APPLICATIONS OF CROP GROWTH MODELS TO COMMON BEAN IN AFRICA

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CONTENTS

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HARICOT BEAN AGROECOLOGY IN ETHIOPIA: DEFINITION USING AGROCLIMATIC AND CROP GROWTH SIMULATION MODELS

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ABSTRACT

Bean (*Phaseolus vulgaris* L.) is an important food and cash crop grown in diverse environmental settings in Ethiopia. Its production is very heterogenous in terms of ecology, cropping system and yield. This study analyses the agroclimatic resources of 18 representative bean growing sites in Ethiopia and assesses the potential yield and moisture deficit stress using DRYBEAN (DSSAT V.3) growth model. Annual rainfall of various locations ranged from 580 mm (Mekele) to 1995 mm (Gore). Seasonal rainfall varied from 270 mm (Babile) to 1650 mm (Gore). The length of the growing period is from only 80 days (Mekele) to more than 220 days (Jimma). Among the agroclimatic variables, annual rainfall, seasonal rainfall, length of the growing period and altitude (temperature) are important factors to cluster the bean growing regions into 3 major and 6 minor homogeneous groups in agronomic sense for strategic planning. Simulated yield potential varied from 1.6 t ha^{-1} (Jijiga) to 3.3 t ha^{-1} (Bako). Planting date has a significant impact on simulated yield in the sub-humid and semi-arid clusters. Yield losses for each day of delayed planting after the effective onset of rainfall reached up to 60 kg ha^{-1} day^{-1}. Moisture deficit stress was found to be an important limiting factor in the semi-arid and moderately limiting in the sub-humid regions. The analysis established that bean improvement work should focus on the development of high-yielding, long-maturing genotypes for multiple cropping systems in the humid regions. In the semi-arid regions emphasis should be on the development of drought tolerant and early maturing cultivars which fit well with efficient soil and water conservation practices.

Key Words: Moisture deficit stress, *Phaseolus vulgaris*, resources, sowing date, yield potential

RÉSUMÉ

Le haricot (*Phaeolus vulgaris* L.) est une culture alimentaire et commerciale cultivée dans divers environments cadres en Ethiopie. Sa production est très hétérogène du point de vue écologique, système de culture et le rendement. La présente étude analyse des resources agroclimatiques de 18 sites représentatifs de production du haricot en Ethiopie et évalue le rendement potentiel et la tension de déficit hydrique en utilisant le modèle de croissance "DRYBEAN (DSSAT V.3). La précipitation annuelle de diverses locations s'est rangée de 580 mm (Mekele) à 1005 mm (Gore) tandis que la précipitation saisonnière a varié de 270 mm (Babile) à 1650 mm (Gore). La longueur de la période de croissance est seulement de 80 jours (Mekele) à plus de 220 jours (Jima). Parmi le variables agroclimatiques la précipitation annuelle, laprécipitation saisonnière, la longueur de la période de croissance et l'altitude (température) sont de facteurs importants pour grouper les régions de production du haricot dans trois

principaux groupes et six petits groupes homogènes dans le sens agronomique pour la plannification stratégique. Le rendement potentiel simulé variait de 1.6 tonnes/ha (Jijiga) à 3.3 tonnes/ha (Bako). La date de semis a un impact significatif sur le rendement simulé dans les groupes sous-humides et semi-arides. Les pertes de rendement pour chaque jour de retard de semis après l'approche effective de précipitatio atteignait 60 kg/hajour. La tension de déficit hydrique était trouvé être un facteur limitatif important dans les régions semi-arides et modérement limitant dans les régions sous-humides. L'analyse a établie que le travail d'amélioration du haricot devrait se concentrer sur le developpement des genotypes à haut rendement, à maturité tardive pour les systèmes multiples de culture dans les régions humides. Dans les régions semi-arides, l'accent devrait etre placé sur le developpement des variétes tolérantes à sécheresse et des cultivars à maturité précoce qui conviennent bien avec les pratiques de conservation efficace de sol et d'eau.

***Mots Clés*: Tension de déficit hydrique, *Phaseolus vulgaris*, resources, date de semis, rendement potentiel**

INTRODUCTION

Bean (*Phaseolus vulgaris)* is an important cash crop and protein source of farmers in many parts of Ethiopia. It is primarily a crop of small-scale producers and generally few inputs are used (Wortmann and Allen, 1994). Bean is compatible with numerous other crops in mixed cropping systems and is grown in diverse agroecologies (Fig. 1). The major cropping systems include beans inter-cropped with maize, sorghum, root crops or bean grown in sole crop in the Rift Valley.

The national average yield of haricot bean is only 0.8-0.9 t ha^{-1} under peasants farming condition (CSA, 1994). The low yields are attributed to various limitations including biotic constraints, low soil fertility, unpredictability of rainfall and poor management. In most bean growing regions rainfall is erratic in its distribution and the soil is often sandy and with low moisture holding capacity (Simane and Struik, 1993). Therefore, the key factor affecting the productivity are the length and distribution of moisture during the crop growing season. Development and implementation of plans for sustainable production require an understanding of the effect of the combined action of these factors. Although these were known, no serious attempts have been made to quantify climatic risks in Ethiopia.

Agroclimatic and crop growth models are useful tools for evaluating alternative management strategies and developing plans and policies for achieving maximum resource use efficiency. They are useful for investigation of long term weather risks. The definition of a dependable starting date and duration of the growing season, and the quantification of dry periods during the growing season represent major challenges in sustainable dryland farming areas (Stern *et al.*, 1994).

Different growth models are used to: i) match crops, varieties and management options to specific weather, soil and farming situations; ii) assess sustainability of cropping systems in specific areas; iii) plan agricultural development on a regional scale; and iv) evaluate uncertainness and risk at field and farm levels. The goal of such systems is to improve the performance of decision makers while reducing the time and human resources required for analysing complex decisions and field experiments. Wafulu (1995) used the crop simulation model CMKEN, a locally adapted version of CERES-maize, to evaluate farmers' decisions with respect to management options and the inherent economic implications in Kenya. Thornton *et al.* (1995) also demonstrated the use of CERES-maize model to provide information concerning management options such as the timing and quantity of nitrogen fertilizer application and to quantify the weather related risks of maize production in Malawi. This paper presents a discussion on the application of agroclimatology and a dynamic crop growth model to define the agroecology of bean production in Ethiopia.

The main objectives of the study were to quantify the physical resource bases of haricot bean growing areas and cluster them for strategic planning, and to assess potential yields and possible cropping systems for sustainable production.

MATERIALS AND METHODS

A total of 18 major bean growing locations distributed throughout Ethiopia were assessed for their agro-ecological characteristics (Table 1). Selections were made based upon completeness of required weather data.

Agroclimatic analysis of the locations to identify major weather constraints was done using INSTAT statistical packages (Statistical Service Centre, University of Reading, UK). In view of rainfall variability, all agronomic events, such as start of the season, were defined using the concept of dependable values, which is the minimum period that can be expected in three out of four years. The start of the season was defined as the first occasion when the available soil moisture content exceeds 40% of field capacity and 10 days running total rainfall exceeds 0.5 potential evapo-transpiration. The end of the growing season was defined to be when available soil water content drops below 10% of field capacity.

