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Full Length Research Paper

Development of a crop growth subroutine for the Watershed Resources Management (WRM) model

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Vegetation has a marked effect on runoff and soil moisture and plays an important the hydrologic cycle. The Watershed Resources Management (WRM) model, a process-based, continuous, distributed parameter simulation model developed for hydrologic and soil erosion studies at the watershed scale lack a crop growth component. As such, this model assumes a constant parameter values for vegetation and hydraulic parameters throughout the duration of hydrologic simulation. A crop growth algorithm based on the original plant growth model used in the Environmental Policy Integrated Climate (EPIC) model was developed for coupling to the WRM model. The developed model was tested for yield simulations using data from a field plot within the Oyun River basin, Ilorin, Nigeria. Model prediction closely matched observed values with R^2 of 0.9 for the years under study. This model will be incorporated into the WRM model in other to improve its representation of vegetation growth stages in a natural basin. This modification will further enhance its capability for accurate hydrologic and crop growth studies.

Key words: Runoff, roughness coefficient, photosynthetic active radiation (PAR), watershed resources management (WRM) model.

INTRODUCTION

Change in the vegetation of a watershed alter the natural hydrologic cycle and significantly affects runoff (Cao et al., 2009). Vegetation, which was once thought to only play a relatively minor role and was ignored or treated as a static component in hydrologic models has now been recognized as one of the most important factors affecting the hydrologic cycle (Chen et al., 2014). The pivotal role that vegetation plays in the global water balance cannot be neglected. The interactions between ecosystems and water resources are important for studying the effects of environmental management (land-use change) on hydrologic processes, and thus to provide solution to problems of water resources and watershed management. Vegetation is an important component of

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terrestrial ecosystem and must be considered in integrated models for simulating hydrologic processes (Strauch and Volk, 2013). Thus, the need to fully represent soil water – crop growth dynamics in hydrologic models for accurate representation of biophysical and hydrologic processes cannot be overemphasized.

Crop growth modeling concepts evolved in the 1960s with the major aim of understanding the fundamental biological processes of single crops (van Ittersum et al., 2003). Crop modeling started in the United States with the development of the Environmental Policy Integrated Climate (EPIC) model in the 1980s to simulate the impacts of soil erosion on soil productivity. Over the years, the EPIC model has evolved into a comprehensive agro-ecosystem model that includes major soil and water processes related to crop growth and environmental effects of farming activities (Wang et al., 2006). Its crop growth component offers major advantage in that it contains a single model with the capability of simulating multiple crop growth and development in any region of the world. Several agro-ecosystem models such as Water Erosion Prediction Project (WEPP) model (Flanagan et al., 1995), Soil and Water Resources Tool (SWAT) model (Arnold et al., 1998), Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) model, Wind Erosion Predictions System (WEPS) model, etc have either simplified or modified the EPIC's crop growth model and incorporated it to suit their different research objectives. Nowadays, crop growth models are not only used to predict crop yield or study crop physiological processes but also part of many hydrologic models and agricultural decision support tools (Multsch et al., 2011). A realistic representation of a hydrologic system is important for water resources development and management at the watershed scale (Kiniry et al., 2008). In most hydrologic models, crop parameters such as hydraulic roughness are kept constant throughout a period/season of hydrologic simulation resulting to a gross oversimplification of reality and inaccurate models results (Pauwels et al., 2007).

The Watershed Resources Management (WRM) model (Mbajiorgu, 1995a) is a process-based, continuous, distributed-parameter hydrologic model. As a continuous simulation model, WRM model requires a crop growth component in other to simulate effect of crop growth on hydrologic processes. Currently, this model lack such capability as it assumes constant parameter values for vegetation and land cover management throughout duration of simulation. Therefore, it is imperative to implement a crop growth module in WRM in other to enhance the model capability to realistically simulate hydrologic processes.

The objective of this study is to develop a crop growth subroutine that is compatible with the WRM model structure. The model was further applied to simulate corn yield for a location in Nigeria.

METHODOLOGY

The crop model follows the general concept described in the EPIC model and consists of a single modeling approach for simulating multiple crops by changing input parameter values. Crop phenological development is based on daily accumulated heat units, harvest index is used for partitioning yield, Monteith's approach for potential biomass accumulation, and actual biomass actual biomass accumulation obtained by determined using Leibig's Law of the Minimum by considering water and temperature stress factors. The crop growth model is capable of simulating annual and perennial crops. Annual crops grow from planting date to harvest date or until accumulated heat units equal potential heat units for the crop while perennial crops maintain their root systems throughout the season.

Crop phenological development

The model use thermal time is represented by heat units (HU) or also commonly referred to as growing degree-days (GDD) for modeling crop phenological development. Arnold et al. (1998) stated this as:

$$HU_i = \left(\frac{T_{mx,i} + T_{mn,i}}{2}\right) - T_{b,j} \qquad HU_K \geq 0 \tag{1}$$

Where, HU_i = value of heat unit on day I; $T_{mx,i}$ = daily maximum temperature (°C); $T_{mn,i}$ = daily minimum temperature (°C); $T_{b,j}$ =crop specific-based temperature of crop J (no growth occurs at or below T_b).

Crop phenological development is generally seen as a heat unit index ranging from 0 at planting to 1 at physiological maturity of a crop. This is calculated as:

$$HUI_i = \frac{\sum_{k=1}^{i} HU_k}{PHU_j} \tag{2}$$

Where, HUI_i = heat unit index for day i; HU_k = sum of daily heat units from planting date to current date; PHU_j = potential heat units required for crop j to grow to maturity.

Crop potential growth

Potential daily biomass accumulation is based on radiation-use efficiency (RUE) using interception of photosynthetic active radiation by crop canopy (as represented by the leaf area index and light extinction coefficients) and an energy to biomass conversion factor (Ascough II et al., 2014). RUE represents the above ground biomass production per unit of light intercepted by the crop canopy. A conversion factor of 0.45 or 0.43 can be easily used to convert incident total solar radiation to photosynthetic active radiation (PAR) above the plant canopy (Kiniry et al., 2008). These authors defined PAR as the definitive band of wavelengths pertinent to photosynthetic response which is inherent in the RUE approach. PAR interception by crop canopy is modeled using Beer's Law (Monsi and Saeki, 1953):

$$PAR_i = 0.5(RA_i)\left[1.0 - e^{-k \times LAI_i}\right] \tag{3}$$

Where, PAR_i = intercepted photosynthetic active radiation on day i

(MJ/m^2/d); RA_i = solar radiation on day i (MJ/m^2/d); 0.5 = factor for converting solar radiation to PAR; k = extinction coefficient; LAI_i = leaf area index on day i.

Accurate value of PAR is very important in crop modeling as it drives photosynthesis and potential biomass simulation. PAR simulation in several ecohydrologic models (SWAT, EPIC, WEPP, etc) assumes a constant (0.65) for light extinction coefficient (k), while the ALMANAC model uses different values of k for different crop species and for different row spacing (Kiniry et al., 1992). Also, Equation 3 shows that PAR is calculated using 50% of daily total solar radiation. However, Kiniry et al. (2008) pointed out that only 2% or less of the energy in the PAR waveband is utilized by crops during photosynthesis and biomass production. These authors developed a function to accurately determine the extinction coefficient of PAR (k_{PAR}) from the extinction coefficient of total solar radiation (k_s) as stated below.

$$k_{PAR} = 1.62 k_s^{1.16} \tag{4}$$

Potential biomass production is modeled using Monteith's (1977) approach

$$\Delta BP_i = 0.0001 (BE_j)(PAR_i) \tag{5}$$

Where, ΔBP_i = potential increase in daily biomass on day i (kg/m^2); BE_j = crop-specific parameter for converting energy to biomass (kg/MJ).

Actual daily biomass accumulation was modeled using Leibig's law of minimum. Therefore, potential biomass accumulation (Equation 5) can be adjusted if any of the crop stress factors (temperature and water) is less than one (1.0) using the Equation 6:

$$\Delta B_i = (\Delta BP_i)(REG_i) \tag{6}$$

Where, ΔB_i = actual biomass production on day i (kg/m^2); REG_i = most limiting crop growth stress factor calculated for day i.

Crop cover and height

Leaf area index (LAI) is the leaf area per unit ground area irrespective of leaf orientation (Wilson, 2011). Accurate simulation of crop light interception, transpiration and dry matter/biomass accumulation depends on the accurate estimation of LAI (Birch et al., 1998). The leaf area development model uses a sigmoid function to represent pre-senescence growth of LAI, while power function is used to represent a decline in leaf area index during post-senescence period (Nair et al., 2012). LAI is simulated as a function of heat units, crop stress and crop developmental stages. From emergence to start of leaf decline, LAI is calculated as:

$$LAI_i = LAI_{i-1} + \Delta LAI \tag{7}$$

$$\Delta LAI = (\Delta HUF)(LAI_{mx})(1 - \exp(5(LAI_{i-1} - LAI_{\max})))\sqrt{REG_i} \tag{8}$$

$$HUF = \frac{HUI}{HUI + \exp(ah_{j,1} - (ah_{j,2})(HUI))} \tag{9}$$

where, LAI = leaf area index; HUF = heat unit factor; REG = value of minimum crop stress factor; LAI_{mx} = maximum value possible for the crop; Δ = daily change; $ah_{j,1}$ and $ah_{j,2}$ = crop parameter that determine the shape of the leaf area index development curve.

From the start of leaf decline to the end on the growing season, LAI is estimated for annuals and perennials using (Neitsch et al., 2005).

$$LAI_i = LAI_{mx}\left(\frac{1 - HUI_i}{1 - HUI_o}\right) \quad \text{if } HUI_i > HUI_o \tag{10}$$

For trees, it is calculated as:

$$LAI_i = \left(\frac{Yr_{cur}}{Yr_{fuldev}}\right).\mathrm{LAI}_{\max}.\left(\frac{1-\mathrm{HUI_i}}{1 - HUI_o}\right) \quad HUI_i > HUI_o \tag{11}$$

Where, HUI_o = HUI when LAI starts declining; Yr_{cur} = age of tree (yrs); Yr_{fuldev} = number of years for tree species to reach full development (yrs)

Crop height is modeled for annuals and perennials using equation as stated in Williams et al. (2008)

$$CHT_i = HMX_j \sqrt{HUF_i} \tag{12}$$

For trees, it is calculated using (Neitsch et al., 2005)

$$CHT_i = HMX_j \left(\frac{Yr_{cur}}{Yr_{fuldev}}\right) \tag{13}$$

Where, CHT_i = daily crop height (m); HMX_j = maximum height of crop j (m).

Root development

Biomass partitioning to roots is calculated when the fraction of daily biomass partitioned to roots changes linearly from 0.4 at emergence to 0.2 at maturity based on phenological stages, with the remainder going to the canopy (Ascough II et al., 2014). These authors calculated daily change in root weight as:

$$\Delta RWT = \Delta BP(0.4 - 0.2 HUI) \tag{14}$$

Where

ΔRWT = change in root weight on a given day (t/ha); HUI = heat unit index

Above-ground biomass is estimated from the equation (Arnold et al., 1998)

$$B_{AG} = (1 - RWT_i) B_{p,i} \tag{15}$$

Rooting depth normally increases from the seeding depth to a crop-specific maximum which is usually attained before the crop phenological maturity (Neitsch et al., 2005). It is calculated as a function of heat units and potential root zone depth and is stated as:

$$RD = 2.5(RDMX)HUI \quad HUI_i \le 0.4 \tag{16}$$

$$RD = RDMX \quad \mathrm{HUI_i} > 0.4 \tag{17}$$

Where, RD = root depth (m); RDMX = maximum root depth for a crop.

Crop yield

Crop yields are mostly reproductive organ removed from the field during harvest. Harvest index is the fraction of the above-ground dry biomass removed as dry economic yield (Neitsch et al., 2005). These authors noted that this index varies from 0.0 – 1.0. The harvest index (HI) concept stated in Williams et al. (2008) was adopted for modeling crop yield. This concept was employed in the EPIC model, SWAT model and so many other models. It is obtained by multiplying harvest index with above-ground biomass.

$$\mathrm{YLD_j} = (HI_j)(B_{AG}) \qquad \text{if } \mathrm{HI_j} \le 1.00 \qquad (18)$$

$$YLD_j = B_{p,i} = \left(1 - \frac{1}{1 + HI_j}\right) \qquad \text{if } \mathrm{HI_j} > 1.00 \qquad (19)$$

$$HI = HI_{opt} \times \frac{100.HUI_1}{[100\,HUI_i + \exp(11.1 - 10\,HUI_i)]} \qquad (20)$$

YLD_j = amount of economic yield of crop j (kg/ha); HI_j = potential harvest index of crop j; B_{AG} = above-ground biomass for crop j (kg/ha); HI_{opt} = potential harvest index for a crop at maturity.

Actual crop yield varies from potential growth due to reduction in harvest index caused by water deficiency. The harvest index is affected by water stress using the relationship:

$$HI_{act} = (HI_{\min} - HI_j) \times \left[1 - \frac{1}{1 + (WSYF_j)(FHU_i)(0.9 - WS_i)}\right] \qquad (21)$$

$$FHU_i = \sin\left[\frac{\pi}{2}\left(\frac{HUI_i - 0.3}{0.3}\right)\right] \qquad 0.3 \le \mathrm{HUI_i} \ge 0.9 \qquad (22)$$

$$FHU_i = 0 \qquad \mathrm{HUI_i} < 0.3 \text{ or } \mathrm{HUI_i} > 0.9 \qquad (23)$$

HI_{act} = daily actual harvest index; HI_j = normal harvest index for crop j; HI_{min} = minimum harvest index; $WSYF_j$ = crop parameter expressing the sensitivity of harvest index to drought for crop j; FHU_i = daily heat unit function; WS_i = daily water stress factor.

Crop water use

Water is the major limiting factor for crop growth. Water uptake by crop roots is driven by transpiration and depends on the moisture content of the soil. In this model, root grows to a crop-specific maximum and water compensation is possible when part of the root is in dry soil layers (van Ittersum et al., 2003). The potential water use is estimated using the leaf-area-index relationship (William et al., 2008):

$$u_p = \frac{E_p}{1 - \exp(\Lambda)}\left(1 - \exp\left(\Lambda\left(\frac{Z}{RZ}\right)\right) - (1 - UC)\left(1 - \exp\left(-\Lambda\left(\frac{Z-1}{RZ}\right)\right)\right)\right) - UC\sum_{K=1}^{l-1} u_K \qquad (24)$$

$$E_p = E_o\left(\frac{LAI}{3}\right) \qquad (25)$$

Where, u_p = water use; E_p = potential water use; E_o = potential evaporation; LAI = leaf area index; ʌ = water use distribution parameter; Z = soil depth; RZ = root zone depth; UC = water deficit compensation factor.

Crop growth stress factors

Crop growth is limited by water, temperature, nutrients and aeration stresses. Only water and temperature stress factors were considered in this study. Lack of water limits biomass production and also affects transpiration. The water stress factor (REG) is computed considering the water supply and water demand (William et al., 2008):

$$WS = \frac{\sum_{i=1}^{nl} u_l}{E_p} \qquad (26)$$

Where, WS = water stress factor (0 – 1); u_l = crop water use in soil layer l (mm); n_l = number of soil layers; E_p = potential crop evaporation (mm) (to be computed in the ET component of WRM model).

The temperature stress factor is calculated as:

$$TS_i = Sin\left[\frac{\pi}{2}\left(\frac{T_{gi} - T_{bj}}{T_{oj} - T_{bj}}\right)\right] \qquad (27)$$

Where, TS = temperature stress factor (0 – 1); T_a = average daily temperature (°C); T_b = base temperature for the crop (°C); T_o = optimum temperature for the crop (°C).

Soil water balance model

The water balance model is normally expressed as root zone moisture depletion and is stated as (Allen et al., 1998):

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{ci} + DP_i \qquad (28)$$

Where, $D_{r,i}$ = root zone depletion at the end of day i (mm); $D_{r,i-1}$ = water content in the root zone at the end of the previous day, i-1 (mm); RO_i = runoff from the soil surface on day i (mm); I_i = net irrigation depth on day i that infiltrates the soil (mm); CR_i = capillary rise from the groundwater table on day i (mm); ETc_i = crop evapotranspiration on day i (mm); DP_i = water loss out of the root zone by deep percolation on day i (mm).

Van Ittersum et al. (2003) reported that the major approaches for modeling soil water balance is either by the tipping bucket approach or the Richards approach. The tipping water bucket was adopted for this study because it is straightforward, used to calculate water available to crops for long time periods and has been used in many crop models.

Watershed resources management (WRM) model: Theory

The hydrologic processes as incorporated in the WRM model are modeled by finite differences of the mass, momentum and energy conservation equations. WRM model is applicable at the basin scale, in planning, forecasting and operational hydrology; in design flow estimation, to the study of environmental impacts of land use

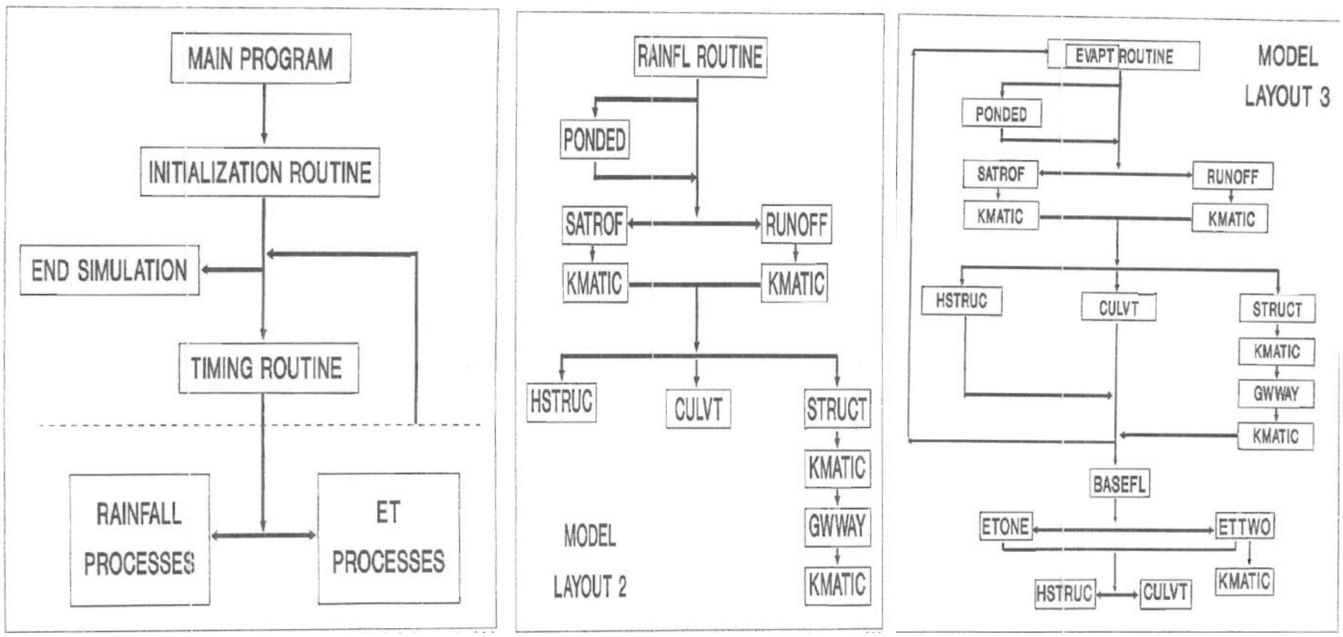

Figure 1. (a) WRM Model Layout (1) (b) WRM Model Layout (2) (c) WRM Model Layout (3).

changes, and to soil and water conservation planning (Mbajiogu, 1995b). Empirical equations, derived from relating physical quantities experimentally and validated independently, are also employed for the development of WRM model. The specific fundamental process equations, and equations used to track the physical state of the system are presented for each of the component program modules as follows: initialization routine; timing routine, rainfall-event routine, ponded-infiltration routine, runoff routine, saturation-runoff routine, kinematic-flow routine, conservation-structures (terraces) routine, culvert routine, evapotranspiration-event routine, baseflow routine, soil-moisture accounting and subsurface-lateral flow routines (Mbajiorgu, 1995a). The spatial structure of the European Hydrological System (SHE) model was adopted for distribution of hydrologic responses and parameter specification. A comprehensive, rigorous and state-of-the-art theory of the hydrologic processes as employed in the WRM model is found in Mbajiorgu (1992).

Mathematical representations of hydrologic and soil erosion processes employed by WRM model to represent a hydrologic system are canopy interception storage, evapotranspiration, infiltration, saturated subsurface flow, overland and channel, reservoir routing, soil erosion and sediment routing, channel-flow transport, terrace-channel flow, grass-waterway flow and culvert flow.

The general layout of the WRM model computer program in terms of its module is as shown in Figure 1(a), (b) and (c) (Mbajiogu, 1995a). The main subprogram is essentially a specification and overall control module. It calls five subroutines, namely: initialization, timing, rainfall event, evapotranspiration event, and an optional report generator. These subroutines as a group are termed 1st Order routines. Other subroutines called directly from them are grouped together as 2nd Order routines, which in turn call 3rd order routines. Operation of WRM model components and its synthesis is fully described in Mbajiorgu (1992, 1995a).

The crop model has a modular structure by design and is compatible with the WRM model framework making it easy to be incorporated into the WRM main program as a subroutine. The default crop parameters were determined based on values from William et al. (2008) and was adopted to develop a crop parameter database for this model.

Model evaluation

Model performance was evaluated using the linear regression coefficient of determination (R^2) which is calculated as:

$$R^2 = \frac{\left[\sum(\hat{X}_1 - \bar{\hat{X}})\left(X_i - \bar{X}\right)\right]^2}{\sum\left(\hat{X}_1 - \bar{\hat{X}}\right)^2\left(X_i - \bar{X}\right)^2} \qquad (29)$$

Where, $\hat{X}_1$, X_i= individual simulated and individual observed values respectively, $\bar{\hat{X}}$, $\bar{X}$ = mean of simulated and the mean of observed values respectively.

The value of R^2 indicates the model's ability to explain the variances in the measured data and range from 0.0 to 1.0. A value of R^2 > 0.5 is used as criteria for evaluating better model performance.

RESULTS

Crop model development

Figure 2 show the logic flowchart of the crop growth subroutine which simulates crop growth, canopy interception of solar radiation, conversion of intercepted PAR to biomass, division of biomass into roots, above ground biomass and economic yield and root growth. Crop development is driven by temperature with growth

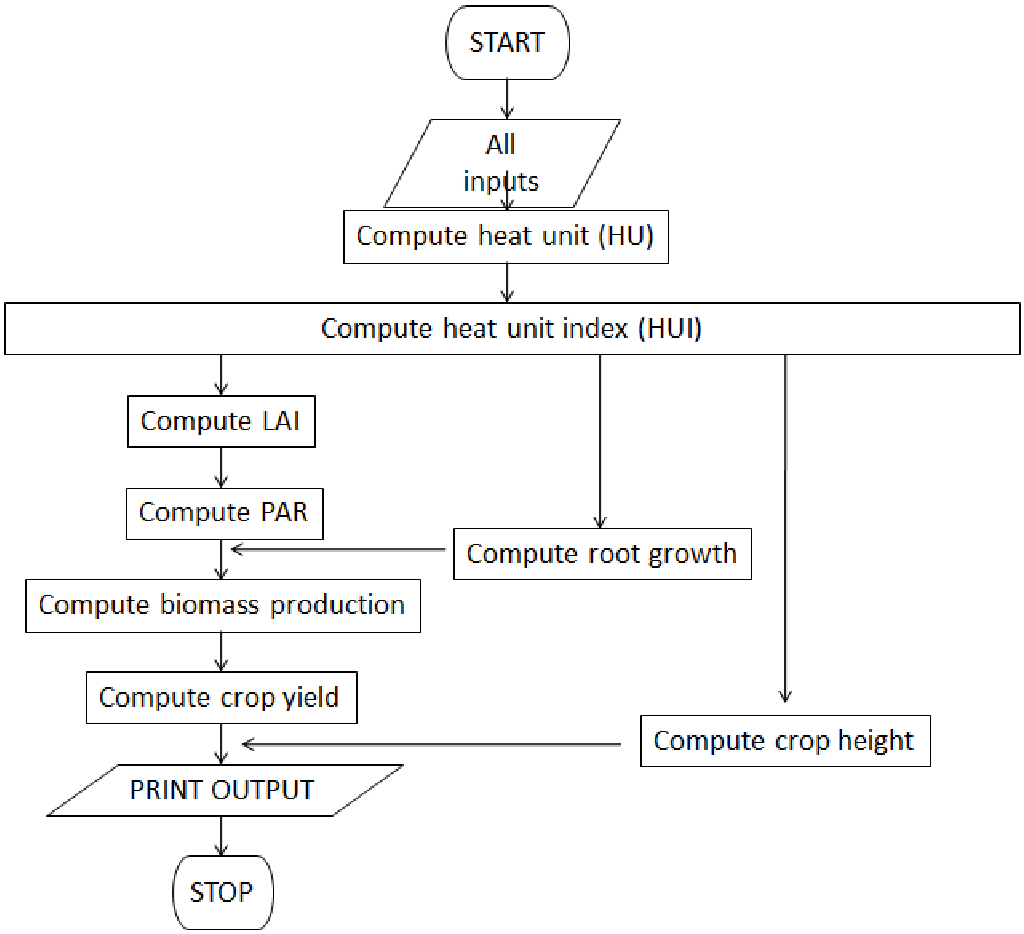

Figure 2. Logic flow chart of the crop growth subroutine.

duration dependent on degree days. Every crop species has a unique base and optimum temperatures which is used to obtain its heat unit index. Daily changes in biomass production are observed when crop available water at the root zone is insufficient to satisfy potential evapotranspiration. Yield is simulated as a fraction of the total aboveground dry matter at maturity.

The crop model is modular in design and was developed with C# programming with a Microsoft Visual Studio-based graphical user interface (GUI). It consists of the above-mentioned crop growth processes and a Microsoft Excel file for crop growth parameters. The model's GUI makes it easier for users to select inputs (climate, crop, soil characteristics), perform simulations and view results.

Simulation starts with the initialization of model parameters and reading of input data from external files. The model during run time implements daily calculations for all growth process equations till crop physiological maturity is attained. The graphical user interface (GUI) has a friendly interface which allows user to create a project/open existing project, select crop type with parameters and perform simulation. Model results are displayed and can be viewed using Microsoft Excel.

Model application

The model was tested with corn yield data from a farmland located within Oyun River Basin, Ilorin, Kwara State, Nigeria to evaluate the model capability for crop yield simulation. This basin is largely used for farming and lies within the grass plains of Nigeria. It has an average elevation of 251 m and lies between Latitude 9°50´ and 8°24´N and Longitude 4°38´ and 4°03´E. The area experiences rainy season from April to October, having a mean annual rainfall of 1700 mm and mean monthly maximum and minimum temperature of 31 and 29°C respectively.

Model input

Weather data of daily rainfall, maximum and minimum

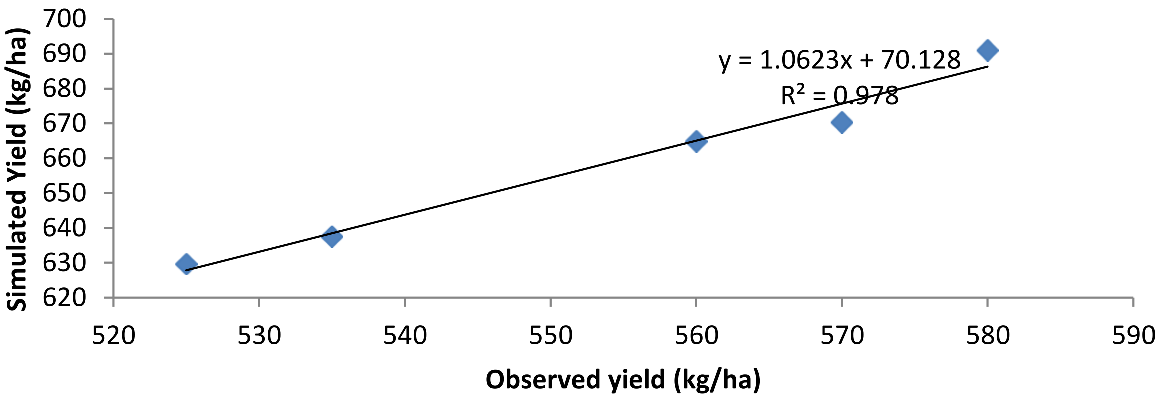

Figure 3. Simulated and measured yield of corn.

temperature, solar radiation, wind speed and relative humidity were obtained from the Meteorological Station of the National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State, Nigeria. Crop specific inputs for corn were obtained from William et al. (2008) and used to perform model runs. Potential heat unit for corn was calculated from planting to maturity and used as input for yield simulation. The water balance was simulated using the FAO Penman Monteith method.

Seasonal corn yield data for 2004 to 2008 were obtained from the National Centre for Agricultural Mechanization (NCAM), Ilorin and used for comparison with simulated yields. Difference between observed and simulated yields for corn is presented in Figure 3. The choice of crop was dependent on continuous yield data availability for the study.

DISCUSSION

Available yield data and period of observed data determined the number of data points for comparison as seen in Figure 3. Measured yield ranged from 525 to 580 kg/ha for the study area. The crop model predicted higher corn yield than was observed when compared on an annual basis for the duration under study. The mean simulated yield is higher than the mean observed yield. The crop model's mean simulated yield is within 18% of the mean measured yield. Model calibration was not performed and this resulted to high simulated values. Default crop parameters were used because field measurements of these parameters were not available and this also affected model outputs. Also, paucity of data on crop management practices may have resulted in the model simulating higher yield than was observed. The value of R^2 at 0.9 showed good model performance in simulating corn yield for the study area. However, more applications for different crops in other locations need to be performed to further test the model capability for yield studies.

Conclusion

A process-oriented crop growth module for simulating annual and perennial crop species developed for the WRM model has been described based on concepts adopted by other USDA hydrologic models. The developed model is capable of simulating annual and perennial crops by changing crop-unique parameters in the crop database. Model testing was performed for simulating corn yield for a farm plot in Ilorin, Nigeria. Obtained results show good performance with measured data. However, the model still needs to be tested for other locations and for different crops. The developed crop model will further be incorporated into the WRM model for improved representation of vegetation patterns in a watershed during hydrologic and crop growth studies. This effort is geared towards improving its capability as an effective tool for decision makers and watershed managers.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Effect of planting date on tepary bean yield and yield components sown in Southern Botswana

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Tepary bean is a crop that is slowly gaining momentum into the cropping system of Botswana. A study was conducted to determine the effect of planting date on yield and yield components of tepary bean and identify the optimum sowing of the crop. A rain-fed experiment was conducted for two seasons (2012 to 2014), using a randomized complete block design replicated three times in a split plot with three sowing dates in main plots and the nine genotypes in sub plots. Genotype × planting date interaction was not significant among the characters (100 seed weight, shoot dry weight, seed yield, crop loss, plant population, and plant height) which implied stability of the utilized genotypes. However, planting dates and year, and also the interaction between planting date and year were highly significant (P>0.001) for all the characters. Plant height had greater association with shoot dry weight (0.783), 100 seed weight (0.70) and seed yield (0.65), suggesting that it is a character which can be useful in selection for improving the tepary bean productivity. Sowing tepary bean in December and January were found to be good options for farmers in the southern part of Botswana.

Key words: Genotype, planting date, tepary bean, yield, yield components.

INTRODUCTION

The world today depends on few number of crops species for food mainly cereals such as wheat, rice and maize; this leaves a significant number of crops with potential benefit neglected (Collins and Hawtin, 1999; Azam-ali, 2010). Climate change and global populations are key issues forcing researchers to be innovative enough to bring about changes in the crop production systems in order to achieve the world food demand (McClean et al., 2011). Climate change put some pressure on food production particularly on major crops, it is crucial to have some options in the likes of underutilized or orphan crops (Mayes et al., 2014). Therefore, further research and development of minor crops such as tepary bean could be useful in the forthcoming new environments (Porch et al., 2012).

Tepary bean (*Phaseolus acutifolius* A. Gray) is a drought tolerant but neglected crop that has the potential to provide greater resilience to cope with the climate

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change challenge (Blair et al., 2012; Jiri et al., 2017). The cultivated tepary is an annual legume that originates from the Mesoamerican region in the Sonora desert; it is well adapted to hot arid climates (Thomas et al., 1983). It has received tremendous interest as an arable field crop in a number of regions around the world (Miklas et al., 1998). The crop is preferred for its high biotic and abiotic stress tolerance (Porch et al., 2013), high protein content in edible grain and its fodder value (Bhardwaj, 2013). As a short duration and high yielding crop, this makes it a quick and easy crop to grow (Hamama and Bhardwaj, 2002) and this is a good character for low and erratic rainfall in Botswana. Tepary bean is one pulse crop that is highly promoted for consumption, especially since there is little or no production of common bean in the country. However, there is inadequate documented information on the per capita tepary bean consumption in the country. Planting date is a key factor in the production of crops in semi-arid environment of Botswana (Moatshe et al., 2015). However, the length of growing crops has significantly decreased; the onset and cessation of growing crops have been October (onset) and March (cessation), respectively but this trend has shifted (Adelabu et al., 2010). The decrease in the growing season is attributed mostly to limited rainfall, occurrence of frost and extreme evapotranspiration (Weare, 1971). The crop yields are however, highly dependent on seasonal rainfall (Tsheko et al., 2015), which is affected by the period of planting (Ezeaku et al., 2015). In addition, changes in the rainfall patterns of Botswana are clearly noticed in high inter-annual variation in the rainfall onset, more number of dry days and decreasing amounts of rainfall at the onset and cessation (Simelton et al., 2012). Climate change has caused some changes in the growing seasons in a number of other regions and these lead to a reduction in crop yield (Ezeaku et al., 2015). Negative impacts of climate change on food production can have a serious consequence on food security in Botswana, since to a great extent it is relying on imports for her food requirements (Dube, 2003).

Earlier work on tepary bean revealed that planting dates significantly affected seed yield seed weight and harvest index when tested over three planting dates in Virginia, United States of America (Bhardwaj et al., 2002). The time of planting is important in determining the final seed yield and is a useful agronomic practice as observed in other leguminous crops such as cowpeas (Shiringani and Shimelis, 2011), bambara groundnut (Ngwako et al., 2013) and faba bean (Thalji and Shalaldeh, 2006). Planting dates can also be used effectively to control several pests in cowpea (Ezeaku et al., 2014) and corn rootworn damage in maize crop (Obopile et al., 2012). Therefore, the technique can be a good cultural control method of pest and diseases among subsistence farmers with limited access to resources (Akande et al., 2012).

In Botswana, the sowing date is dependent on rainfall and planting season can start from September to early February and most planting occurs between September and December (Moatshe et al., 2015). However, the cessation of growing season is based on the occurrence of the minimum temperature of ≤3°C to avoid the growth of crops to coincide with the time when black frost occurs resulting in plant senescence (Adelabu et al., 2010). It was discovered that the period during which frost may occur is much longer or comes much earlier in the Southern Botswana than further north (Andringa, 1984). Hence, the planting dates in Botswana are structured in such a way that the last planting dates in the north and south of the country are usually mid February and end of January season, respectively. Therefore, it is usually critical to know the duration of crops to reach physiological maturity to assist establish the best time to plant when conditions are conducive. However, based on some circumstances such as lack of resources, extension dates are provided for farmers to do their planting after the proposed planting dates (Adelabu et al., 2010).

Date of sowing is one aspect of crop management that is well explored for a number of crops at the Department of Agricultural Research, Gaborone, Botswana. Studies were conducted to compare early planting (December), intermediate (January) and late planting (February) for several crops. The results suggest that early planting was most suitable for most crops such as groundnut (DAR, 1991), cowpeas and sunflower (DAR, 1988). While for mungbean early planted crops produced better yields, but sowing in January did not significantly affect number of pods and start of flowering, therefore, the crop could be planted between 20th December and 20th January (DAR, 1989). The research also revealed that the optimum planting date is not always suitable for all the cultivars used and this makes determining the right time of planting a challenge. No sowing dates studies have been conducted in Botswana for tepary bean crop, the current changes of the growing season also warrant a study to determine the best planting date for this crop in the country. Therefore, the objective of this study is to determine the effect of planting date on yield and yield components of tepary bean and identify the optimum sowing date for tepary bean in Southern Botswana.

MATERIALS AND METHODS

Experimental site

Two field trials were conducted at the Department of Agricultural Research Station in Sebele, Botswana (24°35'S; 25°56'E, 991 m); the climate is semi-arid with a 30 year average annual rainfall of 500 mm. The rains generally starts in October and end in April, and over 90% of the rainfall occurs during November to March (Weare, 1971), however, the rains are not evenly distributed both spatially and temporally with long dry spells within the season. The field site soils are shallow, ferruginous soils, consisting of medium to coarse sandy and sandy loam with low water holding capacity. The site was ploughed and disc harrowed to level the soil and prepare the seed bed for planting. The 2012 to 2013 season was declared a drought year due to prolonged moisture deficiency across the whole country, while 2013 to 2014 season was not considered a drought year (Statistics Botswana, 2015).

Genotypes used

The experiment was performed with a set of nine tepary bean genotypes (GK010, E19, E89, GK012, E105, GK011, E70, GK013 and Motsumi), at three sowing dates (December 19th January 21st and February 19th in the 2012 to 2013 season). The same genotypes were planted in the second season of 2013 to 2014 at three sowing dates (December 18, January 21 and February 19th). Sowing in each season was conducted after every four weeks. December sowing dates are considered early planting while January sowing dates are intermediate planting and the February sowing dates are the late planting dates. These days are within the planting times recommended for Botswana.

Experimental layout

A randomized complete block design was replicated three times in a split plot with three sowing dates in main plots and the genotypes in sub plots. A total plot area of 35 m×54 m was set up after soil preparation by ploughing, and disc harrowing the soil. A unit plot area of 3 m × 5 m, with a row spacing of 0.75 m, and between plant space of 0.2 m, with an expected plant population of 67000 per ha was established.

Data collection and analysis

Climatic data were obtained using weather station (Pessl Instruments, Weiz, Austria). The weather station monitors air temperature, precipitation, air humidity, solar radiation, wind direction and speed, dew point and leaf wetness; the data was recorded hourly. The weather station was located less than 2 km from the planting sites. Data for 2012 to 2013 and 2014 crop season were used to relate the crop yield to the weather conditions.

The agronomic data recorded were the initial plant stand recorded 21 days after sowing; final plant stand recorded at harvest when the plant has reached maturity at 60 to 70 days from sowing. Shoot dry weight is above ground biomass averaged from five plants per plot, it was oven dried (Oven, series 2000) for 48 h at 70°C. Seed yield is the weight of seed recorded per plot collected within the two middle rows, crop loss percentage was estimated from subtracting the initial plant stand from final plant stand, plant population was estimated from the final plant stand count, and plant height was measured from an average of 5 plants per plot within the two middle rows. Hundred seeds were counted using a seed counter (Numigral) and 100 seed weight was measured using (AND HR-300*i*), from each plot. Data was analyzed based on statistical package SAS version 9.4 and the means were compared using Duncan Multiple Range Test.

RESULTS

There were some differences on meteorological observations between 2012 to 2013 and 2013 to 2014 crop seasons (Table 1). The 2012 to 2013 season experienced and average rainfall of 334 mm much less than the 30 year average and temperature of 22.8°C. (Table 1). Only December month received more than 100 mm of rainfall, therefore most field crops in the country failed to produce yield. The 2013 to 2014 season received an average rainfall of 467 mm and an average temperature of 21.9°C (Table 1).

Low genetic variation was observed for 100 seed weight, shoot dry weight, seed yield, crop loss, plant population and plant height among the nine genotypes (Table 2). The average 100 seed weight was relatively low at 7.74 g and a low average seed yield of 136.4 kg/ha, attributed possibly to low rainfall received in both seasons (Table 1). However, E105, GK011 and GK013 produced seed weight of more than 8 g, while E70 produced the highest seed yield of 181.57 kg/ha, within the two seasons.

Early planting (December) in the first season (2012 to 2013), increased 100 seed weight, shoot dry weight, seed yield, plant population and plant height compared to the January planting. While the intermediate (January) planting led to higher crop loss at 64% and reduction in all the selected characters (Table 3). Late planted crops in February did not yield any results; therefore, it is strongly discouraged to grow crops late, when the rainfall is below normal as it was received in 2012 to 2013 season. Some contrasting results were observed in the second season (2013 to 2014), since early planting in December led to a reduction in 100 seed weight, shoot dry weight, seed yield, and plant population as compared to the crops planted in January (Table 3). However, crop losses between the early and the intermediate planted crops were not significantly different in the 2013 to 2014 season. Higher crop losses at 77% were observed in the late planted crops, which led to significantly lower 100 seed weight, shoot dry weight, seed yield and also plant height. In the second season of planting significantly taller plants were identified in the intermediate sowing date and this lead to relatively higher yields 679 kg/ha (Table 3).

A combination of the three planting dates averaged over two years indicated that December and January planting are not significantly different in terms of 100 seed weight and shoot dry weight (Table 4). Early planted crops were not significantly different from the late planted crops for seed yield, crops lost and plant population. The yield realized for these two seasons were relatively low, early planting and late plantings were not significantly different because both plantings had significantly lower plant populations. Poor germination occurred in the early planting and late plantings possibly because the crop received low moisture and the heat dried up the seedlings. Even though January plantings overall seed yield are higher at 348 kg/ha, it could be because intermediate planted crops benefited from moisture received in December and some rains in February and March (Table 1). The January planted crops were also significantly taller than those planted early and late (Table 4).

The analysis of variance results for planting date,

Table 1. Rainfall and temperature recorded when growing tepary beans for two seasons (2012 – 2014) in Sebele Research Station, Gaborone, Botswana.

Months	Total rainfall (mm)		Average temp [°C]		Min temp [°C]		Max temp [°C]	
	2012-2013	2013-2014	2012-2013	2013-2014	2012-2013	2013-2014	2012-2013	2013-2014
October	25.0	32.3	22.9	23.2	22.2	14.7	23.6	31.7
November	37.6	75.9	25.6	25.9	25.0	17.8	26.2	34.3
December	157.0	115.3	23.6	23.5	23.1	18.9	24.1	28.9
January	52.4	46.2	25.2	25.0	24.6	18.9	25.8	32.1
February	22.8	58.3	25.8	23.7	25.1	18.4	26.6	30.2
March	13.8	122.9	24.0	21.2	23.3	16.8	24.7	27.1
April	25.0	15.3	19.8	17.7	19.0	10.4	20.6	26.3
May	0.0	0.7	15.9	15.3	15.0	5.7	16.8	25.5
Total Mean	**333.6**	**466.9**	**22.8**	**21.9**	**22.2**	**15.2**	**23.5**	**29.5**

Table 2. Effects of three planting date on the yield and related traits on tepary genotypes combined across two seasons 2012-13 and 2013-2014

Genotype	100-Seed Weight (g)	Shoot dry weight (g)	Seed yield (kg/ha)	Crop lost %	Plant population	Plant height (cm)
GK010	7.84	20.96	151.31	42	12444	30.9
E19	7.34	24.51	116.26	35	12370	30.5
E89	6.73	16.98	131.91	42	9481	32.8
GK012	7.51	17.59	140.04	35	13185	27.4
E105	8.19	21.43	167.64	37	12941	32.5
GK011	8.00	20.31	116.31	38	10148	27.5
E70	7.97	21.78	181.57	43	8815	27.7
GK013	8.23	21.7	104.63	41	10666	27.2
MOTSUMI	7.85	18.2	118.37	41	10353	31.2
Grand mean	**7.74**	**20.39**	**136.45**	**39**	**11150**	**29.6**

Table 3. Yield and related components of nine tepary beans planted on three planting dates in Sebele, Botswana in 2012-2013 and 2013-2014 seasons.

Seasons	100-Seed Weight (g)	Shoot dry weight (g)	Seed Yield (kg/ha)	Crop lost %	Plant population	Plant height (cm)
2012-13						
December	10.76^{a}	25.09^{a}	41.35^{a}	21.07^{b}	11950.00^{a}	39.35^{a}
January	8.34^{b}	11.56^{b}	16.49^{b}	64.52^{a}	11358.00^{b}	24.45^{b}
February	0^{c}	0^{c}	0^{c}	0^{c}	0^{c}	0^{c}
Mean	**6.37**	**12.22**	**19.28**	**28.53**	**7769.36**	**21.12**
2013-14						
December	8.74b	27.22b	68.47b	32.48b	3787c	34.12b
January	11.37a	45.59a	679.47a	39.19b	26962a	57.46a
February	7.22c	12.85c	13.33c	77.15a	12296b	20.74c
Mean	**9.11**	**28.55**	**253.61**	**50.03**	**14615.68**	**38.50**

Mean with the same letter(s) in a column are not significantly different at 5% level of significance according to Duncan's multiple range tests.

genotype and year and the interactions for the two seasons are presented in Table 5. The genotype effect was not significant for the six characters selected which is an indication of low genetic diversity among the nine

Table 4. Mean of yield and related components for the three planting dates averaged over nine tepary bean genotypes for two seasons in Sebele, Gaborone.

Planting dates	100 Seed Weight (g)	Shoot dry weight (g)	Seed Yield (kg/ha)	CropLost%	Plant Population	Plant height (cm)
December	9.76a	26.15a	54.91b	26.58b	8026b	36.92b
January	9.86a	28.57a	347.77a	51.85a	19160a	42.297a
February	3.61c	6.46b	6.67b	38.57b	6148b	9.542c
Grand mean	**7.74**	**20.38**	**136.44**	**39.15**	**11149.30**	**29.64**

Mean with the same letter(s) in a column are not significantly different at 5% level of significance according to Duncan's multiple range tests.

Table 5. Mean square analysis of variance for yield and related components for nine genotypes evaluated at three planting dates in Sebele in 2012-2013 and 2013-2014 crop season.

Source	DF	100 Seed Weight (g)	Shoot dry weight (g)	Seed Yield (kg/ha)	Crop Lost %	Plant Population	Plant height (cm)
Genotype	8	4.90	104.20	12186.91	204.46	43976974.00	8027.42
Day	2	690.624***	7972.123***	1840070.85***	8443.96***	2683946918***	1318775.143***
Day x Genotype	16	9.26	212.26	15325.02	418.35	34457322.00	8546.84
Year	1	304.496***	10812.014***	2224034.23***	17348.42***	1717160556***	944239.652***
Genotype x Year	8	8.68	123.65	14058.89	216.17	21340168.00	6964.72
Day x Year	2	289.24***	3556.28***	1857327.26***	36425.69***	2159039185***	441689.743***
Day x Genotype x Year	16	8.66	255.77	16368.07	166.76	47709638.00	5791.77
Rep	2	6.07	38.72	24909.74	1156.46	17555070.00	5698.68
R2		**0.673**	**0.634**	**0.841**	**0.758**	**0.743**	**0.87**
CV		45.08	75.14	99.56	49.37	59.89	30.89

***Significant at 0.001 level.

Table 6. Pearson correlation coefficient among the six traits based on nine tepary bean genotypes grown over three planting dates for two seasons 2012-13 and 2013-2014 in Sebele, Gaborone.

Correlation	100-Seed weight (g)	Shoot dry weight (g)	Seed Yield (kg/ha)	Crop Lost %	Plant population	Plant height (cm)
100 Seed Weight (g)	**1.000**					
Shoot dry weight (g)	0.606***	**1.000**				
Seed Yield (kg/ha)	0.37***	0.647***	**1.000**			
Crop Lost %	0.105	-0.108	-0.027	**1.000**		
Plant Population	0.573***	0.526***	0.623***	0.058	**1.000**	
Plant height (cm)	0.7***	0.783***	0.65***	0.139	0.628***	**1.000**

***Correlation is significant at 0.001 level.

cultivars. The genotype × planting date (G × E) was not significant which also imply the stability of the given cultivars in the three environments in the two seasons. However, planting dates and year, and also the interaction between planting date and year were highly significant (P>0.001) for all the selected characters (Table 5). The time of planting on the six selected characters for tepary beans production is very important. The two seasons were significantly different from each other as shown in Table 5 which reveals the contrasting environment experienced by the crops.

The pooled correlation matrix was highly significant (P< 0.001) among most characters (Table 6). The results illustrated that plant height had highly significant and positive association with shoot dry weight (0.783), 100 seed weight (0.70) and seed yield (0.65) demonstrating that these characters can be useful in selection for improving tepary bean productivity (Table 6). Some negative and non-significant associations were observed between crop lost to shoot biomass (-0.108) and seed yield (-0.027), indicating that as more crops are lost, there is a reduction in crop biomass and final seed yield (Tables 3 and 6).

DISCUSSION

Early planting (December), intermediate (January) and late (February) planting dates were utilized to evaluate nine tepary bean genotypes over two seasons. The seasons experienced below average rainfall, with 2012 to 2013 recorded as the driest period in Botswana in 13 years since 2001 (Agromet Update, 2012), while 2013 to 2014 was not considered a drought year (Statistics Botswana, 2015). Even though low rainfall were received in Sebele, tepary bean was able to produce some yields (136.45 kg/ha) (Table 2). Our results confirm previous observations by Jiri et al. (2017), that tepary bean can produce moderate yield under drought stress conditions, they recorded 245.9 kg/ha in the semi-arid environment of Zimbabwe. Under good soil moisture tepary bean has a potential to produce more than 2000 kg/ha (Thomas et al., 1983; Bhardwaj et al., 2002). Future work on the best sowing dates for tepary bean especially in wet years is encouraged since this study was conducted for two years in which they were drought and normal year. For subsistence farmers for the crop to be able to produce some yield in the presence of harsh conditions could be more important than the yield potential under favorable conditions (Porch et al., 2012).

Our results also indicated that when planting early in December more yields were realized, especially under normal rainfall in the 2012 to 2013 crop season. However, in relatively good year such as 2013 to 2014 crop season taller plant and higher yields were expressed in the intermediate planting in January (Table 3). Our findings are in agreement with those of other researchers who discovered that planting dates have a significant effect on yield and yield components of the crops. Similar findings were in observed in peanut in semi-arid environment of Turkey by Canavar and Kaynak (2008) and in cowpeas in the South Eastern Nigeria by Ezeaku et al. (2015), who found early planting to be higher yielding than late planted crops.

The genotype effect was not significant for the six characters selected which reveals low genetic diversity among the nine cultivars (Table 5). Limited diversity in tepary bean was also noted by Blair et al. (2012) and Gujaria-Verma et al. (2016) when using simple sequence repeats (SSR) and single-nucleotide polymorphism (SNP) markers, respectively. Their results suggested it could indicate that tepary bean may have arisen from a single domestication event that led to genetic bottle neck which limits diversity within domesticated cultivars. Our tepary bean were relatively small seeded at 7.74 g (Table 4), compared with those of mean 14.5 g observed by Bhardwaj et al. (2002), possibly because the genotypes they used consisted of more variation such as tan coloured seeds, which are bigger than cream coloured seed found in Botswana. However, small seed size were found to have an added advantage of grain filling and producing higher number of seeds, with less abortion which occurs during drought stress as discovered in a close relative in common bean (Rao et al., 2013).

Genotype × environment interaction is varying responses of cultivars for particular characters in different environments. In this study, genotype × planting date interaction was not significant among the six characters which imply that the genotypes are relatively stable (Table 5), and stable genotypes are useful in the risky varied environments. It is therefore important to have stable performing genotypes across environments to realize higher seed yields (Nath et al., 2013). Lack of cultivar × planting dates interaction in yield was reported in bambara groundnut by Makanda et al. (2009), which they associated with the crop adaptability to the four planting dates. In tepary bean (Bhardwaj et al., 2002) found lack of genotype × environment in seed yield and harvest index which indicates that these characters were stable among the planting dates observed. Even though there is vast difference between the dates, year, and date × year interaction, lack of genotype × environment in all the characters indicates that selection of these traits could therefore be conducted either during the early or intermediate planting dates with similar effects. However, Shiringani and Shemilis (2011), noted that multi-location evaluation of genotypes could reveal genotype × environment better compared to when conducting the study in one location like in our case.

Correlation analyses give a measure of relationship between traits and assist in identifying useful traits in increasing yield. Plant height had significant and positive correlation with most characters such as shoot dry weight, seed weight, and seed yield (Table 6). Selection of relatively taller plant would lead to a significant increase in yield and yield related traits of tepary bean. Bashir et al. (2001), when studying correlation of economically important traits in forage crops cowpea, lab and rice bean discovered that plant height have a significant correlation with pod length, 100 seed weight, straw yield and total dry weight, and argued that it is an important character that maybe exploited to improve production of these forage legumes species.

Conclusions

In conclusions, the purpose of this paper was to identify suitable planting date for sowing tepary bean in Botswana. Although specific dates are not mentioned, the study managed to reveal that different planting dates affected the yield and agronomic characters of tepary bean genotypes. Sowing dates for December and January are identified as options for tepary bean farmers in southern part of Botswana. The fact that some yields were realized under severe drought environment identifies tepary bean as a climate smart crop suitable for production in the semi-arid environment of Botswana. Our study also buttresses the need for good meteorological forecast for farmers to make informed decisions before planting.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Soybean hull and/or white oat grain for steers finished in feedlot

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The aim of this study is to evaluate the performance of feedlot finished steers receiving grain oat and/or soybean hull in their diet. Thirty six Nellore crossbred with Charolais steers, that received diet with concentrate ratio of 50:50 in all diets independently of the treatment, with sorghum silage as forage and concentrate according to the proposed treatment: soybean hull, oat grain and a mixed concentrate with these ingredients (50% of each as energy concentrate), were used. The experimental design was randomized blocks, the data was subjected to analysis of variance and F test using PROC GLM and means were compared by Student's "t", α = 0.05 probability test. Significant difference was not observed between the treatments for daily gain in live weight of the animals tested. The dry matter intake was not altered by neutral detergent fiber content in this study. Both soybean hulls as the oat grain, had similar performance in feedlot finished steers.

Key words: *Avena sativa*, consumption, feed conversion, weight gain.

INTRODUCTION

The rearing of cattle for meat production in Brazil occurs predominantly on native and cultivated pastures (ANUALPEC, 2016), with slaughtering being carried out at specific times during the year, causing fluctuations in prices for producers and consumers due to differences in market offers. Thus, there is harvest season and off-season of beef. The feedlot is an alternative, where animals can be finished at specific periods during the year, allowing the producer to obtain differentiated gains in the commercialization of the animals for the slaughterhouses. It should be noted that Brazil can have production stability to meet the external market where, today, it has a privileged place among the three countries that export the highest beef in the world (ANUALPEC, 2016).

When confinement is used in the finishing of cattle, attention should be paid on the formulation and choice of ingredients used in the diets so that there is no financial loss to the producer, due to the production cost or the low performance of the animals. According to Pacheco et al.

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(2006), feeding is responsible for approximately 73.9% of the total feedlot cost, excluding the value of the animals, with the concentrated fraction of the diet being the most costly.

The increase of soybean production in Brazil (114.9 million tons, 2016/17 crop, IBGE, 2017), mainly for export, and in the second plan, the production of vegetable oil to replace animal fat for human consumption as well as the production of biofuels in Brazil, has led to obtaining by-products available from market for use in confinement. Among these by-products, are the soybean meal and the soybean hulls, which are removed for the extraction of vegetable oil in the Brazilian industry. For each ton of processed soy, about 20 kg is processed into soybean hull (Zambom et al., 2001).

In Rio Grande do Sul, besides this national tendency to increase the areas intended for soybean cultivation, there is an increase in the production of winter grains that are used in the rotation of crops mainly by the increase of the layer of straw on the ground. White oats (*Avena sativa* L.) are an example of the crops preferred by producers. In the 2016 cropping season, 227 thousand hectares were cultivated (IBGE, 2017) due to lower production costs in winter crops.

In relation to the formulation of diets, the producer or technician must provide the maximum consumption of the animals, which is closely related to the performance of the animals, and reducing these factors interfere with the consumption. Among these factors, the neutral detergent fiber content (NDF) of the feed or diet should be less than 55% (Van Soest, 1994). According to Kozloski (2011), besides the regulation of consumption, the animal can still have its performance altered by feed constituents, which reduce the degradation of feed by ruminal bacteria. In this case, the lignin that constitutes a physical barrier, diminishing and/or hindering the degradation of the feed by the ruminal bacteria can be mentioned.

Results of animal performance were verified in the literature where the soybean hulls were replaced by other ingredients such as grain of sorghum (Restle et al., 2004) and maize (Mendes et al., 2006). Restle et al. (2004) working with diets with 40% concentrate, replacing grain sorghum with soybean hulls, concluded that soybean hulls promoted better weight gain in animals, with a treatment of 0% substitution 1,040 kg/day and 100% to 1.208 kg/day. Earlier, Faturi et al. (2003) providing 38% of black oats in the diet, obtained feed conversion of 9.2 kg of dry matter per kg of live weight gain and digestible energy conversion of 25 Mcal/kg of body weight gain.

Therefore, this study was carried out with the objective of evaluating the performance of beef cattle using soybean hulls and/or white oat grain to clarify the potential of these ingredients in the finishing of steers in feedlot.

MATERIALS AND METHODS

The experiment was carried out at the Cattle Breeding Laboratory of the Animal Science Department of the Federal University of Santa Maria, located in the State of Rio Grande do Sul, Brazil, at an average altitude of 95 m, at 29° 43' south latitude and 53° 42' west longitude. Thirty six steers, from a continuous alternating cross-breeding of two races (Charolais-Nellore) of the experimental herd at the laboratory, with age and average initial weights of 20 months and 226 kg of body weight (BW), respectively, were used.

The finishing of the animals was done in semi-covered confinement (50%) with boxes of 20 m² of area paved, provided with feeders for the supply of feed and drinkers with water at will, regulated with float faucet. Treatments were randomly distributed, with two steers in each box. Before the experimental period, the animals were adapted to the facilities and the diets for 28 days. In this period, the control of endoparasites and ectoparasites was performed with subcutaneous application of ivermectin based product (concentration of 1%), in a dosage recommended by the manufacturer. The steers were divided into three treatments denominated according to the diet to be tested, maintaining a roughage concentrate ratio of 50:50. The sorghum silage (*Sorghum bicolor* L. Moench) was used for all the treatments (forage) and the concentrate fraction contained soybean hull and/or white oat grain, soybean meal, urea, calcitic limestone and common salt. The treatments evaluated were: Soybean hull (concentrate containing as energy base, soybean hull); white oat grain (concentrate containing as energetic base, white oats grain); and mixture (concentrate containing as energy base, in equal parts, soybean hulls and white oats grain).

The diet was calculated according to NRC (2001), aiming at daily gain of 1.20 kg/animal, estimating a dry matter intake of 2.55 kg/100 kg of body weight and establishing isonitrogenated diet. The bromatological composition of the ingredients used to prepare the experimental diets is shown in Table 1.

During the experimental period, the animals were fed twice a day, in the morning at 8 h and in the afternoon at 14 h, and daily, before the first feeding, the leftovers from the previous day were collected and recorded in a spreadsheet, to adjust the consumption of the animals. The forage was supplied in the feeder at the same time with the concentrate in a mixed diet. Voluntary consumption of the diet was recorded daily, the amount of feed offered and the leftovers from the previous day were weighed. The feed supply was pre-established between 50 and 100 g/kg higher than voluntary consumption (Faturi et al., 2006) and regulated according to the consumption of the animals the previous day.

The daily gain of body weight (ADG) of the animals was obtained by the weight difference between weightings, divided by the number of days of the interval (final – initial), the weightings preceded by fasting of solids and liquids for 14 h. Body condition score (BCS) was determined by scores of 1 to 5 points, attributed by visual observation, where: 1 = very thin; 2 = lean; 3 = medium; 4 = fat; and 5 = very fat (Machado et al., 2008). The BCS was assigned by the same evaluators (three) throughout the study, and the final weight was averaged between the three observations for each animal. The gain of BCS was verified by the difference between the initial and final body state of the experiment. The animals were sent to slaughter when they presented finishing standards according to the regional market (BCS between 3.30 and 3.70 points), being sent in two lots with equal numbers of animals in each treatment. The termination time was 129 days for the first group and 136 days for the second group.

The diet ingredients and the leftover feed samples were taken three times a week, and well homogenized for better sampling. These samples were pre-dried in a forced air drying oven at a temperature of 55°C for 72 h and afterwards milled in a Willey type mill with a sieve of 1 mm and packed in plastic bags free of air for further chemical analysis. The dry matter content was determined by oven drying at 105°C until constant weight (Table 2) and ashes by calcining in muffle at 550°C until constant weight. The organic matter content was calculated by reducing the dry matter value by

Table 1. Chemical composition of the ingredients used for preparation of the diets.

Levels, % of DM	Sorghum silage	Soybean		White oat grain	Limestone	Urea
		Meal	Grain hull			
DM[1]	31.564	90.816	88.713	91.759	100.00	-
OM	94.976	93.412	95.693	97.303	73.67	-
MM	5.024	6.588	4.307	2.697	36.33	-
CP	4.611	51.136	11.916	11.999	-	281.25
EE	1.817	2.223	0.634	5.449	-	-
ADF	42.855	11.720	52.751	13.171	-	-
NDF	68.567	14.224	72.266	28.881	-	-
NIDN	0.242	0.398	0.778	0.097	-	-
ADIN	0.156	0.220	0.103	0.045	-	-
LDA	5.666	0.208	0.918	2.966	-	-
TDN	56.666	82.147	66.283	80.208	-	-
IVDOM	-	-	91.500	76.400	-	-

[1]g/kg of green matter; -values not determined; DM = dry matter; OM = organic matter; MM = mineral matter; CP = crude protein; EE = ether extract; ADF = acid detergent fiber; NDF = neutral detergent fiber; NDIN = neutral detergent insoluble nitrogen; ADIN = acid detergent insoluble nitrogen; LDA = lignin; TDN = total digestible nutrients; IVDOM = *in vitro* digestibility of MO.

Table 2. Ingredients for green matter and chemical composition of dry matter of the offered diets.

Ingredients of the concentrate (%)	Treatments		
	Soybean hulls	Mixture	White oat grain
White oat grain	-	42.195	81.178
Soybean hulls	86.006	42.195	-
Soybean meal	12.864	13.733	16.284
Limestone	0.047	0.982	1.800
Urea	1.083	0.895	0.738
Chemical composition			
Dry matter, %	60.430	61.126	61.778
Crude Protein, %	12.464	12.225	12.419
Ether extract, %	1.327	2.360	3.299
Mineral matter, %	4.812	4.973	5.115
Acid detergent fiber, %	44.782	35.964	27.717
Neutral detergent fiber, %	66.115	56.388	47.145
Neutral detergent insoluble nitrogen, %	0.440	0.310	0.188
Lignin, %	3.242	3.674	4.055
Total digestible nutrients, %	62.648	65.029	67.725
Digestive energy, Mcal/kg dry matter	2.804	2.914	3.040

the ash value. The total nitrogen content was determined by the Kjeldahl method (AOAC, 1995), modified by using a 4% w/v boric acid solution as the free ammonium receptor during distillation, a 0.2% w/v solution of bromocresol green and 0.1% w/v methyl red as indicator, and a standard solution of sulfuric acid for titration. The ethereal extract content was determined after treating the samples with ether, under reflux, at 180°C for 2 h. The levels of neutral detergent fiber, acid detergent fiber and acid detergent lignin were determined according to Van Soest et al. (1991); and the levels of soluble nitrogen, nitrogen insoluble in neutral detergent and acid detergent insoluble nitrogen according to Licitra et al. (1996). The total digestible nutrient content was analyzed according to Weiss et al. (1992). The digestible energy was calculated according to NRC (2001), in which 1 kg of total digestible nutrients = 4.4 Mcal of digestible energy. *In vitro* degradability of the organic matter of soybean hulls and white oats grain was carried out in the laboratory of the National Institute of Agricultural Technology - Animal Experimental Station - Concepción del Uruguay - Entre Rios (Argentina).

Experimental design and statistical analysis

The experimental design was a randomized block design with three treatments and six replicates, the box being the experimental unit. The animals were blocked by genetic predominance and balanced by fasting initial body weight (solid and liquid) of 14 h between treatments. The data were tested for homogeneity of variance with Levene test and normality using the Shapiro-Wilk test with $\alpha = 0.05$. The following transformations were used to achieve data normality: values exponentiated for final weight, initial body condition and mean body weight score, squared values for feed conversion (kg dry weight/kg live weight), log for conversion feed (% body weight) and total dry matter intake from the termination. After that, data were also submitted to analysis of variance and F test using PROC GLM and means comparison using Student's t-test considering α = 0.05 probability. The mathematical model for all variables was as follows:

$$Y_{ij} = \mu + \beta_i + T_j + (\beta^*T)_{ij} + \varepsilon_{ij},$$

Where, Y_{ij} = response variable value in i^{th} block and j^{th} treatment; μ = general mean of all observations; β_i = effect of the i^{th} block corresponding to the racial predominance of the animal with i = 2; T_j = the effect of the j^{th} treatment with j = 3; $(\beta^*T)_{ij}$ = effect of the interaction between the i^{th} block and the j^{th} treatment; ε_{ij} = residual random error.

Statistical Analysis System SAS 9.2 (Statistical Analysis System, 2009) was used for analysis.

RESULTS AND DISCUSSION

In the study, interaction between treatment and genetic predominance was not observed (Table 3) and results are discussed in relation to treatments. Animals at the beginning of the experimental period presented no significant difference for body weight (BW) and initial body condition score (IBCS) between treatments (Table 3). Final BW and BCS also did not present statistical difference between treatments, since the animals were slaughtered according to finishing of the carcass. In this way, it can also be observed that the gain of BCS of the animals in the different treatments was similar.

Daily gain of body weight (ADG) for the animals did not differ between treatments, presenting range of 109 g or 11.6% between the ends of values of ADG between the treatment mixture and treatment of white oats grain. Soybean hulls can be used to substitute up to 50% of the corn grain in the concentrated fraction of the diet, according to Mendes et al. (2005a) because it does not influence animal performance and carcass characteristics in confined steers, making the decision on the choice of ingredients to be based on economic criteria. Conversion of steers did not differ in the present study, ranging from 7.5 TO 8.2 kg DM/kg BW.

The soybean hull fraction presents neutral detergent fiber (NDF) values (Table 1) which may decrease the feed consumption of the animals. According to Van Soest (1994), the dry matter intake (DMI) is directly related to the NDF content of the food and the diets, since the fermentation and the passage of this fraction through the reticulum-rumen are slower than those of other dietary constituents, presenting great effect on filling and the remaining feed.

When the NDF content present in the diets consumed by the animals was observed (Table 2), it was verified that only the treatment of the soybean hulls showed greater presence in the diet. This occurred because the ingredient, white oat grain had lower NDF value in relation to the soybean hull (Table 1). The DMI was not altered by the NDF content in this study (Table 3), showing that the use of soybean hull did not influence feed consumption by the physical regulation of the digestive tract which is caused by the NDF content in the diet.

According to Faturi et al. (2006), other factors can influence feed consumption of the animals, that is, digestibility, fermentation products, microbial synthesis efficiency, ability to modify pH and degradation rate of energy and protein. Restle et al. (2004) also considered that it is necessary to evaluate factors such as digestibility and degradation and passage rates of NDF present in the animals' diet, since in their study, they did not observe the influence of NDF on consumption.

The white oats grain used had higher lignin content as compared to soybean hulls (Table 1), but when analyzing the diet consumed by the animals, this lignin content did not show much variation among the treatments (Table 2). Lignin is quite resistant to both chemical and biological degradation, (Hatfield and Fukushima, 2005), preventing nutrients from reaching the ruminal microbiota. It belongs to the diverse class of phenolic compounds, a non-carbohydrate of high molecular weight (Li et al., 2008).

The white oat grain did not influence the feed consumption of the animals, and in this work, it was supplied without any processing to reduce the particles in the diet. As there was no difference in the DMI between treatments (Table 3), the result of the fibrous fraction consumed was a result of the concentration in which each fraction was offered in the diet, in relation to leftover feed. All treatments differed (Table 3) for NDF intake (NDFI), where the largest fraction of NDF consumed, was from the soybean hull treatment (1.60% BW), followed by the treatment mixture (1.42% BW) and finally the treatment of white oats grain (1.16% BW).

In the present study, it was observed that the treatment of white oat grain presented NDF consumption of 1.16% of the BW consuming diet with 45.8% NDF. However, it was observed that when the soybean hulls were used in the diet, the consumption of NDF became 1,597% of the BW, a high value, which corresponds to 62.01% of the diet consumed. The higher *in vitro* organic matter degradability of soybean hulls (91.5%) as compared to white oats grain (76.4%) may have provided greater ingestive capacity of the diet offered during the first 72 h, even white oat grain presented higher digestibility in the first 24 h in the laboratory (67.9 vs. 53.5%). According to Müller and Prado (2004), the NDF fraction is rich in pectin, a highly degradable carbohydrate. However, when compared with starch, it does not produce lactic acid, promoting a stable fermentation pattern, similar to

Table 3. Mean weight and body condition scores (BCS), initial and final, daily body weight gain (ADG), total gain in body condition score (TBCS), feed conversion (FC), dry matter intake (DMI), crude protein intake (CPI), neutral detergent fiber intake (NDFI), acid detergent fiber intake (ADFI), ether extract intake (EEI) and digestible energy intake (DEI) of steers fed different types of concentrated feedlot.

Variable	Crossbreed		Treatment			Standard deviation	Efect		
	CH	NE	SH	SH/OG	OG		CB	T	CB x T
Initial weight, kg	230	222	228	224	226	27	0.5737	0.9606	0.9821
Final weight, kg	378	335	354	363	351	31	0.0117	0.7309	0.8366
ADG, kg/day	1.107	0.861	0.952	1.054	0.945	0.125	0.0013	0.2754	0.7830
IBCS, points	2.47	2.57	2.55	2.53	2.47	0.080	0.0224	0.2067	0.7393
FBCS, points	3.46	3.60	3.60	3.57	3.42	0.210	0.1920	0.3519	0.7618
TBCS, points	0.99	1.03	1.05	1.03	0.96	0.170	0.6374	0.6321	0.7299
FC, kg DM/kg BW	7.453	8.417	8.040	7.564	8.203	1.049	0.0751	0.5640	0.8862
DMI, % BW	2.69	2.57	2.58	2.69	2.62	0.100	0.0314	0.2135	0.9259
CPI, % BW	0.32	0.30	0.30	0.31	0.31	0.010	0.0328	0.0770	0.9405
NDFI, % BW	1.42	1.36	1.60[a]	1.42[b]	1.16[c]	0.055	0.0273	<0.0001	0.7863
ADFI, % BW	0.91	0.87	1.08[a]	0.90[b]	0.68[c]	0.035	0.0263	<0.0001	0.7313
EEI, % BW	0.06	0.06	0.03[c]	0.06[b]	0.08[a]	0.002	0.0881	<0.0001	0.9094
DEI, Mcal/% BW	7.95	7.65	7.34[b]	7.96[a]	8.11[a]	0.270	0.0335	0.0008	0.9600

CB = Crossbreed (CH = Charolais; NE = Nellore); T = treatment (SH = soybean hull; OG = white oat grain). [a, b, c]Mean of significant differences with the of Student “t” test (P <0.05) have different letters in the same line.

forages and decreases the incidence of ruminal and metabolic disorders. Pectin from soybean hulls corresponds to 62.4% of non-fibrous carbohydrates, equivalent to 8.8% of the DM (NRC, 2001).

In the study of Faturi et al. (2006), the relationship between diets with soluble fiber and starch as carbohydrate sources in cattle production, showed NDF consumption of 1.27% of BW which could be the limiting factor of ruminal distension in animals fed 48% NDF. The same authors concluded that in diets with high content of NDF, soluble fiber promoted a better performance of steers than the starch of low degradability. The difference may be related to the higher digestibility of DM and NDF of diets with higher soluble fiber content than those with higher starch content. Thus, it can be deduced that the best digestibility of diets with high soluble fiber content is related to the ability to maintain higher ruminal pH in comparison with diets containing high starch content (Bomfim, 2003).

According to Mendes et al. (2005b), the higher amount of fiber in the diet containing soybean hull as compared to maize did not affect the food consumption of the animals, as in this study, as compared to the white oats grain, possibly due to the higher digestibility of its fiber in acid detergent (ADF) or the rate of passage of this ingredient. The digestibility of fractions ADF and NDF were higher, respectively 33.8 and 11.2%, for the diet with soybean hulls when compared with the corn diet (Mendes et al., 2005b).

The ruminal apparent digestibility of the crude protein (CP) is the closest to zero, meaning that there is a synchrony between energy and protein available for ruminal microbial growth (Mendes et al., 2005b). The fibrous fraction and ethereal extract (EE) content were also determined by the concentration in the diet of the animals, since there was no difference in the DMI among the treatments studied.

The digestible energy consumed (Table 3), expressed in absolute values per day, was similar among the treatments, but when expressed in values related to BW, it was observed that the consumption of the soybean hull treatment was lower than the treatments (mixture and white oats grain), which showed no difference between them. This result may be related to the total digestible nutrient (TDN) content of the diets that were different from each other (Table 2).

Different values of TDN should provide different performances (Ezequiel et al., 2006a), but when using coproducts it may not occur, leading to serious questions about the nutritional components analyzed to obtain the TDN. Probably, other components of fibrous origin, such as soluble fiber (Faturi et al., 2006; Ezequiel and Galati, 2005), are part of these ingredients that may favor microbial growth in the ruminal environment. Thus, the soluble fraction of the fiber that has nutritional value would not be part of the TDN, explaining its underestimation. Still, according to Ezequiel et al. (2006b), this fact seems to be aggravated by the conventional methodologies of analysis, which are not able to determine these differentiated fractions and are present in the co-products of agroindustry.

There was no difference in the protein efficiency (Table 4) of the animals in relation to the treatments studied. According to Sujak et al. (2006), oat protein is a good

Table 4. Protein efficiency, neutral detergent fiber (NDF), acid (ADF), lipid (EE) and energy of steers fed different types of concentrates in a feedlot.

Efficiency, kg BW/kg	Crossbreed		Treatment			Standart Deviation	Efect		
	CH	NE	SH	SH/OG	OG		CB	T	CB x T
Protein	1.164	1.009	1.079	1.141	1.039	0.137	0.0344	0.4573	0.9421
NDF	0.262	0.230	0.204[b]	0.252[a]	0.282[a]	0.034	0.0625	0.0055	0.9999
ADF	0.418	0.367	0.301[c]	0.396[b]	0.481[a]	0.056	0.0758	0.0005	0.9951
Lipid (EE)	6.939	5.987	9.690[a]	5.836[b]	3.864[c]	0.756	0.0203	<0.0001	0.4324
Energy (Mcal)	0.185	0.164	0.098[c]	0.180[b]	0.245[a]	0.022	0.0689	<0.0001	0.9333

CB = Crossbreed (CH = Charolais; NE = Nellore); T = treatment (SH = soybean hull; OG = white oat grain). [a, b, c]Mean of significant differences with the Student "t" test (P <0.05) have different letters in the same line.

source of sulfur amino acids and, therefore, it should preferably be used in combination with legumes that are low in methionine and cysteine. In the present study, there was no difference between treatments in relation to feed consumption of animals in absolute values for both DM and CP. According to Mendes et al. (2005b), differences in dietary protein efficiency between treatments may be due to lower intake of DM and, consequently, lower intake of CP.

The treatment of white oat grain showed higher feed efficiency of ADF (Table 4) as compared to the treatment mixture, which in turn, was higher than the treatment of the soybean hulls. When the feed efficiency of NDF was compared, the treatment of white oats grain and the mixture were more efficient than the soybean hulls treatment. In the study of lipid efficiency, the treatment of soybean hulls was superior to the other treatments studied, which also differed, since it was able to provide the same ADG as the other treatments, with a lower content of EE in the diet.

These results demonstrate that the NDF of the soybean hulls treatment was important for the performance of the animals, providing similar ADG to the other treatments that used as body growth, the lipid fraction of the diet, as in the case of treatment with white oats grain.

Energy efficiency was different among the different energy sources evaluated. The treatment mixture was superior to the soybean hulls treatment, which in turn, was superior to that of the white oats grain. When expressing the energetic conversion in Mcal/kg of ADG, the following values: 22.73; 22.22 and 25.00, respectively were obtained for treatments of soybean hulls, mixture and white oats grain. Values similar to that of the treatment of white oat grain were observed by Faturi et al. (2003) when working with two-year-old steers finished in confinement, but fed with black oat grain ground in the concentrate, whose mean value is 25.0 Mcal/kg of ADG. In another study, Restle et al. (2009) found similar values for digestible energy conversion (25.6 Mcal/kg) when evaluating the processing of black oat grain to feed discard cows in feedlot.

With evaluation of the feed efficiency without discrimination by nutritional fractions, calculated DMI, showed ADG values of 0.126; 0.133 and 0.124 kg/kg DMI for the soybean hull, mixture and white oat grain treatments, respectively, demonstrating that there is a small variation of 7.26% between the excesses of the treatments studied, which are the white oats grain and mixture. Mean value of 0.140 kg ADG/kg DMI of feed efficiency was obtained by Marcondes et al. (2011) when evaluating the Nellore cattle feed efficiency (0.133 kg ADG/kg DMI), Nelore-Angus crossbred (0.128 kg ADG/kg DMI) and Nellore-Angus crossbred (0.128 kg ADG/kg DMI) that received 1 or 2% from concentrate in the diet.

Conclusion

The supply of soybean hull or white oat grain as the main energy source of the concentrated fraction in diet shows similar performance for finished steers in feedlot.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

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Rhizome development in *Sorghum bicolor* × *Sorghum halepense* families in the tropical ecosystem of Uganda

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Many landraces and improved cultivars of sorghum (*Sorghum bicolor*) grown in Uganda have late maturity and are susceptible to several biotic and abiotic stresses. Introgression of the rhizomatous trait from perennial sorghum (*Sorghum halepense*) could improve stress tolerance. However, phenotypic characterization of exotic perennial sorghum germplasm under Ugandan environmental conditions is essential to select desirable genotypes. Rhizome-forming capacity of 192 *S. bicolor* × *S. halepense* backcross tetraploid families developed in a temperate North American environment was evaluated at two locations in Uganda over two consecutive growing seasons. Numbers of rhizomes and emerging shoots as well as mean distances from shoot to crown were evaluated. Forty-seven percent of families were moderately to strongly rhizomatous in the first season of growth and this value rose to 91% in the second season. Developing perennial grain sorghum for East Africa will require hybridization between exotic perennial and locally adapted germplasm. Screening for emerging rhizome-derived shoots in early generations is simple, rapid, and effective; however, more detailed selection based on both aboveground and belowground rhizome traits is recommended for later generations. Researchers and farmers should work together to find suitable ways in which perennial sorghum might fit into new types of crop and livestock systems.

Key words: Rhizome, perennial sorghum, rhizome buds, ramets.

INTRODUCTION

In Uganda, sorghum [*Sorghum bicolor* (L.) Moench] is the third most important cereal crop after maize (*Zea mays* L.) and finger millet [*Eleusine coracana* (L.) Gaertn], occupying 285,000 ha (TECA, 1995). It is grown primarily in drier areas of eastern, northern, and southwestern Uganda. The climate in these regions of the country is characterized by frequent droughts and other problems related to water stress. Although sorghum is more drought tolerant than maize, its productivity can be greatly reduced by water stress. As with other annual crop species, sorghum production requires frequent cultivation of the land, accelerating soil erosion, and degradation.

Introducing genes that confer rhizome development

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Table 1. Description of the scores used in assessing rhizome production potential of *S. bicolor* × *S. halepense* germplasm in Uganda.

Rhizome score	Rhizome number	Rhizome production potential
0	0	Not rhizomatous
1	1-2	Very weakly rhizomatous
2	3-4	Weakly rhizomatous
3	5-6	Moderately rhizomatous
4	7-10	Strongly rhizomatous
5	Above 10	Very strongly rhizomatous

from the weedy perennial species *Sorghum halepense* L. into locally adapted grain sorghum cultivars could improve the stress resilience and sustainability of grain production in Uganda. Perennial rhizomatous sorghum plants can maintain extensive living root systems in the soil through several grain harvests, preserving soil structure and capturing water from infrequent rainfall events. Furthermore, the vigorous postharvest vegetative growth often seen in perennial sorghum can be a valuable source of forage to support livestock grazing that is often severely limited in East Africa. Development of tropically adapted perennial sorghum could create many of such opportunities for researchers and farmers to explore new and more sustainable crop and livestock systems in the region.

A collection of perennial sorghum breeding lines was introduced from the United States in order to characterize rhizome development in Uganda's tropical ecosystems and approaches need to be identified that accurately evaluate the potential of *S. bicolor* × *S. halepense* plants and families to produce rhizomes consistently in tropical environments where growth is continuous throughout the year. Rhizomatous lines could then be selected on the basis of such data for use as perennial parents in crosses with locally adapted annual *S. bicolor* cultivars. Thus, the objectives of this study were to investigate phenotypic evaluation methods and identify the most effective selection criteria for future introduction of the rhizome trait from *S. bicolor* × *S. halepense* lines into East Africa-adapted populations under tropical conditions.

MATERIALS AND METHODS

The experiment was conducted at two locations in Uganda representing different agro-ecological zones (Supplementary Figure 1). The National Semi-Arid Resources Research Institute (NaSARRI) in the eastern Lake Kyoga basin, Serere district is located on a plateau (1,140 m.a.s.l), at 1°32'N, 33°27'E, with a minimum temperature of 17°C and maximum temperature of 33°C. The area is relatively dry, receiving bimodal rainfall ranging from 800 to 1,150 mm. The Makerere University Agricultural Research Institute, Kabanyolo (MUARIK) in the Lake Victoria crescent, Wakiso district is located in a lowland (1200 m.a.s.l), at 0°28'N; 32°27'E, with a mean minimum temperature of 17°C and mean maximum temperature of 27°C (Charles, 1998). The area receives a mean annual bimodal rainfall of 1,270 mm.

The 192 experimental entries were produced in Kansas, USA, between 2002 and 2014 as part of a program to develop perennial sorghum as a grain crop (Nabukalu and Cox, 2016) (Supplementary Table 1). Entries included 115 BC_1F_2 tetraploid sorghum families from the cross BTx623 (*S. bicolor*) × [BTx623 × Gypsum 9 (*S. halepense*)] and 77 tetraploid sorghum families derived from backcrossing *S. bicolor* inbred lines as recurrent parents with perennial plants that had been selected from a *S. bicolor* × *S. halepense* population developed by Piper and Kulakow (1994). Additionally, three induced tetraploid *S. bicolor* inbred lines, one U.S.-adapted diploid *S. bicolor* inbred line, and four Uganda-adapted diploid *S. bicolor* inbred lines were included as non-rhizomatous controls (Supplementary Table 1).

Experiments were planted at MUARIK and NaSARRI on April 22 through 25, 2015. Because of the large number of genotypes and the need to reduce experimental error, an alpha-lattice design was used. The experiment consisted of 2 replicates and 25 lattice blocks with 8 entries per block. Experimental plots measured 4.0 m^2 with 2 rows each 5 m long. Rows were spaced at 0.8 m apart and hills 0.5 m apart within the row. Two to three seeds were sown per hill with seedlings thinned to one plant per hill. Recommended agronomic practices were followed for sorghum at each location.

Experiments were conducted over two seasons. In Season 1 (April through August, 2015), the number of emerging rhizome-derived shoots per plant (referred to hereinafter as "Shoots") was recorded 130 days after planting at MUARIK and 140 days after planting at NaSARRI. New shoots were considered to have grown out of rhizomes when they emerged from the ground at least 5 cm from the crown. The distance from each emerging rhizome shoot to the crown from which the rhizome initiated (referred to hereinafter as "Spread") was also recorded. After grain harvest, three plants (20% of each family) were randomly selected from each plot and removed from the soil while ensuring that all rhizomes and rhizome-derived shoots remained intact. The total number of rhizomes, including very short ones growing out just below the crown, was recorded for each extracted plant as the trait "Rhizomes". The total number of rhizomes was used to categorize the different families into "rhizome production potential" (Table 1). Furthermore, the sum of Rhizomes and Shoots per plant was used as an index of rhizomatousness called "rhizomes plus shoots". Grain was also harvested and remaining aboveground biomass was removed and discarded on September 9, 2015 at MUARIK and September 17, 2015 at NaSARRI, marking the end of Season 1 and the beginning of season 2 (September through December, 2015). Plants were allowed to regrow and experiment management and data collection were carried out as described for Season 1. Shoots and spread data were collected 14 days after the completion of season 1 for the season 2 evaluation at MUARIK and 21 days at NaSARRI.

Data for the traits rhizomes, shoots, and spread were subjected to analysis of variance (ANOVA) to test for significance of entry effect, using the package JMP Version 11 (SAS Institute, Cary, NC, USA). Linear regression analysis was carried out to quantify

Table 2. Analyses of variance for number of rhizomes (Rhizomes), number of rhizome-derived shoots emerging (Shoots), and mean distance between emerging shoots and plant crown (Spread) in perennial sorghum experiments at two locations (MUARIK and NaSARRI) over two seasons (Season 1 and Season 2).

Source of variation	Degrees of freedom	Mean square		
		Rhizomes	Shoots	Spread
Season	1	2380.5**	1235.9**	2349.7**
Location	1	33.1*	526.9**	0.1
Season × Location	1	66.8**	26.7**	138.3**
Replicate (Season × Location)	4	272.4**	86.9**	50.7**
Replicate × Block (Season × Location)	192	13.4**	7.4**	7.1
Entry	1	19.3**	12.1**	11.7**
Season × Entry	197	7.5[a]	4.3[a]	6.3[a]
Location × Entry	197	7.3	3.8	6.9
Season × Location × Entry	196	6.7[a]	3.4[a]	5.8[a]
Error (Rhizomes)	567	6.4	-	-
Error (Shoots)	566	-	3.6	-
Error (Spread)	489	-	-	7.1

*Significant at the 0.05 level; **Significant at the 0.01 level; [a] Significance not tested.

Table 3. Mean numbers of rhizomes (Rhizomes), mean numbers of emerging shoots (Shoots) and mean distance from crown to shoots (Spread) over 194 sorghum families in two seasons at two locations in Uganda.

Trait	Location*	Season 1	Mean	Season 2
Rhizomes	NaSARRI	2.6		5.7
	MUARIK	2.8		5.0
Shoots	NaSARRI	3.0		5.1
	MUARIK	2.0		3.7
Spread	NaSARRI	8.0		10.1
	MUARIK	7.3		10.7

***Experimental locations at National Semi-Arid Resources Research Institute (NaSARRI) and Makerere University Agricultural Research Institute, Kabanyolo (MUARIK).

relationships between traits. Statistical analysis of season × entry and season × location × entry interactions was not tested, because it was not possible to randomize families spatially between seasons 1 and 2; therefore, the effect of season on a given family was confounded with any microenvironmental effects that might exist because of the family position in the field. To avoid such confounding, simulated selection and evaluation of selected families were practiced at different locations in different seasons. That is, 20% of families with the greatest rhizome development in season 1 at NaSARRI were selected and their mean was compared to the overall mean in season 2 at MUARIK and vice-versa.

RESULTS

Rhizomes, shoots, and spread showed similar patterns with highly significant variation among families (Table 2). For rhizomes and shoots, differences between overall means at the two locations and in the two seasons were highly significant, whereas family × location interactions were non-significant. At both locations, means over all families (Table 3) showed that plants produced more rhizomes and emerging shoots and greater rhizome spread in season 2 (the regrowth season) than in season 1. Mean numbers of rhizomes per plant across locations were 2.7 in season 1 and 5.4 in season 2. Corresponding means for emerging shoots were 2.5 and 4.4, respectively.

Across-location means for rhizomes and shoots were strongly correlated in season 1 (r=0.81, P<0.0001) and season 2 (r=0.67, P<0.0001). These two variables are structurally related, because a plant producing a larger number of rhizomes is more likely to also produce a large number of emerging shoots. “Rhizomes plus shoots index”, was correlated with spread, strongly in season 1 (r=0.65, P<0.0001) but less so in season 2 (r=0.34, P<0.001).

Rhizome-related variables were normally distributed in

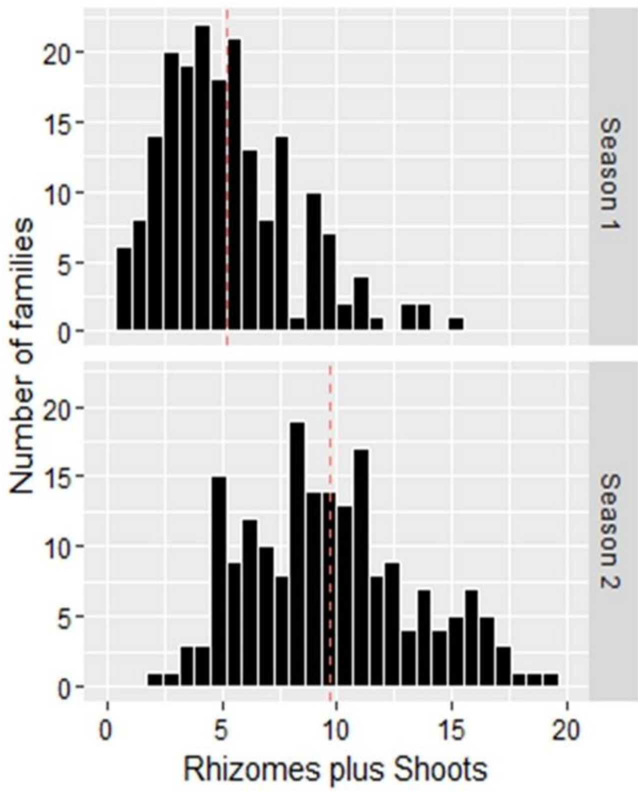

Figure 1. Frequency distributions for the index rhizomes plus shoots among 192 sorghum families in season 1 (top) and season 2 (bottom).

both seasons and across locations. The distribution of family means for the index rhizomes plus shoots (Figure 1) emphasizes the greater rhizome production that occurred in the regrowth season. In season 1, only 6% of families were very strongly rhizomatous with a mean index exceeding 10, whereas the index exceeded 10 for 43% of families in season 2. In contrast, 47% of families were strongly rhizomatous in season 1, and that share rose to 91% in season 2, because many of the weakly rhizomatous plants did not survive and contribute data in season 2 (some weakly rhizomatous plants and the non-rhizomatous checks showed some survival by ratooning after season 1 harvest; however, the ratoon shoots were much less vigorous than the shoots produced by strongly rhizomatous plants).

The results of simulated selection (Table 4) were not symmetrical across locations. The 20% of families with the highest means for the index rhizomes plus shoots in season 1 at NaSARRI had a mean in season 2 at MUARIK that exceeded the experiment mean by 28%. On the other hand, the 20% most strongly rhizomatous families at MUARIK, as evaluated in season 1, did not differ from the experiment mean when evaluated at NaSARRI in season 2.

The trait shoots is strongly correlated with rhizomes plus shoots (r=0.94, P<0.0001). Simulated selection for shoots at NaSARRI increased the mean index rhizomes plus shoots by 25% at MUARIK, while selection at MUARIK increased the mean index at NaSARRI by 9%. Selection also resulted in significant increases in the single trait shoots as well (Table 4). Selection for an alternative index, that is, the sum of the two nondestructive traits shoots and spread resulted in similar significant increases but did not improve on the results of selecting for shoots only.

Families ranking among the top few for rhizome development varied from season to season. In season 1 at MUARIK, the entry S1383-1-R193 produced 14 rhizomes per plant, exceeding all other families; it was followed by entries X117-697-R2 and S1465-2-R02 with 13 shoots per plant (Supplementary Table 1). At NaSARRI, S1383-1-0-R396D-R193D, having the same pedigree as the top family at MUARIK, produced a mean of 24 rhizomes per plant; it was followed by entries S1655-R75A-R146B, S1781-R79S-R214B, S1760-R40, and X117-697-R3 (same pedigree as X117-697-R2) with 20, 19, 17 and 16 rhizome shoots per plant, respectively (Supplementary Table 2). In season 2 at MUARIK, S1265-1-0-R519 and S1312-6-R203A produced 21 rhizomes per plant, while X337, H6-143-4, and S1383-2-2-R121 (which shares a pedigree with the Season 1 top families) produced 19, 18, and 17 rhizomes per plant, respectively. At NaSARRI, S1474-1-dw5-R136 produced 24 rhizome shoots per plant. S1781-R79S-R214B, S1755-dw76-R73A, S1479-6-R61-R76B, X80-968-R3, and X163-RF4 produced 24 rhizome shoots per plant each.

DISCUSSION

In temperate ecosystems, perennial sorghum can survive over multiple seasons due to the presence of rhizomes that are able to overwinter, because of their depth and/or cold tolerance. The ability of rhizomes to survive deep in the soil through extended periods of low air temperatures (Washburn et al., 2013) suggests that they might also ensure survival through dry seasons or droughts at other times of the year in tropical environments (Whitmire, 2013). Most families did in fact display such survival in this study.

In tropical ecosystems, sorghum shows continuous growth over multiple seasons either through ratooning of annual sorghum or by producing rhizomes. Grain yield in the ratoon season is almost always lower than in the first season of growth (Duncan and Moss, 1987), and their survival and productivity depend on an adequate supply of soil moisture during the ratoon growing season. Because of the bimodal rainfall pattern in Uganda, ratoon cropping is rarely practiced. In contrast, plants growing from rhizomes rapidly produce new root systems independent of the parent plant and grow faster and

Table 4. Difference between mean shoots plus rhizomes or mean shoots of the selected 20% of families and the location mean at each location in season 2 when selection was for high values of shoots plus rhizomes, shoots, or shoots plus spread at the other location in season 1.

Trait selected in season 1	Destructive	Selection location	(Mean of selected – location mean) in season 2			
			Shoots plus rhizomes		Shoots	
			MUARIK	NaSARRI	MUARIK	NaSARRI
Shoots plus Rhizomes	Yes	NaSARRI	2.4**	-	1.2**	-
		MUARIK	-	0	-	0
Shoots	No	NaSARRI	2.2**	-	1.1**	-
		MUARIK	-	1*	-	0.3*
Shoots plus distance	No	NaSARRI	2.1**	-	1.2**	-
		MUARIK	-	1.5**	-	0.5*
Grand mean in season 2		-	8.7	10.8	3.7	5.1

*Significantly different from zero (P<0.05); **Significantly different from zero (P<0.01).

larger than those that emerge from aboveground nodes in the second-year, and the second-season grain yields have been shown to be similar to the first-season yields in the temperate zone (Cox and Nabukalu, 2016). If the first crop matures at the beginning of a dry season, some rhizomes can remain in the soil without sprouting until the end of the dry season and then establish a new crop quickly when the next rains begin (Washburn, 2012).

Environments at the two locations in the present study did have differential effects on simulated selection. Families with higher season 2 rhizome production at MUARIK could be predicted in part on the basis of season 1 rhizome production at NaSARRI, but the converse was not true. That is, MUARIK data were not effective in identifying families that were most highly rhizomatous at NaSARRI. This asymmetry between MUARIK and NaSARRI could be attributed to climatic differences and soil types between the two locations. NaSARRI is located within the semi-arid regions and experiences higher temperatures. It also has coarse/sandy soils, while MUARIK in the Lake Victoria crescent which is rain fed, experiences lower temperatures, is humid, has heavy loam soils. Thus, initial screening for rhizome production should be conducted at NaSARRI with further screening of selected genotypes at multiple locations.

Paterson et al. (1995), working in the warm temperate climate of southern Texas, assessed rhizomatousness using both rhizome-derived shoots and underground buds while Washburn et al. (2013) used aboveground shoots alone. Paterson et al. (1995) showed that the rhizome-derived shoot count is a viable measure of the rhizome potential, although higher precision was obtained when underground rhizomes were also considered. A question in tropical environments is whether selecting on the basis of shoot numbers alone will underestimate the capacity of some plants to be rhizomatous, considering that in the tropical environment, rhizomes can continue to grow throughout the year.

In the present study, many families had more rhizomes than they did emerging shoots. All such underground structures have the potential to germinate and produce new plants. The two traits rhizomes and shoots were strongly correlated with each other, so their sum was used as an index of rhizomatousness. For selection in large populations, however, the excavation required to evaluate rhizomes would entail much more effort and expense per family than would evaluating only shoots, and this could reduce the number of families that can be evaluated. It is also destructive. Although it could be possible to re-bury plants after counting rhizomes, their subsequent growth and development would at that point be seriously affected, and screening large numbers would also become doubly laborious. Counting green shoots that have emerged from rhizomes, on the other hand, is simple, rapid, and nondestructive. Data from this study suggest that selection based only on shoots will be as effective as that based on the sum of rhizomes and shoots. Furthermore, including the trait spread in an index with shoots did not improve the effectiveness of selection. All of this implies that the number of rhizome derived shoots can still be a reliable indicator of the potential of rhizome formation of a sorghum hybrid line as suggested by Washburn et al. (2013). It was concluded that with the germplasm pool and environments used in this study, season 1 selection based on shoots alone would be most efficient for choosing more strongly rhizomatous families to carry ahead for more extensive testing or for use as parents. However, in later stages of selection when numbers of plants and families have been reduced, a complete assessment using both aboveground and below ground rhizome traits would be optimum.

The correlation between total number of rhizomes and the distance of the rhizome from the crown was positive and strong. However, not all rhizome-derived shoots emerged from the ground at or beyond 5 cm from the crown. Many very short rhizomes with terminal shoots that would have emerged very close to the crown were observed in the present study (Nakasagga, 2017). In Kansas, the 5 cm threshold was used because very short, shallow rhizomes, like tillers, have no chance of surviving the freezing temperatures of winter, but our observations suggest that this threshold may be too high for tropical environments. However, reducing the threshold could result in some rhizome derived shoots being misclassified as tillers or tillers misclassified rhizome-derived shoots if the 5 cm criterion is used when recording numbers of rhizome-derived shoots based on aboveground observation. On the other hand, some shoots closer to the crown may be misclassified as rhizome-derived when they are actually tillers, especially if soil has been pushed up around the base of the plant during cultivation for weed control. These findings further highlight the need for including both underground rhizomes and aboveground shoots when screening reduced numbers of advanced lines or conducting basic research under tropical conditions. Standard breeding methods can improve perennial sorghum's adaptation and agronomic traits. If selection for those traits is practiced in the second (regrowth) season, the frequency of perennial plants in the population will be higher than in the first season, because the bulk of the regrowth will have come from perennial plants originating from rhizome shoots.

Consistent rhizomatousness and perenniality was expressed by many of the sorghum families in this study. Given this result, they appear to be no insurmountable obstacles to developing grain sorghum with a perennial growth habit in East Africa. However, as with any sorghum germplasm developed in high-latitude environments, it can be expected that introduced perennial sorghum germplasm will not be well adapted in other respects to the photoperiod, climatic conditions, soils, and plant diseases and insects of tropical Uganda. Successful deployment of perennial sorghum in East Africa will require extensive breeding efforts supported by research in genetics, physiology, pathology, and entomology. There are two reasons for this: (1) perennial sorghum is still a crop in the making derived from hybrids between a cultivated and a wild species and (2) at this time, the entire gene pool of perennial sorghum consists of germplasm adapted to the temperate zone. Therefore, parental lines of perennial sorghum will need to be hybridized with germplasm that is well adapted to tropical conditions in general and East Africa's local environments in particular, in order to produce diverse populations that can be selected for local adaptation to East African environments.

On-farm evaluation should be incorporated into research on perennial sorghum in East Africa from the beginning. By necessity, much of the breeding cycle will remain largely in the realm of the research station. But because adaptation traits, plant vigor, seed characteristics, and perenniality can be selected for visually with no reliance on costly infrastructure or technology, selection and progeny-testing of superior plants by people on their own farms must also be carried out.

In all the mentioned efforts, the vigorous postharvest vegetative growth of perennial sorghum can provide additional benefits in East African agriculture, where grazing potential after the end of the rainy season is often limited. Researchers and farmers should work together to find suitable ways in which perennial sorghum might fit into existing crop and livestock systems in the region and foster the development of new types of cropping systems.

Conclusion

Many sorghum families in this study had the capacity to form rhizomes as seen from the results; this therefore showed the potential of these breeding lines to express this trait in a tropical environment. However, selection of which traits to use in evaluation of the rhizomatousness of a family depends on the breeding objective. When screening large populations aboveground shoots is an appropriate measure, while after selections have been made both in aboveground and underground rhizomes should be considered.

Environments at the two locations in the present study did have differential effects on simulated selection. Families with higher season 2 rhizome production at MUARIK could be predicted in part on the basis of season 1 rhizome production at NaSARRI, but the converse was not true. Thus, initial screening for rhizome production should be conducted at NaSARRI with further screening of selected genotypes at multiple locations.

Given their ability to regenerate from vegetative structures, that is to say rhizomes, these materials are good for forage at this stage of the breeding cycle. However, development of grain sorghum will require rigorous selection to identify potential lines that are adaptable to a tropical environment and therefore viable for future use in rhizome introgression with the locally adapted cultivars at later stages of the breeding cycle.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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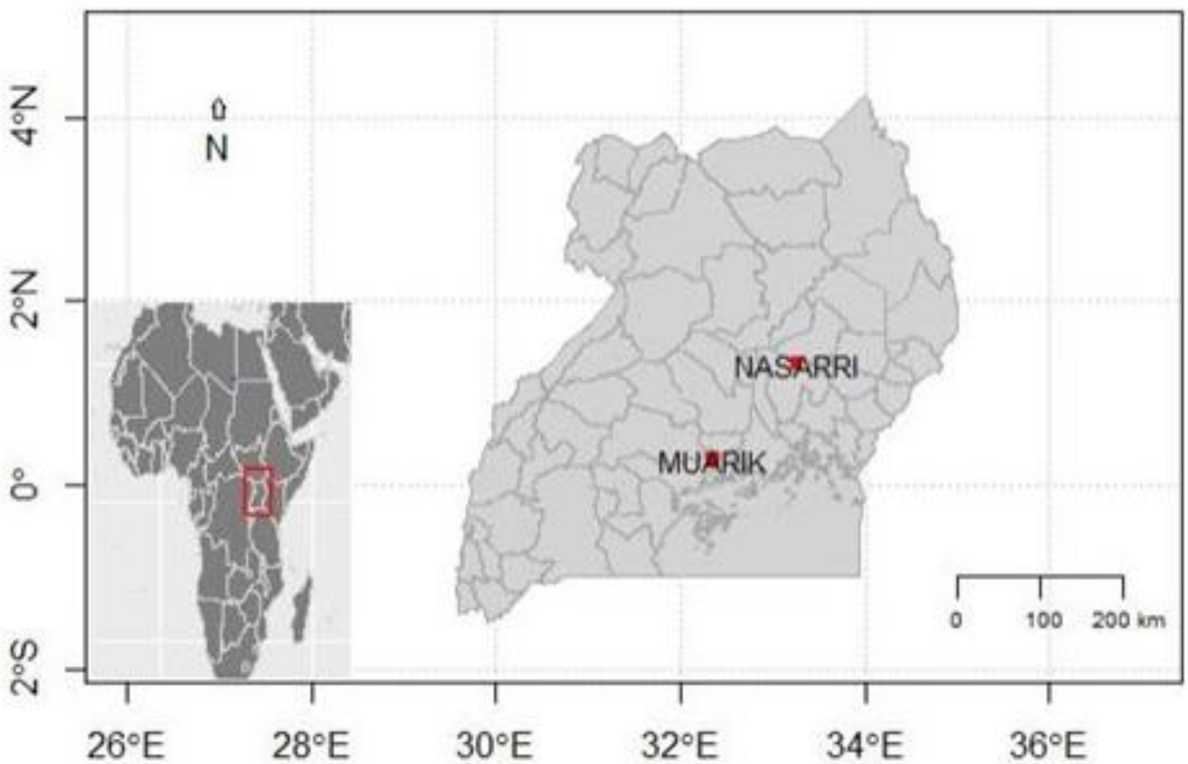

Supplementary Figure 1. Perennial sorghum experimental test sites based at National Semi-Arid Resources Research Institute (NaSARRI) and Makerere University Agricultural Research Institute, Kabanyolo (MUARIK) in Uganda.

Supplementary Table 1. Entry means for the rhizome production traits for *Sorghum bicolor* × *Sorghum halepense* families at MUARIK in two seasons in 2015.

Entry No.	Family	Season 1			Season 2		
		Rhizomes	Shoots	Spread	Rhizomes	Shoots	Spread
1	X423	3.9	0.6	4.6	4.6	3.1	6.9
2	X68	2	0.5	8	3.4	2.2	8.3
3	X615	5.9	1.8	8.4	8.4	3	11.6
4	X337	6.2	2	6	14	5.3	8.1
5	X105	1.9	0.5	9.1	2.5	1.5	6
6	X502	1	16	8.8	0.3	3.6	9.1
7	X606	1	0.2	6.9	1.5	1.4	11.2
8	X612	2.6	1.5	5.5	5.2	3.3	10.2
9	X108	2.2	2.9	6.2	3	2.8	9.9
10	X354	1.3	0.3	6.3	5.5	1.8	10.4
11	X114	3.7	3.4	6.9	6.4	5.3	14.2
12	X107	2	1.3	7.1	3.5	3	9.5
13	X503	1.5	0.2	5.2	5.9	2.6	8.2
14	X154	1.4	0.7	6.6	11.1	3.9	6.9
15	X47	4.7	1.3	6	11.1	3.9	9
16	X41	3.6	3	5.3	3	2.5	7.7
17	X24	3	1.2	6.1	7.7	2.7	9.5
18	X21	0.8	0.7	6	3.3	2.5	11.3
19	X209	2.6	2.1	7.3	7.7	4.7	11.6
20	X99	1.6	2.2	9	1.2	2.8	11.9

Supplementary Table 1. Contd

21	X410	3.8	0.7	6.7	1.8	0.8	7.2
22	TX623(2X)	-0.2	0.6	5.6	1.2	1	9.6
23	X38	2.2	0.8	4.1	5.3	4.7	12.4
24	X42	5.1	2.7	8.3	10.6	2.6	10.5
25	X76	3.4	1.9	8.7	3	3.3	8.3
26	X97	4.3	1.8	7	2.3	2.5	9.9
27	X104	1.8	1.9	5.7	3.7	1	7.7
28	X117	2.3	3.2	7	4.2	2.6	11.3
29	X406	4.1	2	10	6.9	3.3	10.2
30	X731	1.6	0.1	6.3	7.8	5.6	11.9
31	X756	1.2	1	6.3	8.5	2.8	7.4
32	X763	1.9	0.8	9.3	6.2	4.9	8.8
33	X770	2.1	2.2	10.2	3.6	2	9.7
34	X782	1	0.6	6.6	3.7	2.8	10.2
35	X803	1.6	2.8	6	3.9	3.6	13.1
36	X806	2.5	1.9	5.8	6.3	5.1	13.7
37	X1054	1.6	0.9	2.7	2.6	1.7	6.3
38	X1068	4.3	2	6.2	5.1	1.7	11.2
39	X1070	2.2	2.2	6.7	7.7	3.1	10.8
40	X312-290-R1	2.6	1.4	6.1	6.5	6.1	14.2
41	X202-RF4	2.2	0.9	4.7	6.5	8.8	13.6
42	X738-387-R3	3.2	2.4	6.6	4.9	4.4	8.9
43	X83 594 R4	0.7	0.5	11.5	5.4	3.7	10.4
44	X117-697-R2	6.6	6.1	7.5	9.9	5.3	15.9
45	X1076-18-R4	4.9	3	7.3	6.9	5.3	14.2
46	X803-1000-R3	0.4	0.3	5	2.3	2.3	10.1
47	X107-356-R3	1	1.4	6.2	1.8	1.8	11.1
48	X1090-195-R2	3.1	2.1	6.7	3.4	2.4	10.7
49	X1085-736-R4	6	3.3	7.3	4.9	3.4	10.6
50	S1465-2-R01	1.3	0.5	6.6	3.5	1.5	7.2
51	S1465-8-R16	2.6	1.8	6.7	0.9	1.2	17.3
52	S1475-1-R01	4.2	1.9	8	2.2	3.2	8.2
53	S1477-31-R52B	2.6	3.5	9	6.7	6.2	9.3
54	S1465-2-R02	9	3.9	12.7	9	8.2	12.7
55	S1467-1-R01	0.2	0.3	5.9	-1	-0.5	10
56	S1468-4-R17L	3.1	0.6	6.8	0.8	2.4	6.8
57	S1469-7-R21	4	3.1	7.9	5.5	6.7	11.1
58	S1474-2-R31A	2.7	4.4	7.1	6.9	5.8	12.6
59	S1479-1-R56A	3.5	2.3	6.5	3.9	3.6	11.8
60	S1479-3-R58B	1.4	1	7.5	5.7	3.7	11.5
61	S1646-R24A	1.1	0.9	6.1	1.4	0.2	6
62	S1653-3-R200	5.6	6.5	11.7	13.7	7	14.1
63	S1655-R75A	2.4	1.5	6.4	2.6	3.9	16.6
64	S1661-R32	3.2	3.8	7.3	8.6	4.7	12.1
65	S1662-R33A	4.3	2.9	9.5	7.5	6.7	10.8
66	S1686-R35A	4.4	2.6	7.3	4.2	6	12.3
67	S1708-1-R158	3.1	3.6	12.2	5.2	2.8	11.1
68	S1760-R40	4.6	3.8	9.5	10	3.9	13.4
69	S1761-R132A	1.9	0.8	7.2	1.1	0.1	10.7
70	X61-497-R4	1.2	1.1	7	1.9	2.8	8.9
71	X74-120-R3	2.4	4.4	7.2	3.1	3.3	9
72	X74-416-R4	3.3	3.8	5.9	8.7	3	8.9

Supplementary Table 1. Contd.

73	X127-412-R4	3.7	1.1	5.4	6.8	3.7	8.5
74	X129-588-R4	2.6	2.5	6.6	4.1	5.2	15
75	S1814-1-R220B	1.9	2.7	7	3.3	2.3	11.6
76	X151-511-R12	5.5	3.2	7.3	4.7	6.4	9.5
77	X151-511-R1	5	2.9	7.6	2.2	1.4	6.7
78	X151-511-R2	3.1	2	7.7	7.5	5.9	10
79	X151-511-R3	0.6	0.9	6.5	7.6	4.9	12.7
80	X151-511-R4	4.5	2.7	7.3	3.8	2.9	10.9
81	X174-453-R1	2.4	1.9	6.4	3.9	5.3	10.6
82	X413-077-1	3.5	2.8	8.8	3.4	10	13.7
83	X413-077-2	4.4	2	6	2.3	1.3	6.1
84	X413-077-3	2.8	1.2	9.2	6.2	3.5	11.7
85	S1836-1-R89A	1.8	3.4	6.5	2.8	2.5	10
86	X501-156-1	1.3	0.7	5.9	10.3	4.3	10.6
87	X501-156-3	0.9	0.8	5.7	2.9	1.3	13.9
88	S1931-2-R123C	5	3.2	6.7	11.2	4.1	12.5
89	S1939-2-R130	1.9	1.6	5.4	3.7	2.5	11.2
90	S1474>R84A	2.7	1.5	5.9	4.9	2.9	10.2
91	H6-70-8	5.7	1.5	5.5	1.5	2.1	9.8
92	H6-143-4	4.8	3.4	8	10.2	8.1	16.4
93	T321-157	2	1.7	6	5.9	0.4	7.7
94	S1265-1-0-R519	2.3	1.9	12.6	11.8	8.8	18.6
95	S1312-6-R203A	3	2.2	9.6	9.6	11.2	13.9
96	S1438-1-R193	4.5	3.8	9.6	5.9	8.3	14.7
97	TX403(4X)	2.4	1.4	7	1	1.5	8.8
98	D81-34	1.4	1.2	6.1	8.8	2.2	13.6
99	X756-299-R3	2.7	1.1	5.5	2.3	3	8.9
100	X42 987 R2	1.1	1	8.5	1.7	1.5	9.5
101	X148-300-R6	2.1	1.9	7.8	5.5	1.8	9.6
102	X782-560-R4	3.8	3.6	8.7	5	2.4	11.6
103	X107-559-R2	4.2	1.6	7	7.7	1.6	8.1
104	X1054-925-R5	0.6	0.3	5.6	3.8	3	10
105	X117-697-R3	3.3	2.9	6.5	6.9	5.6	10.2
106	X726-881-R4	1.5	1.8	6.7	6	1.3	11.9
107	X25 RF4	3.4	1.4	7.2	4.2	2.3	11.7
108	X163-RF4B	4.5	2.2	6	3.6	3.8	13.6
109	X782-560-R3	1.2	1.7	6.3	1.8	1.2	7.7
110	X731-230-R4	3.9	3.5	10.5	7.2	6.1	13.6
111	X1039-806-R4	3	1.8	6	3.8	3	12.3
112	X228-RF4	4.3	1	6.1	2.7	3.1	11.5
113	X770-829-R3	2.4	0.6	7.5	2.8	2.2	6.4
114	X3818 R4	1.8	1.5	4.7	3.6	5.1	13.1
115	X104-463-R5	1.7	0.9	4.8	4.8	2.2	8.6
116	X117-697-R4	2.6	1.1	6.4	0.9	1.5	8.1
117	X97 361 R3	3.3	2.3	8.7	4.3	3.5	8.3
118	X756-299-R4	0.7	1.5	6.8	-0.3	3	12.7
119	X999-RF4	0.7	0.5	6.3	6.9	3.9	10.7
120	X215-RF4A	4	2.4	5.7	8	6	11.2
121	X1070-470-R3	3.5	3.8	6.2	6.9	4.7	11.8
122	X148-300-R4	2.9	3.5	5.2	4.6	3.6	12.6
123	X797-953-R1	0.3	0.1	4.7	1.4	1.8	5.9
124	X104-463-R6	1.7	0.7	6.3	5.1	4	9

Supplementary Table 1. Contd.

125	X1052-220-R2	0.3	0.6	6.9	-1.1	1.3	8.1
126	X406-935-R4	3.5	3.7	7.1	4.8	2.9	11.8
127	X1222-755-R3	0.8	1.3	6.7	2.6	1.5	9.3
128	X215-RF4B	0.3	0	5.1	3.4	3.8	10.1
129	X166-RF4	4.2	3.3	5.6	7.9	3.7	13
130	X114-136-R1	1.3	1.4	6.6	3.1	2.7	8
131	X80 968 R3	1.5	0	8.1	6.4	4.6	8.4
132	X163-RF4C	0.5	0.2	7	8.1	4.1	8.1
133	X803-1000-R2	2	0.9	6.1	2.1	1	6
134	X780-850-R4	3.2	2.6	4.3	1.8	2	9.3
135	X1059-401-R2	1.8	5.5	7.1	3	1.3	6.7
136	X85 RF4	3.1	5.3	6.4	2	2.3	12.4
137	X1222-755-NR4	3.1	1	6.5	8.1	4.4	11.1
138	X438-RF4	2.1	1.9	6.8	3.9	1.5	8.9
139	X466-679-R3	3.1	0.5	8.7	3.5	2.6	8
140	X468-RF4	1.8	1.8	5.1	3.3	3.9	12.2
141	X148-300-R5	4.4	3.4	7.3	7.2	4.3	10.6
142	X763-132-R4	2.9	2.7	5.5	5.3	3.6	11.2
143	X321-458-R3	1.8	2.9	8	3.9	3.9	12.3
144	X756-299-R2	2.1	0.7	9	5.1	4.3	9.2
145	X121-327-R3	3.5	3.1	6.3	3.8	3.7	11.6
146	TX623(4X)	0	-0.3	*	3	2	10.9
147	T115>163A-1	1.5	2.2	5.8	3.4	2.1	8.8
148	S1219-15-354D	0.8	1.1	11.1	7.6	3.8	9.4
149	S1264-1-14-R304	1	0.8	7.9	4	3	18.2
150	S1312-6-R203A	1.7	0	6.4	1.5	2.1	8.7
151	S1374-18-R117	4.9	2.2	7.2	2.3	1.2	7.4
152	S1383-1-0-396D	1	1.2	4.8	3.2	2.8	10.8
153	S1383-1-R193	9.4	4.2	9.6	5.2	6.4	14.4
154	S1383-2-1-R121	3.3	2.6	7.7	10.4	6.2	12.5
155	S1477-30-R51	7.3	4.5	12.7	7.7	6	12.1
156	S1477-31-R52G	3.6	3.9	12.3	3	3.4	12.1
157	S1477-31-R52H	2.7	3.9	9.5	7.5	6.8	14.6
158	S1481-1-R69	4.5	2.8	8	4.2	3.3	8.1
159	S1482-1-R01	4.4	2.9	6.7	4.1	4.8	10.9
160	S1498-2-R106	5.4	2.5	9.4	6.1	5.1	10.2
161	S1662-R33C	4.3	6.7	12.3	5.1	4.6	10.7
162	S1662-R33F	2.7	2.6	7.8	8.6	4.2	12.3
163	S1836-1-R89	4.6	2.9	7.6	2.8	2.8	8.9
164	S1265-1-0-R519-R85	1.1	0.7	6.3	2.9	2.2	9.2
165	S1383-1-0-R396D-R193D	3.3	3.2	9.4	7	3.7	11.4
166	S1383-1-0-R396D-R193D	4.5	2.4	6.4	10.9	1.2	7.7
167	S1465-4-dw14B-R157A	0.4	0.4	7.8	6.6	2.7	9.6
168	S1465-4-dw14B-R157E	3.2	2.4	8.7	0.4	0.4	8.9
169	S1473E-2-R29C-R25D	2.8	2.1	6.6	3.2	2.3	10.4
170	S1474-1-dw5-R136	3.8	3.1	9.1	4.2	5.4	14.7
171	S1474-2-R31A-R235B	5.6	2.9	7.2	6.1	5.7	9.9
172	S1477-30-R51-R229A	0.1	0.4	6	2.7	2.2	12.3
173	S1477-30-R51-R229C	2.7	2.8	9.6	3.5	2.2	9.9
174	S1477-30-R51-R229D	0.1	0.2	5.7	2.1	2	8.7
175	S1477-43-dw54B-R181	1.1	1.7	9.1	7.8	4.4	12
176	S1477-43-dw54C-R89A	2.2	2.3	9.3	3.4	3.2	10.3

Supplementary Table 1. Contd.

177	S1477-43-dw54C-R424A	1.5	1	6.3	2	3.3	11.5
178	S1477-X-R55A-R122	3.3	2.7	7.2	3.7	2.3	10.8
179	S1479-6-R61-R78B	0.4	0.1	6	2.2	3.1	12.1
180	S1479-6-R61-R78C	2.5	4.2	10.4	5	3.5	9.7
181	S1479-1-R56B	3.7	4.5	12.3	5.6	5.5	15.1
182	S1481-1-R01-R213B	2.4	2.5	7.5	7.9	7.1	13.8
183	S1481-1-R01-R213D	3.7	3.6	8.2	4.2	5	12.8
184	S1481-1-R01-R213F	5	2.7	10.3	5.6	2	10.5
185	S1498-15-R182B-R184A	2.8	1.6	7.1	5.5	4.1	12.8
186	S1655-R75A-R146B	0.4	1.6	7.3	6.9	6.3	11.4
187	S1662-R33C-R177A	1.3	2	9.5	9.9	6.2	14.6
188	S1662-R33C-R177E	1.4	2.3	5.9	6.7	7	13.2
189	S1755-dw76-R73A	1.8	3.5	6.9	4.8	3.7	7.1
190	S1755-dw76-R73B	3.2	3	8.1	5.5	6.9	14.6
191	S1781-R79S-R214A	2.6	1.9	8.1	5.4	8.1	10.2
192	S1781-R79S-R214B	5	3.4	9.2	4.2	5.2	11
193	S1811-3-R17A	2	1.3	6.1	3.2	3.4	11
194	X61-497-R4-R204A	1	0.8	7.7	2.7	1.8	9.9
195	X61-497-R4-R204D	2.4	0.6	10.8	3.4	3.1	10
196	X74-120-R3-R19	5.1	3.1	7.5	8.2	6	12.8
197	SESO 1	0.1	0.2	*	1.1	0.9	*
198	SESO 3	0.1	0.1	*	-0.4	-1.1	*
199	EPURIPUR	0.2	0.1	*	-0.1	-0.5	*
200	SEKEDO	0.2	0	*	1.3	0.8	*
LSD	-	3.5	2.6	4.6	6.7	4.8	6

Supplementary Table 2. Entry means for the rhizome production traits for *Sorghum bicolor* × *Sorghum halepense* families at NaSARRI in two seasons in 2015.

Entry No.	Family	Season 1			Season 2		
		Rhizomes	Shoots	Spread	Rhizomes	Shoots	Spread
1	X423	1.1	1.5	6.8	4.4	5.8	9.7
2	X68	1.4	1.5	5.6	3.5	2.3	10.2
3	X615	1.8	2.1	5.4	4.1	2.9	8.5
4	X337	3.9	1.4	9.4	9.3	6.7	10.1
5	X105	1.7	1.8	7.8	9.2	5.1	12.2
6	X502	2	1.8	6.5	7.2	5.2	8.1
7	X606	-0.2	0.7	6.3	4.5	4.3	8.4
8	X612	0.6	0.7	5.9	6	4.2	7.3
9	X108	7	3.9	9.5	9.6	7.4	11.8
10	X354	3.4	4.6	6.7	6.6	5.8	8.4
11	X114	1.5	1.6	7.6	2.2	4	5.7
12	X107	1.2	1.3	5.9	7.3	4.9	9.4
13	X503	1.3	1.7	7.3	5.3	3.6	10
14	X154	1.4	1.4	8.4	6.4	8.6	10.7
15	X47	2.6	3.5	8	6.4	6.8	9.7
16	X41	1.3	1.2	6.1	2.7	3.5	7
17	X24	1.1	2.2	7.3	9	6.1	8
18	X21	2.5	3.7	7	4.6	4.7	8.7
19	X209	2	2.6	9.3	2.3	3.6	7

Supplementary Table 2. Contd.

20	X99	0.7	0.1	5	5.8	3.9	8.3
21	X410	0.6	0.3	11.8	5	5	10
22	TX623(2X)	-0.1	0.3	4.9	1.3	5.4	6.9
23	X38	2.3	1.3	6.9	3.6	5.3	7.1
24	X42	2	4.2	9.9	3.8	3.6	10.4
25	X76	3.1	2.8	6.3	5.2	7	14.9
26	X97	0.9	1.9	5.5	5.3	4.1	10
27	X104	0.2	0	0	4.3	4	8.2
28	X117	2.7	2.4	9	5.3	2.7	9.3
29	X406	1.5	2	6.8	5.7	5	10
30	X731	2.1	1.5	10.4	5.9	4.8	7.9
31	X756	2.5	2.8	9.2	8.6	6.7	10.9
32	X763	1.1	2.3	6.8	1.2	3.4	8.7
33	X770	1.8	1.3	7.2	13.8	4.9	13
34	X782	2.1	2.3	9.6	9	8.2	12
35	X803	1.3	1.5	5.4	3.9	2.8	8.6
36	X806	1.9	4.1	9.2	1.6	3.7	8.6
37	X1054	1.9	2.8	6.8	8.1	3.5	11
38	X1068	2.6	3.4	9.6	7.5	5.9	8.9
39	X1070	3.7	5	9.8	5.4	5.8	8.8
40	X312-290-R1	1.9	1.2	7.1	5.7	7.1	15.7
41	X202-RF4	2.3	2	6.2	2.1	3.4	8.1
42	X738-387-R3	1.8	1.8	7.9	5.6	4.1	7.4
43	X83 594 R4	3.4	2.7	8	6.1	5.6	11.3
44	X117-697-R2	1.9	4.3	8.4	10.1	7.1	13
45	X1076-18-R4	0	-0.1	7.4	2.9	2.6	7.9
46	X803-1000-R3	1.3	0.7	5.9	3.9	5	9.4
47	X107-356-R3	0.8	1.2	6.3	3.7	4.3	7.7
48	X1090-195-R2	2.9	6.2	7.4	7.3	5.4	13
49	X1085-736-R4	1.7	2.6	6.7	4.1	6.1	10.5
50	S1465-2-R01	1.5	0.9	5.3	3.6	3.6	8.8
51	S1465-8-R16	-0.1	0.5	5.6	3.7	3.7	9.2
52	S1475-1-R01	4	4.2	14	2.1	2.4	7.8
53	S1477-31-R52B	3.5	4.8	6.8	4.5	4.8	11.4
54	S1465-2-R02	3.1	4.1	9.9	3.7	2.8	15.2
55	S1467-1-R01	0.2	1.2	7.2	2.3	2.7	15.9
56	S1468-4-R17L	0.1	0.6	7.6	-0.9	1	9.5
57	S1469-7-R21	4.4	5.6	6.7	6.3	5.8	11.5
58	S1474-2-R31A	2.8	2.9	6.7	8.4	6.9	12
59	S1479-1-R56A	0.7	2.1	9.3	4.5	3.2	9.2
60	S1479-3-R58B	2.2	2	7.9	2.5	4	11.2
61	S1646-R24A	0.3	1	5.5	2.9	2.2	6.5
62	S1653-3-R200	5.3	8.6	8.8	6	5.4	9.3
63	S1655-R75A	3.1	5.2	9.4	4.3	4.4	11.3
64	S1661-R32	6.9	8.2	10.6	12.9	6.1	13.6
65	S1662-R33A	5.2	5.9	11.2	11.3	6.4	13.4
66	S1686-R35A	3.6	4.6	7.6	6.1	5.5	14.1
67	S1708-1-R158	0.9	1.7	8	5.9	7.2	8.8
68	S1760-R40	7	10.4	13.5	8.3	6.1	14.3
69	S1761-R132A	2.1	1.7	7.7	4	4.7	8.7
70	X61-497-R4	1.7	1.6	18.6	1.9	2.8	4.4
71	X74-120-R3	2	2.5	7.6	4.8	6.9	11.7

Supplementary Table 2. Contd.

72	X74-416-R4	2.3	2	6.8	6.6	7.9	14.6
73	X127-412-R4	3.2	2.2	6.1	8.2	5.3	13.4
74	X129-588-R4	0.4	1.4	5.7	6.6	3.2	9.6
75	S1814-1-R220B	4.9	2.7	7.4	3.1	2.8	5.5
76	X151-511-R12	8.6	6.4	8.9	7.1	7.6	14.8
77	X151-511-R1	1.3	0.7	8.5	3.2	3.1	6.2
78	X151-511-R2	2.8	3	7	3.4	5.5	8.8
79	X151-511-R3	1.3	3.1	7.8	3.4	3.9	7.3
80	X151-511-R4	1.7	2	6.4	6.5	5.6	11.7
81	X174-453-R1	0.9	2.5	6.9	1.7	6.5	8.1
82	X413-077-1	1.4	2.4	7.4	9.7	7.9	17.7
83	X413-077-2	0.5	2	5.8	5.9	5.7	11.9
84	X413-077-3	0.1	0.3	5.1	8.7	8.2	16.9
85	S1836-1-R89A	0.9	2.3	5.8	1.6	2.1	3.5
86	X501-156-1	1.7	2.3	6.6	5.3	6.1	11.6
87	X501-156-3	0.8	0.5	5.1	3.1	3	5.8
88	S1931-2-R123C	1.7	1.6	6.7	5.1	2.6	7.4
89	S1939-2-R130	3	2.4	8.6	7.7	5.2	13
90	S1474>R84A	4.9	8.2	7.6	6.8	7.9	14.7
91	H6-70-8	1.7	1.4	9.2	3.6	4.2	8
92	H6-143-4	6.5	6.3	13	6.8	5.4	12.2
93	T321-157	4.4	5.1	7.3	9.2	7.3	16.3
94	S1265-1-0-R519	3.1	1.7	7.2	6.1	6.3	12.4
95	S1312-6-R203A	5.4	8	11.4	4.6	5.5	9.7
96	S1438-1-R193	5.8	4.9	9	-0.2	6.7	6.5
97	TX403(4X)	2.2	1.5	7.2	2.6	4.7	7.1
98	D81-34	0.3	1.8	6.4	6.4	5.9	12.3
99	X756-299-R3	0.3	1.8	6.6	2.8	4.4	7.3
100	X42 987 R2	0.2	0.4	5.2	1.7	3.7	5.3
101	X148-300-R6	3.3	3.7	9.7	6.9	5.4	12.4
102	X782-560-R4	1.5	3.3	9.1	2.1	2.5	4.8
103	X107-559-R2	0.7	1	6.5	13.9	4.5	18.1
104	X1054-925-R5	2.1	2.2	6.8	2.8	3.2	5.8
105	X117-697-R3	9.3	6.6	9.4	3	4.7	7.3
106	X726-881-R4	1.7	0.9	5.9	4.2	3.6	7.7
107	X25 RF4	2.1	1.8	6.6	5.1	4.4	9.5
108	X163-RF4B	2	2.8	7.1	7.6	5.8	13.5
109	X782-560-R3	0.5	0.5	5.2	6.1	5.4	11.4
110	X731-230-R4	2.5	3.7	8.1	11.5	8	19.6
111	X1039-806-R4	3.4	3.2	8	7.5	4.3	12
112	X228-RF4	1.8	1.2	7.1	7.4	7.6	15
113	X770-829-R3	0.3	0	5.2	3.2	3.4	6.7
114	X3818 R4	2.7	2.8	6.5	2.7	3.2	5.9
115	X104-463-R5	0.5	0.8	5.6	4.9	2.3	7.4
116	X117-697-R4	1.8	1.8	7.2	5.1	3.8	8.9
117	X97 361 R3	1.4	1.2	8.8	9.7	5.7	15.6
118	X756-299-R4	3.4	3.7	6.8	6	4.2	10
119	X999-RF4	2.2	1.5	7.3	1.3	5.3	6.5
120	X215-RF4A	2.4	3	7.5	10.6	8.7	19.5
121	X1070-470-R3	5.4	5.7	9.5	4.9	4.2	9
122	X148-300-R4	3.7	2.3	8.1	10.7	4.9	15.6
123	X797-953-R1	1.5	1.1	6.6	5.8	5.4	11.1

Supplementary Table 2. Contd.

124	X104-463-R6	0.8	3.4	8.8	6.2	5.7	11.9
125	X1052-220-R2	0	0.1	5.3	-0.5	-2.6	-2.9
126	X406-935-R4	4.2	3.3	8.3	8.7	8.6	17.2
127	X1222-755-R3	0	0.4	8.6	5.9	5.1	10.9
128	X215-RF4B	2.5	2.6	8.1	5.7	5	11
129	X166-RF4	1.6	2	7	7.8	7.6	15.6
130	X114-136-R1	1.1	6	8.8	9.1	6.7	15.9
131	X80 968 R3	5.5	2.2	9.7	13.2	7.6	20.9
132	X163-RF4C	0.5	1	5.2	10.7	10.2	20.8
133	X803-1000-R2	1.2	2.1	6.4	1.6	4.9	6.5
134	X780-850-R4	0.6	1.3	6.7	2.8	3.1	5.7
135	X1059-401-R2	1.6	2.5	5.7	7.5	4.6	11.4
136	X85 RF4	2.1	1.6	6.1	5.8	5.4	9.3
137	X1222-755-NR4	2.5	1	7.1	5.6	4.7	7
138	X438-RF4	3.7	1.9	6.2	1.1	3.2	8.4
139	X466-679-R3	2.3	2.5	6.5	4.3	4.1	7.8
140	X468-RF4	1.3	2.4	6.7	6.7	6.6	8.8
141	X148-300-R5	1.6	2.3	9.5	3.4	2	11.9
142	X763-132-R4	1.2	1.4	12.4	3.5	5	10.8
143	X321-458-R3	4.5	6.1	8.6	9	6.1	11.3
144	X756-299-R2	1.1	0.8	6.5	4.7	7.4	6.5
145	X121-327-R3	0.6	2.4	5.7	7.2	4.1	6
146	TX623(4X)	0	0.9	6.6	4.5	2.5	5.7
147	T115>163A-1	1.3	3.2	8.9	2.6	5.2	9.5
148	S1219-15-354D	0.4	2.4	8	1.4	0.8	5.1
149	S1264-1-14-R304	2.6	2.7	7.4	5.5	5.4	10.2
150	S1312-6-R203A	0.8	1	7.2	5	3.7	11.5
151	S1374-18-R117	4.1	3.6	8.3	6.1	5.3	11.6
152	S1383-1-0-396D	2	2	8.5	4.4	6.1	10.9
153	S1383-1-R193	3.5	2.2	8.2	4.9	5.8	11.3
154	S1383-2-1-R121	3.2	4.8	8.5	8.6	6	11.5
155	S1477-30-R51	6.7	8.3	10.2	7.3	5	13.4
156	S1477-31-R52G	5.2	4	8	5	6.5	11.7
157	S1477-31-R52H	3.7	3.8	7.8	6.9	5.1	10.8
158	S1481-1-R69	6.1	6.2	9.5	8.9	6.5	10.9
159	S1482-1-R01	4.3	3.5	12.1	5	4.3	9.6
160	S1498-2-R106	4.3	3.5	6.7	8.5	6.8	10.6
161	S1662-R33C	4.7	6	11.6	8.7	5.3	10.8
162	S1662-R33F	3.4	3.2	8.2	4.7	3.5	10.5
163	S1836-1-R89	3.3	5.1	9.6	5.1	5.8	21.1
164	S1265-1-0-R519-R85	3.4	2.7	9.1	6.3	4.4	8.5
165	S1383-1-0-R396D-R193D	10.9	13.3	13.5	5.2	7.5	13.5
166	S1383-1-0-R396D-R193D	2.8	2.3	6.6	3.8	3.8	9.9
167	S1465-4-dw14B-R157A	1.7	1.8	6.8	6.8	6.4	7.7
168	S1465-4-dw14B-R157E	2.5	2.2	11.5	5	3.7	7.9
169	S1473E-2-R29C-R25D	2.8	5	8.8	4	5.6	8.2
170	S1474-1-dw5-R136	6.1	6	9.4	14.6	9.9	19
171	S1474-2-R31A-R235B	5.1	4.8	10.1	6	6.4	14.9
172	S1477-30-R51-R229A	1.3	1	6.6	3.4	2	9.7
173	S1477-30-R51-R229C	3.8	6.1	9.5	8.7	5.1	11.2
174	S1477-30-R51-R229D	0.3	0.9	6.4	1.3	3.8	6.5
175	S1477-43-dw54B-R181	2.7	2	6.6	4.8	4.3	7

Supplementary Table 2. Contd.

176	S1477-43-dw54C-R89A	2.5	4.7	7.8	3.2	5.6	9.6
177	S1477-43-dw54C-R424A	0.9	2	8.3	6.7	8.2	10.4
178	S1477-X-R55A-R122	2.4	2.9	8.2	3.6	4.6	8.5
179	S1479-6-R61-R78B	0.4	0.6	6.2	12.2	9.2	14.3
180	S1479-6-R61-R78C	4.5	6.2	11.3	7.1	3.6	7.2
181	S1479-1-R56B	5.1	1.8	8.7	7.6	5	12.1
182	S1481-1-R01-R213B	2.4	3.3	7.6	10.5	6.3	11.5
183	S1481-1-R01-R213D	5.7	4.7	9.3	4.7	6.1	12.7
184	S1481-1-R01-R213F	5.1	5.7	9.3	6.1	6.9	10
185	S1498-15-R182B-R184A	5.3	8	10.7	6	4.7	11.8
186	S1655-R75A-R146B	9.4	10.1	14.7	4.8	3.5	10.8
187	S1662-R33C-R177A	4.9	3.4	9.7	11.3	7.4	12.1
188	S1662-R33C-R177E	0.8	2.7	8.1	5.6	5.3	8
189	S1755-dw76-R73A	2.7	3	8.9	13.6	7.6	17.1
190	S1755-dw76-R73B	3.1	3.2	6.6	1.7	2.7	5.4
191	S1781-R79S-R214A	8	5	9.3	6.3	10.5	16.2
192	S1781-R79S-R214B	9.4	9.7	8.4	12.5	9	9.6
193	S1811-3-R17A	5.1	6.3	10.6	4.9	3.8	12
194	X61-497-R4-R204A	2	5.2	8.9	2.8	4	9.1
195	X61-497-R4-R204D	5	3.3	11.3	6.5	6.2	10.7
196	X74-120-R3-R19	5.5	4.3	9.3	5.7	5.9	13
197	SESO 1	0.1	0	*	-0.5	-0.9	*
198	SESO 3	0	0	*	-1.1	-1.2	*
199	EPURIPUR	0	0	*	0.2	-0.4	*
200	SEKEDO	0.1	0	*	-1.1	-2	*
LSD	-	3.5	3.5	4.7	6.9	4.3	6.6

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Spatial econometric analysis of the main agricultural commodities produced in Central-West Region, Brazil

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The aim of this paper is to present novel variables in the Brazilian Central-West Region to evaluate the spatial dependence of the Gross Domestic Product of agriculture and livestock (GDPagri) and the Gross Value of Production (GVP) on the main agricultural and livestock commodities in order to identify clusters of high and low spatial correlations. Data on the municipalities of Mato Grosso do Sul State (MS) between 2000 and 2010 is used. Initially, a spatial exploratory data analysis is performed to verify the hypothesis of global spatial randomness of the evolution of GDPagri and GVP, with Moran's I statistic as the instrumental measurement. In addition, econometric and spatial models were utilized. The results of the three spatial models used indicated that the SAR model (Spatial Auto Regressive) is most appropriate for the evaluation of GDPagri in MS. Despite beef cattle having presented the greatest GVP, the culture of sugar cane allowed for a greater increase in GDPagri.

Key words: Agribusiness, gross domestic product, spatial econometrics, Brazil.

INTRODUCTION

The ideas of commodity systems have been constantly changing over the decades; however, we can say that knowledge of supply chain management in business and studies of commodities have become important influences in economic development (Jackson et al., 2006). Brazilian agribusiness represents more than 20% of the national Gross Domestic Product (GDP), yielding more than R$ 1.0994 trillion in 2012. The amount involving exports accounted for approximately R$ 252 billion (Fraga and Silva Neto, 2017).

Agriculture, through poverty reduction and food supply strategies, has been instrumental for economic

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development in past years in many countries. However, it is essential that the theory of studies from agricultural research results in practices, technologies and applicable knowledge to be more effective, leading eventually to global changes in socio-economic, political and institutional contexts (Thornton et al., 2017).

In past decades, the Central-West Region of Brazil performed remarkably, emerging as the new agricultural and livestock power in the country. Silva et al. (2017) citing data from the Brazilian Institute of Geography and Statistics - IBGE, verified that the key for the increased development was the agricultural expansion based on land incorporation, exemplified by the 1995/6 to 2006 panel data, which indicates that the crops presented growth of 20% in the total area occupied, while planted pasture areas grew approximately 2% over the same period. The main regional representative was the Center-West, in which the crop areas grew +64%, followed by the North (+37%) and Northeast (+29%) regions of Brazil (Silva et al., 2017).

Considering Brazil's importance to worldwide food production, the occurrence of inter-regional movements of this nature may represent a change in the regional economic growth pattern, whose impact affects not only the productive structure of the country but also the social structure (Diao et al., 2010; Penna et al., 2012; Rada, 2013). In this context, as part of the Center-West – the region that most contributes to the Brazilian agribusiness – the State of Mato Grosso do Sul ('MS') there was a great economic and social transformation. According to IBGE (2015), in the past decade, the MS was fairly representative as driver and developer of agribusiness in the country, as in this period, the state occupied the 18th position in relation to the total GDP and the 11th position among the agricultural GDP (IBGE, 2015).

Thus, to address the importance of economic activity for measuring the wealth value for one or more commodities produced in a particular region, it is necessary to cover its production system and the value aggregator that this chain comprises in order to assess their economic and social growth. For this, two economic indicators can be used as agricultural activity measures produced in space and time: the Gross Value of Production (GVP) and the agricultural GDP (GDPagri).

The GVP shows the evolution of the performance of crops and livestock throughout the year and corresponds to the gross income within the establishment based on the agricultural crops and livestock production and the prices received by producers "inside the gate", that is, excluding freight, taxes, and other costs (MAPA, 2015). The GDPagri is calculated starting with the input-output matrices, summing the value added by the segment of each sector of the economy. The GDP the economic sector represented is obtained from the difference between the GVP and intermediary consumption in the period considered.

The economy is regarded then as a large set of productive chains that sequentially involve several segments, each producing inputs for the next segment. There is a high correlation between GDPagri and GVP because the agriculture and livestock GDP is the GVP agriculture less the value of purchased inputs of the upstream segment, that is, GVP less stocks, if any exist (Barros et al., 2011; Mahmood and Munir, 2017; Rehman et al., 2017). Thus, if GDPagri and GVP grow, the holders of labor, capital and land, as well as business owners, can share a higher real income among themselves.

It is important to note that within the agricultural productive dynamics, the producer will choose the agribusiness that will make more sense, taking into account its internal production structure, external logistics structure, and the cost-benefit factors to optimize profit. Therefore, the consolidation of a certain agricultural business determines the spatial pattern of production in their respective regions. This pattern also arises from the creation and use of technological and logistical packages that provide high-income area with higher productivity growth rates than those in other regions. In addition, political incentives to encourage local production can create production standards.

In this sense, Gomes et al. (2013) stated that the municipalities that have good management skills, concentration of fertile land and adequate infrastructure tend to better organize their production locally, regionally, nationally and even globally and make provisions for the promotion of a common development model that articulates the social, environmental and economic dimensions.

Thus, analyzing the economic indicators for the producing regions may capture a spatial effect for the results. Therefore, it is natural to assume that the economic and social processes meet the First Geographic Law – "All things are similar, but closer things are more related than distant things" (Tobler, 1970) – that is, the role of physical proximity to the emergence of spatial interaction phenomena must be discarded. Thus, it is very important to detect the spatial interactions in the GDPagri and the GVP agricultural commodities by the observed dependence of the regions on various streams, such as income, information, people, possessions and services.

Considering the aforementioned factors, this article aims to evaluate the spatial dependence of the GDPagri and GVP evolution on the following commodities: beef cattle, cotton, maize, soybean and sugar cane between the years 2000 and 2010 in Mato Grosso do Sul State municipalities. The objective is to detect and infer a spatial pattern of such indicators, that is, locating clusters subject to their spatial interactions.

Therefore, this study followed a classical framework of economic analysis contemplating two steps: in the first step the global and local spatial randomness were tested with the *Moran's Index* statistic as the instrumental measurement, and in the second step econometric

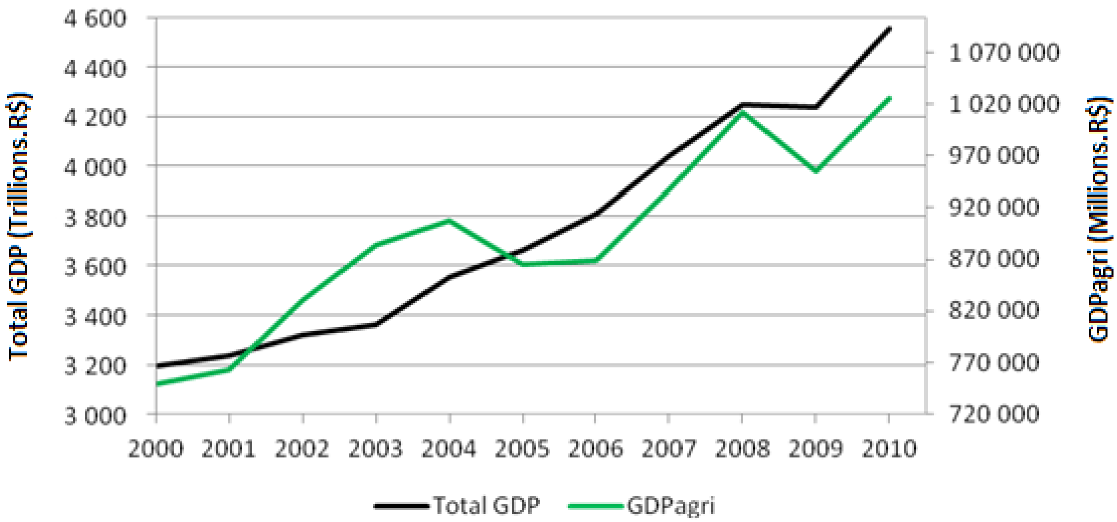


Figure 1. Brazilian gross domestic product (GDP) and agriculture and livestock GDP (GDPagri) from 2000 to 2010.
Deflated values corrected to actual values by the general price index (IGP) from the Getúlio Vargas Foundation (FGV). Data: IBGE (2015) and CEPEA (2015).

models were applied to explain the spillover effects.

Agribusiness behavior from 2000 to 2010 in Brazil

Between the years 2000 and 2010, Brazil experienced a period of great economic development, in which the Brazilian GDP grew year by year. According to the Brazilian Institute of Geography and Statistics – IBGE (2015), in 2000, Brazilian agribusiness accounted for 5.60% of its GDP; however, this percentage decreased in 2010 to 5.30%, losing part of the economic contribution to the commerce and services sectors, common in developing countries, due to the strong internal urbanization in that period.

Thus, GDP growth rates in agribusiness in Brazil, published by the Center for Advanced Studies in Applied Economics – CEPEA (2015) and based on IBGE data, showed an average GDPagri growth of 3.02% per annum during the years 2000 to 2010, practically accompanying the average growth of total GDP in this period, which was 3.70% per year (Figure 1).

In this context, it is important to highlight the period 2001 to 2004, in which the growth of GDPagri was more aggressive than the total GDP, which corresponded to an increase of approximately 4.30% per annum, while the total GDP growth year was 2.30%. Thus, at the beginning of that decade, it was found that much of Brazil's economic growth resulted from agribusiness growth.

In contrast to the urban phenomena, in which the visibility of economic and social outcomes for the populations affected by the growth is more easily perceived by analysts, the agricultural development is characterized by presenting results that are both diffused in time and less obvious in view, that is, the territorially dispersed character of this economic activity. Thus, changes in the structure and performance of the primary sector and the effects on income generation, employment, and improved living conditions are not easily quantifiable, and comprehensive analysis is not even clearly perceived by the economic agents, including local governments (Bonelli, 2001; Dethier and Effenberger, 2012).

Among the various factors that may influence the development of agricultural production in a particular location, and consequently the increase of GDP, some constitute the most important: the increased area produced, the increase in credit to sectors of agricultural production chain, the increase in average crop yields, the increase in exports and domestic consumption (Valdés and Foster, 2010).

In this sense, Corrêa and Figueiredo (2006) observed that at the beginning of 2000, agricultural modernization in Brazil was associated with the rapid growth in the intensity of land use and work capital ratio. The results were reflected in the production and development gains in the agribusiness production chain during that period.

In addition, it was found that during the study period, there was a large increase in the use of biotechnology in the national territory, mainly of derived products and in the use of genetic engineering. The development of transgenic varieties resistant to pests and pathogens and tolerant to herbicides has been accredited as one reason for the reduction of crop losses, causing a decrease in production costs as well as in environmental conservation, making producers and consumers able to obtain food at lower cost, which is considered the current challenge in preserving the environment and food safety (Gomes and Borém, 2013).

Another interesting study related to the development of the national agribusiness was that of Melo et al. (2015), who noted that the increase in credit in the country from 1995 to 2009 had an impact on Brazilian agriculture, promoting agricultural production, which is also based on input for livestock production. Nevertheless, the authors noted that the livestock credit line led to a significant drop in real GDP of the agricultural sector. Possibly, according to the authors, the wrong design of loan contracts for cattle producers caused such a distortion.

However, the adoption of genetic improvement programs for the cattle herd, the use of more productive pastures, and the use of integrated production contributed significantly to the main qualitatively and quantitatively advanced systems for the livestock sector in recent years (Lopes et al., 2012; Da Silva et al., 2014). As for exports, the agribusiness sector experienced a gradual and moderate growth among the total Brazilian exports from 2000 to 2010. Freitas (2014) studying the Brazilian trade balance of agricultural products, noted that there was a structural surplus in Brazilian agricultural trade; however, this signaled that some groups oscillated between surplus and deficit and could represent possible opportunities to produce better results for the country, citing cotton as an example.

In Mato Grosso do Sul State (MS)

Mato Grosso do Sul State is one of the 27 federative units of Brazil, located in the Center-West Region. The state is divided into 4 mesoregions (“Pantanal Region”, “North-Central Region”, “Eastern Region” and “South-Western Region”) and 77 municipalities as of 2010 (Figure 2). Over the years, the main agricultural commodities from MS showed an increase profile but it was from 2000 the State’s contribution was more effective, particularly noteworthy the period 2000 to 2010, with a strong growth in sugar cane production (Figure 3). To understand the interactions among the indicators as well as evaluate its implications in certain period, the cross-section analysis has been heavily used in statistics and econometrics.

According to Fagundes et al. (2014), as of 2003, agriculture no longer served as the main economic activity of Mato Grosso do Sul State; however, it still contributed to contemporary development and economic growth of the region. Technological innovations have resulted in qualitative and productive increases in agriculture. This complementary economic growth occurred because agriculture had a positive correlation between growth and the growth of other sectors of the economy by generating wellbeing, employment, income and product (Souza et al., 2011; Christiaensen et al., 2011).

Thus, MS gained prominence in the Brazilian agricultural scene, as their national participation in the production value of temporary crops jumped from 3.29% in 2000 to 4.24% in 2010 (IBGE, 2015). Regarding livestock, MS showed a decrease in their participation in the national GVP of livestock from 7.02% to 5.96% between 2000 and 2010. In this context, there was a decline in the cattle herd in the period 2003 to 2007 in the state (Figure 4). This reduction was the result of changes in the productive chain of livestock, which includes reproduction, fattening, slaughtering and meat processing in the state itself (Dos Santos et al., 2010).

It is noteworthy that in 2000, MS was the Brazilian state with the largest number of cattle; additionally, even though in 2010 it lost its position to other states, such as Mato Grosso and Minas Gerais (1st and 2nd place, respectively), MS continued to have national relevance in the livestock industry, occupying the third position in domestic cattle, with 22,354,077 animals (IBGE, 2015).

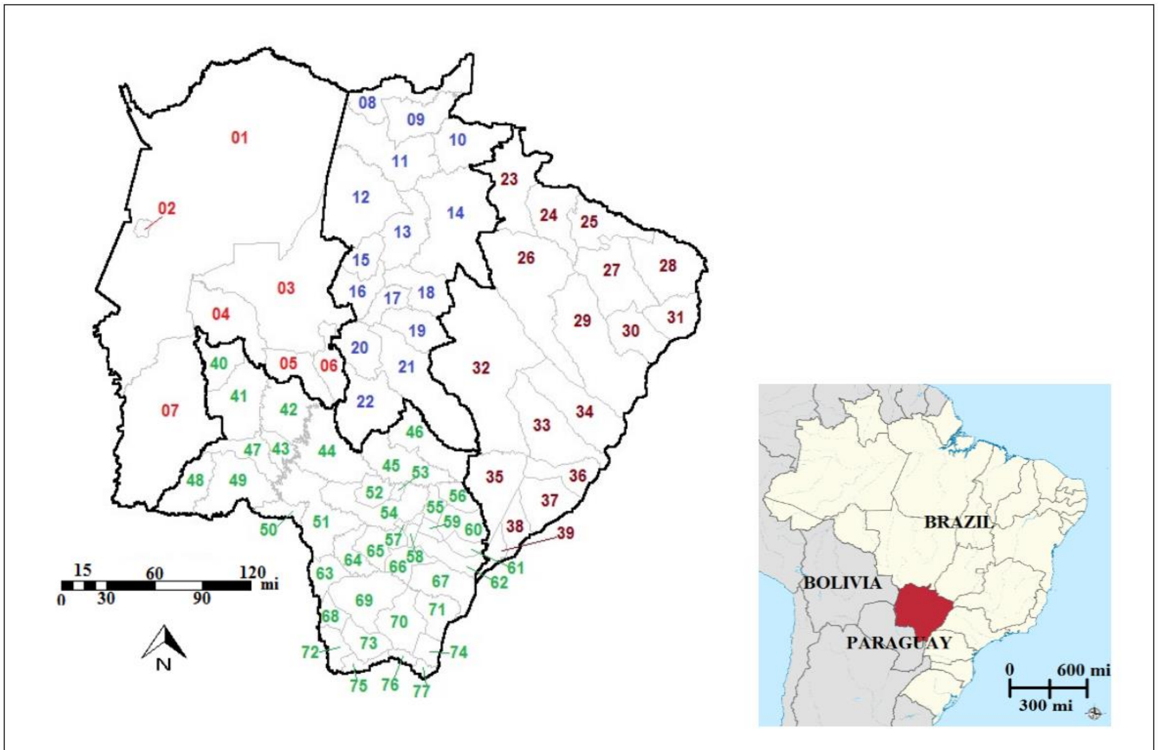
Regarding the soybean planted area, it could be observed in Figure 4 that between 2005 and 2007, there was a decrease in acreage of this crop and an increase of the planted maize area. In this period, due to the high cost of soybean production, producers chose to produce maize in the summer harvest with a temporary crop rotation, as traditionally the maize is planted in winter (PAM-IBGE, 2008).

Additionally, in Figure 4, it was found that after 2005, there was an increase in the acreage of sugar cane from approximately 136,000 ha to 400,000 ha in 2010. Thus, the new areas of sugar cane began to replace pastureland and soy, resulting in a reduction in the number of cattle and the soybean acreage between 2005 and 2010.

The cotton sector hardly changed in the planted areas between 2000 and 2010 (Figure 4), as this commodity production structure is different from other crops, mainly because of the use of more expensive machinery, the requirement for longer periods between sowing and harvesting, and the closed production chain, with traditional production by either settlements or large farms in the state (PAM-IBGE, 2010).

With respect to production gain, MS showed a growth in the sugar cane production of approximately 500% in the period 2000 to 2010 (Figure 5), thus moving from the 9th position to the 5th position in the national ranking (IBGE, 2015), surpassing traditional crop states. This increase was justified by the expansion of harvested area, mainly by producers seeking fertile and cheaper land compared to those in traditional states for this crop, especially lands with good weather conditions and high quality of soil, such some municipalities in MS (PAM-IBGE, 2010).

In addition, in Figure 5, it is possible to see that there was a significant increase in maize production in MS between the years 2000 and 2010 (approximately 250%)



Pantanal Region		01	Corumbá	02	Ladário	03	Aquidauana
04	Miranda	05	Anastácio	06	Dois Irmãos do Buriti	07	Porto Murtinho
North-Central Region		08	Sonora	09	Pedro Gomes	10	Alcinópolis
11	Coxim	12	Rio Verde do MT	13	São Gabriel do Oeste	14	Camapuã
15	Rio Negro	16	Corguinho	17	Rochedo	18	Bandeirantes
19	Jaraguari	20	Terenos	21	Campo Grande	22	Sidrolândia
Eastern Region		23	Costa Rica	24	Chapadão do Sul	25	Cassilândia
26	Água Clara	27	Inocência	28	Paranaíba	29	Três Lagoas
30	Selvíria	31	Aparecida do Taboado	32	Ribas do Rio Pardo	33	Santa Rita do Pardo
34	Brasilândia	35	Nova Andradina	36	Bataguassu	37	Anaurilândia
38	Batayporã	39	Taquarussu				
South-Western Region		40	Bodoquena	41	Bonito	42	Nioaque
43	Guia Lopes da Laguna	44	Maracaju	45	Rio Brilhante	46	Nova Alvorada do Sul
47	Jardim	48	Caracol	49	Bela Vista	50	Antônio Joao
51	Ponta Porã	52	Itaporã	53	Douradina	54	Dourados
55	Deodápolis	56	Angélica	57	Fátima do Sul	58	Vicentina
59	Glória de Dourados	60	Ivinhema	61	Novo Horizonte do Sul	62	Jateí
63	Aral Moreira	64	Laguna Carapã	65	Caarapó	66	Juti
67	Naviraí	68	Coronel Sapucaia	69	Amambaí	70	Iguatemi
71	Itaquiraí	72	Paranhos	73	Tacuru	74	Eldorado
75	Sete Quedas	76	Japorã	77	Mundo Novo		

Figure 2. Mato Grosso do Sul State political division in municipalities and mesoregions.
Data: IBGE (2015).

and an increase in soybeans of approximately 100%, resulting in MS ranking in the 7th and 5th positions among the Brazilian states in the national production, respectively (IBGE, 2015). Figure 6 shows the Gross Value of Production of the five agricultural commodities evaluated in the 2000 to 2010 period in MS, with the actual values corrected by the Extended National Consumer Price Index – IPCA (IBGE, 2015), where in beef cattle exhibited the greatest GVP in the assessed period, followed by soybean.

Two factors may influence the agricultural commodity GVP: the quantity produced and the price paid to the

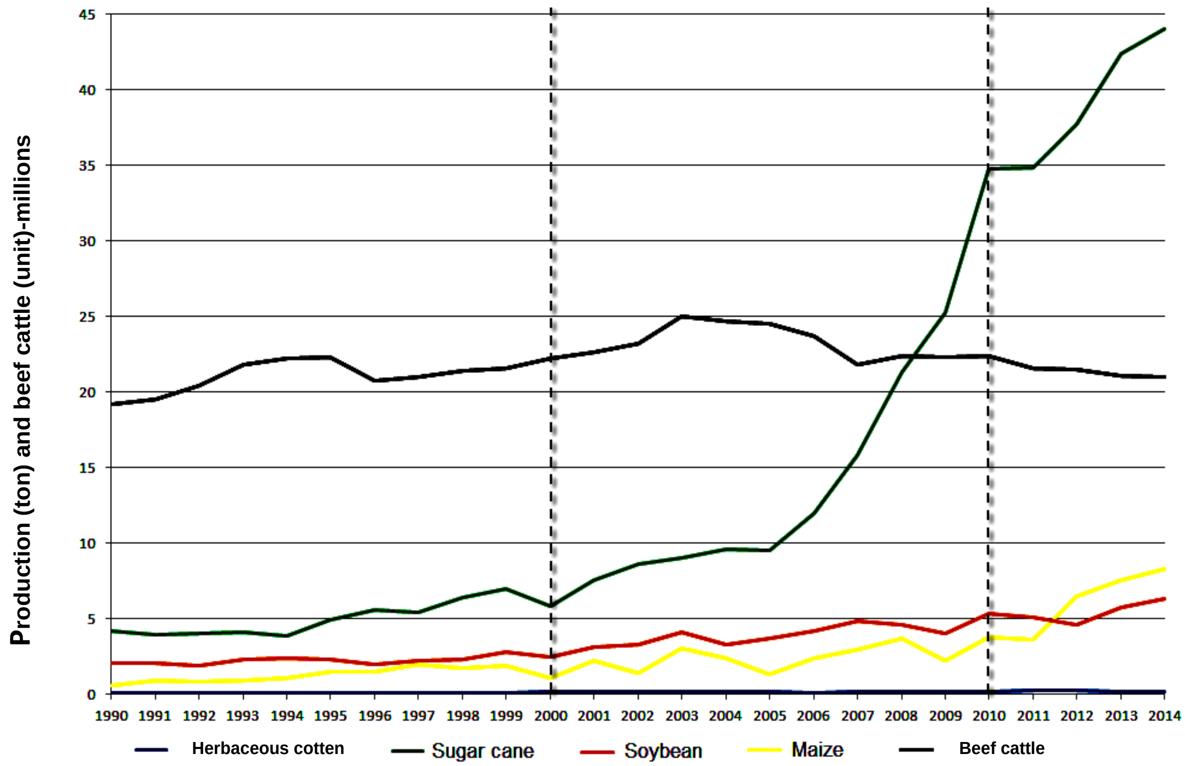


Figure 3. Production of main agricultural commodities and the effective number of beef cattle between 1994 and 2014 in Mato Grosso do Sul State.
Data: IBGE.

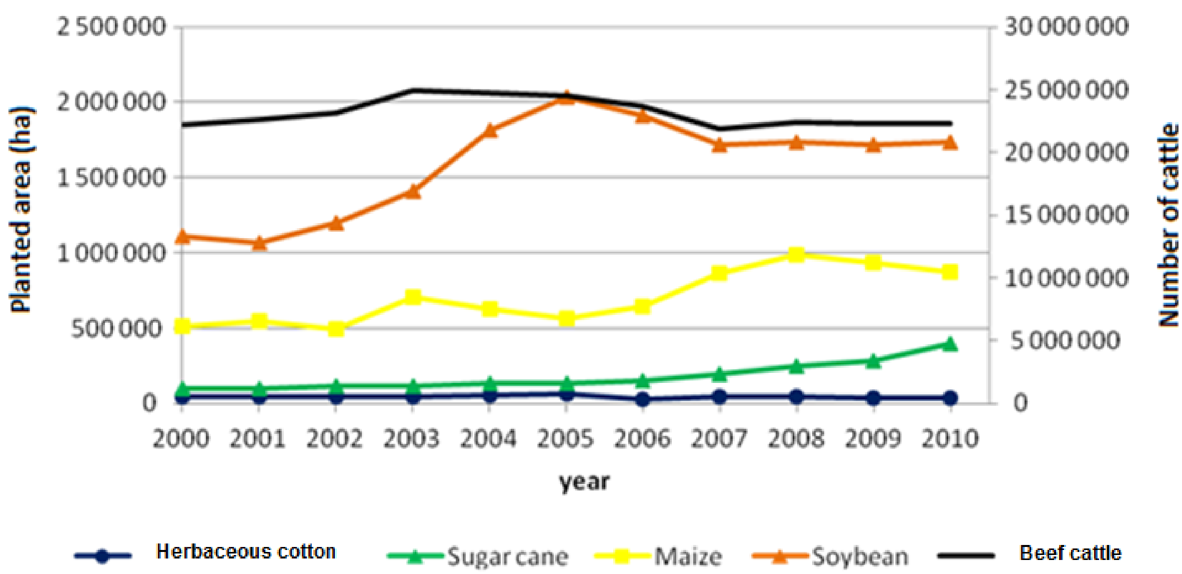


Figure 4. Evolution of the planted area and the number of cattle in the Mato Grosso do Sul State from 2000 to 2010.
Data: IBGE (2015).

producer. In this case, it was observed that even though sugar cane always had less acreage than maize crops (Figure 4), sugar cane experienced an increase in GVP due to the new areas opened for cultivation since 2005

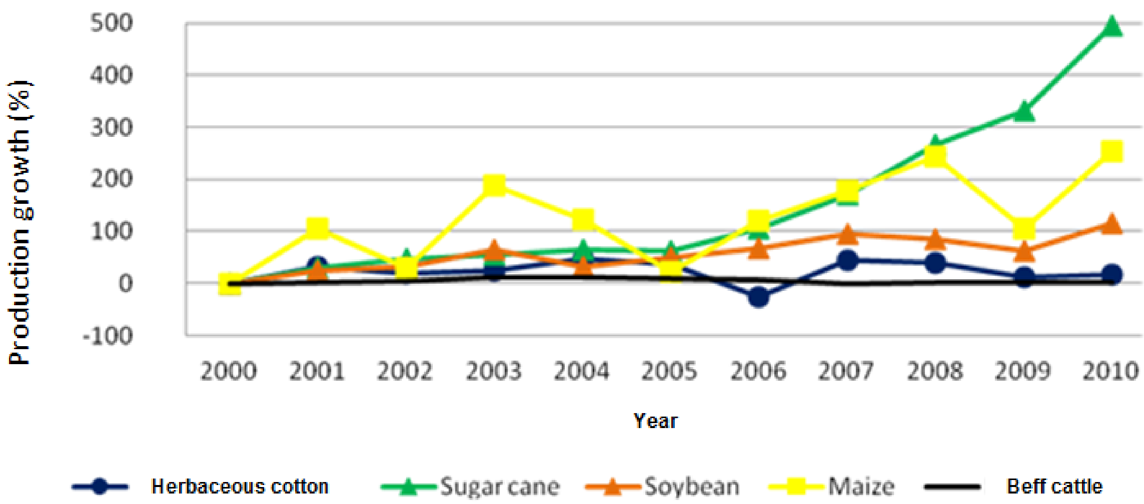


Figure 5. Evolution of the production of cotton, sugar cane, soybean and maize (in tons) and beef cattle (number of cattle) in the Mato Grosso do Sul State in 2000 to 2010.
Data: IBGE (2015).

(Figure 5).

METHODOLOGY

Exploratory spatial data analysis (ESDA)

According to Chen (2013), among the indices of spatial autocorrelation in the geographic analysis, the Moran's index is the most recommended to evaluate data from the spatial population. Thus, the *Moran's I* statistic was used to test the hypothesis of agricultural GDP in municipalities from MS presents global spatial randomness. In matrix notation, the equation is written as follows (1):

$$I = \frac{N}{\sum i \sum_j Wij} \frac{x'Wx}{x'x} \tag{1}$$

Where:

N is the number of elements surveyed; W_{ij} are the spatial weights of the matrix elements; i and j are the spatial units; and Wx corresponds to the average values of the variables x within a spatial matrix (Lins et al., 2015).

To test the hypothesis of non-existence of spatial autocorrelation (H_0), the following formula was used (2):

$$E(I) = \frac{-1}{N-1} \tag{2}$$

It is expected that the greater the number of N (approaching infinity), the Moran index will approximate to 0. In this sense, the values of I may vary between -1 and 1. The negative values of I indicate negative spatial autocorrelation, while the positive values express positive spatial autocorrelation (Lins et al., 2015). The local indicators of spatial association (LISA), proposed by Anselin (1995), was also be applied in this study. When there are significant correlations between the geographic variables, the LISA allows capturing local specificities as clusters with transition zones and spatial agglomeration zones. Depending on the spatial regime, these spatial patterns may present spatial correlations as follows:

high-high, high-low, low-high, and low-low.

Thus, LISA uses local autocorrelation from the second-order estimate, or from the covariance analysis between different area units. While the *Moran Global Index* reports the level of spatial interdependence between all the polygons under study, the *Moran Local Index* evaluates the covariance between a given polygon and a certain neighborhood defined as a function of the distance between them. The LISA equation is described as follows (3):

$$I_i = z_i \sum_j w_{ij} z_j \tag{3}$$

Where:

z_i and z_j are the deviations from the average, and w_{ij} is equal to the value in the neighborhood matrix for region i with region j as distance's function (Anselin, 1995).

Econometric model

According to LeSage (2014), when using spatial modeling it is necessary to identify the type of overflow present (local or global) and which model is most appropriate to capture this process. In spite of being global indicators, the following spatial econometrics models will be tested in this study: Spatial Autoregressive Model (SAR), Spatial Error Model (SEM) and Spatial Autocorrelation Model (SAC). These models were chosen for the following reasons:

(1) Presenting endogenous interaction and feedback effects, thus a new equilibrium in the steady state of the studied region arises (LeSage, 2014).
(2) The recent local models have an excessive reliance on statistical tests to find the appropriate model, and instead, the theory or specific context of empirical application should be the most important criterion for selecting a local or global spillover model (Vega and Elhorst, 2013).

Recent studies indicate that traditional spatial econometric models

Table 1. Variables used in the work to simulate spatial econometric modeling.

Variable	Dependent variable	Unit
GDPagri	**Gross domestic product of agriculture and livestock**	**R$**
Variable	**Explanatory variables**	**Unit**
GVPcat2009	Gross value of beef cattle production from 2009	R$
GVPsoy2009	Gross value of soybean production from 2009	R$
GVPmai2009	Gross value of maize production from 2009	R$
GVPcan2009	Gross value of sugarcane production from 2009	R$
GVPcot2009	Gross value of herbaceous cotton production from 2009	R$
Pop2009	Municipal population of 2009	Units

have been widely used to capture local spatial effects: SAR (Lacombe et al., 2016; Lv et al., 2016; Liu et al., 2017); SEM (Long et al., 2016; Yılmaz and Murat, 2016; Hajizadeh et al., 2016; Guimarães and Almeida, 2017) and SAC (Laryayekar and Mukhamadhyay, 2016; Song et al., 2017). The SAR (4), SEM (5) and SAC (6) models are expressed as follows (Lins et al., 2015; LeSage, 2008):

$$y = \rho W y + X\beta + \varepsilon, \text{ wherein } \varepsilon \sim N(0, \sigma^2 I_n) \quad (4)$$

$$y = X\beta + \xi, \text{ in which } \xi = \lambda W \xi + \varepsilon, \text{ wherein } \varepsilon \sim N(0, \sigma^2 I_n) \quad (5)$$

$$y = \rho W_1 y + X\beta + \xi, \text{ in which } \xi = \lambda W_2 \xi + \varepsilon, \text{ wherein } \varepsilon \sim N(0, \sigma^2 I_n) \quad (6)$$

In the SAR model, the dependent variable of a given location is spatially correlated with the dependent variable value of their peripheral neighboring regions, where in the signal and magnitude of spatial coefficient will define the type and strength of spillover effects. If it is not able to model the total spatial dependence on the data, the SEM is shown as a suitable model since part of the non-modeled dependency is estimated by the standard random error between neighboring regions, such that the errors are not spatially auto-correlated. As for the SAC model, it is a mixed model constructed with both presented types of overflow applied in a single equation (Lins et al., 2015). In order to validate the models, the spatial coefficients must always be less than 1, and should allow a dilution of the overflow as far as the distance from the analyzed shock region occurs (Lins et al., 2015).

Database

Data on the Gross Value of Livestock Production made available by the MAPA (2015) were used. Official data on municipal agricultural GDP (National Accounts), municipal population (Census), municipal agricultural research (PAM) and municipal livestock research (PPM) for the years 2000 to 2010 were obtained through the aggregated data system of SIDRA-IBGE (IBGE, 2015). Territorial meshes and statistical analysis were conducted through the IPEAGEO program (IPEA, 2015).

For the exploratory spatial data analysis (ESDA), the information for agricultural GDP and the gross production values of the following commodities from the period of 2000 to 2010 was used: beef cattle (GVPcat), soybean (GVPsoy), maize (GVPmai), sugar cane (GVPcan) and herbaceous cotton (GVPcot). When comparing GDPs and GVPs in a historical series, it should be observed whether the disclosed economic indicator was the real price (corrected by the depreciation of the purchasing power) or if it was applied at current (nominal) prices. Therefore, for the latter, the deflator must be used to be able to compare it between years. Thus, these indicators were corrected to the values of the year 2010 through the Extended National Consumer Price Index (IPCA), which adjusted the official inflation rate in the period. In this period, according to the IBGE (2015), inflation from January 2000 to December 2010 was 101.18%. For the spatial econometric modeling of GDPagri of Mato Grosso do Sul State, explanatory variables were used as seen in Table 1.

The independent variables used in the model were related to the year 2009, as it was sought to avoid possible problems of endogeneity as well as to construct the GDPagri at the end of the studied decade. The municipal population of 2009 was also used to capture a possible population effect in the formation of agricultural GDP. Thus, after estimated the *Moran's I* and in the case of a statistical significance, the global spatial econometric models (SAC, SEM and SAR) were estimated. Therefore, through the Akaike (AIC), Schwarz (BIC), likelihood function (LIK) and significance level of spatial coefficients, it is possible to find a more appropriate model to estimate Mato Grosso do Sul State's GDPagri in the analyzed period.

RESULTS

Global and local spatial dependence

Under the leadership of 'Corumbá' (Table 2), a municipality in the Pantanal region, the municipalities of 'Maracaju', 'Rio Brilhante', 'Dourados', 'Sidrolândia' and 'Ponta Porã' were among the top ten with the highest agricultural GDP, located in the center-south region, as well as 'Costa Rica', 'São Gabriel do Oeste', 'Chapadão do Sul' and 'Ribas do Rio Pardo', located in the northern region of the state. The ten municipalities, among the seventy-seven municipalities of MS, held approximately 35% of the state's GDPagri in the period evaluated (Table 2).

To test the null hypothesis of spatial randomness of GDPagri and commodity GVP, the spatial autocorrelation test *Moran's Global I* was used. The positive and significant result of the statistics for the GVPs (Table 3) allowed for the conclusion that there are strong indications of positive spatial dependence for these variables; in other words, cities that had high indicators, in general, are close to each other.

However, a significant spatial correlation was not found

Table 2. Annual average of the agricultural GDP of the Mato Grosso do Sul State's municipalities in the period from 2000 to 2010.

Position	City	Thousand Reais (R$)	Share (%)
1º	Corumbá	211,148	4.47
2º	Maracaju	200,454	4.25
3º	Rio Brilhante	167,651	3.55
4º	Costa Rica	166,723	3.53
5º	Dourados	162,384	3.44
6º	São Gabriel do Oeste	149,791	3.17
7º	Chapadão do Sul	146,492	3.10
8º	Ribas do Rio Pardo	145,846	3.09
9º	Sidrolândia	141,828	3.01
10º	Ponta Porã	139,855	2.96
-	Others (67 cities)	3,086,974	65.41
	Total (MS)	4,719,148	100

Deflated values for the year 2010 corrected by the Extended National Consumer Price Index (IPCA). Data: IBGE (2015).

Table 3. Value of the moran global index for the total of the economic indicators surveyed, from 2000 to 2010, in Mato Grosso do Sul State's municipalities.

Variable	Moran index	*p*-value
GDPagri	-0.0338	0.6640
GVPcan	0.1859	0.0220
GVPmai	0.2969	0.0000
GVPcot	0.2104	0.0200
GVPcat	0.1915	0.0080
GVPsoy	0.2899	0.0000

for agricultural GDP in the period evaluated. According to Almeida (2012), the indication of global patterns of spatial autocorrelation may not be in line with local standards, and it may often occur that global autocorrelation conceals distinct local patterns. Due to this potential problem, the *Moran's Local I* statistic was estimated with the Local Indicator of Spatial Association (LISA) in order to capture local patterns of statistically significant spatial autocorrelations (Almeida, 2012; Travnikar and Juvancic, 2015). In this way, the hypothesis of non-existence of spatial association was tested by comparing the values of each location with the values of its neighbors and conditioning them to the level of statistical significance used in the spatial autocorrelation test at a 5% probability.

Generally, through the municipal GVP between the years 2000 and 2010, it was verified that MS has well-established characteristics regarding the spatial correlations of agricultural production; in the north of the state, there was a strong correlation between municipalities that produce beef cattle and cotton producers, while in the south of the state, the spatial correlations were directly related to soybean, maize and sugar cane crops (Figure 7).

In Figure 7, it was also possible to verify a high spatial correlation of agricultural GDP between the municipalities of 'Nova Alvorada do Sul', 'Rio Brilhante', 'Sidrolândia', 'Maracaju' and 'Dourados'. These municipalities together accounted for approximately 16% of agricultural GDP in the MS between 2000 and 2010. It is important to note that although 'Corumbá' had the highest average annual agricultural GDP of the period (Table 2), there was no spatial correlation for this variable between this municipality and its neighbors. However, there was a strong correlation between 'Corumbá' and its proximities with respect to the beef cattle GVP, being positive in the municipalities of 'Porto Murtinho' and 'Aquidauana' (municipalities in the "Pantanal Region"); 'Rio Verde do Mato Grosso', 'Coxim', 'Camapuã' and 'Água Clara' (municipalities in the "North-Central Region"); and 'Três Lagoas', 'Brasilândia', 'Ribas do Rio Pardo' and 'Santa Rita do Pardo' (municipalities in the "Eastern Region").

This beef cattle spatial autocorrelation in MS occurred because these municipalities were established in areas of marshy plains and predominantly sandy lands, factors that limit agricultural production in this region. There were also negative correlations with 'Sonora' (an agricultural region), 'Bodoquena' (an environmental preservation region) and 'Ladário' (a marshland municipality with low numbers of cattle).

In the Northern Region, there was also a strong spatial correlation of the GVP of the cotton crop between the municipalities of 'Costa Rica', 'Chapadão do Sul' and 'Alcinópolis', which were the 1st, 2nd and 4th largest producers of herbaceous cotton in the state in the years researched. 'São Gabriel do Oeste' and 'Maracaju' (the 3rd and 5th largest cotton producers) did not have spatial correlations with their neighbors at the 5% probability

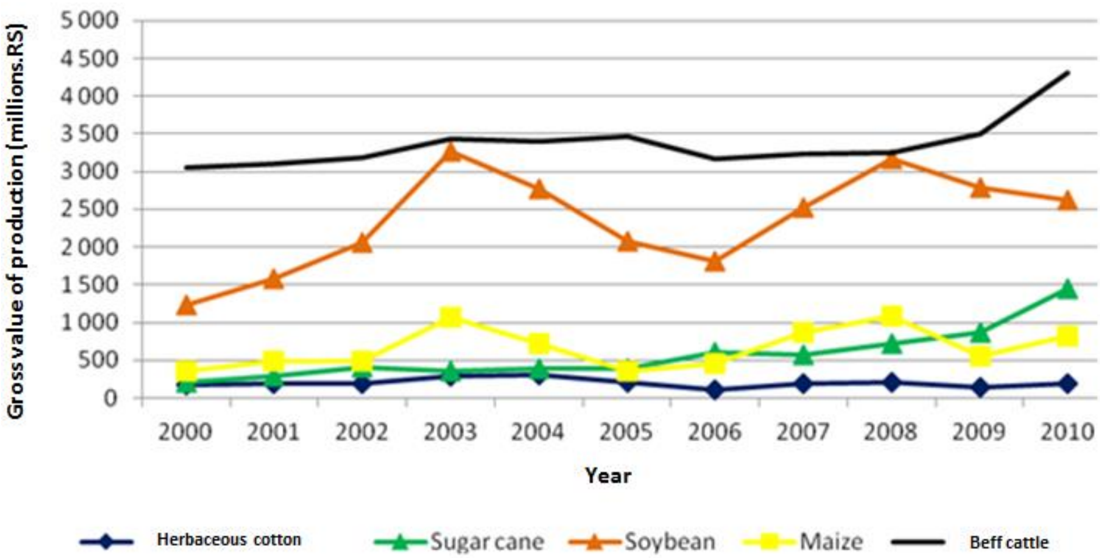


Figure 6. Commodity gross value of production in the Mato Grosso do Sul State from 2000 to 2010. Deflated values corrected to actual values by the Extended National Consumer Price Index (IPCA). Data: IBGE (2015) and MAPA (2015).

level.

In Mato Grosso do Sul State, cotton cultivation began in the Southern Region however, according to AMPASUL (2015), it was only in the 1990s that the cotton crop was developed in the Northern Region of the state, particularly in the municipalities of 'Chapadão do Sul', 'São Gabriel do Oeste' and 'Costa Rica', where cotton developed its new productive profile, resulting from the favorable conditions for the development of the crop and the use of varieties that were adapted to the local conditions, tolerant to diseases and had greater productive potential, together with modern cultivation techniques.

Regarding the culture of sugar cane, there was a high correlation between municipalities in "South-Western Region" (Figure 7). Among the factors already mentioned, such as the provision of fertile land with attractive prices in these places (PAM-IBGE, 2010), two other factors were determinant for sugar-alcohol development in that region: the first was the fact that sugar cane could not be produced in the Paraguay River Basin, and the crop was only released in the Paraná River Basin according to State Law no. 328 of 1982, wherein Article 1 – prohibited the installation of alcohol distilleries and sugar mills in the Pantanal area represented by the Pantaneira Plain Zone as well as in adjacent areas. Another factor is the compatible transmission lines from the Southern Region so that the industry could sell the energy produced by sugar cane bagasse (bioelectricity) to local and neighboring energy companies, according to the Sugar Cane Industry Union (UNICA, 2015).

It was also verified in Figure 7 that the municipalities that had the highest positive spatial correlations for soybean and maize were located in the Southern Region and near the border with Paraguay, confirming the conclusions of Bertholi (2006) that when studying the formation socio-spatial of MS, an increase in the migration of producers from the south of the country who sought fertile land in the state and with lower prices than their home states was found. Another factor was that at the beginning of the decade, producers had access to cheaper (and even illegal) inputs from neighboring countries, thus reducing the cost of production.

Within the "North-Central Region", the municipality of 'São Gabriel do Oeste' was highlighted in the production of soybean and maize, in which it presented a low spatial correlation with its neighbors (Figure 7). The municipalities surrounding 'São Gabriel do Oeste' presented its agricultural GDP based heavily on the production of cotton and beef cattle; in addiction, a larger municipality is formed by a plateau region, characterizing an important agricultural hub producing animal feed for local swine production farms.

Results of estimated models

Three spatial models of global scope were used: the SAR model, the SEM model and the SAC model. According to Lins et al. (2015), the most suitable model will be the one with the lowest AIC and BIC information criteria as well as a higher value for the LIK criterion. Almeida (2012) suggests that if the spatial lag coefficients are not significant, consider that these coefficients will be zero; therefore, there is no evidence that there is a spatial

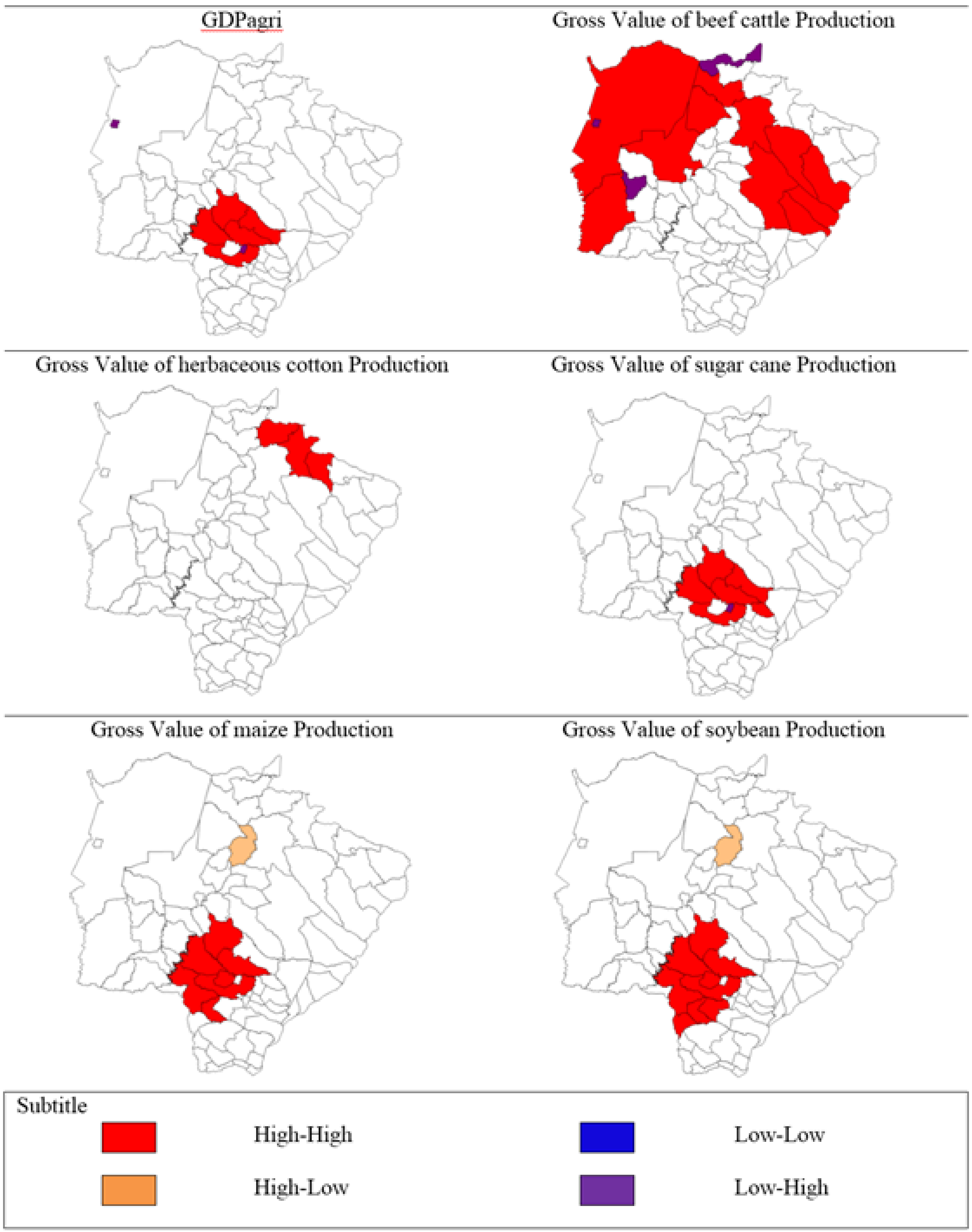


Figure 7. Map of clusters and outliers and their spatial correlations at 5% probability level for the factors evaluated in the period of 2000 to 2010 in Mato Grosso do Sul State.

correlation, either positive or negative.

Since the AIC, BIC and LIK values showed no evident differences among them, it was not possible to choose the most suitable model using these criteria (Table 4). In this sense, was used the coefficient values to distinguish the models. In Table 4, it was also observed that the coefficient λ in the SAC and SEM models were not significant at a 5% probability; therefore, it was neglected. Thus, presenting a significant *p*-value at the studied probability it was concluded that the spatial lag model

Table 4. Estimation of the spatial econometric models for GDPagri 2010 based on the gross values of production.

Variable	SAR		SEM		SAC	
	Coefficient	***p*-value**	**Coefficient**	***p*-value**	**Coefficient**	***p*-value**
CONSTANT	6.969.337364	0.000011	4.594.320652	0.000024	7,429.764123	0.000208
Pop2009	0.035787	0.000000	0.034947	0.000000	0.035225	0.000000
GVPcan2009	0.699196	0.000000	0.689347	0.000000	0.688395	0.000000
GVPmai2009	0.360229	0.000005	0.318835	0.000164	0.317552	0.000119
GVPcot2009	0.679186	0.000000	0.689701	0.000000	0.687465	0.000000
GVPcat2009	0.545381	0.000000	0.550645	0.000000	0.546468	0.000000
GVPsoy2009	0.322314	0.000000	0.341892	0.000000	0.343783	0.000000
ρ	-0.022349	0.032588	-	-	-0.02829	0.091932
Λ	-	-	0.28084	0.145077	0.309783	0.089123
LIK	-740.841.498		-740.659.113		-739.380.344	
AIC	1.499.318225		1.499.682995		1.498.760688	
BIC	1.520.412474		1.520.777244		1.522.198742	

SAR better explains the spatial dependence effect.

According to Almeida (2012), if the spatial coefficient *ρ* is positive, that means that there is a positive global spatial autocorrelation. In other words, a positive *ρ* means that a high (low) value of *y* in the neighboring regions increases (decreases) the value of *y* in the region *i*. If the parameter *ρ* is negative, it indicates that there is a negative global spatial autocorrelation. In other words, it signals that a high (low) value of *y* in neighboring regions decreases (increases) the value of *y* in region *i*.

Therefore, it was possible to verify that the agricultural GDP in Mato Grosso do Sul State in the analyzed period was concentrated in more structured cities, located at the South-Central Region. These municipalities (in which 'Dourados', 'Maracaju', 'Rio Brilhante' and 'Nova Alvorada do Sul') received a good part of the production of the surrounding municipalities, mainly to supply the sugar-ethanol plants and the processing industries of soybean and maize meal as well as being the main suppliers of agricultural inputs to the other municipalities through cooperatives and local trade representatives.

It was also possible to analyze that through the GVP coefficient of sugar cane, this crop contributed the most to the GDPagri. One of the reasons was that the processing of the crop is usually logistically limited to there being a distance within 35 km between the fields and the industry due to the cost of transport (UNICA, 2015). The cotton crop also contributed heavily to the GDP, probably through the state production chain that owned local cotton / producing cotton (AMPASUL, 2015).

Other commodities, such as soybean and maize, had a smaller contribution in the econometric model, as these crops were processed outside the production sites, often being sent to other Brazilian states, even to other countries, departing through the Santos Port or Paranaguá Port (APROSOJA, 2015).

The population effect was also tested to assess the migratory flow and to verify whether this variable has some correlation to the GDPagri, and it was verified that the population direction followed the same spatial dependencies of the analyzed GVPs, tending for people to concentrate in the metropolitan area and improving the economic activity and consequently the GDP of that municipality.

Conclusions

Although the spatial correlation calculated by the *Moran's Global I* statistic was not significant, there was local spatial dependence when the *Moran's Local I* statistic was estimated with the LISA, and it was possible to create clusters in the analyzed period. Among the three spatial econometric models tested, the SAR was the model that best explained the effect of spatial dependence. Commodity metropolization was also observed, that is, the GVP was concentrated in more structured cities, and there were positive and negative spatial autocorrelations among these municipalities. Therefore, the objective of the work was achieved once it was possible to do comparisons between the municipalities and identify their interactions.

Spatial analysis studies are very important because, in the same way that spatial correlations between municipalities can affect in a positive or negative way in regional agribusiness, the impact of these interactions will influence the national and even international agricultural scenario. In MS, if a municipality grows economically, this region could promote the growth in other municipalities and thus raise the GDPagri of the State.

Despite the fact that beef cattle had the highest GVP in the period, swampy plains areas and predominantly sandy soils are limiting factors for livestock production. In addition, the production growth of sugar cane crop allowed for a larger increase in GDPagri, followed by the maize crop. As part of the commodities exporting region, the main impact on MS would be on beef cattle and soybean export, and even on domestic sugar cane market. In this sense, the economic growth of the MS impacts closely on the production of Brazilian agricultural commodities, and thus on the role played by Brazil in the agricultural world scene.

New proposals for studies should emerge after the discussion of this article, increasing the research of novel variables and the support for the methodology and approaches proposed in this study. Thus, by knowing the influence of agribusiness on territoriality and on local development, it will be possible to direct efforts and public policies towards improving the performance of the sector and the quality of life for the residents of a region that occupies a significant global position in the agricultural commodities production.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Conilon plant growth response to sources of organic matter

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In the production of quality plant, it is important to consider the growing substrate since it provides plants with very important physical and chemical characteristics of the soil. Many organic materials of vegetal or animal origin have been used in mixtures of substrates for plant production. This study evaluated the development, quality and physiological components of Conilon coffee plants as a function of substrates containing organic materials of different origins. The experiment was carried out in a greenhouse, in a randomized block design with five treatments: T-Control treatment with 100% of soil and the other treatments with 85% of soil and 15% of organic matter derived from urban waste compost, mature cattle manure, dairy residue, and tannery sludge. Development, quality and physiological characteristics of plants were evaluated. All sources of organic matter favored the development of the Conilon coffee plants in relation to the plant receiving no organic matter in the substrate. Dehydrated tanning sludge in the proportion of 15% provided inferior plant performance compared with treatments with the other organic sources and a greater production of flavonoids. The treatments T-Compound, T-Dairy, and T-Manure provided better results than the other treatments for most of the evaluated characteristics, and can be recommended as components of substrates in the production of Conilon coffee plants.

Key words: *Coffea canephora*, alternate substrate, sustainability, Dickson quality index, multiplex.

INTRODUCTION

Coffee belongs to the genus *Coffea* of the family Rubiaceae. It originates from Ethiopia and is a tree or shrub with a woody, lignified, straight and almost cylindrical stem (Silva et al., 2017). *Coffea canephora*

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Pierre ex. Froehner, also called Conilon, is among the species commercially exploited in Brazil. *C. canephora* is a diploid (2n = 22 chromosomes) plant, self-sterile and alogamous (outcrossing) due to gametophytic self-incompatibility (Conagin and Mendes, 1961; Dalcomo et al., 2017).

Coffee production is an important activity of the Brazilian agribusiness, generating many direct or indirect jobs and accounting for most of the country's exports (Vallone et al., 2009). Coffee is one of the most important commodities in the world trade and its beverage is appreciated in many countries, being consumed by millions of people due to its organoleptic characteristics and its stimulating effect (Alves et al., 2009).

Brazil is the largest producer and exporter of coffee beans in the world, reaching a record harvest in 2016 of 56.1 million bags, with 19% represented by *C. canephora* (Porto et al., 2015; Teixeira et al., 2017). According to census data from the Brazilian Institute of Geography and Statistics (IBGE, 2017), the Conilon (*C. canephora*) coffee had in 2016 a planted area of approximately 431,104 ha, with production of 468,486 tons, with an expected increase of 11% in its production for the 2017 harvest. Dardengo et al. (2013) explained that the increase in coffee plantations is due to the territorial expansion used for planting, renewal of the coffee plantations, and adaptation to the current planting systems.

The initial formation of a coffee crop is a critical phase, and a good initial development of the plants in the field may result in more vigorous plants, with a larger stand, and the ability to express the productive potential to the maximum. According to Mendes and Guimarães (1998), the first step toward success of a coffee production is the use of high quality plants, with green and shiny leaves, thick stem, and large absorbent root system (Henrique et al., 2011).

The main factors for the production of coffee plants are related to the type of substrate, the container, and the matrix used (Silva et al., 2017). The substrate is very important for quality plants, as it is related to the structure, capacity of moisture retention, aeration, nutrition, and other characteristics (Soares et al., 2016).

Nogueira et al. (2011) pointed that there is a significant increase in research related to substrate, which is one of the main agents influencing quality of plants, and species may respond similarly or not to a specific substrate (Gonçalves et al., 2014).

Organic matter is one of the main components of substrates; it increases water and nutrient retention capacity, and reduces apparent and overall densities (Caldeira et al., 2008). Several authors report that the mixture of organic residues to the substrate has promoted improvement of the chemical, physical and biological properties, creating a suitable environment for root growth and whole plant development (Bertone et al., 2007), reducing soil use and, consequently, avoiding risks of contamination by pests and diseases. In addition, it is important to note that the use of soil and consequently avoid risks of contamination by pests and diseases (Vallone et al., 2010a; Vallone et al., 2010b; Sales et al., 2016).

Organic matter also has the ability to change primary and secondary metabolism (Biasi et al., 2009), since it supplies different beneficial or non-beneficial chemical elements. In addition, different sources of organic matter can promote different populations of microbiots and may change plant performance. The use of organic waste of various origins in the production of seedlings may be appropriate to reduce the pollutant effect of such residues in addition to being low cost organic compost (Berilli et al., 2016).

Therefore, the objective of this work was to evaluate the development and physiology of Conilon coffee plants produced in substrates with different organic sources, aiming to obtain plants with greater prospects of success in the field.

MATERIALS AND METHODS

The study was carried out at the Federal Institute of Education, Science and Technology of Espírito Santo - Campus Itapina, located in the municipality of Colatina, in the northwestern region of Espírito Santo in Brazil (19°32'22" S, 40°37'50" O and 71m altitude). The experiment was conducted in a nursery, in the period from February to November 2016, with Conilon coffee plants (*Coffea canephora*) in a randomized complete block design. Five treatments were tested according to different organic sources in the substrate composition, arranged in five replicates for each treatment, with ten experimental plots. The treatments were as follows:

T-Control: 100% soil; T-Compost: a mixture in the proportion of 85% of soil + 15% of urban waste compost; T-Manure: a mixture in the proportion of 85% soil + 15% of mature cattle manure; T-Dairy: a mixture in the proportion of 85% soil + 15% dairy residue; T-Sludge: a mixture in the proportion of 85% of soil + 15% of tannery sludge.

All treatments received 10 g of limestone and 10 g of single superphosphate (SSP) per l of substrate. The soil used for the substrate mixtures is classified as a Red Distrophic Latosol (EMBRAPA, 2013) with characteristics described in Table 1, and classification of soil attributes according to Prezotti et al. (2007). The tannery sludge was supplied by the company Capixaba Couros LTDA ME, located in the municipality of Baixo Guandu – ES, and derived from the processing of bovine leather after dehydration.

Cattle manure was obtained from the facilities of confined animals at the Ifes Itapina campus. Dairy residue was obtained from the dairy company Damare LTDA, located in the municipality of Montanha-ES, derived from the equipment cleaning processes and the factory floor from cheese, butter, whey, and ultra-high temperature processing (UHT) milk productions, with all fat removed by the effluent treatment system (ETS). The urban waste compost came from the Municipal Solid Waste Plant (SWP) in the municipality of Montanha. Table 2 shows the chemical characterization of each organic matter used in the substrates.

The sources urban compost waste and tannery sludge presented the best characteristics for macro and micronutrients, with the highest values of TOM, C, N, K, Fe and Na for the urban waste

Table 1. Chemical soil characteristics used as substrate component for plants.

pH	P	K	P rem	Ca	Mg	Al	H+Al	MO	SB	CEC	t	m	V
	--mg/dm^3--		mg/ml	-------mmol$_c$/dm^3-------				g/dm^3	----mmol$_c$/dm^3----			Percentage (%)	
5.3	4.0	52.0	20.0	11.6	9.3	0.5	14.0	1.5	22.2	36.2	22.7	2.2	61.4
-	B	B	TM	M	M	B	B	B	M	B	B	B	M

B: low; M: medium; TM: medium texture: P rem: remaining phosphorus; MO: organic matter; SB: sum of bases; t: effective cation exchange capacity; CEC: cation exchange capacity at pH 7; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; H + Al: potential acidity; Al: aluminum; m: aluminum saturation; V%: percentage base saturation.

Table 2. Physical and chemical characteristics of the organic materials used in the substrate for plants.

Parameter	Unit	Tannery sludge	Cattle manure	Dairy residue	Urban waste compost
Moisture at 60-65°C	%	8.89	8.52	5.39	7.58
pH in $CaCl_2$	-	7.65	6.78	6.96	7.30
Density	g/cm³	0.6	0.6	0.75	0.6
TOM	%	23.72	46.33	33.17	50.52
C	%	12.98	20.19	17.31	23.08
C/N	-	7/1	10/1	9/1	9/1
N	g/dm^3	17.40	21.00	20.20	24.90
P	g/dm^3	7.21	11.93	4.54	5.63
K	g/dm^3	2.49	7.47	5.64	15.02
Ca	g/dm^3	230.20	21.80	111.10	40.70
Mg	g/dm^3	17.50	5.40	16.90	5.10
S	g/dm^3	83.30	4.50	2.00	5.20
Fe	g/dm^3	2.50	0.40	7.50	8.70
Na	g/dm^3	4.80	3.70	2.40	6.30
Zn	mg/dm³	71.00	357.60	141.60	119.20
Cu	mg/dm³	12.50	135.00	17.00	32.50
Mn	mg/dm³	102.20	553.40	158.50	160.00
B	mg/dm³	409.20	16.10	17.20	39.50
Cr	mg/dm³	60.00	20.00	19.50	36.08

Results on dry matter basis (mass/mass); TOM: Total Organic Matter; C/N: Carbon/nitrogen ratio; C: Organic carbon; N: Nitrogen; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; S: Sulfur; Fe: Iron; Na: Sodium; Zn: Zinc; Cu: Copper; Mn: Manganese; B: Boron; Cr: Total chromium.

compost and pH, Ca, Mg, S, B, Cr for the tannery sludge. The dairy residue presented the worst performance compared to the other sources of Organic Matter.

The plants were planted in 8 x 18 cm plastic bags manually filled with previously mixed materials in the treatment proportions, observing the compaction of the parts. The substrates were rested in the plant nursery of for 30 days before planting the cuttings. Cloning was carried out 30 days after the filling of the plastic bags, using cuttings selected from shoots of clone no. 02, Var. Conilon "VITORIA INCAPER 8142". Variety with recommendation of the planting of clones in line, high vegetative vigor, average yield of 70.40 bags benefited ha, uniform maturation, tolerance to rust and hydric stress At the time of planting, the main stem of the shoot was cut about 3 cm below and 1 cm above the petiole. The secondary stems were cut 1 cm from the main stem, as well as 2/3 of the leaf area. All cuttings were treated by immersion in antifungal solution. Cultural treatments of plants over the experimental period were as recommended by Ferrão et al. (2012).

At 3 and 4 months after planting, foliar spraying of 20 g of urea and 20 g of potassium chloride dissolved in 10 l of water was applied to the plants using a watering can. About 30 min after fertilization, the plants were manually irrigated, so that the excess of fertilizer retained on the leaves was washed. At the end of the experiment, 120 days after cutting preparation, the plants reached planting size and compounds were estimated with a Multiplex® fluorometer (Force-A).

The following compounds were estimated: nitrogen balance (NBI-G and NBI-R), chlorophyll (SFR-G and SFR-R), anthocyanin (ANT-RG and ANT-RB), and flavonoids (FLAV). The measurements were carried out by pointing the device to the canopy, from top to bottom, at an angle of approximately 45°. Multiplex® indices were derived from different combinations of wavelengths emitted by the device.

The following parameters were also evaluated: leaf number (LN); plant height (H), measured from the shoots at the base to the apex of the plant; stem diameter (STD), by a digital caliper; leaf area (LA); fresh and dry shoot mass (SFM, SDM); fresh and dry root mass (FRM, DRM); and total fresh and dry mass of the plant (TFM, TDM). Dry mass was obtained by incubating the material in a forced circulation oven at 72 °C for 72 hours, and then weighing on a precision analytical balance.

To assess plant quality, we evaluated the ratio between plant height and collar diameter (H/CD), ratio between shoot dry mass and roots (SDM/R), and Dickson Quality Index DQI (Dickson et al., 1960) as a function of shoot height (SH), collar diameter (CD), shoot dry mass (SDM), root dry mass (RDM), and total dry mass (TDM) using Equation 1:

$$DQI = \frac{TDM(g)}{\frac{SH(cm)}{CD(mm)} + \frac{SDM(g)}{RDM(g)}} \quad (1)$$

Analysis of variance was performed using the open source program R (R *Core Team* 2016) followed by the Scott-Knott's test at 1% probability.

RESULTS AND DISCUSSION

The statistical analysis of data revealed significant differences between the treatments for several characteristics evaluated. Tables 3, 4 and 5 show the means of the variables in response to the treatments with different sources of organic matter in the substrate and the treatment containing only soil with chemical fertilizer for the Conilon coffee plants, at 120 days after planting. As Table 3 shows, there was no effect of the source of organic matter on the leaf number, and the treatment without organic matter equals the other treatments, wherein all had on average 3 leaves.

Plant height is one of the main characteristics to be observed by Conilon plants and coffee growers in order to determine trade time (Berilli et al., 2014). The lowest means found for this variable were 4.05 and 4.22 cm for the treatments T-Control (without organic matter), and 4.22 cm for T-Sludge (with 15% of tannery sludge and 85% of soil, without significant differences between them. The treatment with cattle manure showed growth of 25% higher than the treatment with tannery sludge, which was the only treatment that differed from the others with organic matter.

Although all treatments showed no significant difference for leaf number (Table 3), the same did not occur for leaf area, and the treatments with urban waste compost, cattle manure, and dairy residue differed from both the treatments with tannery sludge and the treatment without organic matter. This shows that only leaf number cannot be indicative of plant vigor, because leaf size plays a relevant role in plant development, represented by the leaf area, with very important role in plant metabolism. The treatment with urban waste compost had a gain of 130% when compared with the treatment without organic matter.

Thus, it is clear that the urban waste compost provided the plants with a larger leaf area and, consequently, a greater production of photoassimilates, since leaf area is one of the main responsible for photosynthesis and can be characterized according to Silva et al. (2011), as an indicative of productivity. Other authors have reported the importance of the leaf area, including Severino et al. (2004), who affirmed that leaf area has a very important role in plant development, and leaves are the main responsible for capturing solar energy (Table 3).

Stem diameter (Table 3) was the same in the different treatments; however, the use of organic matter can provide the plants with a small gain in this characteristic when compared with the treatment without organic source, except for the treatment with cattle manure. Nevertheless, the treatment with cattle manure resulted in 2.61 mm, which was close to the value found by Vallone et al. (2010a), who reported diameter of 2.66 mm for Arabica coffee plants at 120 days using substrate with 30% of cattle manure, showing that even using twice the organic matter, the results were close. Other authors found no differences for stem diameter in Conilon plants: Braun et al. (2007) and Silva et al. (2010) evaluated different levels of shading and containers, respectively; it is possible therefore to say that this variable is an already intrinsic characteristic of the plant, and hence, it undergoes little influence from sources of variation.

The treatment with cattle manure provided the best result for crown diameter, 119 mm (Table 3). This is probably because the plant has used its photoassimilates mainly for crown gain, since the faster the plant uses its photo assimilates for shoot development, the greater its growth. Table 4 shows the biometric analyzes of fresh and dry matter masses of the shoot and root system. The fresh and dry matter of the root system showed no significant difference among the treatments. Although there was no difference, when comparing the gain provided by the different sources of organic matter, we found that the treatment with dairy residue increased dry and fresh matter of root in more than 40% compared with the treatment without organic matter. Hermann (1964) argued that the dry matter weight of the root is one of the most important parameters to estimate the survival and initial growth of plants in the field.

We found the lowest weight for fresh mass of shoot for the treatment with tannery sludge, which was lower than dairy residue in 128%. Tannery sludge has higher chromium content than the other treatments, and large quantities of this element can be toxic to plants, causing oxidative stress and damaging cell membranes (Berilli et al., 2015). For this reason, tannery sludge showed lower performance than the other treatments, including the treatment without organic matter.

The dry matter of shoot (Table 4) followed the same pattern of the fresh matter, in which the treatments with tannery sludge and the treatment without organic matter were inferior to the others. The organic matter that most stood out for this characteristic was the urban waste compost, with 0.78 g, more than 100% higher than the treatment without organic matter. Oliveira et al. (2002) pointed out that application of urban waste compost to cultivated soils has the capacity to increase the phytoavailability of the nutrients P, K, Ca and Mg, as well as increase the pH and CEC, together with the reduction

Table 3. Morphophysiological analysis of *C. Canephora* plants grown in different sources of organic matter.

Treatment	LN	H(cm)	CRD (mm)	STD (mm)	LA (cm²)
T-Control	3.14[a]	4.22[b]	83.46[b]	2.71[a]	41.65[b]
T-Compost	3.14[a]	4.61[a]	93.50[b]	2.76[a]	96.41[a]
T-Manure	3.32[a]	5.08[a]	119.47[a]	2.61[a]	95.51[a]
T-Dairy	3.36[a]	4.73[a]	97.58[b]	2.92[a]	84.53[a]
T-Sludge	2.99[a]	4.05[b]	87.36[b]	2.99[a]	44.45[b]
OM	3.19	4.54	96.27	2.79	72.51
CV(%)	14.65	6.32	14.39	8.86	12.68

Means followed by different letters in the column are significantly different by the Scott-Knott's test at 1% probability level. OM: Overall mean; LN: leaf number; H: plant height; CRD: crown diameter; STD: stem diameter; LA: leaf area.

Table 4. Biometric analysis of *C. Canephora* plants grown in different sources of organic matter.

Treatment	SFM (g)	RFM (g)	SDM (g)	RDM (g)	TFM (g)	TDM (g)
T-Control	1.38[b]	1.00[a]	0.36[b]	0.36[a]	2.39[b]	0.82[b]
T-Compost	2.85[a]	1.26[a]	0.78[a]	0.44[a]	4.11[a]	1.12[a]
T-Manure	2.75[a]	1.35[a]	0.66[a]	0.43[a]	4.09[a]	1.09[a]
T-Dairy	2.95[a]	1.40[a]	0.56[a]	0.51[a]	4.35[a]	1.07[a]
T-Sludge	1.29[b]	1.14[a]	0.41[b]	0.44[a]	2.43[b]	0.85[b]
OM	2.24	1.23	0.55	0.44	3.47	0.99
CV(%)	20.35	21.90	18.54	16.34	18.58	12.09

Means followed by different letters in the column are significantly different by the Scott-Knott's test at 1% probability level. OM: Overall mean; SFM: shoot fresh mass; RFM: root fresh mass; SDM: shoot dry mass; RDM: root dry mass; TFM: Total fresh mass; and TDM: total dry mass.

Table 5. Analysis of quality of *C. Canephora* plants grown in different sources of organic matter.

Treatment	H/DC	SDM/R	DQI
T-Control	1.57[b]	1.06[b]	0.28[a]
T-Compost	1.68[b]	1.77[a]	0.34[a]
T-Manure	1.95[a]	1.64[a]	0.31[a]
T-Dairy	1.64[b]	1.11[b]	0.39[a]
T-Sludge	1.37[c]	0.93[b]	0.37[a]
OM	1.63	1.30	0.34
CV(%)	10.60	29.00	14.55

Means followed by different letters in the column are significantly different by the Scott-Knott's test at 1% probability level. OM: Overall mean; H/CD: ratio between plant height and collar diameter; SDM/R: ratio between dry matter of shoot and roots; DQI: Dickson quality index.

in soil potential acidity (Table 4). The variables fresh matter and total dry matter had the highest values in the treatments with urban waste compost, dairy residue, and cattle manure, being superior to the treatments with tannery sludge and the treatment without organic matter. The treatment without organic matter was inferior to the treatment with urban waste compost in more than 35% for the characteristic dry matter, thus showing the strong influence that the non-use of organic matter can cause in plants that are at the initial stage of development.

Dardengo et al. (2013) mentioned that there are in the literature different quality indices that serve as an association between plant growth parameters. However, they are commonly used in plants of forest species, and few studies have used these indices in Conilon coffee. Among them, we can highlight the ratio between plant height and collar diameter (H/CD), ratio of dry mass of shoots and roots (SDM/R), and the Dickson quality index, which is one of the best quality indicators for plants (Chaves and Paiva, 2004).

The H/CD index ranged from 1.37 to 1.95, in which the treatment with cattle manure had the best result, followed by the treatments urban waste compost, dairy residue, and treatment without organic matter. The lowest value of H/CD was found for tannery sludge, 12% lower than the treatment without organic matter and 42% lower than the best result (T-Manure). In forest species, a greater ratio between height and collar diameter reflects the accumulation of reserves, ensures greater resistance and

Table 6. Average flavonoid, anthocyanin, chlorophyll and nitrogen balance indices obtained using the Multiplex® equipment on leaves of Conilon coffee plants at 120 days, grown under different organic matter sources in the substrate.

Treatment	FLAV	SFR-G	SFR-R	NBI-G	NBI-R	ANTH-RG	ANTH-RB
T-Control	0.21[b]	1.23[a]	1.19[a]	0.96[a]	0.95[a]	-0.05[a]	-0.73[a]
T-Compost	0.07[c]	1.28[a]	1.23[a]	1.17[a]	1.13[a]	-0.02[a]	-0.66[a]
T-Manure	0.23[b]	1.50[a]	1.43[a]	1.29[a]	0.82[a]	-0.11[b]	-0.75[b]
T-Dairy	0.18[b]	1.53[a]	1.42[a]	1.45[a]	1.26[a]	-0.09[b]	-0.80[b]
T-Sludge	0.29[a]	1.36[a]	1.38[a]	0.91[a]	1.02[a]	-0.10[b]	-0.78[b]
OM	0.19	1.38	1.33	1.16	1.03	-0.07	-0.74
CV(%)	27.99	11.52	12.33	22.97	22.56	25.32	9.49

Means followed by distinct letters in the column differ statistically from one another by the Scott-Knott test at the 1% level. Flavonoids (FLAV), OM and anthocyanin (ANT-RG and ANT-RB), chlorophyll (SFR-G and SFR-R) and nitrogen balance (NBI-G and NBI-R).

better fixation in the soil; but its inversion can cause the plants greater difficulties to stand erect after planting, which can cause damping (Artur et al., 2007), and the same consequences can be associated with the coffee crop.

The ratio between dry matter of shoot and roots showed the best results for cattle manure and urban waste compost, according to Table 5. However, the treatment without organic matter showed no significant difference from the treatments tannery sludge and dairy residue, showing that for this characteristic, the treatment without organic matter was satisfactory. There is a lack of studies on this ratio (SDM/R) for Conilon coffee. However, in the initial phase of development, high values of this variable could be harmful to the crop, since the root system is responsible for the absorption of water and nutrients, and to support the plants, as they will be subjected to adverse weather conditions when taken to the field (Table 5). The results for the Dickson quality index indicated that there was no difference between plants grown with and without organic matter, with results varying from 0.28 in the treatment without organic matter to 0.39 in the treatment with dairy residue. However, higher values were found for plants that used organic matter in their substrate.

Table 6 shows the physiological indices of coffee plants. The indices chlorophyll and nitrogen balance showed no significant differences, but differences were found for both secondary metabolites, flavonoids and anthocyanins. Excitation of the anthocyanins by the green (ANTH-RG) and blue (ANTH-RB) lights showed the same behavior. The highest productions of these compounds were obtained in the treatments T-Control and T-Compost (values closer to zero). According to Lopes et al. (2007), anthocyanins have functions as antioxidants, defense mechanism, and biological function.

This suggests that T-Control may have promoted an increase in the anthocyanins synthesis due to some disturbance or stress, inferring that the non-use of organic matter promotes a greater increase of this metabolite in the plant. However, the same cannot be suggested for T-Compost since the higher values of anthocyanins were not found in the flavonoids. We may associate this result with the higher value of potassium found in organic matter of Urban waste compost (Table 2), as this nutrient is responsible for the synthesis of carbohydrates and proteins (Trevisan et al., 2006), and these plants can use carbohydrates to produce anthocyanins (Table 6).

Regarding the flavonoid index, it is apparent from Table 6 that T-Sludge provided higher production of flavonoids, and this may be associated with the higher chromium content in organic matter of Tannery sludge (Table 6), which may have caused greater stress to these plants, as also observed by Berilli et al. (2016) in Conilon coffee plants. There are several classes of flavonoids such as anthocyanins, flavans, flavones, flavonols, and isoflavonoids (Coutinho et al., 2009), then we may infer that the flavonoid index is not controlled by only the behavior of anthocyanins, which may explain why T Sludge has provided low values of anthocyanins.

The use of the organic matter is as important for plant development as is an alternative for reducing production costs. Its addition to the substrate can provide considerable gains to plants, moreover, a considerable number of organic origin materials are often discarded for their toxicity and the use of these residues in turn, may be an alternative for improving the environment conditions.

Conclusions

Conilon coffee plants produced from cuttings in substrate with 15% organic matter showed a better development performance. The use of organic matter derived from dehydrated tannery sludge induced the plants to produce a higher index of flavonoids. In the morphophysiological analysis, biometric, physiological indices and analysis of quality of *C. Canephora* plants showed that the source of organic matter from the dehydrated tannery sludge presented the resulting minors when compared with other sources of organic matter, evidencing to cause stress and damage to the plant. The plants grown in 15% of organic matter from urban waste compost, cattle manure, and dairy residue favored the characteristics of growth, therefore this organic matter could be used as components of substrates in the production of Conilon coffee plants. The sources of cattle manure and urban waste compost, presented the best performances in the propagation of Conilon coffee plants, followed by the source of dairy residue.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Demographic and socio-economic characteristics of cassava farmers influencing output levels in the Savannah Zone of Northern Ghana

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The research studied the effects of demographic and socio-economic characteristics of cassava farmers on output levels in the Savannah Zone of Northern Ghana. One hundred and fifty cassava farmers were sampled randomly. The data were collected through a structured questionnaire from respondents. The farmers were drawn from three regions that fall under the Savannah Zone. Six districts were purposively selected from the regions. One hundred male cassava farmers and fifty female cassava farmers were considered for the study. An econometric model was specified to determine the relationship between the socio-economic characteristics and cassava output levels. The estimated linear regression model revealed that gender, education, experience, farm size and primary occupation of farmers were statistically significant. Other factors as marital status and land ownership of producers were found to be negative. The findings showed that producers whose primary occupations were not farming do not realise as much output as their counterparts who consider farming as their profession.

Key words: Demographic, socio-economic characteristics, smallholder farmer, cassava, savannah zone, Ghana.

INTRODUCTION

Cassava is regarded as the fastest transition crop globally and remains a staple food for some one billion people in 105 countries the world over, where a third of the caloric needs of the people are met (OECD-FAO, 2015). The relevance of the crop to Africa's age-old problem of food insecurity is not in doubt. The tropical root crop, cassava, could help protect the food and energy security of poor countries now threatened by volatile food prices (United Nations Food and Agriculture Organisation [FAO], 2008a). Cassava in Ghana is largely produced by smallholders on marginal and degraded lands of the humid tropics. Its production is influenced by several factors ranging from geographical to socio-economic. Production levels of the crop have been increasing on a yearly basis and constitute about 22% of Ghana's agricultural Gross Domestic Product [GDP]

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(FAO, 2013b). For sub-Saharan Africa (SSA), cassava is regarded as one of the most important crops due to its ability to withstand extreme weather conditions of the terrain and coupled with its less input demand.

Smallholder farmers remain one of the most important stakeholders in Ghana's agrarian economy. Even though the contribution of agriculture to Ghana's GDP continues to decline, about half of the population are still employed in the sector (FAO, 2015c). Cassava farmers in Ghana are mainly smallholder producers with fragmented land holdings who engage the land to feed their family and sell surplus produce for income. About 90% of the food basket of Ghana comes from these small-scale producers (MOFA, 2011). The operation is rarely held in commercial quantities. Nonetheless the smallholder sector plays a crucial role as far as livelihoods for the vast rural population is concerned. Already job creation and employments are considerable challenges for developing country governments and their private sector partners. According to World Bank about 75 million youth are unemployed worldwide and the International Labour Organisation (ILO) also forecast an increase in unemployment of about 1 million people in the developing world in the next two years (World Bank, 2015; ILO, 2016). Hence, the neglect of the smallholder farm sector, which holds a chunk of the population in the rural areas would only worsen their social and economic conditions resulting in rural-urban mass exodus.

Socio-economic factors continue to play crucial role in determining the levels of production undertaken and the sort of crops planted. The production levels are not the only areas affected but also the way business enterprises are managed which put the socio-economic characteristics of the farmers into focus (von Braun and Mirzabaev, 2015). Previous studies have concluded that if support is to be extended to crop producers in production locations, their basic characteristics are worth studying to fully understand their needs for need-driven assistance. For instance, Mwaniki (2006) stressed that, boosting agricultural production capacity of farmers requires that adequate information about the socio-economic characteristics of the farmers become part of the wider strategy to improve production. Many producers often missed out from supports due to their geographic and socio-economic characteristics and these influence their production output levels. The wealthy ones are easily noted as they have voices to be heard while the poor remain voiceless. Primary areas of interest identified in earlier studies consist of a mixture of some socio-economic and demographic factors.

Presently, this study focuses on the effects of socio-economic factors on output levels and other results of production. Evidence from empirical studies have shown an educational level of farmers to increase their output levels through increase knowledge of the production processes and easy understanding of research materials of new agronomic practices (Seyoum et al., 1998; Hassan and Ahmad, 2005; Kyei et al., 2011). Further, the magnitude of time and efforts needed to convince producers to undertake innovative and improved farming practices are reduced with literate farmers. Illiterate producers are sometimes trivial and unnecessarily focused on the personality of the extension personnel rather than the message (Onubogu et al., 2014). Of late, there is burgeoning concerns for farm size and output level relationship. Continuously, the empirical literature is flooded with arguments for and against farm sizes in productions. Many studies have concluded that the larger farm size is preferable to smaller farm size in terms of outputs obtainable from the production process (Hassan and Ahmad, 2005; ibid). However, findings of other investigators in the same area assert otherwise (Badunenko et al., 2006; Masterson, 2007). Their conclusive assertions lend credence that farms with smaller land sizes produce higher output than their larger size counterparts. There has not been a consensus on this, but quite strangely the approach adopted by researchers from both sides of the block raises more questions than it answers. Importantly, one thing that is driving the debate in a subtle manner is the productivity level of the land or the fertility level of the land under cultivation. That is to say how much is obtained from a parcel of land is a function of several factors rather than just the number of acreages engaged. Additionally, in making a case for either of them, there is always some unintended neglect of the influences of other factors of production in the production process which may lead to erroneous conclusions of one being preferable to the other (Masterson, 2007). Conventionally, age and experience are directly proportional in the smallholder farmer operations. The relationship between age of farmers and their potential output levels has engaged and continue to engage at least for some time. The argument surrounding age as far as efficiency, productivity and output potentials are concern gathered momentum and show no sign of ending anytime soon. Depending on the effects of other demographic and socio-economic factors on age, it can either enhance or reduce the output levels of farmers in production process. According to some studies age influences output levels positively because farming is an activity that the farmers perfect through practice over time (Abdul-kareem and Isgin, 2016; Ören and Alemdar, 2006; Erhabor and Emokaro, 2007; Siddighi-Balde et al., 2014). Other studies conclude otherwise as young farmers being more positioned to realised higher outputs than older farmers (Backman, 2009; Latruffe, 2010; Sibiko et al., 2011; Ramat et al., 2013; Samuel et al., 2014). They hold the view that older farmers may be reluctant to change and sometimes their unwillingness or inability to adopt technological innovations could affect their production abilities leading to low level of outputs realised.

The gender of farmers according to studies has some production implications. Many studies have concluded that male farmers are likely to obtain higher outputs than their female counterparts from the employment of the same factors of production (Abdulai et al., 2013; Asante et al., 2013; Onumah et al., 2013). They contend that in some geographical localities, the culture of the people will likely exclude women in extension information dissemination because they are not considered as farmers like their male counterparts. Also, due to gender alignment issues, extension information content may not address the needs and conditions of women producers. Few researchers, however, assert that the women off-farm time could be used to gain more knowledge and information thereby increasing their knowledge of the production process (Latruffe, 2010; Onumah, 2013b).

Although, there are studies on socio-economic characteristics of other crop farmers in the Savannah Zone, there are a number of reasons this study is worthwhile; considering the relevance and importance of the crop to the Saharan region, basic socio-economic information on its producers would interest policymakers and provide a foundation for other studies involving the crop. The present study intends to model an econometric relationship between those specific characteristics of cassava farmers in the Savannah Zone of Northern Ghana and the corresponding output levels. The relationship between output levels and socio-economic factors is described to produce relevant policy information to agricultural stakeholders and researchers alike. Government has been continuously called upon to streamline policies for the development of the cassava; sufficient policy recommendation cannot be made to stakeholders if proper studies are not done.

MATERIALS AND METHODS

Research area

The study was carried out in the Savannah Zone of Northern Ghana which consists of the Guinea Savannah and the Sudan Savannah zones. The area covers the three northern regions (Northern Region, Upper West Region and Upper East Region) and the northern parts of both Brong-Ahafo and Volta Regions. The Northern Region is located within latitude 10° 39' 0'' N and 8° 6' 30''N and longitude 2° 35' 30''W and 0° 27'30'' E covering an area of 70, 383 km^2. The Volta region is located at 3° 45’ latitude N and 8° 45’ longitude N covering a total land area of 20572 km^2. The Brong Ahafo region is located within longitude 0° 15’ E-3° W and Latitude 8° 45’N-7° 30’S covering a total land area of 39,557 km^2 (Adanu et al., 2013). Upper West and Upper East Regions were not considered for this study though they are part of the Northern Savannah Zone because cassava is rarely cultivated in those regions. The vegetation and climatic condition of this part of the country is characterised by short deciduous trees and shrubs with mono-modal rainfall pattern. Majority of the farmers are small-scale producers involved in mixed cropping and mixed farming systems to guarantee constant food supply in this risky climatic area.

The nature of production of the population and also the sizes of land under production qualify them as typical small-scale farmers. Other empirical studies refer to this group of producers as smallholder farmers. The categorization of small-scale farmers according FAO is in terms of the size of their lands under cultivation. Their primary aim of cultivation is for their own consumption and to sell off surplus for income. Many of the farmers in Brong Ahafo are settler farmers from Upper East and Upper West regions that rent land from owners under some form of agreements. The majority of the producers are engaged in agriculture as their primary source of livelihood even though it is not seen as an occupation by them. There is a belief among some farmers that agriculture is a cultural heritage bequeathed to them by their ancestors.

Data collection

A cross sectional data of one hundred and fifty (150) cassava farmers were sampled randomly in 2014 farming season through a farmer survey. The data were collected in six (6) districts of the regions using a simple random sampling methodology. One hundred (100) male cassava farmers and fifty (50) female cassava farmers were considered for the study. This was done because the numbers of male cassava farmers are more than female counterparts. Information on demographic, socio-economic characteristics of farmers that affect their output levels were obtained using focus group discussions and questionnaire administration.

Data analysis

An econometric model was specified for the study and regression technique used to obtain the estimates of the parameters of farmer specific socio-economic characteristics with their corresponding output levels. Stata 12 statistical software was adopted for the estimation of the parameters. Dummy variables were used to capture the subtle effects of some factors. A multiple linear regression model was estimated using Ordinary Least Square (OLS) technique. The theoretical regression model designed for study is stated as follows:

$$Y_i = \beta_0 + \sum_{j=1}^{K} \delta_j D_j + \sum_{i=1}^{N} \beta_i X_i + \varepsilon_i \quad (1)$$

where Y_i = Quantity of output, βs = A vector of unknown parameters of the variables to be estimated, X_i = A vector of variables influencing output levels, D_i = Dummy variables, δ_j = A vector of unknown parameters of the dummy variable, and ε_i = Error term $\varepsilon i \sim NID(0, \sigma_u^2)$.

RESULTS AND DISCUSSION

In Table 1, the average amount of cassava output realised is 7746.10 kg. The gender variable was modelled into a dummy to obtain the different output levels of male and female producers. The number of years stay in school defines the education variable in the study. The mean age of the farmers is 42. This reflects the fact that the active farming age group still cultivate the crop. Experience as seen in Table 1 refers to the number of years farmer has been farming. The average years of experience are 12. The income level of farmers depicts that of a typical smallholder farmer. Farm sizes are also smaller, averaging around 2.4 acres which is characteristic

Table 1. Descriptive statistics of producers (Field Survey, 2014).

Variable	Minimum	Maximum	Mean	Std. Dev.
Cassava output (kg)	600	31450	7746.10	6621.68
Gender (Dummy Variable male = 1 otherwise 0)	0	1	0.67	0.47
Marital status (Dummy variable married =1 otherwise 0)	0	1	0.81	0.40
Education (number of years)	0	16	6.24	5.26
Age (Number of years)	19	70	42.19	10.62
Experience (Number of years)	2	32	11.96	7.42
Land ownership (Dummy variables Owned = 1 otherwise 0)	0	1	0.80	0.40
Household size (Number)	2	25	8.25	4.04
Farm size (Acres)	0.5	12	2.45	1.80
Primary occupation (Dummy variable Farming = 1 otherwise 0)	0	1	0.53	0.50

Table 2. Estimates of the regression model (Field Survey, 2014).

Variable	Parameter	Coefficients	Std Error	t Stat	P-value
Gender	δ_1	1867.82*	960.92	1.94	0.05
Marital Status	δ_2	-754.41	1031.23	-0.73	0.47
Primary Occupation	δ_3	3064.28***	930.78	3.30	0.00
Land Ownership	δ_4	-539.82	971.13	-0.56	0.58
Intercept	β_0	-4015.60*	2083.34	-1.93	0.06
Education	β_1	218.86**	89.51	2.45	0.02
Age	β_2	67.26	45.44	1.48	0.14
Experience	β_3	162.59**	68.09	2.39	0.02
Household Size	β_4	42.48	97.10	0.44	0.66
Farm Size	β_5	1407.99***	227.46	6.19	0.00
R Square	R^2	0.55	-	-	-
Adjusted R Square	R^2(bar)	0.52	-	-	-
F Statistics	F	18.77	-	-	0.00

Significant at *, ** and *** significant at 10, 5 and 1%, respectively.

of smallholder farmers. The average household size for the study area according to the survey is 8.3. This figure is larger compare to that of the Northern Region of 6.1 (UNEP, 2014). About 80% of the farmers cultivate on their own land.

Empirical model

The empirical model adopted for the study is indicated as:

$$Y_i = \beta_0 + \sum_{j=1}^{4} \delta_j D_j + \sum_{i=1}^{5} \beta_i X_i + \varepsilon_i \quad (2)$$

where Y_i = Cassava output (kg), X_1 = Education, X_2 = Age (years), X_3 = Experience in farming (years), X_4 = Household size (number of persons), X_5 = Farm Size, D_1 = Gender (Male = 1 otherwise 0), D_2 = Marital Status (Married = 1 otherwise 0), D_3 = Primary Occupation (Farming = 1 otherwise 0), D_4 = Land Ownership (Land Owned = 1 otherwise 0), β_i = Coefficient of the input variable, δi = Parameter estimates of dummy variable, and ε_i = Error term $\varepsilon i \sim NID(0, \sigma_u^2)$.

The results of the estimates of parameters in the regression model are presented and discussed in Table 2.

The estimates of the regression analysis as shown in Table 2 indicate that gender, primary occupation, education, experience and farm size were statistically significant. These factors have been shown to be the most important factors influencing the output levels of cassava in the study area and are positively correlated with cassava output. The results also showed that producer-specific characteristics such as age, household size and farm size positively correlated with cassava output levels though some of their estimates were not statistically significant. The regression analysis reported an R-Square of 0.54.68 with a statistically significant F value of 18.77. Other factors as marital status, land ownership and primary occupation of producers were found to be negatively correlated with output levels and statistically insignificant. The findings showed that producers whose primary occupations were not farming do not realise as much output as their counterparts who consider farming as their profession.

F test

H_0: $\delta_1 = \delta_2 = \delta_3 = \delta_4 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$
H_1: At least one of them is different from zero

$$F_{(k-1,n-k)} = \frac{ESS/(k-1)}{RSS/(n-k)} \quad (3)$$

$$F_{(9,140)} = \frac{3572556876/9}{2960584223/140}$$

$$F = 18.77$$

$$F^{*}_{0.05\ (9,140)} = 1.94$$

The null hypothesis was rejected implying the existence of linear relationship between cassava output level and the farmer specific characteristics that influence it. Also, the significant value is an indication that the R^2 of the regression line reflects the true relationship.

Factors influencing output levels

Education of farmers

The estimate of the educational variable was positive and statistically significant at 1% implying educational level increase output of farmers. The finding is consistent with others in the empirical literature (Asadullah and Rahman, 2005; Msuya et al., 2008; Awunyo-Vito et al., 2013). This is apparently due to the fact that educated farmers are able to assimilate materials on improved methods of farming with ease. Even though the educational level of farmers increases outputs, yet surprisingly about 68.7% of the farmers had no formal education.

Experience of farmers

The number of year's engagement in the cultivation of cassava by a farmer is considered the experience. The majority of the producers experiences range from 1 to 20 years. The average year of experience among the farmers is 12 years. Like other business enterprises, experience is crucial to increase output levels in production. Longevity in the occupation exposes the producers to all the nuances in the production process and strengthening them significantly for proper decision making. The estimate was statistically different from zero at 1% significant level. The conclusion is in line with that of Danso-Abbeam et al. (2012). In a study on the technical efficiency in Ghana's cocoa industry, evidence from in the Bekwai district they concluded that farming experience does not only increase efficiency but also increase the quantity of output realised from the farm.

Farm size

Cassava farmers in the Savannah Zone of Northern Ghana are typical smallholder producers. The average number of acres of land used in the cultivation of cassava is 2.4 acres. Commercialisation of the sector is still an issue in Ghana. The concerns range from capital, markets to spoilage. The high water content level of the crop makes it perishable shortly after harvest. The crop is known to be marketed locally with high rate of spoilage. The parameter estimate for this factor is 930.57 and statistically significant at 1% level indicating that an acre increase in farm size leads to 930.57 kg increase in output of cassava. Farmers who have the monetory resources and able to increase their farm size have the tendency to increase their farm output *ceteris paribus*. The findings support that of Onu and Edon (2009), Martey et al. (2012) and Etwire et al. (2013). This means more output are realised with marginal increase in the quantity of land under production.

Primary occupation of farmers

The occupational status of producers of cassava is either primary farmers or they are engaged in farming as a secondary business opportunity. About 43.3% of the farmers are engaged in farming as their main occupation while the rest have other occupations and employ farming as secondary business enterprise. The estimate of this factor in the regression model is positive and statistically significant level of 5%. The finding is similar to the conclusion drawn by Abdulai and Huffman (1998). In their study on the examination of profit efficiency of rice farmers in Northern Ghana, they concluded that rice farmers who were engaged in farming as the main occupation realised more output than those who were not into fulltime farming businesses. The intuition behind this is partly to do with risk.

Farmers would likely do everything to realise more output with knowledge that their only source of livelihood is farming. The non-farm enterprises are supposed to diversify the income structure of the smallholder thereby strongly building them against shocks. The study however revealed that farmers with other businesses do not attach seriousness to the farming leading to low levels of outputs.

Gender and farm size

The interaction between gender and farm size produced a positive statistically significant estimate giving combined increase of 658.28 kg of cassava output. Meaning the gender of a farmer influences the size of land available for production. This is a reflection of a socio-cultural phenomenon that makes situations difficult for female farmers to acquire land for production.

The main challenge of this study was the measurement of output quantities. During the course of the survey, it was realised that the farmers had measurement issues. For this reason a conversion technique was adopted to convert all output quantities into kilograms.

Conclusions

The results of the findings permit us to draw some very important conclusions about the demographic and socioeconomic factors that influence output levels of cassava producers. The purpose of the study was to determine those factors and their level of influences on cassava output in the study areas. The study revealed that gender, education, farming experience, farm size and primary occupation of farmers are the statistically significant factors that affect the output of cassava in the Savannah Zone of Northern Ghana. The results as shown revealed that farmer' output levels were generally low and also they do not use fertilizer in cassava production. According to MOFA/SRID (2013), average output of cassava production is 19.71 mt/acre. However, the average output level realised in the production is 7746.1 kg/acre.

The results relating to farm size are particularly reinforcing the call made by other researchers for the commercialisation of agriculture. Farm size is positively related to production output levels. Again, farmers with higher level of education also produce commensurately higher outputs. This is consistent with empirical knowledge about agricultural production. The intuition is that farmers are able read educational materials and other documents; decipher information on improved agronomic practices. This inevitably increases their output levels. Despite the importance of education to cassava production, the majority of producers were found to be illiterates. It was also observed that the experience gained over a period of time by farmers is an invaluable asset in increasing production output levels.

RECOMMENDATIONS

The situations of the farmers depict typical smallholder farmers characterised with small land areas under cultivations. Efforts to proffer remedy for the present challenges of lower cassava output level facing cassava farmers require cautious planning taking into consideration their demographic and socio-economic situations. Another area that needs attention is the adoption of strategies to make use of experienced farmers. To this effect farmer field schools could be instituted to enable young farmers tapped into the experiences of their experienced counterparts through open field demonstrations. Farmers should also be provided with content related education through extension agents and other appropriate means.

It is recommended that government partners the private sector to promote large scale production or government and development partners make grants and loans for smallholder farmers to increase their farm size and efficiencies. High production potential exists in this industry which could be harnessed by commercialisation. Government should give incentives to farmers to retain the experience ones for increase production and reduce the tendencies of farmers picking up non-farm business enterprises that reduce their focus on the farm business.

Income from cassava production and post-harvest cassava processing represents around one fifth (22%) of Ghana GDP (SRID, 2013). There exist research programmes that strives to find workable solutions to pressing challenges of smallholder farmers. Farmer Participatory Researches should be instituted to include farmers in the search for solutions to their problems. There should be an urgent need to reconsider the current system and structure of agricultural research research for maximum farmer benefits. Ghana's agriculture is still natural and depends so much on rainfall. For the nation as a whole to develop and improve its agriculture potential, irrigation should be promoted. The Technical, Vocational, Education and Training (TVET) programme that is already in place should be redesigned to give much emphasis to agriculture. Small scale producers require tailor-made education to face the difficulties of agricultural production heads on. The Good Practice Centres (GPC) that have sprung across Ghana should be developed further to spur rural economic development through increased technical skills in the cassava value chain.

The cassava crop remains arguably the most promising for sub-Saharan Africans as far as food security is concerned. Cassava production industrialization in Ghana is just beginning to show potentials. However, the potential for starch markets for producers is great. Although the Presidential Special Initiative (PSI) on cassava was formulated, there exist no policy framework as the development of the crop matters. Ghana produces an average of 15 million metric tonnes yearly with about 9 million metric tones available for consumption (SRID, 2013). The surplus is often rot as Ghana is yet to take advantage of international trading in cassava. Trade is usually involves raw cassava at the local level, which is always in the bulk form. With frantic efforts Ghana small scale farmers could sell off their surplus to other processing giants. Gradually cassava starch is replacing other known producers as maize and potatoes. This will trigger an increase in the amount of cassava that will be demanded by industries. Also, the supply chain of cassava offers a very significant opportunity for job creation among producers and locals. Cassava has got numerous uses that have the ability to spur rural community growth and agricultural transformation. The demand for cassava for the manufacturing of ethanol is growing giving farmers chance to increase production quantities. The local markets of cassava are often overlooked, leading wastage as very little is consumed.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Effect of application of flowering inhibitor on sweet sorghum

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Studies on sweet sorghum have been conducted in countries like Brazil, USA, India and Argentina to complement ethanol production. In Brazil, it is cultivated in areas for sugarcane renovation, and can be used in sugarcane industries. However, the use of chemical flowering inhibitor can increase sucrose in stalks, resulting in higher production. Therefore, the goal of the present study is to evaluate the effect of Etefom application on two sweet sorghum hybrids. The experiment was carried out with cultivation in "D" productive environment, using the Nexsteppe J53 and Embrapa BRS511 hybrids of sweet sorghum. Application of the flowering inhibitor was done 70 days after sowing. From the beginning to the end of the experiment, the plants' development was evaluated according to their biometric aspects: height, diameter of the stalk, moisture, tons of stalks per hectare (TSH), tons of dry matter per hectare (TDM), Brix, liters of juice per hectare and liters of ethanol per hectare. Results of flowering inhibitor application in sweet sorghum are dependent on the hybrid used, with a higher response to J53 between 90 and 110 days after sowing.

Key words: Bioenergy, *Sorghum bicolor*, Etefom, ethanol.

INTRODUCTION

The sugarcane sector has been gaining prominence in the Brazilian economy, with an approximate growth of 65% in the sector in the last ten years. There is a prediction that in 2017/2018 harvest, 647 million tons of sugarcane will be produced, in detriment to the 431 million processed in 2005/2006 (CONAB, 2017).

Ethanol and energy are responsible for the production of sugar, and the sector already shows signs of insufficiency in meeting a higher demand, since there is a growing increase in the automotive industry. In 2015, there was an increase from 40 to 50 million of flex-fuel vehicles (UNICADATA, 2017).

In this sense, there is a search for new technologies that can increase the annual production of ethanol in the country, without increasing the production costs and the planted area (Jaiswal et al., 2017), and also, the use of new raw materials that can be grown in sugarcane renovation areas during off-season (Barcelos et al., 2016; Santos et al., 2015).

Among these, sweet sorghum stands out, with a

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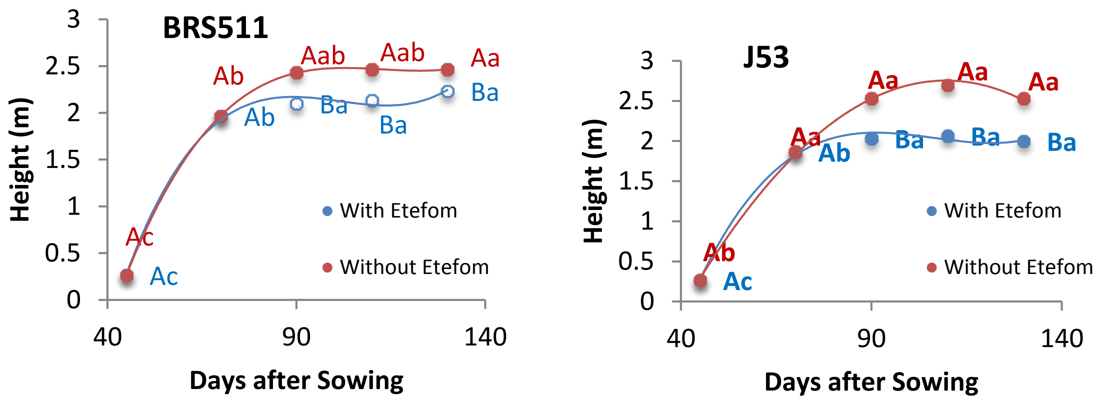

Figure 1. Average values obtained for the height of sweet sorghum stalks, subjected to the application of flowering inhibitor, for BRS511 and J53 hybrids, 2017/2018 Harvest, Bauru-SP.

vegetative cycle of 90 to 120 days, yield of 40 to 60 t/ha, mechanized planting and harvest, the possibility of using agroindustrial infrastructure present in the sugarcane industries, high sugar concentrations in the stalks (Masson et al., 2015) and production of up to 3000 L of ethanol per hectare (Almodares and Hagi, 2009).

However, the useful period of industrialization of this raw material is short, maximum of 30 days, making agroindustrial planning difficult, considering that the harvest can occur in a period in which there are still considerable precipitation indexes in the country. After this period, much of the sucrose stored in the stalks is translocated to the panicles, and stored as starch, with a marked decrease in the amount of juice (Freita et al., 2015).

In this way, there is search for alternatives that can increase harvest and enable adequate management of the crop in off season. Among these, the use of flowering inhibitors, which prevent the formation of panicle, resulting in no displacement of the sucrose from the stalk to the tassel, can be highlighted (Blanco et al., 2017).

Thus, the aim of this study is to evaluate the effects of flowering inhibitor application on sorghum culture.

MATERIALS AND METHODS

The experiment was conducted at the experimental farm of the Universidade Sagrado Coração (USC) located in the municipality of Agudos in the State of São Paulo in 2017/2018 harvest season. The soil of the area is yellow dystrophic Oxisol, the region climate is classified as Cwa subtropical climate, according to Köeppen, and is classified as "D" productive environment. The farm is located at latitude 22.283°S and longitude of 48.980°W with average altitude of 530 m. The experimental area is 400 m^2, with 6 plots of 33 m^2 each, being previously subjected to pH correction (90 days before planting), elimination of weeds, plough and harrowing.

The Nexsteppe J53 and Embrapa BRS511 sweet sorghum hybrids were used. The sowing was carried out on 07 January 2017, using a 3-row seeder, with a rate of 5 to 6 seeds per meter, and 0.5 m spacing between lines. 20 days after sowing (DAS), manual thinning was performed to adjust the final stand of the crop to 110.000 plants per hectare.

The soil fertility correction was adjusted at planting time (180 kg/ha 4-14-8), 29 DAS (500kg/ha 20-5-20) and 45 DAS (200kg/ha 20-5-20). At 70 DAS, Etefom, at a dose of 918 g/ha, was applied through a costal spray, to inhibit flowering. During the development of the hybrid sorghum (45, 75, 90, 110 and 120 DAS), 10 plants per plot were evaluated, considering the following biometric aspects: plant height (cm) (using a graduated ruler); diameter of the third stalk internode (cm) (using a pachymeter) (Abascal et al., 2014); moisture (%) (five stalks were triturated and 100 g was dried in a kiln for 48 h); tons of stalks per hectare (TSH) (10 plants were weighed and extrapolated for 110.000 plants for hectare); tons of dry matter per hectare (TDM) (the weight of TSH descanted from the moisture) (Tavian et al., 2014); Brix (%) (CTC, 2005); liters of juice per hectare; liters of ethanol per hectare (Fernandes, 2003).

The experimental design used was subdivided plots with two treatments and three repetitions. The primary treatments were constituted by the application or not of flowering inhibitor, while sampling times constituted the secondary treatments. Each sorghum hybrid was evaluated separately. The results were subjected to analysis of variance by F test and the averages compared by the Tukey test (5%), using the Agroestat program (Barbosa and Maldonado Junior, 2017).

RESULTS

Figure 1 shows the average values observed for stalk height of the BRS511 and J53 sweet sorghum hybrids subjected to flowering inhibitor application. For the BRS511 hybrid, the growth stopped at 75DAS, whereas for J53, the growth paralysis only occurred at 90 DAS. Considering the inhibitor application, this input decreased plant height values. Figure 2 shows the values obtained for the stalk diameter of the BRS511 and J53 sweet sorghum hybrids.

The stalk diameter of the BRS511 variety showed a decrease in values after 90DAS, with little difference between the inhibitor treatments. The J53 variety, when subjected to the flowering inhibitor at 75 DAS, interrupted its growth. The BRS511 variety showed greater diameter

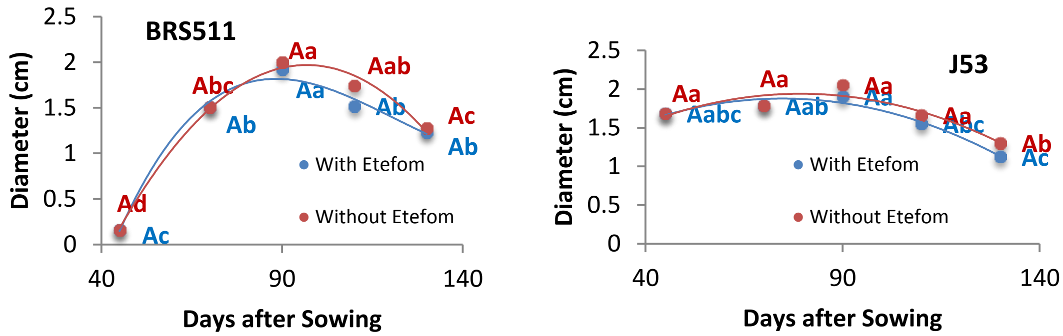

Figure 2. Average values obtained for the diameter of sweet sorghum stalks, subjected to the application of flowering inhibitor, for BRS511 and J53 hybrids, 2017/2018 Harvest Bauru-SP.

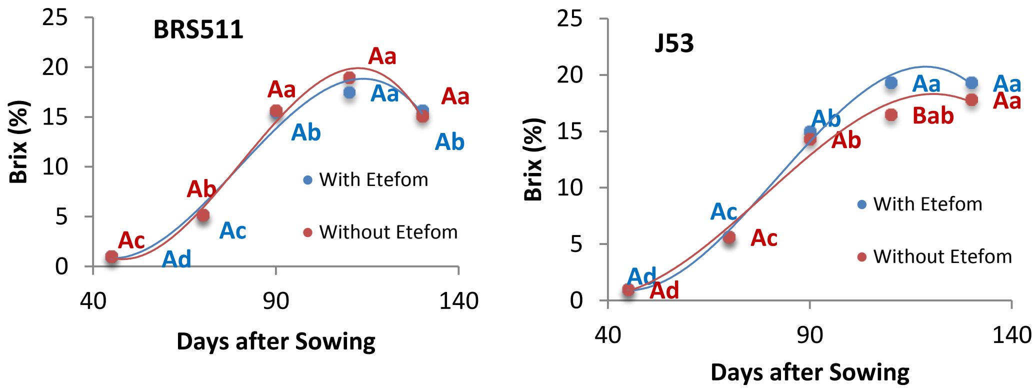

Figure 3. Values obtained for the percentage of Brix in sweet sorghum, subjected to the application of flowering inhibitor, for BRS511 and J53 hybrids, 2017/2018 Harvest, Bauru-SP.

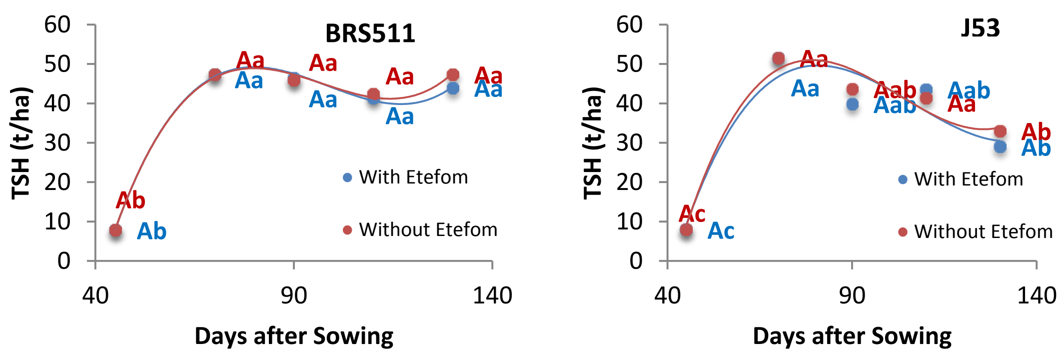

Figure 4. Values obtained for tons of stalks per hectare of sweet sorghum hybrids of BRS511 and J53, subjected to the application of chemical flowering inhibitor, 2017/2018 Harvest, Bauru-SP.

variance from sowing to maturation. Figure 3 shows the values determined for the Brix percentage of the BRS511 and J53 sweet sorghum hybrids. The BRS511 variety showed a percentage of Brix in the control treatment similar to the one with the inhibitor. The J53 variety had the highest percentage of Brix in the sample where the chemical flowering inhibitor was inserted at 110 DAS. Figure 4 shows data for the number of tons of stalks per hectare for each hybrid, with and without the use of the flowering inhibitor.

The BRS511 cultivar presented increasing numbers until 75 DAS; when the inhibitor was applied, the

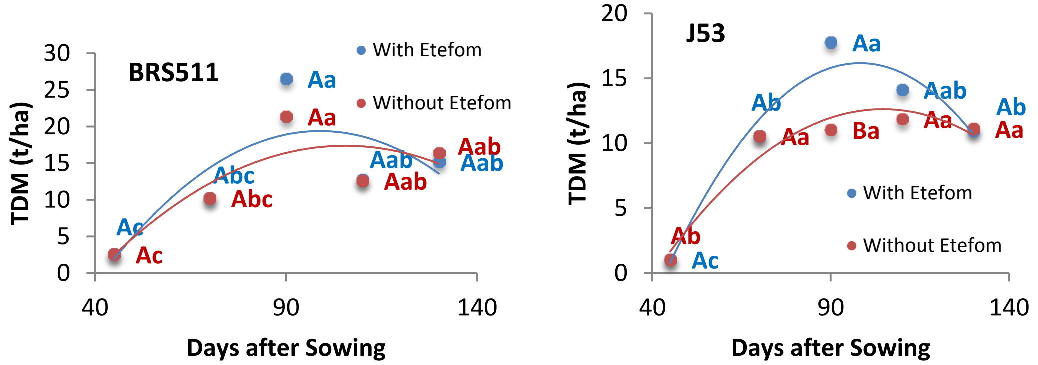

Figure 5. Data obtained for the amount of dry matter content per hectare of BRS511 and J53 sweet sorghum hybrids subjected to the application of chemical flowering inhibitor, 2017/2018 harvest, Bauru-SP.

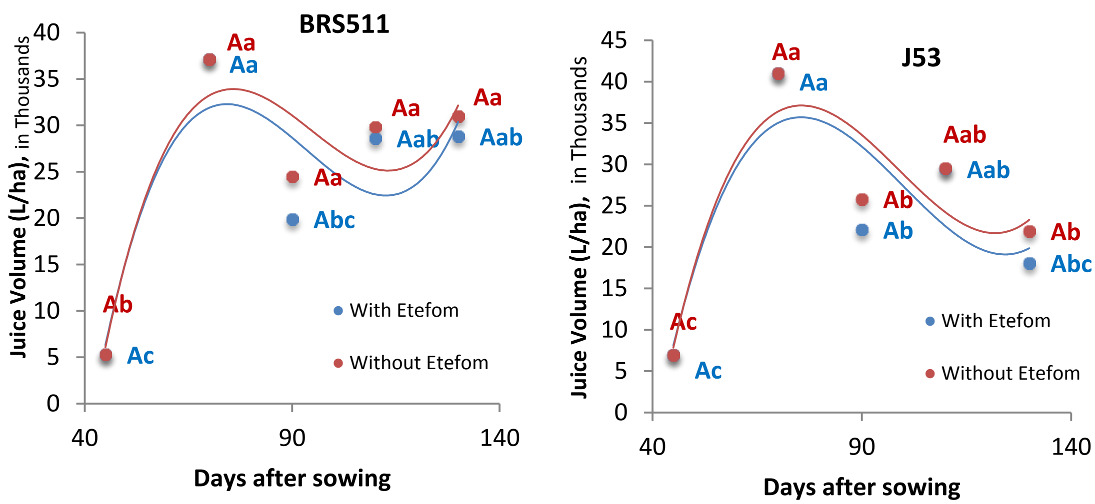

Figure 6. Data obtained for the juice volume of BRS511 and J53 sweet sorghum hybrids subjected to the application of chemical flowering inhibitor, 2017/2018 harvest, Bauru-SP.

numbers reduced and at the end of the cycle, they increased again. The J53 variety presented lower results after application of the chemical flowering inhibitor; however, it did not differ significantly from the sample without treatment. The data for dry matter quantity produced per hectare of the sweet sorghum hybrids subjected to the application of chemical flowering inhibitor are shown in Figure 5. For the BRS511 and J53 varieties, the inhibitor treatments presented better conditions for the dry matter production, especially the J53 variety. Considering the volume of juice obtained per hectare (Figure 6), there was a decrease in this parameter after 75 DAS and increment at the end of the plant cycle for both hybrids and treatments (with and in inhibitor). Figure 7 shows the values of ethanol obtained per hectare for each hybrid of cultivated sweet sorghum subjected to treatment with chemical inhibitor.

The highest values were obtained for J53 hybrid at 110DAS, with application of flowering inhibitor. From 90 DAS, the application of this input in this hybrid resulted in larger quantities of ethanol produced in relation to the control. However, the flowering inhibitor did not result in positive reflections for the BRS511 hybrid, which presented an average of 20% less ethanol produced per hectare of the plant.

DISCUSSION

Considering the physiology of sweet sorghum, it is expected that it will grow until panicle emission, stage where the plant directs metabolites to produce and fill the grains (Borém et al., 2014). This behavior was observed in this study. However, in hybrids that were subjected to

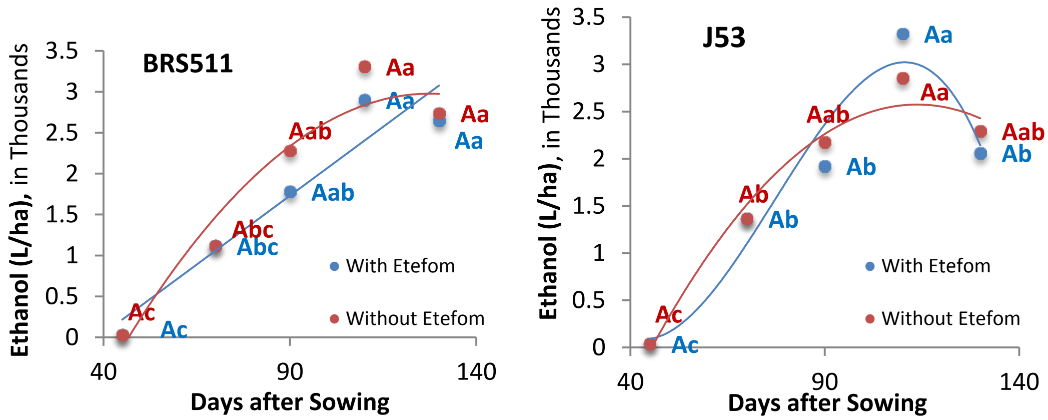

Figure 7. Data obtained for the production of ethanol per hectare of BRS511 and J53 sweet sorghum hybrids subjected to the application of chemical flowering inhibitor, 2017/2018 harvest, Bauru-SP.

Etefom application, the height was lower as compared to the control treatment. It probably occurred because the Etefom stopped the stalks growth, but in the control, the growth of panicle occurred, resulting in increase in height.

The values for height are lower than those obtained by Abascal et al. (2014), who studied the biometry of two hybrids of sorghum cultivated in the region of Jaboticabal-SP and determined values were about 3 m at 130 DAS. The soil of that region is considered "Terra Roxa", "A" environment, while the soil of the research was in sandy "D" environment. Although, the application of flowering inhibitor changed the height, the diameter was not affected by this treatment, for Malibu J53 and BRS511. However, it should be highlighted that in 90 days, this parameter decreased for all treatments. It is expected, because plant losses moisture (Borém et al., 2014). In media, the diameter of stalks were 2 cm, values similar to that obtained by Abascal et al. (2014) and Tsuchihashi and Goto (2004), which determined diameters of 1.70 cm.

The Brix was influenced by Etefom only for hybrid J53, in 110 DAS, stage that showed an increase of this parameter. This result is motivating since the sugars of the plant were not translocated to the panicle during the flowering period. Viana et al. (2017) observed that Etefom increase in 1% Brix of sweet sorghum hybrids BRS508 and BRS509, at 110 DAS, as compared to the control treatment. Therefore, it can be inferred that the Etefom results in different behavior for hybrids. In media, the Brix was 19%, values higher than that obtained by Silva et al. (2016) who found 16.6 for the BRS508 hybrid. Freita et al. (2014), studying the genotypes, CVSW80007 and CVSW80147 determined 18% at 130 DAS. The J53 variety cultivated in the same soil of this research, presented 17.8°Brix at the end of its cycle, as pointed out by Nogueira et al. (2017). Other fact observed was the non-influence of Etefom in TSH. It is important because the goal of this product is only to increase the sugar content of stalk, and increase the harvest period (Viana et al., 2017). However, data from Jardim et al. (2016) indicate that the BRS511 variety can reach up to 69.7 t/ha at the end of its cycle when cultivated in "A" environment soils. The J53 variety, when subjected to cultivation in the same environment in which the research was carried out, can present up to 33 t/ha, as reported by Nogueira et al. (2017).

Although, the Etefom did not affect the TSH, it showed increase of TDM for J53 with flowering inhibitor application. This makes the production of biomass to become interesting. The J53 variety can present up to 11.12 t/ha at the end of its cycle, as pointed out by Nogueira et al. (2017). The greater the dry mass of the plant, the more bagasse the agroindustrial unit will generate, benefiting the energy production. Thus, the inhibitor can also aid in the energetic gain of the factory. Considering that, the juice volume per hectare did not show differences between treatments. It is interesting, because the inhibitor did not promote drying of the stalk. However, this behavior is detected as time goes by. This occurs in function of the senescence stage of sweet sorghum that occurs after the period of panicle emission (Taiz and Zeiger, 2004). These results are similar to those obtained by Gonçalves et al. (2016), who studied the BRS511 hybrid, and determined the production of 33290 L/ha of extracted juice.

The most important information of this study is the increase of 500 L of ethanol produced per area when Etefom is used in hybrid J53, at 110 days. It is interesting, because it promoted the production of 3000 L of this fuel per area, and Almodares and Hadi (2009) obtained the maximum potential of this raw material. Besides that, this value is similar to that obtained for sugarcane producers in Brazil (CONAB, 2017). Considering that the renovation area at 2017 was 12% of the total (CONAB, 2017), it will increase the ethanol production in this country to 3.5 billion liters.

Other point to discuss is that the hybrids of sweet sorghum present a different behavior from the flowering inhibitor, and may even differ in relation to the dosage to be applied. Thus, future studies with different doses of Etefom for BRS511 hybrid may demonstrate different behavior.

Conclusion

The results of the flowering inhibitor application in sweet sorghum are dependent on the hybrid used, with a higher response to J53 between 90 and 110 days after sowing.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Maize leaf area estimation in different growth stages based on allometric descriptors

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The literature points out the need for leaf area (LA) calibration models that are suitable for specific varieties (variety-specific). These models should be capable of coping with different crop conditions, growth stages, and agronomic practices. The objective of the current study was to develop a model for estimating the LA of maize (*Zea mays* L.), considering the entire growth cycle, based on non-destructive allometric measurements. The proposed model was derived from a multiple regression analysis of LA data obtained from digital image processing, including the number of leaves per plant (NL) and the product of major leaf length per major leaf width of the greater leaf (MLL × MLW). A high percent of data variability in the LA of maize plants was explained by the model, both in the calibration and validation phases (R^2 = 0.90; n = 30). Overall, the selected model presented good performance in the estimation of LA of maize, variety PAN 53, cultivated under the conditions of the present study area. Additionally, the model enabled the estimation of LA at different stages of the crop cycle. The results indicated a positive potential for using the developed model to support several maize cultural practices.

Key words: Allometry, non-destructive measurement, modelling, *Zea mays*.

INTRODUCTION

Leaf area (LA) is a determinant factor in many physiological and agronomic processes, particularly in terms of growth, photosynthesis, transpiration, water and nutrients use and productivity (Gao et al., 2012; Nangju and Wanki, 1980; Pandey and Singh, 2011).

Therefore, implementation of operational and accurate processes for measuring and estimating crop LA has long been a concern for researchers. There are currently several approaches for LA determination, which include direct and indirect methods. Direct methods include

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planimetric or gravimetric analyses of leaves, harvested directly or indirectly (Breda, 2003; Jonckheere et al., 2004). Portable scanning planimeters (e.g., LI-3000, Licor, NE, USA) are often used as a reference method for obtaining the LA.

Direct methods are more accurate but have the disadvantages of being very time-consuming, not user-friendly, and having constraints regarding equipment acquisition, price, and operation (Jonckheere et al., 2004). Moreover, direct methods can be destructive, not allowing successive measurements of LA (Peksen, 2007; Rouphael et al., 2010). One of the most frequently used indirect methods for LA estimation is based on observations and measurements of allometric parameters of the plants, which are used as inputs in mathematical models (Montgomery, 1911; Peksen, 2007). Such mathematical models are based on the correlation between the allometric measures of plants and the area of the leaves. These methods are non-destructive and allow for faster LA determination, eventually being suitable for automation. Nevertheless, an adequate parameterization and calibration of such methods is necessary.

The development of model for maize LA estimate based on alometrics has long been a concern for growers, breeders and researchers. A generalized leaf area equation $LA = \alpha \times L \times W$ for maize plants was proposed by Montgomery, (1911), based on a rectangle area $L \times W$ (L – leaf length, W – leaf width) and on a weighing factor (α) equal to 0.75. However, several authors indicated that the weighting factor may vary depending on the maize variety (Bange et al., 2000; Carvalho and Christoffoleti, 2007; Tivet et al., 2001), plant development stage (Bange et al., 2000), environmental conditions and agronomic practices (Elings, 2000; Sezer et al., 2009). Therefore, application of this classic equation requires a measurement of length and width of all leaves on a plant, which is very labour and time consuming, and can be a source of errors.

An alternative approach for estimating the maize LA based only on the largest leaf allometric measurements was developed for varieties adapted to temperate regions (Valentinuz and Tollenaar, 2006). When it was used on tropical varieties, these equations underestimated LA (Elings, 2000). Mondo et al. (2009) estimated maize LA based on one leaf, but not necessarily the largest. Although these models can perform well in estimating the LA at specific stages of the season, their portability to estimate the LA in different stages of maize development are not yet known.

According to Costa et al. (2016), the flexibility of LA models for use at different crop development stages is an important feature to support, throughout the crop cycle, different agricultural practices of high agronomic, economic and environmental importance, such as management of crop water requirements and dosage parameterization of pesticides applications.

The objective of this study was to develop a non-destructive and expeditious method and mathematical model for estimating TLA in the maize crop, variety PAN 53, at different phenological stages. The specific goals included (i) the development of an estimation methodology based on biometric measurements of specific plant leaf using image processing; and (ii) the development of a dynamic mathematical model that estimates the TLA of the crop stems throughout the cultural cycle of the maize.

MATERIALS AND METHODS

The current study was conducted in a field of 3 ha operated by the Joint Aid Management (JAM), a non-governmental organization, in the district of Vilankulo, within the province of Inhambane in southern Mozambique, latitude: 21° 58`S, longitude: 035° 09`E and altitude of 31 m above sea level (Figure 1).

The district of Vilankulo is characterized by a semi-arid to arid climate, with sandy soils of low fertility, and a high risk of agricultural production failure due to drought. The total annual rainfall is 733.9 mm, while the total annual evapotranspiration is 1135.1 mm, and the average annual temperature is 24.5ºC. The hot and rainy season occurs between November and March, with February being the hottest month (average monthly temperature of 26.9°C), and the average rainfall is about 166 mm. The cold and dry season occurs from April to October. July is the coldest month (average monthly temperature of 19.4°C) and drier, with about 17 mm of monthly rainfall.

Maize seeds of PAN 53 variety (from PANNAR Seeds Company) were used for the present study. Sowing was done on June 9, 2015 in the cold and dry season, and following geometry of 0.50 × 0.20 m. A drip irrigation system was used and fertilization was applied during irrigation. Harvest was done in October 2015. The PAN 53 variety has an average maturity, is resistant to major maize diseases and has a potential yield from 8 to 10 t/ha (PANNAR, s/d).

The alometrics measures took place from June to September 2015 in different phenological stages. The Lancashire et al. (1991) phenological stages description was adopted and data were collected at the following stages: plants with 3 (V3), 6 (V6), 8 (V8), 12 (V12) and 15 (V15) leaves unfolded; flag leaf just visible (VT); inflorescence emergence (R1) and medium milk (RT). Fourteen maize plants were randomly selected and monitored at each phenological stage. The recorded variables in each stage were: i) length and width of the largest leaf, ii) number of leaves per plant and iii) height and diameter of the stem. Additionally, in the stages V8 and R1, the full set of leaves of 30 randomly selected plants was collected, identified, marked and transported to the laboratory for measurements of length and width, using a graduated ruler.

The leaves were also digitized using a camera (Sony - Optical SteadyShot ® DSC - W730; 16.1 megapixels; 8x optical zoom), while keeping constant the distance of the image acquisition. The area of each leaf was determined by digital image processing, using the Image J software 1:48 (Wayne Rasband National Institute of Health, USA) and following the methodology described by Glozer (2008). Previous studies have shown reasonable results of LA estimations using Image J software and other image processing software (Costa et al., 2016). In fact, several authors showed the occurrence of no statistically significant differences between the results provided by this approach and the portable leaf area meter (Liquor Inc., Lincoln, Nebraska, US), which is considered the most accurate equipment for measuring LA (Dombroski et al., 2010; Santos et al., 2014).

A linear regression analysis was performed to assess the relationship between the total leaf area (TLA, which is the sum of

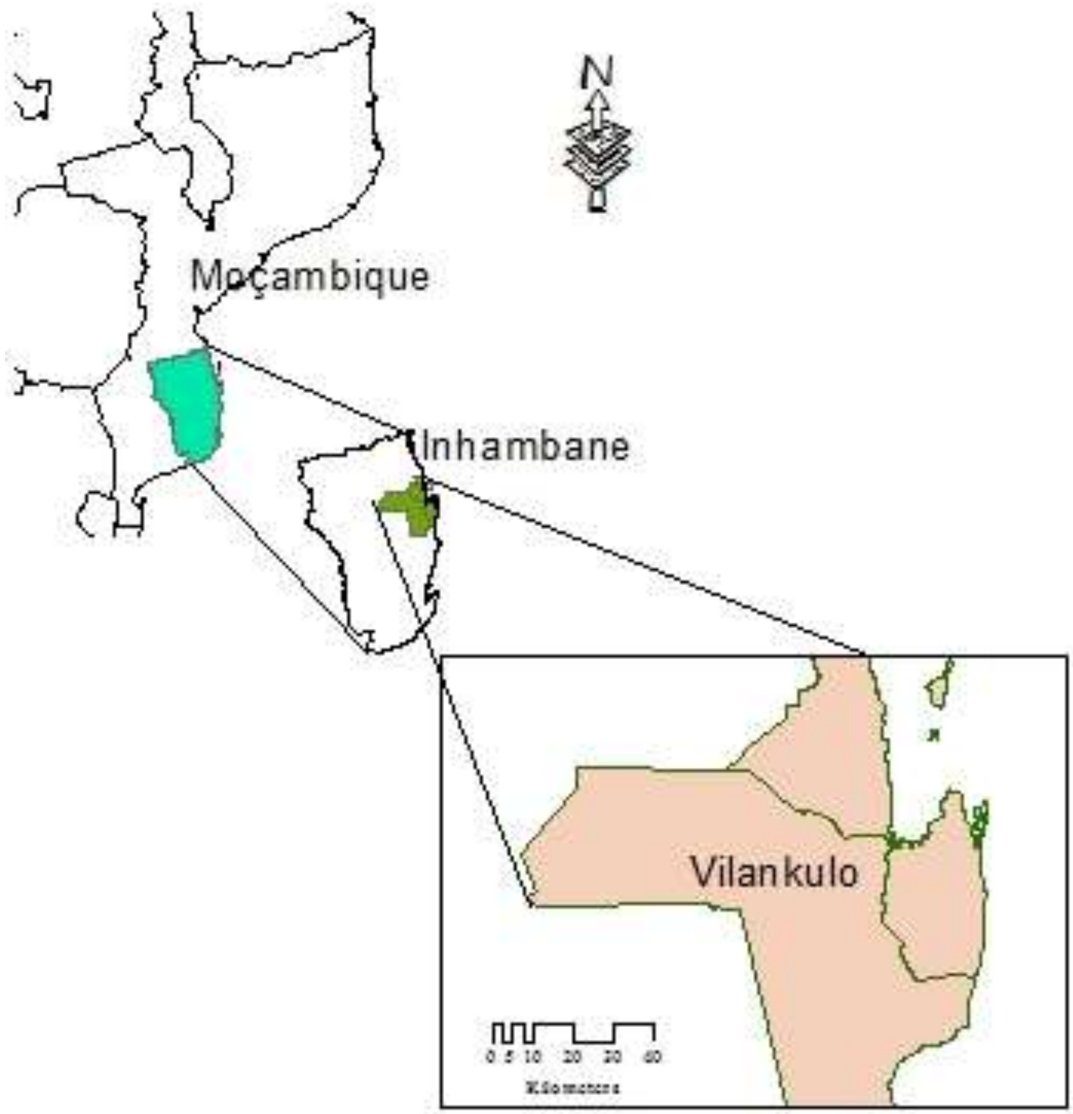

Figure 1. Geographic location of study area in Vilankulo, Mozambique.

LA for all leaves on a plant) and the measured allometric variables.

The dependent variable (TLA) was estimated according to the allometric measurements and their derivatives (transformations), to test the following linear regression models:

$$TLA= \beta 0 +\beta 1 \times NL \times L \times W \quad (1)$$

$$TLA = \beta_0 + \beta_1 \times NL + \beta_2 \times L + \beta_3 \times W \quad (2)$$

$$TLA=\beta_0+ \beta_1 \times NL+ \beta_2 \times L \times W \quad (3)$$

$$TLA= \beta_0 + \beta_1 \times NL +\beta_2 \times L + \beta_3 \times W +\beta_4 \times H + \beta_5 \times D \quad (4)$$

where NL is the number of leaves on a plant; L and W are the length and width of the largest leaf; H is the plant height; D is the stem diameter; β_0, β_1, β_2, β_3, β_4 e β_5 are the regression parameters estimated specifically for each model using the ordinary least squares method. For the model calibration, data from the 60 (30 + 30) plants collected at the phenological stages V8 and R1 were aggregated into one sample. The aggregated sample was then divided into two independent random samples, one used for calibration and the other for validation.

Analysis of variance was performed to test statistical differences (F test) for each model. In addition, the standard deviation (SD) was computed for each parameter, and the statistical significance of model parameters were determined using the t-test. For each model, the normality and homoscedasticity assumptions were tested, and the absence of multicollinearity between independent variables assessed. The normal distribution of the residuals was determined through the Jarque-Bera test (Gujarati, 1995). The Breusch-Pagan test (Breusch and Pegan, 1979) was used to identify the homoscedasticity by testing the dependence of the residuals variance on the independent variables. In both tests, the null hypothesis assumed a homogeneous variance of residuals, or a normal distribution of the residuals. The null hypothesis was rejected for p value lower than 5% for the distribution of $X^2_{(2df)}$. The diagnosis of extreme observations or "outliers" was processed through the leverage test, establishing a maximum acceptable value of 1.5 (Montgomery et al., 2012).

The assessment of the model`s goodness-of-fit was done using the coefficient of determination (R^2), the efficiency coefficient – Nash-Sutcliffe – NSE, the linear regression through the origin and the index of agreement (IoA) between simulated and observed values. The NSE is a standard statistics that compares the relative magnitude of the residual variance with the variance of the observed data (Cunha et al., 2016). It has a range of -∞ to 1; the closer to 1, the more accurate is the model. Compared to R^2, the NSE is less sensitive to differences between the means and variances of the observed and predicted values. However, both are sensitive to extreme values, as reported by Legates and McCabe (1999) cited in (Cunha et al., 2016). The IoA has values ranging from 0 – 1, with 0 indicating lack of agreement and 1 perfect agreement.

Analysis of the residuals between observed and estimated values was used to evaluate the model accuracy and precision. Several indicators were considered: i) the absolute average error (AAE), ii) the mean squared error (MSE), iii) the mean root square error (MRSE) and iv) the relative mean root squared error (RMRSE). The Durbin Watson test (DW) was used for evaluating the auto-correlation between residuals assuming that values close to 2 denote the absence of autocorrelation.

For selection of the model with best performance, the Akaike information criteria (AIC, dimensionless), was also used based on the maximum likelihood function that allows generic comparison of models with different number of predictors. The AIC is calculated as follows:

$$AIC = N x ln\left(\frac{SQE}{N}\right) + 2k \qquad (5)$$

where N is the number of observations, SQE is the sum of square error, and K is the number of parameters + 1. Lower values of AIC indicate better models.

Evaluation of the regression assumptions and the model validation are very important for verifying the model suitability as a forecasting tool when using observations of new independent variables. In fact, the regression model can provide a good fit for the calibration sample data, but not when transposed outside the calibration confidence interval. For this reason, the statistical indicators of both calibration and validation phases, were used for model evaluation and selection. In addition to the statistical indicators, the easiness of application and the biophysical meaning were also taken in consideration.

Two validation procedures were applied: cross validation and external validation. The cross validation was applied over the full set of data (n = 60) using the “leave-one-out” (LOO) cross-validation method (Cunha et al., 2016). The LOO cross-validation evaluates the model performance for observations not considered in the estimation step, thus providing independent estimates of the predictive capability of the selected models. This technique consists of the removal of one observation from the dataset used, and the estimation of a new regression model with the remaining observations. This new regression model is then used to estimate the stem LA.

For the external validation, about 50% of the observations (30 plants) not used in the model parameter estimation, were used to evaluate the quality of the predictive model for these observations. We assume that the quality of the model validation is greater when the values of the indicators MSE, RMSE, AAE and the RRMSE are similar for the calibration and validation samples. The SPSS 23 software was used for the implementation of all statistical analysis.

RESULTS AND DISCUSSION

The dates for the occurrence of phenology and dynamics of plants growth are presented in Table 1. The maximum height (2325 mm) was recorded when plants presented the flag leaf just visible. The growth rate is in agreement with the expected patterns of crop growth (Table 1). Initially, there was an exponential growth up to the 15th leaf stage and hereafter the growth rate becomes very small.

The mean and standard deviation values for all the allometric descriptors presented in Table 2 were very close for the calibration and validation samples.

Predictors and their corresponding regression coefficients for the proposed models tested for estimating the TLA Equations 1 to 4 are presented in the following equations:

$$TLA = 564.2 + 0.48 \times NL \times L \times W \qquad (1')$$

Int. conf. (95%) (-135.4|1263.8) (0.42|0.55)
t_student (0.11) (0.000)

$$TLA = -10834.3 + 415.6NL + 65.7L + 557.5W \qquad (2')$$

Int. conf. (95%) (-13717.4|-7951.3) (308.4|522.8) (38.7|92.7) (363|751.9)
t_student (0.000) (0.000) (0.000) (0.000)

$$TLA = -4672.8 + 420.3NL + 5.9L \times W \qquad (3')$$

Int. conf. (95%) (-6035.4|-3310.2) (315|525.8) (4.4|7.6)
t_student (0.000) (0.000) (0.000)

$$TLA = -8537.9 + 306.1NL + 45.6L + 564.4W + 3.6H + 180.9D \qquad (4')$$

Int. conf. (95%) (-11593.6|-5482.1) (183.9 |428.4) (17.6|73.6) (370.7|758.2) (1.1|6.1) (-79.3|441.1)
t_student (0.000) (0.000) (0.000) (0.000) (0.000) (0.164)

Table 3 presents the statistical indicators for each model, when applied to the calibration and validation samples. Models 2’, 3’ and 4’ show slightly better calibration statistics but there were large differences in the validation statistics, particularly for the residuals indices and AIC (Table 3). The models 2’ and 4’ presented for the validation data-set a value of b in the regression 1:1 much lower than 1 (0.79 and 0.76, respectively) indicating a considerable underestimation when used as predictive tool (Table 3). In the particular case of model 4’, the estimated parameter for diameter and the respective estimation interval are not significant. Instead, model 1’ shows, for the calibration and validation sets, similar results of residual indices and AIC (Table 3), suggesting greater robustness and transferability when compared to the other models. Based upon these findings, the model 1’ was selected for estimating the TLA of maize, variety PAN 53.

The model 1’ explains 90% of the variability of maize TLA at different stages of crop development (R^2 = 0.90, n = 30; P <0.000) in both calibration and validation data-sets. The value of the regression coefficient β_1 was significantly different from zero (t_{test} P < 0.000) and the confidence interval for its estimation does not include

Table 1. Day of the year (DOY) for the occurrence of phenological stages and parameters of crop growth dynamics.

Phenological stage	DOY	Crop height (mm)	Growth rate (mm/day)
Sowing	160	---	---
3 leaves unfolded (V3)	177	67	3.9
6 leaves unfolded (V6)	198	207	6.7
8 leaves unfolded (V8)	211	507	23.1
12 leaves unfolded (V12)	224	1345	64.5
15 leaves unfolded (V15)	231	2094	107.0
Flag leaf unfolded (VT)	238	2325	33.0
Inflorescence emergence (R1)	246	2325	0.00
Medium milk (RT)	273	2325	0.00

Table 2. Descriptive statistics for the allometric descriptors used for model calibration and validation.

Allometric descriptors	N	Minimum	Maximum	Mean	Standard deviation
Number of leaves (NL)	30|30	80|90	140|140	111|117	15|13
Leaf length (mm)	30|30	925|860	1145|1170	1043|1043	57|64
Leaf width (mm)	30|30	78|74	115|116	93|98	7|9
Plant height (mm)	30|30	310|310	2306|2640	1105|1560	804|812
Stem diameter (mm)	30|30	150|220	45|45	30|32	6|6
Total leaf area (mm^2)	30|30	36939|41469	79468|85929	58297|65358	11575|11434

The vertical line separates the statistical indicators for the calibration and validation samples, respectively.

Table 3. The assumptions diagnostic and goodness-of-fit indicators for the calibration and the validation of the models proposed for estimating the total leaf area.

Statistics	Model (1’)		Model (2’)		Model (3’)		Model (4’)	
	Calibration	Validation	Calibration	Validation	Calibration	Validation	Calibration	Validation
Model assumptions								
Leverage test	< 0.1	< 0.1	< 0.1	< 0.03	< 0.06	< 0.06	< 0.16	< 0.16
Jarque-Bera test	17.2	12.2	17.2	12.2	17.2	12.2	17.2	12.2
Beuch-Pegan test	0.55	0.16	0.55	0.16	0.55	0.16	0.55	0.16
Association measures								
R^2	0.90	0.90	0.91	0.88	0.91	0.88	0.89	0.89
R^2 [1:1]	0.89	0.89	0.90	0.87	0.91	0.89	0.93	0.85
b [1:1]	0.99	0.90	0.99	0.79	0.90	0.90	0.99	0.76
NSE	0.90	0.91	0.91	0.89	0.90	0.88	0.93	0.88
IoA	0.84	0.84	0.83	0.81	0.84	0.80	0.86	0.88
AIC	357.7	364.1	359.7	375.7	358.3	375.3	354.3	380.0
Durbin Watson	1.45	1.55	1.43	1.74	1.51	1.69	2.05	1.82
Residual indices								
MSE	131560.7	163339	115578.4	197103.7	118106.2	209252.5	84430	198804.5
RMSE	362.7	404.1	339.9	443.9	343.7	457.4	290.5	445.8
AAE	299.3	328.8	291.3	367.9	284.1	384.7	242.7	329.4
RRMSE	0.06	0.06	0.05	0.06	0.05	0.06	0.05	0.06

zero, which proved its statistical significance (model 1’). Additionally, the application of model 1’ was operational throughout the entire crop growth cycle, while the other models showed limitations by presenting negative values of TLA in the initial stages of crop growth (data not shown).

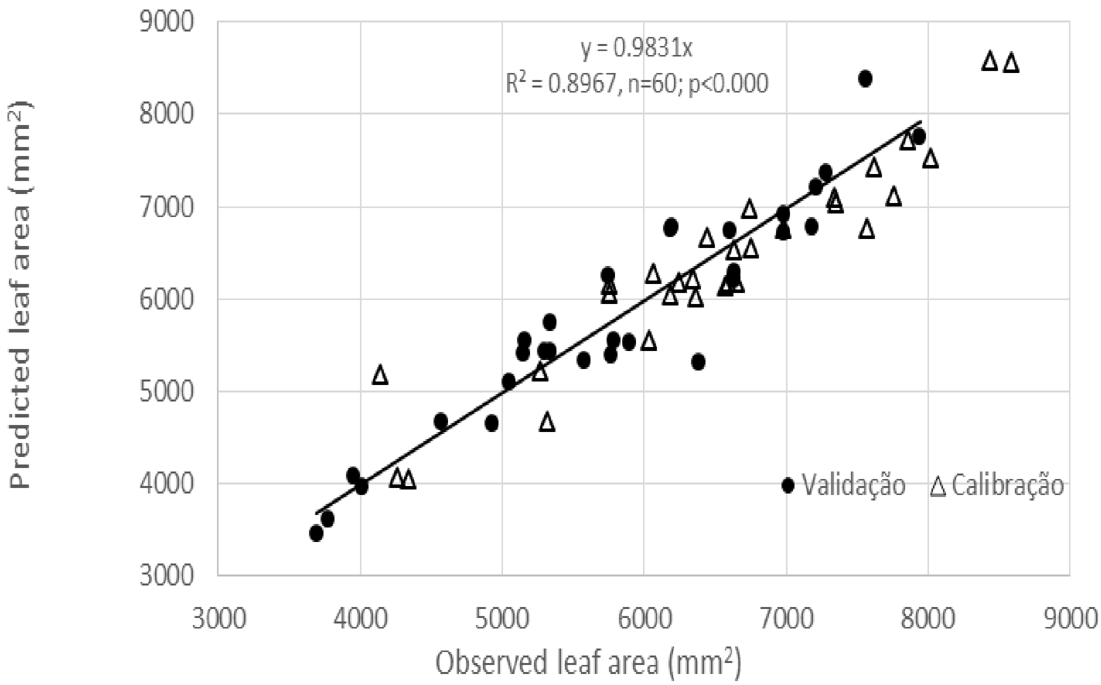

Figure 2. Linear regression through the origin between predicted and observed leaf area for calibration and validation data-sets.

The Jarque–Bera test was statistically significant for both calibration and validation samples, indicating normality of the residual variance, and the homoscedasticity of the variance could be confirmed by the statistical significance of the Breusch–Pegan test (Table 3). The efficiency coefficient for calibration (NSE = 0.90) and validation (NSE = 0.91) are within the range defined for accurate models. Additionally, the model indicates an excellent predictive power, if one considers its high level of agreement (IoA = 0.84). The measures of association suggest strong correlation between observed and predicted TLA, with the coefficient b higher than 1 for both calibration and validation data sets suggesting good accuracy. The slope of the regression through the origin was very close to one (0.99 for calibration and 0.90 for validation) and the coefficient of determination was 89%, showing that the model produced TLA values with high accuracy and precision at different plant development stages (Table 3).

Figure 2 illustrates the relationship between observed and predicted TLA for all data-set (n=60). The slope of the regression line (b) is very close to 1 (0.98), and the value of the coefficient of determination is high (0.89), indicating a good agreement between the observed and predicted values.

The relative difference between observed and predicted leaf area is less than 10% in over 91% of the cases, as shown in Figure 3. The deviations exceeded 10% only in 6.7 and 10% of the cases respectively for the calibration and validation data. The largest deviation (24.6%) was registered in the validation series, with all other cases presenting deviation lower than 20% (Figure 3).

The model relating the product between the number of leaves, length and width of the largest leaf (model 1') proved to be the most suitable for estimating the TLA of maize, variety PAN 53, in the agro-ecological conditions and agronomic practices of the study area. This model performed well when applied to the validation dataset, which suggests its accuracy in forecasting maize TLA. On the other hand, the selected model enabled the estimation of LA at different stages of the crop cycle, unlike other evaluated models which resulted in negative LA values at the initial stages of crop development (data not shown).

Studies using temperate (Valentinuz and Tollenaar, 2006) or tropical (Elings, 2000; Mondo et al., 2009) maize varieties demonstrated that the product of the length and width of the largest leaf is an important descriptor to estimate the total LA. These models were developed for a specific stage of crop development and therefore, do not include the number of leaves as the model developed in the current study. According to Elings (2000), models developed for temperate varieties are not suitable for application in tropical varieties. Likewise, in the current study, an attempt to apply the models developed by Mondo et al. (2009), Sezer et al. (2009) and by Montgomery (1911), resulted in substantially lower fit (R^2 = 0.597, 0.6416 and 0.6453, respectively, data not shown) when compared with the model '1'. As noted by

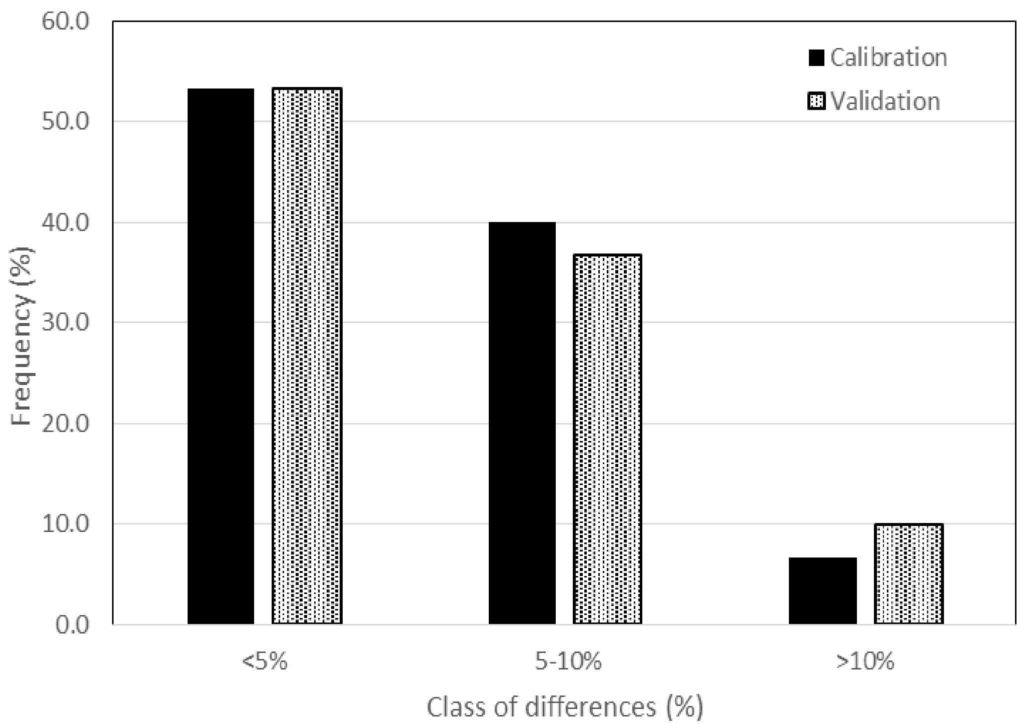

Figure 3. Frequencies (%) of differences between observed and predicted leaf area for calibration and validation sets.

several authors, these differences probably stem from genetic aspects of the studied varieties, agro-ecological conditions and agricultural practices of the study areas (Stoppani et al., 2003; Tsialtas et al., 2008).

Conclusion

The model equation developed from the current study is deemed suitable for estimating the total leaf area of maize plants based on data collected from various stages of the crop cycle. The accuracy of the leaf area estimation results, and the operability of the model developed in the current study are indicators of the model's potential use in different agricultural practices whereby decision-making depends on plant leaf area, such as spraying, fertilization and irrigation as well to support research project.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Genotype × environment interaction and yield stability of Arabica coffee (*Coffea arabica* L.) genotypes

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Lack of suitable varieties that exhibit stable yield performances across wide ranges of environments is the major factor among several production constraints contributing to low productivity of Arabica coffee in Ethiopia. Eleven advanced Limmu coffee genotypes were evaluated in eight environments (four locations over two years) to determine the existence of GEI and yield stability performances. The experiment was laid out in a randomized complete block design of two replications under all locations. Combined analysis of variance showed a highly significant effect of genotype by environment interaction indicating the differential yield response of genotypes across different environments. The major proportion of the variation explained by environments was 42.74% of the total variation. Nevertheless, the contribution of the genotypes to the total variance was much smaller than the environments, and the genotype by environment interaction. Different stability models such as additive main effect and multiplicative interaction (AMMI), AMMI stability value, cultivar superiority index and yield stability index were used for stability analysis. The first two Interaction Principal Component Axis (IPCAs) of AMMI exhibited a highly significant effect and cumulatively contributed about 63.21% of the total interaction sum of squares. Two high yielding genotypes, namely (L52/2001) and (L55/2001), on average, showed stable performance across environments. On the other hand, the study also illustrated the presence of location specific high yielding coffee genotype such as L56/2001. Regarding the test environments, Gera 2015/16 (E5) is considered as a more stable site over the rest environments, while Agaro 2015/16 (E7) was considered to be the most interactive environment. Based on the result of the study, coffee breeders or farmers would be recommended for wise selecting either for location specific or wider adaptable coffee genotypes leading to substantial yield increase under Limmu coffee growing areas.

Key words: Arabica coffee, environment, G x E interaction, stability.

INTRODUCTION

Arabica coffee is the most widely consumed and highly preferred international beverage mainly for its best quality and is also one of the most important agricultural commodities in the world contributing to more than 60%

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of the world coffee production (Van der Vossen and Bertrand, 2015). Particularly in Ethiopia, coffee cultivation plays a fundamental role both in the cultural and socio-economic life of Ethiopians. It represents the major agricultural export crop, providing 20 to 25% of the foreign exchange earnings (ECFF, 2015). The coffee sector contributes about 4 to 5% to the country's Gross Domestic Product (GDP) and creates hundreds of thousands of local job opportunities (EBI, 2014).

Ethiopia is the largest producer of coffee in sub-Saharan Africa and is the fifth largest coffee producer in the world next to Brazil, Vietnam, Colombia and Indonesia, contributing to about 7 to 10% of total world coffee production (Gray et al., 2013). The total area coverage of coffee in Ethiopia is estimated to be about 800,000 ha of land with an annual production capacity of 500,000 tons of which about 95% is produced by 4 million small scale farmers (Berhanu et al., 2015). Despite the high genetic diversity of Arabica coffee and naturally suitable climate condition in Ethiopia, the coffee production and productivity is not yet fully improved. Lack of high yielding improved varieties for each agro ecological zones and lack of suitable varieties that exhibit stable performance across wide ranges of environments are the major constraints in coffee production and productivity in Ethiopia (Bayetta, 2001; Yonas and Bayetta, 2008).

Crop performance is the product of the interaction between the genotype and the environment in which the crop is grown (Acquaah, 2007). The differential response of genotypes to environmental changes refers to genotype x environment interaction (GEI) (Crossa et al., 1990). Significant G x E interaction represents a major challenge to plant breeders to fully understand and obtain the genetic control of variability (Luthra and Singh, 1974). Measuring and understanding G x E interaction and stability performance of genotype should be an essential component in plant breeding programs for the decision making process such as identification of the most relevant testing environments, allocation of resources within a breeding program, and choice of germplasm and breeding strategies (Lean et al., 2016).

In fact, Jimma Agricultural Research Center (JARC) has been conducting coffee research work for about five decades to improve production and productivity in the country. As a result, about 34 improved pure lines and six hybrid coffee varieties were released for the various major coffee growing agro-ecologies of the country. Although, many high yielding and disease resistance varieties were developed and released, the released varieties did not relate to the whole coffee growing region due to the existence of vast and divers agro ecologies in the country. It was shown that, coffees grown under these environments are different in quality, disease resistance and yield potential. Therefore, development of varieties that have the potential for wider adaptation would be of paramount importance to overcome the shortage of improved varieties in the potential coffee growing regions of the country.

In Ethiopia, to increase production and productivity of coffee using stable varieties, the first adaptation tests across different environments was carried out by Mesfin and Bayetta (1987). They reported that some of the genotypes showed poor adaptation to major coffee production areas outside the high land forest which showed location specific nature of Arabica coffee genotypes. Similarly, Yonas and Bayetta (2008), Meaza et al. (2011) and Yonas et al. (2014) also confirmed that varieties that exhibit better adaptation at one location did not perform well at other locations. On the other hand, some reports at the same time stated the presence of high yielding genotypes with regular responses to changes in environment. However, in spite of the G x E interaction impacts on production and productivity of coffee yield, due emphasis have not been given on this particular area of investigation. Based on this evidence, testing coffee genotypes across environments has vital prominence before deciding either for specific or extensive uses of genotypes. Therefore, this study was undrtaken with the objective to determine the existence of G x E interaction and stability performance of Arabica coffee genotypes for bean yield.

MATERIALS AND METHODS

Description of experimental site

The trials were conducted in different major coffee producing agro ecological zones of southwestern Ethiopia, Oromia Regional state at four specific places: Jimma, Agaro, Manna and Gera for two consecutive cropping seasons (2014/15 and 2015/16). The first three locations represent mid altitude, while Gera represents high land area. Description of the testing locations with some of their climatic and soil characteristics are presented in Table 1.

Experimental materials

The experimental materials used in this study comprised 11 Arabica coffee (*Coffea arabica* L.) genotypes. The genotypes were the only common genotypes at all locations; obviously the trials consisting of thirteen genotypes and therefore, the genotypes which did not exist at all locations were not incorporated in this study. The genetic materials were selected from Limmu Kossa and Limmu Seka collection of 2001 based on their yield, cup quality and disease resistance during the initial investigation at Gera and Agaro research centers. The geographical origin and description of the experimental materials are presented in Table 2.

Experimental design and management

Randomized complete block design (RCBD) was used and treatments were replicated two times in each location. The experimental plots consisted of ten trees 2 m x 2 m between rows and between plants have a plant density of 2500 per hectare. All field management practices were conducted according to the recommendations for the crop in the region (Endale et al., 2008).

Table 1. Descriptions of the study areas.

Location	Altitude (m.a.s.l)	Latitude	Longitude	Temperature (°C)		Annual rainfall (mm)	Soil	
				Min	Max		Type	pH
Jimma	1753	7°40’37’’N	36°49’ 47’’E	11.3	26.2	1531.8	Redish brown/nitosols	5.2
Agaro	1630	7° 50’35”	36°35’E	12.4	28.4	1616	Mollic Nitosols	6.20
Gera	1940	7°7’ N	36° 0’E	10.4	24.4	1880	Loam	NA
Manna	1600	7°49’N	36°41’E	13	24.8	1467	Nitosols & Combsol	NA

Source: Jimma Agricultural Research Center, Center profile.

Table 2. Description of coffee genotypes used in this study.

S/N	Genotypes	Place of origin		Altitudes (m.a.s.l)	Characteristics
		Woreda	Specific place		
1	L01/01	Limmu Kossa	Weleke	1550	High yielder, vigorous, stiff stem, Internediate canopy nature, many primary and secondary bearing branches, medium quality
2	L03/01	Limmu Kossa	Weleke	1550	High yielder, vigorous, compact, late maturing nature, many primary and secondary bearing branches, moderate CBD resistance, medium quality
3	L32/01	Limmu Kossa	Mecha	1500	Moderate yielder, compact, stiff stem, resistant to CLR and CWD, good performance, medium quality
4	L45/01	Limmu Kossa	Eledi	1660	High yielder, large number of fruits on top to bottom branches, vigorous, compact , moderate to CLR, medium quality
5	L52/01	Limmu Kossa	Eledi	1660	High yielder, vigorous, large fruit size, many primary, secondary and teritiary bearing branches, moderate to CLR & CBD, medium quality
6	L54/01	Limmu Kossa	Kolba	1500	Moderate yield, vigorous, open canopy, moderate to CLR , medium quality
7	L55/01	Limmu Kossa	Gube A/Mada	1500	Medium yield and quality, vigorous, Compact, resistance to CWD, CBD and CLR
8	L56/01	Limmu Seka	Osso	1500	Good yielder, vigorous, moderate to CBD, acceptable quality
9	L63/01	Limmu Kossa	Weleke	1550	Good yielder, moderate to CLR and CBD, medium quality
10	L67/01	Limmu Kossa	Eyru	1600	High yielder, moderate to CLR, medium quality, flexible nature of stem
11	L68/01	Limmu kosa	Eyru	1600	High yielder, large fruit size, acceptable level Compact , vigorous, large number of primary, secondary and teritary bearing branches, good quality, tolerant to CLR

Source: JARC Coffee Breeding and Genetics Division data base.

Data collected

Total fresh cherry yield was harvested and recorded in grams from ten trees in a plot and used to compute mean yield per each tree. Clean coffee yield in kg/ha was obtained by multiplying the yield of the fresh cherry by percent out-turn.

Statistical analysis

Analysis of variance (ANOVA) was done for each location separately based on the the standard procedure developed for a randomized complete block design. Bartlett’s (1974) test was used to determine the homogeneity of error variances between environments. Comparison of treatment means was done using least significant difference (LSD). A combined analysis of variance was done to determine the significant effects of the genotypes, environments and their interactions. The SAS version 9.2 (SAS, 2008) statistical software was used for statistical computations and estimation of differences among genotypes. The effects of the genotypes and environments as well as their interactions were determined from ANOVA. Analysis of genotype stability across eight environments (locations and years) was computed using Additive Main effect and Multiplicative Interaction (AMMI), AMMI stability value (ASV), cultivar superiority index (Pi) and yield stability index. The detail of each stability model is separately presented as follows:

AMMI model which combines standard analysis of variance with principal component analysis (PCA) analysis was used to investigate genotype x environment interaction. To show a clear insight into specific GE interaction combinations and the general pattern of adaptation, a biplot of genotype and environment interaction (Kempton, 1984) was developed. In the AMMI1 biplots, the first IPCA was used as ordinate (Y-axis) and the main effects or means of genotypes and environments represented abscissa (X-axis). AMMI2 biplot is generated using genotypic and environmental scores of the first two AMMI components. The AMMI analysis was done using GenStat version 16th software according to the model suggested by Crossa et al. (1990).

$$Y_{ij} = \mu + G_i + E_j + \left(\sum_1^n K_n U_{ni} S_{nj}\right) + Q_{ij} + e_{ij}$$

Where: i=1, 2…….11; j=1, 2….8; Y_{ij} is the performance of the i^{th} genotype in the j^{th} environment; μ is the grand mean; G_i is additive effect of the i^{th} genotype (the genotype deviation from the grand mean); E_j is additive effect of the j^{th} environment (the environment deviation from the grand mean); K_n is Eigen value of the IPCA axis n; U_{ni} and S_{nj} are score of genotype i and environment j for the IPCAs; Q_{ij} is residual for the multiplicative components; e_{ji} is random error.

AMMI stability value (ASV), which is stability value based on the AMMI model's IPCA1 and IPCA2 values for each genotype and each environment was calculated as suggested by Purchase (1997). The larger the ASV value either negative or positive, the more the genotypes specifically adapted to certain environments. Conversely, lower ASV values indicate greater stability of genotypes to different environments (Purchase, 1997).

$$\text{ASV} = \sqrt{\left[\left(\frac{\text{IPCA1 SS}}{\text{IPCA2 SS}}\right)(\text{IPCA1 score})\right]^2 + (\text{IPCA2 score})^2}$$

Where, $\frac{\text{IPCA1 SS}}{\text{IPCA2 SS}}$ is the weight resulting from dividing the sum of IPCA1 squares by the sum of IPCA2 squares.

Cultivar superiority index (Pi) was done using GenStat version 16th software as described by Lin and Binns (1988). Mathematically, the value of Pi was obtained as follows:

$$Pi = \frac{(Y_{ij} - Y_{ij}max)^2}{2n}$$

Where, *Y* is the yield means of the *i* th genotype in the *j* th location, Y_{ij} max is the yield mean of the genotype with maximum yield in the *j* th environment and nl is the number of environments. A small Pi value indicates a better fit of a genotype to this stability concept.

The new approach known as yield stability index (YSI) that was developed by Mahmodi et al. (2011) is recommended as a measure of genotype stability. YSI incorporate both mean yield and stability in a single criterion. Low value of this parameter shows desirable genotypes with high mean yield and stability.YSI is calculated as:

$$YSI = RASV + RY$$

Where, RASV is the rank of AMMI stability value and RY is the rank of mean yield of genotypes across environments.

RESULTS AND DISCUSSION

The combined analysis of variance for yield of the tested coffee genotypes is shown in Table 3. The result showed that testing environments testing environments were significantly different at P<0.05. The significant difference observed between environments indicates that the mean bean yield value of genotypes differed from one environment to another due to dissimilarity of environments. In this case, unpredictable variations such as fluctuating features of the environment for instance; rainfall, relative humidity, temperature and soil characteristics might cause differential performances of genotypes from one environment to another environment. Fehr (1993) also reported that every factor which is a part of the environment has the potential to cause differential performances of the genotypes that is associated with genotype x environment interaction. Similar findings on the existence of genotype x environments were also reported by many authors (Mesfin and Bayetta, 1987; Meaza et al., 2011; Yonas et al., 2014). The genotypes also revealed highly significant difference (P<0.01). The significant difference among the genotypes demonstrated the presence of variability in the inherent genetic constitute of the *Coffea arabica* L. genotypes tested.

The result of the study also indicated the existence of genotype by environment interaction and the interaction was highly significant (*P<0.01*) reflecting the differential response of genotypes in various locations and seasons. This variation could be attributed to differences in climatic and edaphic conditions at different testing environments. In the presence of the G x E interaction, the phenotypic expression of one genotype might be superior to another genotype in one environment but inferior in another environment. Hence, such presence of a significant G x E interaction complicates breeding strategy because superiority of genotypes across environments cannot be identified by considering their mean performance and the need to develop genotypes that are adapted to specific environmental conditions or the need to identify genotypes that are exceptional in their stability performances across environments. Similarly, the significant effect of G x E interaction in Ethiopia in different types of the quantitative traits of Arabica coffee was reported by previous researchers (Mesfin and Bayetta, 1987; Meaza et al., 2011; Yonas et al., 2014). Agwanda and Owuor (1989) and Agwanda et al. (1997) with Arabica coffee and Montagon et al. (2000) with *Coffea canephora* also reported the presence of

Table 3. Combined analysis of variance for bean yield (kg/ha) of tested coffee genotypes across environments during the 2014/15 and 2015/16 cropping seasons

Source of variation	DF	Sum Square	Mean Square
Genotypes	10	8764603.52	876460.35*
Environments	7	40228113.74	5746873.39**
R (Env)	8	5229984.29	653748.04**
GEI	70	30417114.02	434530.20**
Error	80	9465535.29	118319.19
Total	175	94105350.86	
Mean=1239.02 CV = 27.76			

*, ** = Significant difference at P<0.01 and P<0.05; CV = coefficient of variation, DF=degree of freedom; Env= environment, GEI = genotype x environment interaction, R=replication.

Table 4. ANOVA of AMMI model for bean yield (kg/ha) of tested coffee genotypes across locations during the 2014/15 and 2015/16 cropping seasons.

Source of variation	DF	SS	MS	% explained
Total	175	94105371	537745	
Treatments	87	79409845	912757**	84.38
Genotypes	10	8764625	876462**	9.31
Environments	7	40228128	5746875**	42.75
Block (Env)	8	5229987	653748**	5.55
GEI	70	30417093	434530**	32.32
IPCA1	16	11606145	725384**	38.15
IPCA2	14	7624438	544603**	25.06
IPCA3	12	5393035	449420**	17.73
IPCA4	10	3476200	347620**	11.43
IPCA5	8	1287481	160935^{ns}	4.23
IPCA6	6	716084	119347^{ns}	2.35
Residuals	4	313710	78427^{ns}	1.03
Error	80	9465539	118319	

*, ** = Significant difference at P<0.01 and P<0.05.

significant genotype × environment interaction in bean yield and yield components.

Additive main effects and multiplicative interaction (AMMI) analysis for bean yield

In this study, the estimated magnitude of different variance for yield variation of the genotypes tested across environments showed that the largest portion of variation was accounted to environment contributing to the bean yield of Arabica coffee with 42.75% (Table 4). The large sum of square and highly significant mean square of environment indicated that the environments have significant influence on bean yield performances of the genotypes tested. Genotypes and G × E interaction accounted for 9.31 and 32.32% of the total variation explained, respectively (Table 4). The current finding indicated that bean yield of genotypes was found to be significantly affected by changes in the environment, followed by G × E interaction and genotypic effect. Thus, the large differences among environmental means causing most of the variation in bean yield of Arabica coffee was mainly due to environments.

The result is in agreement with the discoveries of Yonas and Bayetta (2008), Meaza et al. (2011) and Yonas et al. (2014) who reported the significant influence and/or largest portion of environments on Arabica coffee bean yield performances.

Genotype by environment interaction effects were further partitioned into six possible interaction principal component axes (IPCA) along their contribution of sum of squares with decreasing importance (Table 4). Among these, the first four IPCAs exhibited highly significant difference (P<0.01). The first and second interaction principal component axis (IPCA) explained 38.15 and

25.06% of the total variation accounted by the G × E interaction sum of squares, respectively (Table 4). The third and fourth interaction principal component axis (IPCA3 and IPCA4) explained 17.73 and 11.43% of sum of squares of G × E interaction, while the first four IPCAs cumulatively explained 92.37% of sum of squares of G × E interaction (Table 4). Meaza et al. (2011) also reported significance of first four IPCAs for Arabica coffee bean yields which is in agreement with the current finding. The cumulative sum of squares of the first two IPCAs accounted for a total of 63.21% of the interaction. The first six interaction principal component axis (IPCA 1-6) accounted for 98.95% of total G × E interaction, leaving 1.05% of the variation in the residual. The first two principal components showed sum of squares greater than half of all and evaluation using F-test revealed highly significant $P<0.01$, indicating the capability of the first two principal components axis for cross-validation variation explained by G × E interaction (Zobel et al., 1988; Gauch and Zobel, 1996).

Stability analysis

AMMI 1 biplot for yield

In Figure 1, the mean yields of the genotypes grown across different environments, the environment means and the first IPCA scores can be clearly understood. Based on the biplot analysis, genotypes or environments with large IPCA1 scores, either positive or negative had large interactions, whereas genotypes with IPCA1 score of zero or nearly zero had smaller interactions and was considered as stable over wide range of environments (Crossa et al., 1990; Gauch and Zobel, 1996). Accordingly, genotypes G4 (L45/2001), G9 (L55/2001), G7 (L63/2001) and G11 (L67/2001) had low IPCA1 value closest to zero score indicating that these genotypes were more stable than other *C. arabica* L. tested (Figure 1). However, for genotypes to be stable or generally adaptable to all environments, the genotypes should attain above average mean performance and the IPCA score would be nearly zero. Therefore, genotypes G9 (L55/2001), G7 (L63/2001) and G4 (L45/2001) registered above average yield together with the IPCA1 score close to zero, whereas, G1 (L68/2001) with low average mean performances was the most unstable as its IPCA1 score is largest when compared with the others, while G9 (L55/2001) showed the most stable performance than the rest *C. arabica* L. genotypes tested.

Environments with IPCA score located farther away from the origin in the biplot interacted more with the genotypes and made the selection difficult. In this study, E7 was high yielding environment but the most interactive as its IPCA1 score is largest when compared with the others. On the other hand, the environments E8, E5 and E4 had IPCA1 score close to zero (Figure 1), but low yielding environments, except E5 which have above average yield. E5 (Gera) is characterized by high altitude, high rainfall, cool temperature and long maturity period; thus, genotypes constantly exploit their genetic potential giving average mean yield under this particular location. Moreover, this biplot also indicated E7 as the highest yielding environment and E8 as the lowest yielding environment. In general, high yielding environments were sparsely distributed in quadrant II (E1, E5 and E6) and III (E2 and E7), while the lower yielding environments were sparsely distributed in quadrant I (E3, E4 and E8); but none of the environment was plotted in quadrant IV (Figure 1). In addition, genotypes plotted in quadrant II G4 (L45/2001), G5 (L54/2001), G9 (L55/2001) and G10 (L56/2001) and quadrants III G3 (L52/2001) and G7 (L63/2001) were also high yielding genotypes, while genotypes plotted in quadrant I G6 (L03/2001) and G8 (L32/2001) and quadrant IV G1 (L68/2001), G2 (L01/2001) and G11 (L67/2001) were considered as low yielding genotypes.

Similar signs of IPCA1 score for both genotype and environment implies positive interaction and thus higher yielder at that particular location. Therefore, environments E1, E3, E4, E5, E6 and E8 and G4 (L45/2001), G5 (L54/2001), G6 (L03/2001), G8 (L32/2001) and G9 (L55/2001) among the genotypes had positive IPCA1 score and positively interacted and these environments were considered as the favorable environments for these genotypes. Likewise, the genotypes G1 (L68/2001), G2 (L01/2001), G3 (L52/2001) and G7 (L63/2001) and the environment E2 and E7 had negative IPCA1 score for genotypes and environments respectively and therefore, exhibited positive interaction.

AMMI 2 biplot for yield

The AMMI 2 biplot (Figure 2) was generated using the genotype and environment scores of the first two AMMI components (Vargas and Crossa, 2000). The first interaction principal component captured 38.2%, while the second interaction principal component captured 25.1% of the total G x E interaction sum of square. The first two IPCAs cumulatively captured 63.3% of sum of square of the G × E interaction of tested coffee genotypes. From earlier yield trial of G × E interaction in Arabica coffee, Yonas et al. (2014) reported that the first IPCA alone accounted for 36% of the total interaction sum of square and Meaza et al. (2011) reported that AMMI with the first two IPCAs explained 74% of the total interaction sum of squares.

According to Purchase (1997), the genotypes and environments that are located far away from the center are more responsive or unstable, while genotypes that are closer to the center of biplot have higher stability performance. Hence, genotypes like G7 (L63/2001), G11 (L67/2001), G2 (L01/2001) and G3 (L52/2001) were

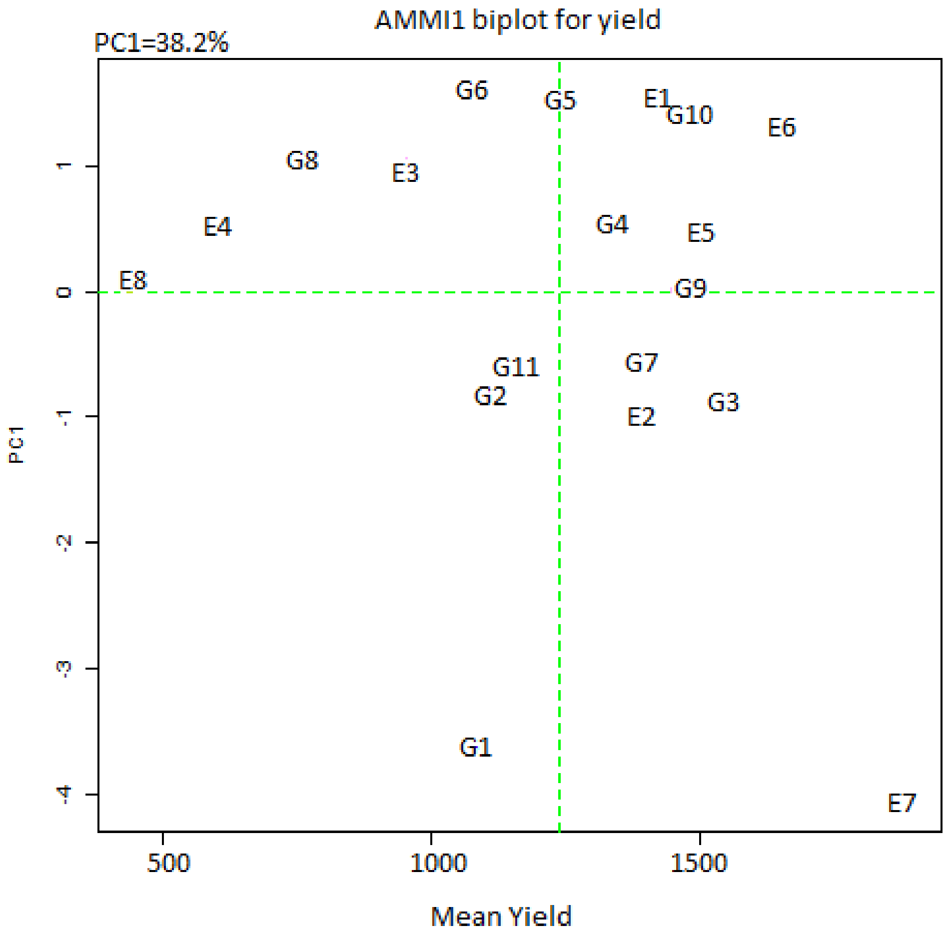

Figure 1. Biplot of IPCA1 versus mean yields of 11 Arabica coffee genotypes tested across eight environments. G1=L68/2001, G2=L01/2001, G3=L52/2001, G4=L45/2001, G5=L54/2001, G6=L03/2001, G7=L63/2001, G8=L32/2001, G9=L55/2001, G10=L56/2001, G11=L67/2001, E1=Gera 2014/15, E2=Jimma 2014/15, E3=Agaro 2014/15, E4=Manna 2014/15, E5=Gera 2015/16, E6=Jimma 2015/16, E7=Agaro 2015/16 and E8=Manna 2015/16

plotted relatively close to the center designating their minimum involvement in the total G x E interaction sum squares and considered as stable genotypes. However, for genotypes to be considered as stable, it should attain high mean performance having greater than grand mean. Therefore, only G7 (L63/2001) and G3 (L52/2001) could be considered as most stable genotypes with their high bean yield performance and being closer to the origin as compared to the others. Whereas, genotypes G1 (L68/2001) and G4 (L45/2001) were farthest from the center of biplot having substantial involvement in G x E interaction sum squares. Therefore, these genotypes were considered as unstable genotypes. Similarly, E4 and E8 can be considered as stable environments due to closeness of its vector end points to the center of biplot. In contrast, the farther away from the center of biplot for the environments, the more interaction the environment has with genotypes. As was already identified, E7 was the most interactive environment on AMMI1 biplot, AMMI2 biplot also identified E7 and E5 as the most interactive environments as it was farthest from the center of biplot. In addition, the response of the locations for the genotypes performance was different from one season to the other. Such imbalance genotypes performance over the two seasons is largely attributed to the very conducive or unconducive environment prevailing at all locations during the experimental period.

In Figure 2, the association between the genotypes and the environments can be clearly seen. Genotypes with similar performance and those that are close to the environment indicate their better adaptation to that particular environment. For instance, genotype G4 (L45/2001) strongly associated with E5 and G3 (L52/2001), G7 (L63/2001) and G11 (L67/2001) are particularly suitable for environment E2. The direction of genotypes and environments from the axis center also contains important information on the interaction. Genotypes and environments that fall into the same

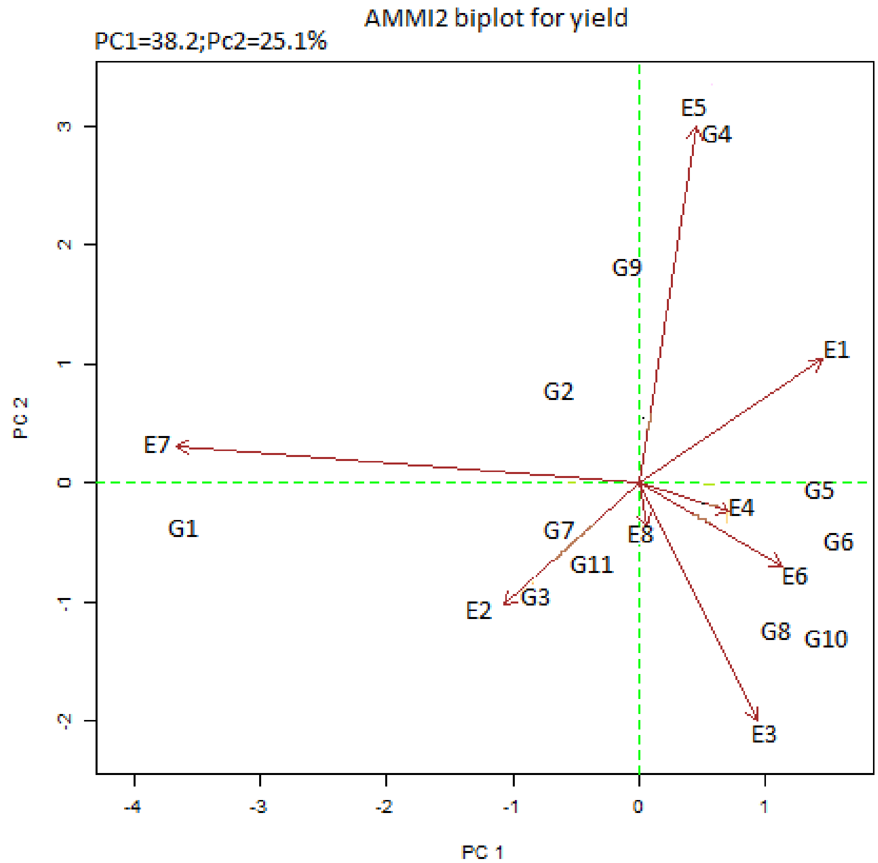

Figure 2. Biplot of IPCA1 versus IPCA2 for yield of 11 Arabica coffee genotypes tested across eight environments. G1=L68/2001, G2=L01/2001, G3=L52/2001, G4=L45/2001, G5=L54/2001, G6=L03/2001, G7=L63/2001, G8=L32/2001, G9=L55/2001, G10=L56/2001, G11=L67/2001, E1=Gera 2014/15, E2=Jimma 2014/15, E3=Agaro 2014/15, E4=Manna 2014/15, E5=Gera 2015/16, E6=Jimma 2015/16, E7=Agaro 2015/16 and E8=Manna 2015/16.

sector interact positively, and negatively if they fall into opposite sectors (Osiru et al., 2009).

Cultivar superiority index (Pi)

The superiority index (Pi) values ranged from 204137 to 1202144 (Table 5) which indicated large differences among tested genotypes for this stability model. Abtew et al. (2015) also reported the large differences among tested wheat genotypes under their investigation. Regarding superiority index (Pi), the genotypes with minimum Pi-value could be considered as stable (Lin and Binns, 1988). Accordingly, the high yielding genotypes, namely G3 (L52/2001), G9 (L55/2001) and G7 (L63/2001) displayed the greatest yield performance and the lowest Pi-values. On the other hand, genotypes with maximum Pi-value could be considered as most unstable. Therefore, genotype G8 (L32/2001) but with maximum Pi-value; could be considered as most unstable genotype. The strong association between mean bean yield and Pi was expected because the values of this stability parameter were high for high-yielding genotypes, that is, the top-ranking in bean yield could also be the top-ranking in this stability parameter. In the dynamic concept of stability such as in cultivar superiority model, it is not required that the genotype response to environmental conditions should be equal for all genotypes (Becker and Léon, 1988). This type of stability parameter is preferable for commercial farming with high mean yields and the potential to respond to agronomic inputs or better environmental conditions rather than for resource poor farmers who prefer lower but stable optimal environmental conditions and inputs.

AMMI stability value (ASV)

The ASV parameter is used to quantify and classify the genotypes according to their stability performance. In this

Table 5. Mean bean yield (kg/ha), estimated yield stability parameters and their ranking order of 11 coffee genotypes tested across 8 environments.

Genotypes	ID	Bean yield		Pi		IPCA1		ASV		YSI	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
L68/2001	G1	1068	10	672144	9	-36.61	11	55.85	10	20	9
L01/2001	G2	1134	8	500074	6	-7.64	5	14.16	3	11	4
L52/2001	G3	1558	1	204137	1	-8	6	15.61	4	5	1
L45/2001	G4	1320	5	441859	5	6.12	3	57.9	11	16	7
L54/2001	G5	1246	6	572720	8	15.79	9	24.05	7	13	6
L03/2001	G6	1068	9	719105	10	16.29	10	25.58	8	17	8
L63/2001	G7	1379	4	338573	3	-4.56	2	10.67	1	5	1
L32/2001	G8	750	11	1202144	11	9.73	7	19.07	6	17	8
L55/2001	G9	1473	2	260145	2	0.25	1	18.3	5	7	2
L56/2001	G10	1464	3	402143	4	15.28	8	26.39	9	12	5
L67/2001	G11	1167	7	525327	7	-6.66	4	11.4	2	9	3

Pi= Cultivar superiority index, ASV = AMMI stability value, IPCA1 = the first interaction principal component axis, YSI = yield stability index; DF=degree of freedom, GEI = genotype x environment interaction, IPCA=interaction principal component axis, MS= mean square, SS= sum of square.

model, genotypes with least ASV or have smallest distance from the origin are considered as the most stable, whereas those which have highest ASV are considered as unstable (Purchase, 1997). Accordingly, genotypes G7 (L63/2001), G11 (L67/2001) and G2 (L01/2001) were found to be the most stable, whereas genotypes G4 (L45/2001), G1 (L68/2001) and G10 (L56/2001) were the most unstable (Table 5). AMMI stability value which defines stable genotypes by the distance of the genotypes from the zero point of the IPCA1 vs. IPCA2, is consistent with the AMMI2 model but have a little relationship with AMMI1 model which has only genotype G7 (L63/2001) in common. Genotypes, G3 (L52/2001) and G9 (L55/2001) which ranked first and third in their bean yield performance according to their order, are considered as moderately stable by this stability model.

Yield stability index (YSI)

Yield stability index (YSI) proposed by Mahmodi et al. (2011) incorporates both stability and yield performance in one criterion. AMMI stability value (ASV) takes into account both IPCA1 and IPCA2 that justify most of the variation in the G × E interaction. The rank of ASV takes the rank one, at the same time the highest yield mean takes the rank one and then the ranks are summed in a single simultaneous selection index of yield and yield stability called yield stability index (YSI). The genotypes with low YSI would be considered as high yielding and stable genotypes. Hence, YSI identified G3 (L52/2001) G7 (L67/2001) and G9 (L55/2001) as most stable genotypes, whereas G1 (L68/2001) was identified as least stable (Table 5). This stability parameter was also used by Tadesse and Abay (2011) in sesame genotypes to describe the stability performance of genotypes studied.

Conclusion

In Ethiopia where coffee production plays a major role in the national economy, yield fluctuation and yielding pattern of coffee being varied with small geographic variation and thus, attributed to low productivity. To this effect, assessments of the stability as well as the performance of coffee genotypes across diverse environmental conditions are important for selection of wider adaptable or superior genotypes for the target environments before variety release. In this study, eleven Arabica coffee genotypes which were common at all locations were evaluated at different agro-ecologies of southwestern Ethiopia; at eight environments (four locations for two cropping seasons) to determine the existence of G × E interaction and yield stability performances.

Combined analysis of variance exhibited highly significant difference among the genotypes. The finding showed significant effects of both environments and G x E interaction. The major proportion of the total variation in bean yield was explained by environments (42.75%) followed by G x E interaction (32.32%) and genotypes (9.31). The finding indicated that the genotypes G3 (L52/2001) and G9 (L55/2001) with high mean yield of 1558 and 1473 kg/ha^{-1}, respectively proved to be the best in stability among the studied genotypes. On the other hand, environment, