), at the border (8 to 10) and outside (11 to 13) the maize belt and the period of the availability of rainfall data in Zimbabwe

Meteorological Station name	Latitude (° S)	Longitude (° E)	Elevation (m.a.s.l)	Period	Number of years
Belvedere	17.83	31.02	1471	1971-1999	29
Chinhoyi	17.37	30.22	1143	1964-1999	33
Kadoma	18.32	29.88	1149	1981-1999	19
Karoi	16.83	29.62	1343	1971-1999	29
Kutsaga	17.92	31.13	1479	1971-1999	29
Mt Darwin	16.78	31.58	965	1964-1999	36
Rusape	18.53	32.13	1430	1971-1999	26
Chivhu	19.03	30.88	1458	1968-1998	30
Gokwe	18.22	28.93	1282	1967-1999	33
Mutare	18.97	32.67	1113	1968-1999	31
Hwange	18.40	26.50	750	1971-1999	21
Masvingo	20.07	30.87	1095	1953-2001	39
West Nicholson	21.05	29.37	861	1971-1999	27

m.a.s.l = metres above sea level

estimated values were statistically evaluated using indices that evaluate the fit between observations and simulations, including model efficiency (EF) (Nash and Sutcliffe, 1970), root mean squared error (RMSE) and mean bias error (MBE) (Loague and Green, 1991).

Crop and soil characteristics for the water balance simulations. The soil water balance model BUDGET (Raes *et al*., 2006a) uses crop-specific coefficients (K_c) to convert reference evapotranspiration (ET_o) to actual crop evapotranspiration (ET_a) according to:

$ET_a = K_c * ET_o$ …………......……………. Equation 1

The crop characteristics of maize (Table 2) were adopted from Doorenbos and Kassam (1979) and Allen *et al*. (1998). The allowable fraction (p) of the total available water (TAW) that maize can deplete from the root zone before water stress is induced was assumed constant over the season at 0.5, the default value in BUDGET.

Lengths of growth cycle of common maize varieties were considered to evaluate the suitability of the region for maize production. In this study, the ranges considered were below 130 days for early maturing varieties, 130 to 150 days for medium maturing varieties; and over 150 days for late maturing varieties. However, for purposes of evaluating seasons of varying lengths, the crop characteristics from mid-season stage were maintained constant in the simulations to let the crop transpire until all the soil water was expended at the end of the season. In this way, the simulated transpiration was made crop specific while being allowed to continue beyond the normal length of the crop's growth cycle, provided that the water availability permitted it.

Two soil types were selected for this study from the six major soils of agricultural significance in Zimbabwe (Hussein, 1983; Hall, 1991) varying in total soil available water (TAW). A uniform sandy soil (TAW = 90 mm m^{-1}) was considered for simulations for Hwange and Gokwe weather stations; while a sandy clay loam soil (TAW = 127 mm m^{-1}) was considered at two depths for each of the remaining stations. To account for effects of variations in soil depths, two depths of 0.6 and 1.2 m were considered in the simulations. The maximum effective rooting depth (Z_r) was assumed to be the same as the depth of the soil profile considered.

Determination of LGP and relative transpiration (T_{rel}). The LGP for each of the 13 stations was calculated as the period in calendar days between the onset and the cessation date for each of the climate seasons studied. The onset date was determined using the DEPTH criterion (Raes *et al*., 2004), which defines the onset date of the rainfall season as the first day in a period of 4 days after 1 October in which the cumulative total rainfall exceeds 40 mm. The cessation date was accustomed to the selected maize crop by picking the first day after 15 February when the ratio of the crop evapotranspiration (ET_a) to reference evapotranspiration (ET_o) drops below 0.35. The initial search day of 15 February was selected to exclude mid-season dry spells which may occur within the rainfall season. The ET_a was simulated with the soil water balance model, BUDGET (Raes *et al.*, 2006a) for each day of the growing season by considering the climate data and soil characteristics of each station and the characteristics of the maize crop. As such the cessation date, and consequently LGP became functions of the crop type and soil type in

TABLE 2. Crop parameters for maize (Dorenbose and Kassam, 1979; Allen *et al.,* 1998)

	Growth stage		
	Initial	Crop development	Mid-season till end of season
Length of growth stages (days)	20	35	Variable (variety)
Rooting depth (m)	0.3	0.3 – soil depth	Soil depth (0.6 or 1.2 m)
K_c (crop coefficient)	0.17-1.1	1.1-1.17	1.17 – 0.35

addition to the rainfall and evaporative demand of the location. The value of 0.35 for ET_a/ET_o was selected since it is the crop coefficient (K_c) for maize at harvest (Table 2).

Relative transpiration (T_{rel}) during the rainfall season was simulated by BUDGET with daily time steps as an indicator of the adequacy of rainwater availability for plant growth. T_{rel} was defined to be the ratio of the actual crop transpiration (T_a) to the potential transpiration under no-drought stress conditions (T_c). T_a and T_c for the maize crop were simulated by the BUDGET model. In the simulations, the expected length of growing cycle was ignored, and the crop was allowed to keep on transpiring (by considering $K_{c,mid}$ as the crop coefficient) until permanent wilting point was reached. The T_{rel} becomes, as such, an index for the availability of soil water for maize transpiration. It fluctuates between 100% when soil water is readily available and 0% when the soil reservoir is completely depleted (Raes *et al.*, 2004).

Time series of the mean daily T_{rel} averaged over all the years were plotted with the 95% confidence interval to serve as local water satisfaction profiles. They show the long term average quality of the rainfall season at a specific site and for the various soil types with the expected year to year variation indicated by the confidence interval. T_{rel} values could also be averaged for specific time periods such as the LGP of each year, the growing cycle of different varieties or period covering specific phenological stages such as flowering to indicate the quality of specific sections of the growing period (Mhizha, 2010).

Spatial results presentation and development of a decision support tool. For each station, LGP and seasonal T_{rel} were subjected to frequency analysis using RAINBOW, a software tool designed for studying meteorological or hydrological records (Raes *et al.*, 2006b). The frequency analysis involved selecting a probability distribution best fitting the data. The fit was tested by graphical and statistical methods, and when inadequate, a mathematical transformation of scale was applied to get the best fit for the probability density function and cumulative density function. From the frequency analysis, events in wet, normal and dry years were obtained using the standard probabilities of exceedance (PE) of respectively 20, 50 and 80% according to the thresholds selected by FAO (Smith, 1992; Raes *et al.*, 2006b). LGP was similarly classified as short (20%), normal (50%) and long (80% PE).

The results of frequency analysis were entered into a GIS data library for the maize belt, using ArcGIS version 9.1. The library stores the dry, normal and wet T_{rel} and the short, normal and long LGP for each of the 13 agro-climatic stations analysed and for two soil types. Grid layers were generated by performing a geo-statistical analysis for each parameter. This analysis is explained in detail in Geerts *et al.* (2006). It consisted performing ordinary kriging to interpolate the point results.

In order to yield a sound interpolation for each agro-climatic indicator, a suitable kriging model (ordinary or ordinary anisotropic), a suitable lag distance and a good distribution for the semi-variogram (e.g. Gausian, exponential) were selected in a trial-and-error procedure. The RMSE of cross-validation (Isaaks and Srivastava, 1989) was used to evaluate the prediction quality of the interpolation models. The geographical uncertainty that is related to the sample density is assessed by a pixel-wise mapping of the standard errors of the kriging model.

The rainy season characteristics of LGP and T_{rel} were applied to develop a simple tool to guide decision making on choice of maize variety length to grow for different seasons and different locations. The procedure consisted of matching the variety lengths of growth cycles to rainy season characteristic parameters corresponding to events for wet (20% PE), normal (50% PE) and dry seasons (80% PE) for the different environmental conditions studied. LGP was the main parameter for choice of variety, while a threshold for T_{rel} was developed to guide cut-off conditions when the quality of the rainfall season was regarded unsuitable for rainfed maize cultivation. The K_y yield relation of Dorenbos and Kassam (1979) was used to estimate relative yield of maize as influenced by water stress. T_{rel} was used in place of relative evapotranspiration in a relation of the form Equation 2:

$Y_a/Y_p = 1 - K_y(1 - T_{rel})$ …………………….. Equation 2

Y_a and Y_p are actual yield and potential yield, respectively.

A seasonal K_y factor of 1.25 for maize (Allen *et al*., 1998) was applied. Assuming an allowable minimum relative yield of 60% resulted in a threshold for T_{rel} of about 70%. The developed guideline tool consisted of selecting from the range of common maize varieties grown in Zimbabwe (SeedCo, 2006) as characterised by length of growth cycle, a variety with length of growth cycle not exceeding LGP and a seasonal T_{rel} exceeding 70%. When either of these conditions was not met, it was concluded the respective season was not conducive for rainfed production of the concerned maize variety.

RESULTS AND DISCUSSION

Length of the growing period (LGP). The normal (50% PE) LGP is plotted for Zimbabwe for maize cultivated on deep soils (Fig. 2). The normal LGP (50% PE) varied across the country, with a range of 75 days. A similar range in growth cycles of common maize varieties grown in Zimbabwe covers the whole range of variety classes from early (about 120 days) maturity to late maturity (about 160 days), (SeedCo, 2005). The results showed that in Zimbabwe, there are opportunities for objective variety selection to match the prevailing LGP of a given site, in light of the wide variation in LGP across the country. As such, LGP can be an important rainfall season parameter for crop management, particularly variety selection.

Relative transpiration. Time series plots of average daily T_{rel} are shown in Figure 3 for Chinhoyi in the maize belt and West Nicholson outside the maize belt. Averages and confidence intervals were determined for all the years in the climate series of the input data. The daily T_{rel} profiles showed a symmetrical pattern with a peak around early to mid January; which is linked to the uni-modal pattern of the rainfall season. Since

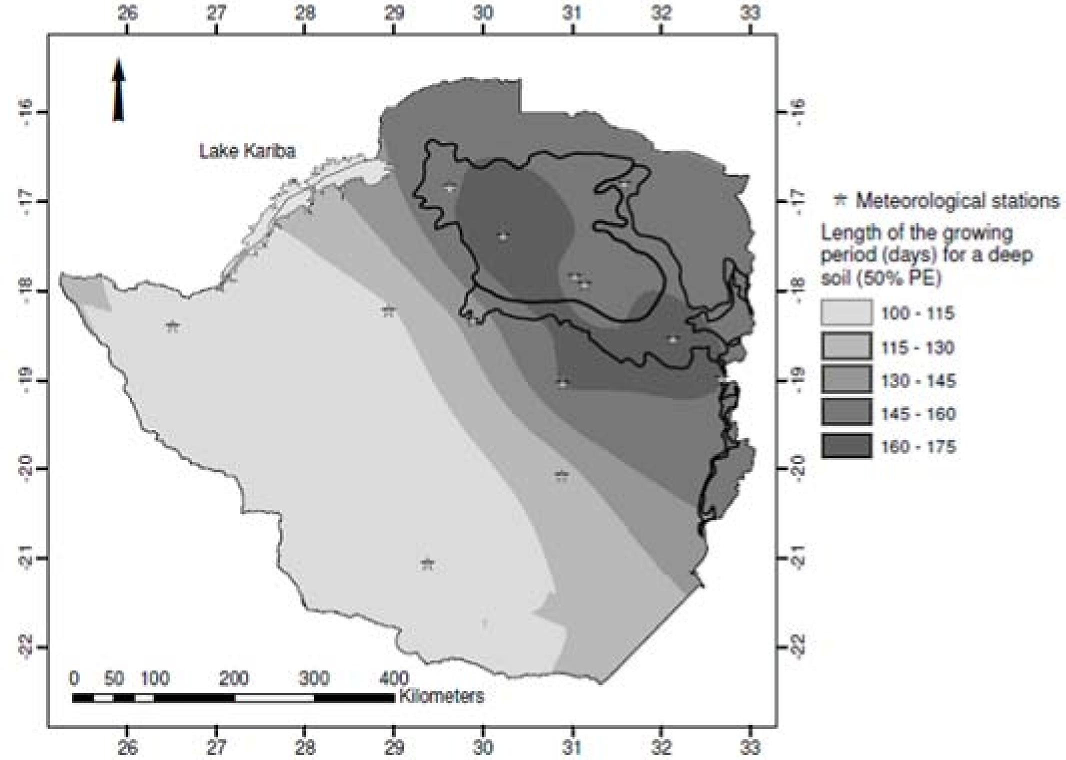

Figure 2. Normal (50% PE) length of the growing period in Zimbabwe for maize on deep soils (Ordinary kriging with anisotropy (314°), circular semi-variogram distribution; relative root mean squared error 4%).

the period around flowering is the most sensitive stage to drought stress, the selection of maize varieties and the timing of sowing dates should be aimed at matching flowering with the peak of the T_{rel} curve.

The peak period of beneficial T_{rel} was broader on deep than on shallow soils (Fig. 3). This is logical because the shallow root zone has a lower water storage capacity and, therefore, requires more frequent rainfall events to keep the soil water content above the water stress threshold. Comparing different stations, West Nicholson (outside the maize belt) had a lower peak of average T_{rel} profile (Fig. 3) than Chinhoyi (within the maize belt).

Analysis of the 95% confidence interval of T_{rel} for stations in the maize belt (with example of Chinhoyi, Fig. 3), shows that variation is greatest at the start and end of the season. These variations are due to high inter-annual rainfall variability that is typical of semi-arid climates (Rockström, 2000; Kahinda *et al.*, 2007). During these periods, the quality of the rainfall season is less reliable than in the middle of the season (December to January). Narrowest confidence intervals are found in December and January for both soil depths within the maize belt (Fig. 3). Stations outside the maize belt showed much larger variation in intra-seasonal quality, which is consistent with the fact that they are located in marginal zones, generally without maize production due more severe dry spells and droughts (Mupangwa e*t al.*, 2011). Although a decrease in soil depth increased the average intra-seasonal quality, the inter-annual variation in T_{rel} remained similar for stations outside the maize belt. The broadest confidence interval (highest inter-annual variation) for these stations is found in the middle of the season as opposed to the stations within the maize belt.

Although averaging T_{rel} over the whole LGP period makes it a course parameter for assessing intra-season dry spells, the high correlation between seasonal T_{rel} and the number of dry days

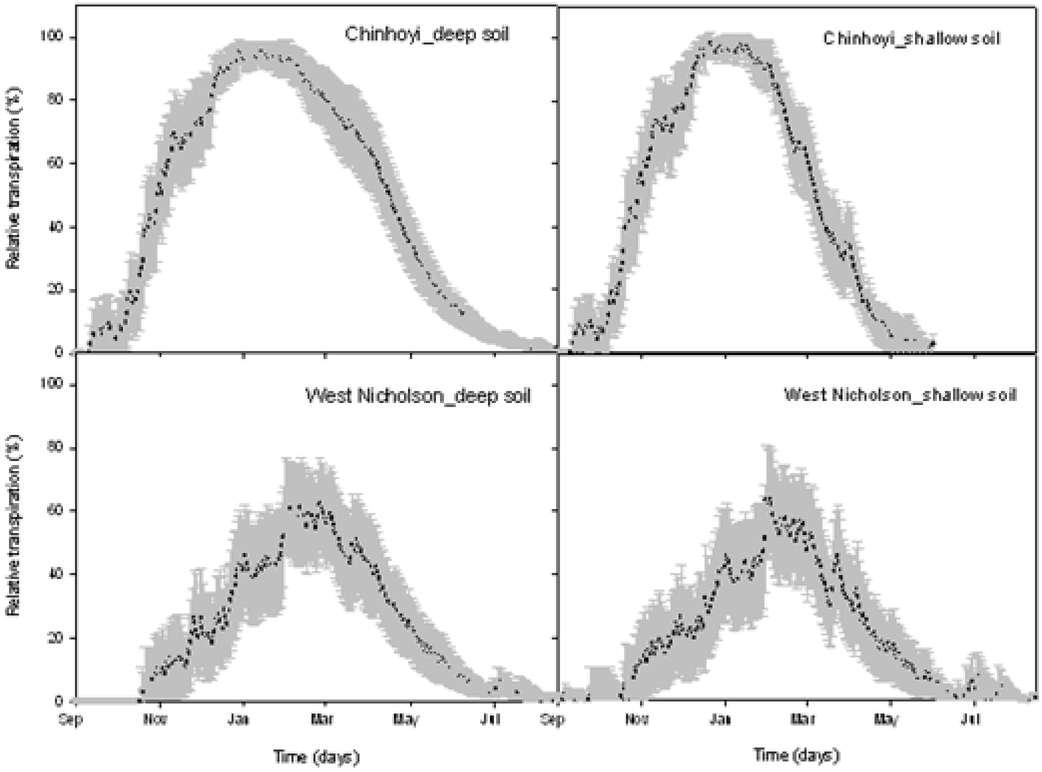

Figure 3. Mean relative transpiration (T_{rel}) for Chinhoyi and West Nicholson for shallow and deep soils. Vertical bars show the 95% confidence interval for mean T_{rel}.

(T_{rel} < 35%) within LGP (r = -0.79) shows that T_{rel} can still be a good summary indicator for intra season dry spells. Therefore, the calculated average T_{rel} within the limits of the LGP can be considered a good indicator of the quality of the growing period, including the effects of intra-seasonal dry spells on the availability of water for crop growth. Although LGP was shorter for shallow than for deep soils, the T_{rel} within the limits of the LGP was similar. This is because there was a weak correlation between the T_{rel} and LGP (r = 0.36) (Mhizha, 2010) and this justifies the need to use both indices instead of only one in characterising the season.

Figure 4 presents a geographical coverage of the seasonal quality (T_{rel}) in a dry year (80% PE) on a shallow soil. This map shows the worst case scenario of the growing conditions for the study area with a return period of 5 years. Under these conditions, the north-west of the maize belt had the best quality with T_{rel} around 85%, while the south of the maize belt had the worst quality with T_{rel} around 70%. Outside the maize belt, quality dropped gradually to about 30% in the South of Zimbabwe. This is due to more severe effects of dry spells and droughts which are known to affect rainfed agriculture as pointed out in Mupangwa *et al.* (2011) who studied growing season characteristics in the southern parts of Zimbabwe.

Linking the rainfall season characteristics to maize production. The rainfall season characteristics developed are summarised in Table 3. For all parameters, values corresponding to three return periods selected here to represent typical wet (20% PE), normal (50% PE) and dry (80% PE) conditions are presented.

Table 3 gives general guidelines for long term planning of maize cropping systems. To use it, shaded cells on either LGP or T_{rel} should be avoided unless there are plans for supplemental irrigation. The results showed that outside the maize belt, growing early maturing varieties can

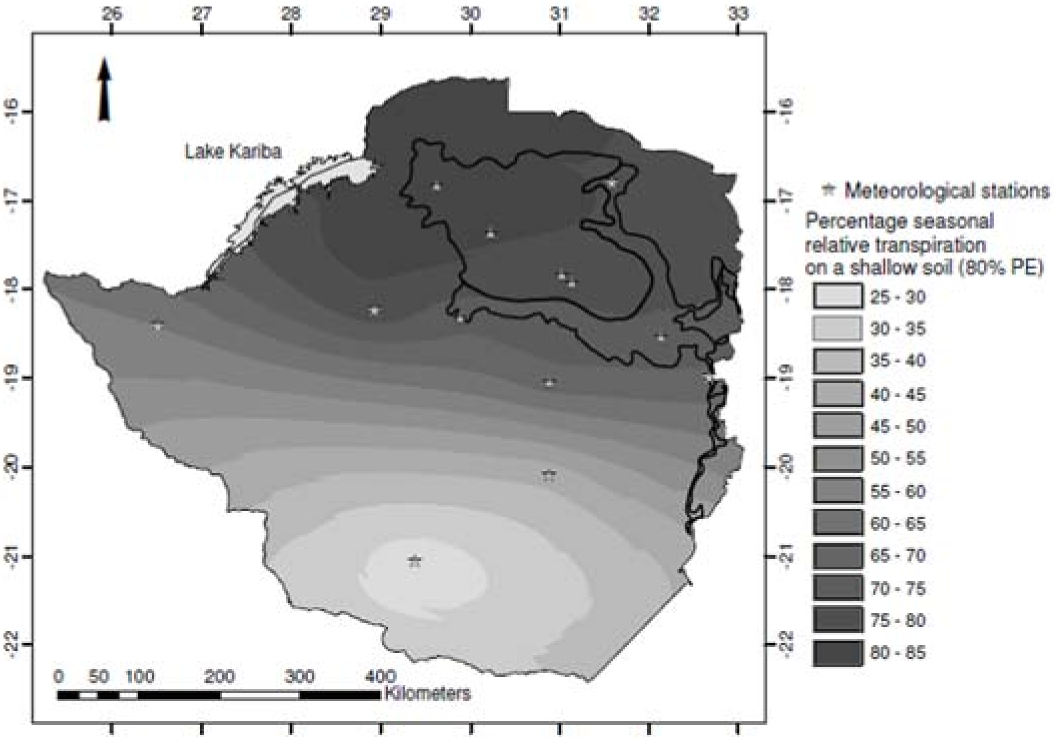

Figure 4. Seasonal relative transpiration within the LGP in a typical dry year (80% PE) on shallow soils (ordinary kriging with anisotropy (279°), circular semi-variogram distribution; relative root mean squared error 12%).

TABLE 3. Simple management tool for matching maize variety to rainfall season quality as indicated by Trel and LGP for three regions of Zimbabwe. **Bold** cells marks conditions not recommended for growing rainfed maize

Region	Type of season	Wet	Normal	Dry	Wet	Normal	Dry
	PE (%)	20	50	80	20	50	80
Soil depth		Deep			Shallow		
Maize belt	LGP (calendar days)	187***	157***	125*	141**	117*	93
	Trel^{+} (% of potential)	90	81	71	94	86	77
	Relative yield (% of potential)	87	76	64	92	83	72
Border	LGP (calendar days)	174***	144**	109*	142**	116*	90
	Trel^{+} (% of potential)	89	80	69	91	81	68
	Relative yield (% of potential)	86	75	61	89	76	60
Outside	LGP (calendar days)	149**	112*	75	128*	97	66
	Trel^{+} (% of potential)	82	64	46	77	56	34
	Relative yield (% of potential)	77	55	32	72	45	18

* Only early maturing maize varieties (growth cycle between 100 and 130 days) are recommended

** Medium maturing maize varieties (growth cycle between 130 and 150 days) are recommended

*** Late maturing maize varieties (growth cycle of over 150 days) are recommended

\+ Trel above 68% recommended for rainfed maize

be viable in wet seasons only, which have a return period of 5 years. In the maize belt and surrounding areas, rainfed maize can be viable for all rainfall conditions with shorter varieties preferred for conditions of shorter LGP such as dry years and shallow soils.

Current recommendations from seed houses and extension services are rather coarse and based on the natural zones of Vincent and Thomas (1961). SeedCo (2005), for example classified maize varieties into four categories of very early (below 120 days), early (120 to 140 days), medium (140 to 150 days) and late maturing (over 150 days) varieties and recommend them in order of increasing rainfall availability as length of growth cycle increases. While such a recommendation can be correct, not linking it to the actual rainfall regimes of specific areas may leave farmers uncertain as to the exact variety suitable to their location.

This study contributes to the current knowledge by linking more directly the water requirement of different varieties to the expected rainwater availability at specific regions using T_{rel} together with LGP. For instance, while in normal years there is not enough rainwater for maize cultivation outside the maize belt region in Zimbabwe, it is recommended that in wet years (20% PE) rainwater becomes adequate for cultivation of short season varieties in this region. In this regard, accurate seasonal rainfall forecasts (predicting occurrences of wet or dry seasons) would help farmers decide on the appropriate maize variety for production for a given season and region (Zinyengere *et al*., 2011). In the case of the region outside the maize belt, use of water conservation options such as intercropping, within field rainwater harvesting, mulching and precision water conservation agriculture (Twomlow *et al*., 2008) would help reduce the risk of crop failure.

CONCLUSION

Using LGP and T_{rel} as characteristic parameters for the rainfall season and length of growing cycle of common maize varieties as well as a threshold for T_{rel} of 68% (corresponding to a relative yield of 60%), rainfall climate conditions for rainfed production of various varieties has been identified in Zimbabwe. The Maize belt is confirmed to be the best region for rainfed maize production but with restrictions in dry years and on shallow soils. On shallow soils, wet years are suitable for medium season varieties, while normal years can only supply enough water for short-maturity varieties. In dry years, a deep soil would sustain short-maturity varieties, while a shallow soil will have LGP too short even for short-maturity varieties, and hence, is not recommended for maize.

Even outside the maize belt, rainfed cropping is possible under conditions of wet years and deep soils. In wet years, medium season varieties can be grown on deep soils; with shallow soils good enough for short-maturity varieties. In addition on deep soils, short-maturity varieties can be grown in normal years too. It is clear that with the use of a simple soil water balance model, the length and the quality of the growing period can be assessed for its suitability to rainfed production of maize varieties. As a result, a simple tool that can be used to indicate whether to grow maize varieties of particular length of growth cycle in a specified region for typical wet, normal or dry rainfall seasons was developed for Zimbabwe.

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