Correlation analysis was made to identify the most important climatic variables to bean production. The variables used are longitude, latitude, altitude, annual rainfall, modality of rainfall distribution, main season rainfall, length of growing season, maximum temperature and minimum temperature. Altitude, longitude, annual rainfall amount and distribution, seasonal rainfall and length of the growing period are used to classify bean growing regions into homogeneous ecoregions.

The dynamic crop growth DRYBEAN model (Hoogenboom *et al.*, 1994), a process oriented model of DSSAT v3, was used to test management

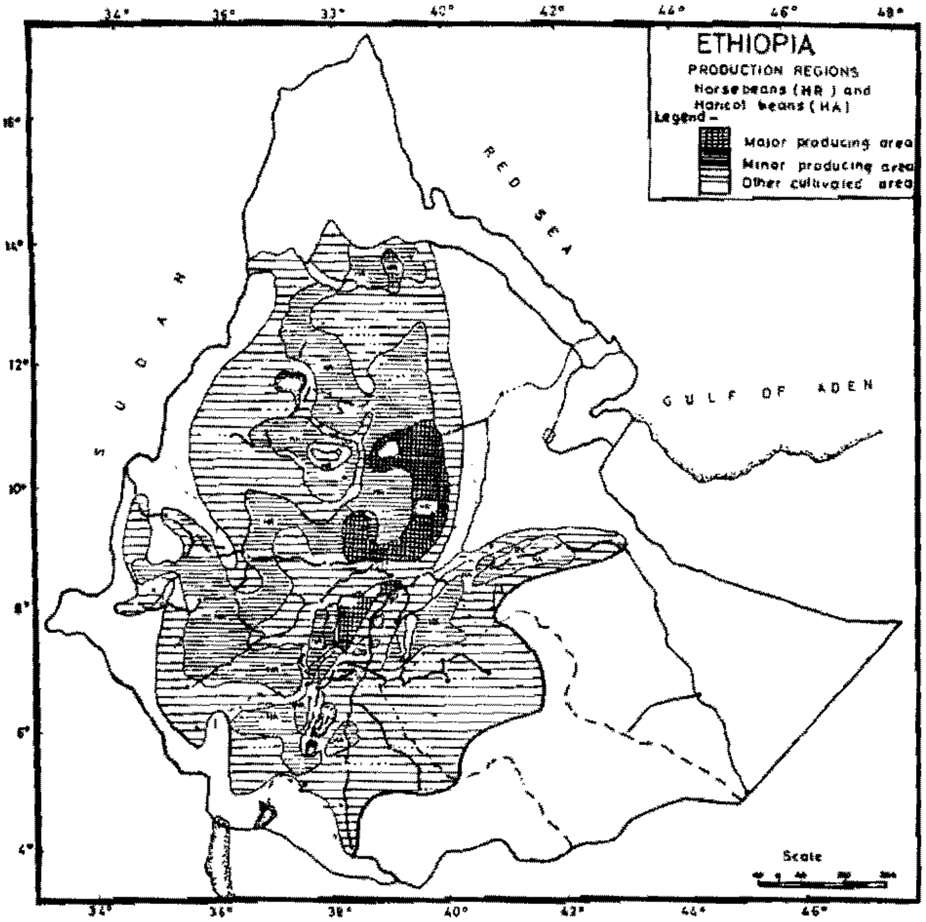

Figure 1. Major and minor bean production regions in Ethiopia.

alternatives for different scenarios in bean growing regions. The model allows the quantitative determination of growth and yield of bean with crop growth simulated with a daily time step on the basis of physiological processes. The soil water balance component simulates surface run-off, evapotranspiration, drainage and water extracted by the plant. Four different varieties representing different growth habits and phenologies were used to estimate potential yields for each cluster group (Table 2). Based on the out come of the agroclimatic analysis and research recommendations, three planting dates (July 1, July 15 and August 1) were used to determine the effect of planting date. Simulations started two weeks before sowing. Six sites, one from each cluster, were selected to represent the different agroclimatic conditions. Selected sites were judged to be representative of the bean growing region in Ethiopia.

The importance of stress at a location is determined as the sum of the products of frequency of occurrence and severity of stress with severity grouped as <0.10 (no stress), 0.1-0.3 (mild stress), >0.3 (stressful environment). Stress severity (index) is calculated as the ratio of available soil moisture (extracted water) to total plant water requirement during a specified growth stage, where 0 represents no stress and 1.0 extreme moisture stress.

All data were subjected to ANOVA, using the MSTAT software (Michigan State University, 1991). LSD values were used to determine the significance levels.

RESULTS

The agroecology of bean growing locations in Ethiopia is diverse (Table 1). Altitude ranges from 1200 to 2212 m, while annual rainfall varies from 580 to 1950 mm. The length of the growing period is from as short as 80 to 220 days. Accordingly the seasonal rainfall during the growing period ranges from 120 to 1636 mm.

Annual rainfall, main season rainfall, length and end of growing period are negatively correlated with longitude (r= -0.73**, -0.81**, -0.78**, -0.63** and -0.48*, respectively) (Table 3). The

TABLE 1. Geo-physical characteristics and length of the growing season of selected bean growing sites in Ethiopia

Site	Lat (°N)	Long (°E)	Alt (m)	ANP (mm)	Growing season				
					Month	SP (mm)	LGP (days)	Tmax (°C)	Tmin (°C)
Gore	9.20	35.33	2002	1950	Apr-Nov	1636	199	22.3	13.3
Nekemte	9.20	36.35	2005	1784	May-Nov	1450	217	22.0	12.4
Jimma	7.40	36.49	1740	1436	Apr-Nov	1323	220	26.0	12.7
Bahir Dar	11.36	37.23	1790	1450	Jun-Nov	1197	150	25.2	14.0
Gondar	12.33	37.25	1967	1115	Jun-Oct	880	150	23.9	13.3
Arba Minch	16.40	37.37	1290	1092	Apr-Jul	379	110	28.8	18.7
Bako	9.60	37.40	1590	1249	Apr-Oct	1050	190	25.5	14.0
Hosana	7.33	37.52	2200	1137	Apr-Nov	523	125	22.0	10.7
Awassa	7.05	38.29	1750	862	Apr-Oct	515	134	26.1	13.4
Alem Tena	8.18	38.46	1200	690	Jul-Sep	350	83	25.9	13.6
Mojo	9.52	38.61	1822	823	Jun-Oct	544	127	26.1	12.1
Nazreth	8.32	39.26	1622	745	Jul-Sep	434	90	27.0	15.3
Mekele	13.29	39.28	2212	582	Jul-Sep	377	80	23.0	11.4
Kombolcha	11.30	39.44	1903	987	Jul-Oct	570	110	27.6	14.6
Alemaya(1st)	9.25	42.20	2125	753	Apr-Jun	261	90	22.2	14.7
	(2nd)				Jul-Oct	405	103	21.6	14.0
Babile	9.80	42.30	1856	683	Jun-Sep	272	90	27.7	15.1
Jijiga	9.20	42.47	1644	804	Jul-Sep	366	38	25.9	14.5

(LAT= latitude, LON= longitude, ALT= altitude, ANP= annual rainfall, SP=seasonal rainfall, LGP= length of the growing period, Tmax= maximum temperature, Tmin= minimum temperature) modality of rainfall distribution is positively correlated with longitude (0.66*). Altitude is negatively correlated with only maximum and minimum temperatures (r=-0.63** and -0.86**, respectively). Annual rainfall was found to correlate positively with main season rainfall and length of the growing period (r=0.96** and 0.77**, respectively).

Based on the result of the correlation analysis latitude, altitude, annual rainfall and its modality, seasonal rainfall and length of the growing period were found to be the most important variables that affect distribution and productivity of beans. Using these variables, bean growing regions in Ethiopia are grouped into three major (humid, sub-humid and semi-arid) groups which are sub-divided based on temperature resource (Table 4).

The annual rainfall distribution of all the sites is highly variable. The pattern of rainfall distribution is mono-modal in all the regions with the exception of the eastern highlands due to the influences of Inter-Tropical Convergence Zone. The length of the season lasts for 120-220, 100-150 and less than 100 days for humid, sub-humid and semi-arid regions, respectively (Table 4). In the eastern highland (sub-humid high altitude) region the short (***Belg***) rainy season extends from April to June and receives about 25%, whereas the long rainy season (***Meher***) extends from July to October and receives about 45% of the annual rainfall.

A simulation of more than 12 years of historical weather data was run using DRYBEAN crop growth model at three different planting dates for the four varieties. Simulated grain yield shows significant differences among sites and planting dates, while the difference among varieties is not significant (Fig. 2). Mean yields over sites ranged from 1.6 t ha^{-1} (Jijiga) to 3.3 t ha^{-1} (Bako). The average long term yield potentials in decreasing order are 3.3 t ha^{-1} in humid low altitude, 2.3 t ha^{-1} in sub-humid low altitude, 2.2 t ha^{-1} in humid high altitude, 2.2 t ha^{-1} in sub-humid high altitude, 1.7 t ha^{-1} in semi-arid high altitude and 1.6 t ha^{-1} in semi-arid low altitude.

Date of planting was found critical in the sub-humid and semi-arid regions (Fig. 2). The analysis established that delayed planting after July 1, or July 15 resulted in yield losses for low rainfall northern, eastern and central Rift Valley regions. Yield losses are about 35, 42, 62 and 1.5 kg of grain yield per day delay in planting in Alemaya, Nazareth, Mekele and Jijiga, respectively. However, different planting dates between July and August gave similar simulated yields for both Bako and Nekemte due to their long length of the growing season.

Early varieties flower in a mean of 42 days, while the late ones flower in 54 days (Table 2). Number of days to physiological maturity is 76 days for early maturing and 90 days for late maturing varieties. Different planting dates do not have any effect on the phenology.

Analysis of variance to evaluate the importance of moisture deficit stress revealed that there was a significant difference among sites, cultivars and planting dates (Tables 5, 6 and 7). Moisture stress deficit, using the average of the products of the frequency of occurrence and the severity of the stress was greatest during the seed filling stage (S3) in all cases. Among the sites, moisture deficit stress was most important in the semi-arid regions (Jijiga and Mekele) and sub-humid regions (Nazareth and Alemaya) (Table 5). However, in the humid regions bean production is not limited by moisture deficit stress. The indeterminate long maturing variety experienced the greatest stress

TABLE 2. Varieties used to evaluate different bean phenology types for yield potential using DRYBEAN growth model

No. Variety	Origin	Growth habit	Time required for development	
			Sowing to Flowering	Flower to Phy. maturity
Seafarer	CIAT	Det.	Short(42 days)	Short(35 days)
Rabia de Gato	CIAT	Ind.	Short(41 days)	Short(34 days)
Kilyumukwe	Ruwanda	Ind	Long(53 days)	Short(34 days)
Carioca	CIAT	Ind.	Long(55 days)	Long(42 days)

TABLE 3. Correlation coefficients analysis of longitude (LON), latitude (LAT), altitude (ALT), annual rainfall (ANP), below normal rainfall (BNP), above normal rainfall (ANP), modality (MOD), main season rainfall (MSP), length of growing season (LGS), start of the growing season (SGS), end of growing season (EGS), minimum temperature (Tmn), and maximum temperature (Tmx)

Variable	LON	LAT	ALT	ANP	MOD	MSP	LGS	SGS	EGS	Tmn
LAT	-0.34									
ALT	0.12	-0.37								
ANP	-0.75**	0.20	-0.02							
MOD	0.66**	-0.29	0.03	-0.33						
MSP	-0.82**	0.29	-0.05	0.94**	-0.54*					
LGS	-0.65**	-0.01	0.26	0.76**	-0.60*	0.80**				
SGS	0.42	-0.30	0.07	-0.39	0.59*	-0.49*	-0.53*			
EGS	-0.43*	0.02	0.01	0.44	-0.21	0.44	0.55*	-0.05		
Tmn	-0.28	0.68**	-0.64**	0.11	-0.14	0.13	-0.09	-0.33	0.20	
Tmx	-0.21	0.58*	-0.87**	0.01	-0.13	0.08	-0.27	-0.26	-0.05	0.77**

TABLE 4. Agroclimatic classification of haricot bean growing locations in Ethiopia using altitude (ALT), annual rainfall (ANP), length of the growing period (LGP) and precipitation during the growing period (SP)

Classification		ALT (m)	ANP (mm)	LGP (days	)SP (mm)	Sites
Major	Minor					
Humid	1. humid-highlands	>1900	1100-2000	150-220	>850	Gore, Nekemte
	2. humid-lowlands	1600-1900	1100-2000	150-220	>850	Jimma, Bahir Dar, Arba Minch, Bako
Sub-humid	3. highlands	>1900	850-1100	100-150	450-850	Gondar, Hosana, Kombolcha, Alemaya
	4. lowlands	1600-1900	850-1100	100-150	450-850	Awassa, Mojo, Nazareth
Semi-arid	5. highlands	>1900	<850	<100	<400	Mekele
	6. lowlands	<1900	<850	<100	<400	Alem Tena, Babile, Jijiga

during the grain filling stage? (Table 6). The latest planting date was most affected by moisture deficit stress during the grain filling stage (Table 7). Correlation coefficients for moisture deficit stress levels with yield are generally highest for seed filling stage (S3, r=-0.73**), intermediate during mid season (S2, r=-0.59**) and non significant during early stage (S1, r=-0.28).

DISCUSSION

The bean growing ecosystems of Ethiopia are numerous and highly diverse. Their potential for production and their management requirements are determined by the interplay of many factors, including climate, soil type and a range of socioeconomic and biological factors. Development of appropriate technologies requires a good understanding of constraints and different opportunities of the bean growing ecosystems. Such understanding is needed for the identification of problems, setting of research priorities and targeting of technology that is agroecosystem specific.

Among the climate variables studied in the bean growing region, precipitation, altitude (temperature) and soil type are found variable in the space dimension. Rainfall is the most important factor influencing the choice of crops and management practices in the semi-arid tropics. Other studies (Singh and Byerlee, 1990; Simane and Struik, 1993) have also clearly demonstrated that rainfall is the predominant factor influencing yield variability and thus the major climatic factor

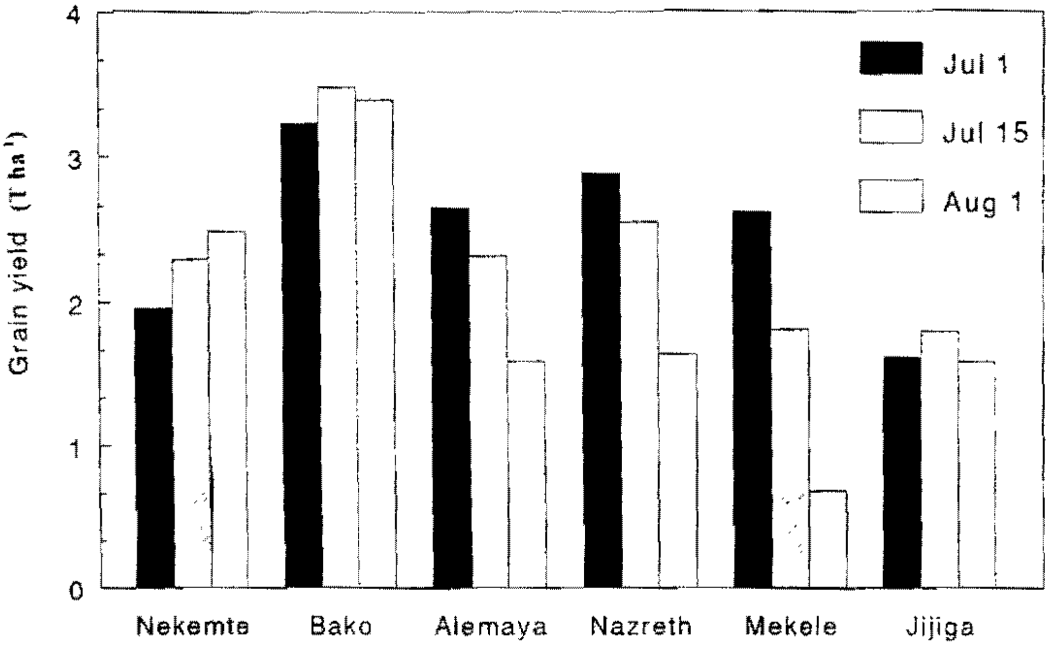

Figure 2. Average simulated grain yields of the four varieties at three different planting dates of haricot bean in Ethiopia.

TABLE 5. The cumulative average severity of stress at the six sites for the different growth stages

Site	Growth stages		
	S1	S2	S3
Nekemte	0.00	0.00	0.00
Bako	0.00	0.00	0.01
Alemaya	0.00	0.02	0.14
Nazareth	0.10	0.09	0.26
Mekele	0.00	0.11	0.39
ijiga	0.18	0.23	0.35
Mean	0.05	0.02	0.20
LSD 0.05	0.03	0.04	0.06

TABLE 6. The average severity of moisture deficit stress for the three growth stages

Variety	Growth stages		
	S1	S2	S3
Seafarer	0.08	0.07	0.07
Rabia de Gato	0.05	0.06	0.15
Kiiyumukwe	0.02	0.05	0.07
Carioca	0.04	0.12	0.27
Mean	0.05	0.07	0.19
LSD 0.05	NS	NS	0.07

TABLE 7. The average severity of moisture deficit stress for the different planting dates for the three growth stages

Planting date	Growth stages		
	S1	S2	S3
July 1	0.05	0.05	0.10
July 5	0.04	0.07	0.17
August 1	0.07	0.11	0.31
Mean	0.26	0.15	0.19
LSD 0.05	NS	NS	0.11

affecting crop production in dry-land agriculture. Other factors, temperature, evapotranspiration, wind speed and radiation are fairly stable and ranged within the optimum limits of haricot beans requirements (data not presented). The thermal characteristics are typical of the tropics. However, cloudiness in the western and low temperature in the eastern highlands are sometimes important yield limiting factors.

Amount and mode of rainfall distribution decreases along the west-east dimension. This agrees with the previous findings of Simane *et al.* (in press). Rainfall distribution in the eastern part, in the longitude zone between approximately 39.5° E to 42.5° E, is effectively bimodal as a consequence of the movements of the Inter-Tropical Convergence Zone. The western, southern and northern regions have mono modal rainfall pattern. The total length of the growing season ranged from 80 days in the north-east to 200 days in the west humid region. However, released varieties of bean need only 90 to 110 days and under-utilise the rainfall in the humid and sub-humid regions when grown in sole crop.

In Ethiopia, the choice bean cultivars and the cropping systems are not well designed using the inventory of the physical resources. For proper placement of cultivars and choice of associated management practices, clustering of bean growing regions into homogenous environmental groups based on natural resources is believed to be a stepping stone for sustainable strategic planning. Accordingly, the bean growing regions in Ethiopia are classified into three major regions viz: humid, sub-humid and semi-arid which are sub-divided based on temperature (altitude). This result disagrees with the previous classifications made by Wortmann and Allen, (1994), where they classified the bean areas into only southern, eastern (above and below 1500 m), central Rift Valley and western regions .

The humid (western) cluster is basically characterised by very high rainfall with monomodal distribution, long growing season and ecologically high production potential. However, in terms of rainfall use efficiency, growing beans in these environments as a sole crop may not be economically optimal. Rather inter-cropping of indeterminate bean types or relay cropping or double cropping using determinate types should be considered. Other negative effects, such as waterlogging and cloudiness should be considered to maximise resource use efficiency.

The sub-humid regions are more optimal in terms of rainfall use efficiency for bean production. In these environments terminal moisture stress is often a problem with late planting. The moisture availability period in the eastern region shows that two alternatives are possible: single cropping and double cropping. In the first case, the two rainy seasons are considered as one growing season. Therefore, late maturing crops/cultivars of sorghum and maize could be planted in April and harvested in November, but before frost occurs. In the second option, early maturing haricot beans could be grown in the small-rainy season. Crops with intermediate length of growing season (e.g., maize cv. Katumani, wheat or barley) may be grown during the long-rainy seasons.

In the semi-arid regions potential yields are low and variable due to moisture deficit stress. In the northern, central Rift Valley and much of the eastern region, development of terminal drought tolerance with determinate growth habit should be the primary focus of breeding programmes. Date of planting is critical in the dry sub-humid and semi-arid regions of the country and as a result there is always a yield loss associated with a delay in planting after the onset of rainfall.

Economic, political and social factors, however, have to be taken into account for detailed recommendations about how best to respond to the assessment in terms of land preparation, cultivars, cropping system, seeding and initial fertilisation rates, and time of seeding for the different agroecological regions.

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AN ADAPTATION BREEDING STRATEGY FOR WATER DEFICIT IN BEAN DEVELOPED WITH THE APPLICATION OF THE DSSAT3 DRYBEAN MODEL

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ABSTRACT

Bean (*Phaseolus vulgaris* L.) productivity is much constrained by water deficits in many production areas in eastern and southern Africa. The DSSAT 3 Drybean model was used to analyze the effects of water deficits on bean using genetic coefficients of four cultivars including an early, determinate type and early, intermediate and late maturity indeterminate bush types. More than 2300 simulations were run using meteorological data from 19 locations. The late maturing ideotype gave highest yield in less stressful environments but its yield was the least stable. In more stressful environments, early maturing ideotypes had highest mean yield and their yield was most stable in all environments. Stress was most severe and frequent in the later stages of growth; stress affected yield most during pod formation and fill, less during the early reproductive stage and least during the vegetative stage. Elements of a possible strategy for improving adaptation to water deficits are discussed, and specific information for the application of such a strategy is given for three locations which appear suitable as primary screening sites.

Key Words: Africa, bean, crop growth simulation, DSSAT3 Drybean Model, water deficit

RÉSUMÉ

La productivité du haricot (*Phaseolus vulgaris* L.)est bien contrainte par les déficits hydriques dans beaucoup d'aires de production en Afrique de l'est et du sud. Le DSSAT3 drybean model a été utilisé pour analyser les effets de déficits hydriques sur le haricot en utilisant les coefficients génétiques de quatre cultivars comprenant les types précoces déterminés et les types nains indeterminés à maturité intermédiaire et tardive. Plus de 2300 simulations étaient performées en utilisant les données météorologiques de 13 stations écologiques. L'idiotype à maturité tardive a donné le plus haut rendement dans les environnements moins stressants mais son rendement a été le moins stable. Dans les environnements plus stressants, les idiotypes à maturité précoce ont eu le plus haut rendement et leur rendement a été le plus stable dans tous les environnements. Le stress était plus sévère et fréquent dans les derniers stades de croissance et a affecté plus le rendement pendant la période de formation et de remplissage des gousses; il était moins durant le stade précoce de reproduction et moins plus durant le stade végétatif. Les éléments d'une stratégie possible pour améliorer l'adaptation aux déficits hydriques sont analysés et l'information spécifique pour l'application d'une telle stratégie est donnée pour trois stations écologiques qui apparaissent convenables comme sites primaires pour le criblage.

***Mots Clés*: Afrique, haricot, simulation de la croissance de culture, DSSAT3 Drybean Model, Déficit hydrique**

INTRODUCTION

Bean (*Phaseolus* vulgaris L.) crop performance in eastern and southern Africa is severely constrained by periodic water deficits in some production areas (Fig. 1). Frequency of occurrence of water deficits, severity of stress, timing of stress relative to plant age, and sensitivity of the plant at different stages of growth interact to determine yield loss associated with water deficits. These factors have not been quantified for bean production in Africa but the information is potentially useful for identifying some characteristics of bean ideotypes for stress environments and for devising a breeding strategy for drought tolerance.

Three classes of mechanisms of drought tolerance might be exploited for improving bean for water deficit conditions (White and Castillo, 1992). Drought escape might be achieved with early maturing genotypes or through plasticity such that drought stress accelerates the maturation process; the first is highly heritable but associated with lower yield potential than with later maturing genotypes. Drought tolerance with high plant water potential or drought avoidance might be achieved by plants conserving water or extracting a greater amount of soil water: studies involving use of carbon isotope discrimination (CID) (Ehleringer, 1988; White *et al.*, 1990) to evaluate water use efficiency show large differences between genotypes, although CID is not always related to genotypic differences for yield under water deficit (White *et al.*, 1994a); differences in root growth on deep soils are related to ability for water extraction (Sponchiado *et al.*, 1989; White and Castillo, 1992); and drought yield has been correlated with a leaf thickness index (White and Izquerido, 1991). Drought tolerance with low water potential might be improved with increased desiccation tolerance or better maintenance of turgor (White and Izquierdo, 1991). Bean is especially sensitive to water deficit stress during the early podfill stage, less so during the vegetative stage and little during late podfill.

Narrow sense heritability for yield under water deficit can be high (White *et al.*, 1994b) ranging from 0.09 to 0.75 for different environments. Realised gains in seed yield ranged from 0.4 - 7.4% and 2.9 - 15.7% at locations in Mexico and Colombia, respectively, due to selecting the top 20% from the F_2 generation. However, performance under water deficit is related to environment; general combining abilities of parents tended to be higher in their environments of origin than in other environments. This may indicate the importance of good adaptation to drought tolerance.

Computer simulation models are able to capture nuances in weather and estimate their effects on crop growth giving a better understanding of the effects of soil water deficits. The DSSAT3 Drybean Crop Growth Model predicts dry matter growth, leaf area index, crop development and final seed weight and other yield components of bean. This is a function of daily weather data, characteristics of a one-dimensional multi-layered soil profile and crop management conditions. Genetic coefficients are required to simulate the differences in crop performance among varieties. Complete documentation of the DSSAT3 Drybean model is provided elsewhere (Hoogenboom *et al.*, 1994; Tsuji *et al.*, 1994). The Drybean Model has not been verified for prediction of bean yield in Africa where productivity is constrained by numerous abiotic and biotic stresses which the model does not consider. However, it appears to be particularly well suited for research on water deficits, assuming absence of other constraints, as it considers soil water and daily changes in weather (CIAT, 1992).

MATERIALS AND METHODS

Four genetic ideotypes were used in this study represented by the genetic coefficients previously estimated for four cultivars (Table 1; Tsuji *et al.*, 1994). Seafarer is an early maturity, determinate type; Rabia de Gato, Kilyumukwe and Carioca are early, medium and late maturity types, respectively, of indeterminate bush growth habit.

Meteorological data were obtained from 19 locations. The locations were grouped into five climatic categories for eastern and southern Africa i.e., I Sub-humid, medium altitude, low latitude; II Sub-humid, high altitude, low latitude; III Semi-arid, low latitude; IV. Sub-humid, medium latitude; and V. Semi-arid, medium latitude (Table 2).

Locations of Category I fall in areas where soil

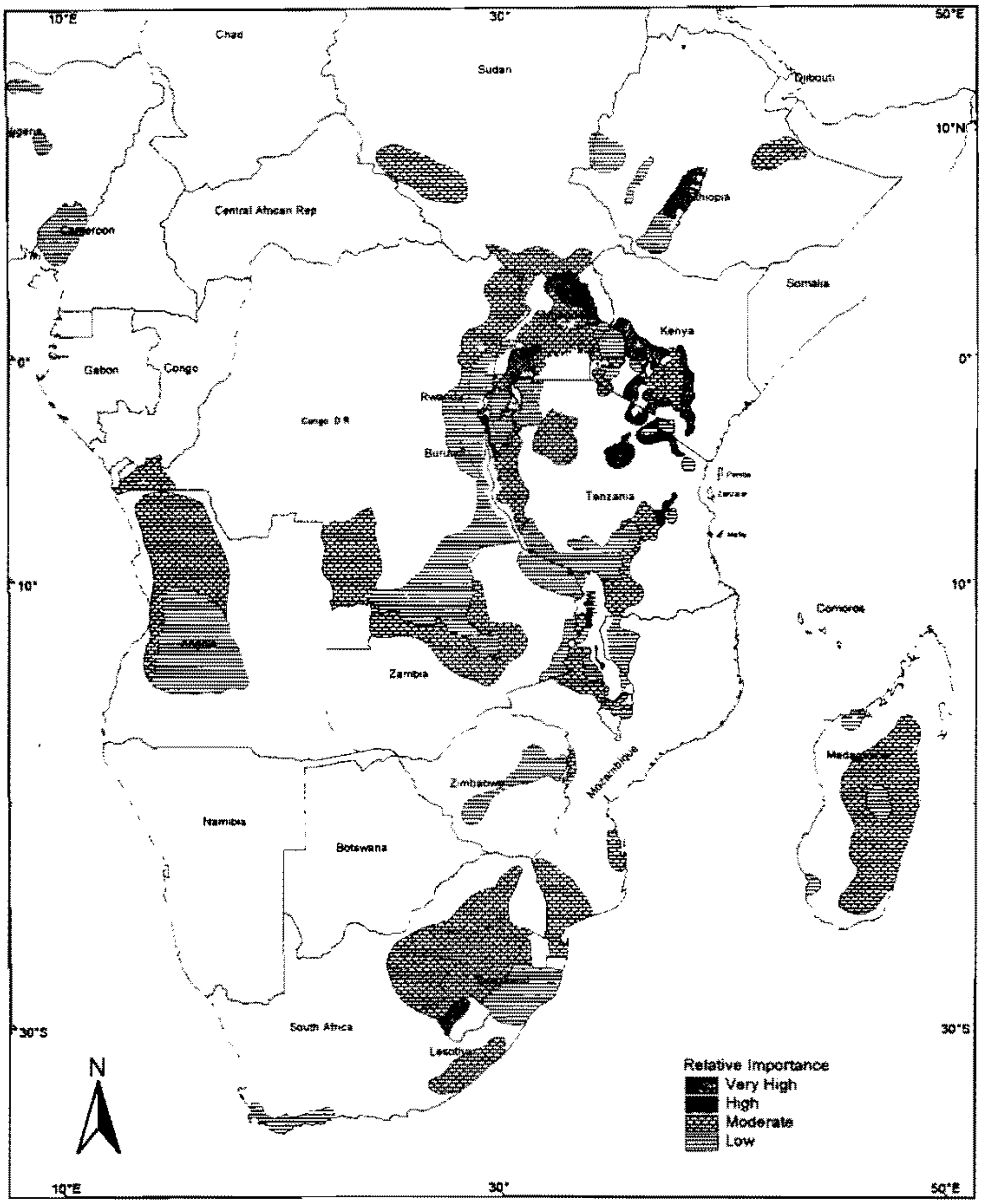

Figure 1. Map of the relative importance of soil water deficits in bean production areas in sub-Saharan Africa.

TABLE 1. Characteristics of the genotypes used in the study and days required for emergence to first flower (S1), first flower to first seed (S2) and first seed to physiological maturity (S3) when grown near the equator at 1200 m asl

Genotype	Growth characteristics	S1	S2	S3
Seafarer	Early maturity, determinate	26	10	23
Rabia de Gato	Early maturity, indeterminate	26	9	21
Kilyumukwe	Medium maturity, indeterminate	35	9	21
Carioca	Late maturity, indeterminate	35	12	24

TABLE 2. Characteristics, years of simulations and planting dates (PD) for the locations of eastern and southern Africa used in analysing the effects of water deficits on bean yield

Location	Lat	Long.	Alt.	Years	PD1	PD2	PD3	PD4
Category I, sub-humid, medium altitude, low latitude (n = 580)								
Ikulwe	0.6	33.7	1200	10	15/3	1/4	15/9	1/10
Kisumu	-0.1	34.7	1146	12	15/3	1/4	15/9	1/10
Kawanda	0.3	32.6	1195	7	15/3	1/4	15/9	1/10
Masaka	-0.3	31.7	1313	3	15/3	1/4	15/9	1/10
Lira	2.3	32.9	1085	10			15/7	1/8
Category II, sub-humid, high altitude, low latitude (n = 744)								
Embu	0.5	37.4	1493	10	1/4	15/4	1/9	15/9
Meru	-0.1	37.6	1554	12	15/3	1/4	15/10	1/11
Mbale	1.0	37.1	1494	9	15/3	1/4	15/7	1/8
Kitale	1.0	35.0	1875	12	1/3	15/3	15/8	1/9
Bushenyi	-0.5	30.2	1616	6	15/3	1/4	15/9	1/10
Category III, semi-and low latitude (n = 404)								
Kilimanjaro Airport	-3.4	37.1	896	12	20/3	1/4	15/11	
Katumani	-1.6	37.3	1646	9	1/11	15/11	15/3	30/3
Nakuru	-0.3	36.1	1871	12	15/3	1/4	1/10	15/10
Category IV, medium latitude (n = 520)								
Awasa	7.0	38.5	1750	12	15/4		15/7	30/7
Harare	-17.9	31.1	1478	12	1/12	30/12		
Rusape	-18.5	32.1	1430	7	15/1	15/12	30/12	
Mbeya	-8.9	33.5	1704	8	X	X	15/2	1/3
Morogoro	-6.8	37.6	526	6	1/3	15/3	15/11	1/12
Category V, semi-and medium latitude (n = 64)								
Bulawayo	-20.0	28.6	1326	9	1/12	30/12		

Lat., Long. and Alt refer to the longitude, latitude and altitude of the locations water deficits are of moderate importance (Fig. 1). Category II overlaps areas where water deficits are rated as being of moderate or high importance. Deficits are of very high importance at the sites of Category III. Semi-arid Category V falls outside of the bean production area shown for Zimbabwe due to the low importance of bean around Bulawayo. Some sites in Category IV are in areas where water deficits are of low importance, but some common sowing dates do result in periodic stress. Early sowing dates which result in low probability of water deficits were excluded for Lira, Awasa and Mbeya; for these locations, the analyses were for typical mid-season sowing times whereby the bean crop takes advantage of the late rains but is more likely to encounter water deficits. Assuming that farmers generally sow only after enough rain has fallen to establish the crop, simulations were excluded if cumulative rainfall was less than 18 mm at one week after sowing. Actual daily rainfall data were used in all places. Daily maximum and minimum temperatures were available for most locations, but estimated monthly means were used for some locations in Category I and III. Estimated monthly mean values were used for solar radiation. WGEN option of Weatherman (Pikering *et al.*, 1994) was used to estimate missing values. The profile description for a deep sandy clay loam soil of moderately low pH was used for all simulations; the soils and landforms in all major production areas are heterogeneous and it is recognised that the soil profile description used may have caused over- or under-estimation of the typical soil water availability for some locations. Simulations started two weeks before sowing with the water holding capacity of the soil at 20% of full. The nitrogen sub-routine of the model was switched off so nutrient supply to the plants was not limiting. Also, the effects of diseases and insect pests were not considered by the model although these can be important to a crop's water use efficiency and tolerance to water deficits. The simulations were done for sole crops of bean; intercropping effects were not considered due to limitations of the model.

The importance of stress at a location was determined for each of three growth stages as the sum of the products of frequency of occurrence and severity of stress. The stages of growth were emergence to first flower (S1), first flower to first seed (S2) and first seed to physiological maturity (S3). Severity was grouped as <0.10, 0.10 - 0.39, 0.40 - 0.69, 0.70 - 1.00, with 0.00 and 1.00 equal to no stress and plant death due to stress, respectively.

Optimal sowing dates of screening for adaptation to water deficits were determined for three locations representing Categories II, III and IV. The three locations have bean research programmes; proximity to the equator was considered to have temperatures and day lengths similar to those of the normal bean production seasons. Simulations across years were done for several sowing dates for each location and the optimal sowing date was considered to be the date that gave medium yield of 40% of the potential yield. Initial soil water was assumed to be 70% of field capacity as sowing normally commences once the early rains for the season have fallen, but before the profile has completely filled. Simulation was started 2 weeks before the sowing date. The same sandy clay loam profile as above was used.

RESULTS

Water deficit stress was most important for Categories III and V (Fig.2, Table 3) with 48-49% mean yield loss and approximately 50% of the cases having a yield loss of 50% or more due to inadequate water. The model estimated yield loss to be 30-35% for Categories II and IV, but water is adequate in 50% of the years to achieve at least 75% of the yield potential. Category I was least affected by water deficits with a 15% mean yield reduction and with adequate water to achieve at least 90% of the potential yield in 50% of the cases.

The Seafarer, Rabia de Gato and Kilyumukwe ideotypes experienced similar levels of stress in Categories I, II and IV. Stress was greatest for late maturing Carioca in most cases. The results do not indicate any difference due to determinacy of growth habit.

The late maturing ideotype, Carioca, gave the highest mean simulated yield in Categories I and IV, but had little or no advantage in the other Categories (Table 4). Carioca also suffered the greatest yield reduction due to stress, and had the least stable yield. The intermediate maturity ideotype, Kilyumukwe, had a yield advantage over the earlier maturity ideotype in Category I only, but with less stability.

Drought escape is important in Category III and V, and early maturity cultivars have the most potential. Early maturity cultivars may be preferred for Category II as well; although mean yields are slightly less, yield is more stable with the short season ideotypes. In Category IV as well, small scale farmers may prefer to reduce risk, and sacrifice some yield potential, by using earlier maturing cultivars.

Early cessation of rainfall and depletion of soil water reserves resulted in the most severe and most frequent occurrence of stress during the seedfill stage (Table 4). Stress levels increased as the crop aged, and the seed fill stage of growth (S3) was most affected by water deficits due to a higher frequency and greater severity of stress than at other stages. Stress was more severe for the later maturing ideotypes for all stages of growth.

Water deficit stress was negatively correlated with yield (Table 5). The relationship was strongest during the S2 and S3 stage, emphasising the need for more tolerance during the later stages of growth.

Three sites have been considered here as primary screening sites (Table 6). Optimal sowing dates for screening for water deficits for these potential sites were determined to be: Embu (Category II), 5 May for short season germplasm; Katumani (Category III), 15 April for short season germplasm; and Mbeya (Category IV), 10 March for short season and 5 March for long season germplasm. Mbeya appears to be the least

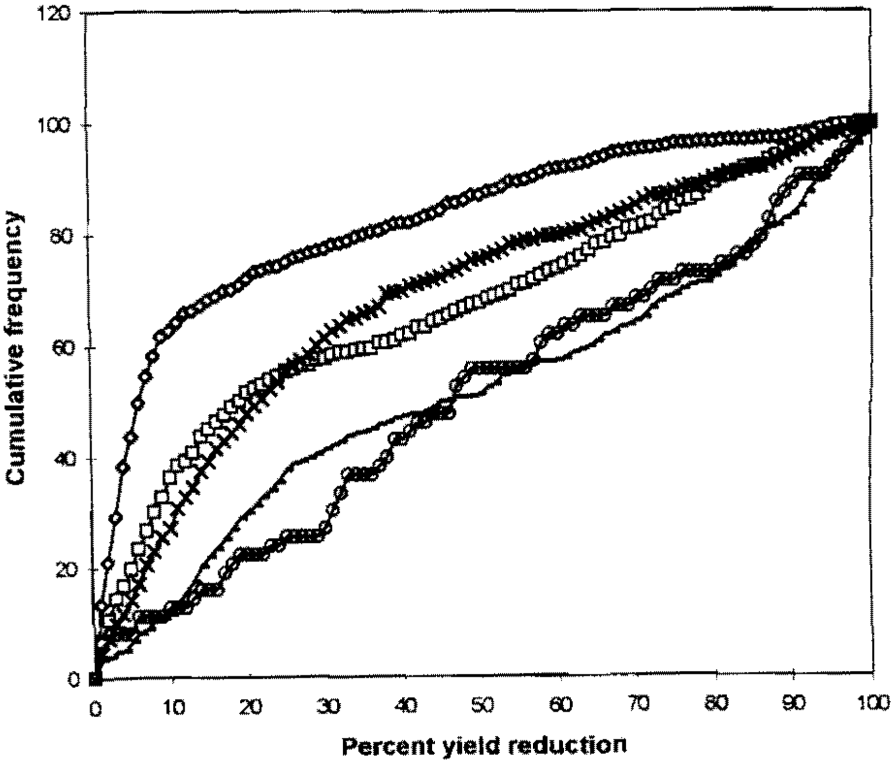

Figure 2. Cumulative frequency of yield reduction due to soil water deficits in six climatic categories of Eastern and Southern Africa.

TABLE 3. Stress levels at three stages of growth (S1-3) for four bean ideotypes in five climatic categories of eastern and southern Africa as indicated by the sum of products of stress level and frequency

Climatic category[a]	Seafarer			Rabia de Gato			Kilymukwe			Carioca		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
I	0.025	0.046	0.094	0.027	0.050	0.103	0.027	0.063	0.094	0.060	0.163	0.276
II	0.053	0.071	0.196	0.058	0.063	0.172	0.051	0.112	0.184	0.052	0.121	0.278
III	0.046	0.166	0.289	0.073	0.136	0.241	0.114	0.171	0.323	0.100	0.192	0.413
IV	0.034	0.089	0.155	0.031	0.091	0.155	0.040	0.101	0.157	0.041	0.105	0.220
V	0.050	0.169	0.337	0.050	0.194	0.319	0.069	0.225	0.369	0.081	0.300	0.356

[a] I = Sub-humid, medium altitude, low latitude, II = Sub-humid, high altitude, low latitude; III = Semi-arid, low latitude; IV = Sub-humid, medium latitude; and V = Semi-arid, medium latitude

satisfactory for screening as the cessation of rains is most variable resulting in much variation in stress during the screening period.

DISCUSSION

The DSSAT3 Drybean Model as a tool in bean breeding. The Drybean model has been informative in the study of water deficits for:

- assessment of the effects of water deficits on bean productivity in different Categories,
- assessment of the interaction effects of maturity times of cultivars and water deficits on yield and its stability,
- determination of the stage of growth for which tolerance is most important,
- evaluation of the potential of sites for screening under conditions of natural rainfall, and
- determination of likely sowing dates for achieving desired stress conditions.

The model did not reveal any difference due to the use of indeterminate lines, while an advantage is expected during the S2 stage of growth as prolonged flowering increases the probability of pollination and seed set occurring when there is adequate rainfall.

For the more extreme categories, the results generally agree with the author's expectations. Early maturity for drought escape has been perceived as important in Category III. Much on-farm testing has been done in Category I locations of cultivars of varying time to maturity and farmers seldom express concern about later maturity. Similarly, in parts of Malawi which would be in Category IV, farmers seldom express concern about time to maturity. These observations suggest that either early or late maturity cultivars can be acceptable to farmers in Categories I and IV.

Simulated yields are much higher than yields typically obtained in the field where crops encounter numerous biotic and abiotic constraints to yield. These constraints are likely to affect the ability of plants to use soil water efficiently. Uptake may be inhibited by damaged root systems due to insect or disease damage. Defoliation due to disease or insect attack affects transpiration, as well as growth, and water uptake and use efficiency are likely to be affected. Nutrient inadequacies are expected to result in less root growth and less capacity for water uptake, and in less shoot growth with reduced transpiration. The cumulative effects may result in more or less stress depending on the distribution of rainfall during the growing season.

We opted to switch off the nitrogen sub-routine in order to consider water deficits alone. However, N deficiency is often a major constraint to crop production. Adequacy of N might result in much growth initially and earlier depletion of water reserves, but the root system should be more efficient in capture of deep water. The effects of N availability are expected to vary with rainfall distribution.

The model would be more useful for such *ex ante* evaluation of bean ideotypes if certain physiological processes could be adjusted by the user. It would have been of interest to adjust the root to shoot growth ratio, or even root architecture, and determine the simulated effects on performance with water deficits. The roles of leaf size, thickness, and orientation in performance with water deficits might be investigated with a more flexible model.

A regional bean breeding strategy for tolerance to water deficits. The results indicate that improved adaptation to conditions of water deficit

TABLE 4. Mean yields (and SE's) and yield reductions due to water deficits for four bean ideotypes in six climatic categories of eastern and southern Africa

Ideotype	Yield, kg ha^{-1}	S.D for yield	% yield reduction
Climatic category I, n = 580			
Seafarer	2753	680	14.2
Rabia de Gato	2650	709	16.6
Kilymukwe	3020	936	18.2
Carioca	3359	1039	20.6
Climatic category II, n = 744			
Seafarer	2259	894	29.9
Rabia de Gato	2307	873	27.3
Kilymukwe	2235	1185	35.9
Carioca	2450	1334	37.8
Climatic category III, n = 408			
Seafarer	1899	1079	42.6
Rabia de Gato	1925	1115	41.6
Kilymukwe	1778	1196	51.7
Carioca	1743	1323	58.0
Climatic category IV, n = 520			
Seafarer	2494	967	28.2
Rabia de Gato	2469	1001	30.6
Kilymukwe	2594	1142	30.4
Carioca	2704	1292	35.0
Climatic category V n = 64			
Seafarer	1949	1153	43.2
Rabia de Gato	1828	1047	47.2
Kilymukwe	1921	1281	52.2
Carioca	1999	1385	53.0

TABLE 5. Correlation coefficients for bean yield with water deficit stress at three stages of growth for four bean ideotypes in five climatic categories of eastern and southern Africa

Climatic category	Seafarer			Rabia de Gato			Kilymukwe			Carioca		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
I	-0.50	-0.70	-0.84	-0.60	-0.63	-0.76	-0.63	-0.78	-0.85	-0.53	-0.74	-0.84
II	-0.21	-0.69	-0.86	-0.28	-0.67	-0.80	-0.18	-0.74	-0.93	0.09	-0.76	-0.94
III	-0.55	-0.83	-0.87	-0.36	-0.79	-0.77	-0.52	-0.74	-0.86	-0.45	-0.71	-0.88
IV	-0.59	-0.79	-0.84	-0.62	-0.76	-0.82	-0.61	-0.74	-0.81	-0.54	-0.67	-0.78
V	-0.65	-0.53	-0.76	-0.72	-0.57	-0.88	-0.52	-0.83	-0.94	-0.44	-0.79	-0.87

[a] I = Sub-humid, medium altitude, low latitude; II = Sub-humid, high altitude, low latitude; III = Semi-arid, low latitude; IV = Sub-humid, medium latitude; and V = Semi-arid, medium latitude

[b] S1 = first flower to first seed; S2 = first seed to physiological maturity; and S3 = Severity was grouped as <0.10, 0.10 - 0.39, 0.40 - 0.69, 0.70 - 1.00, with 0.00 and 1.00 equal to no stress and plant death due to stress

stress is very important for Categories III and V, and of importance in Categories II and IV as well. Early maturing cultivars are likely to be more productive and more stable than late maturing cultivars in some environments.

A programme for improving adaptation to water deficits may include one or more of the following: selection of drought tolerant lines from existing cultivars and breeding lines; incorporation of drought tolerance in commercial cultivars; improvement of breeding parents for drought tolerance; and breeding for drought tolerance *per se*. Improved stress escape, and/or tolerance during the seedfill stage of growth, is most needed.

Stress levels vary much from season to season (Fig. 2). Therefore, breeders should evaluate materials either under field conditions with controlled water supply, or by planting towards the predicted end of the rainy periods to achieve good early growth with stress during the later stages of growth. Initially, priority might be given to identification of well-adapted cultivars that perform well in spite of water deficits, but eventually breeding for tolerance should be emphasised. Test materials might be of three types: materials known to perform well in spite of water deficits; agronomically superior materials from national and regional breeding programmes

TABLE 6. Optimal sowing dates for screening bean for tolerance to water deficits under natural rainfall conditions at four locations in eastern and southern Africa

Location	Embu	Katumani	Mbeya	Mbeya
Maturity group	Early	Early	Early	Late
Sowing date	5 May	15 Apr.	10 Mar.	5Mar.
Stress at first seed	0.18	0.13	.17	0.17
Stress during seed fill	0.54	0.47	0.55	0.53
Yield reduction (YR) (%)	60	60	61	62
Std. Dev. of YR[1]	12	17	30	26

[1] Std. Dev. of YR: standard deviation of the reduction in yield across years

in Africa as these materials are likely to be otherwise well adapted and of preferred types; and populations bred for drought tolerance beginning evaluations with the F_1 generation (White *et al.*, 1994).

A regional screening approach might be similar to that used for screening for tolerance to low soil fertility conditions (Wortmann *et al.*, 1995). A large set of well-adapted entries (>100) of the desired maturity range would be screened at one or two primary screening site for two seasons. Then, the most promising materials (best 10 to 15% for drought yield) can be evaluated more widely. Environment effects, especially temperature, on the expression of drought tolerance are expected (White *et al.*, 1994) and good selection of primary screening sites is crucial.

CONCLUSION

Water deficits are a major constraint to bean productivity in many production areas of eastern and southern Africa, reducing mean yields by 50% or more in some semi-arid areas. The later maturing ideotypes have the greatest yield potential in non-stress environments, but where water deficits are often severe, the early maturing ideotype gives higher mean yield. Yield was also more stable with the early maturing type in stress environments; this stability may be more attractive to risk-prone small scale farmers than a slight advantage in mean yield. The results indicate that drought escape through the use of early maturing varieties provides a valuable defence against unpredictable water deficits.

Achieving improved adaptation to water deficits is a major challenge and should be approached in a collaborative manner at a regional level. Preliminary screening of lines proven to be well adapted in the region for tolerance to stress at a few locations where stress can be well managed can be followed by multi-location testing of the most promising lines at drought prone sites throughout the region. This needs to be complimented by breeding to incorporate tolerance traits into preferred and agronomically superior cultivars.

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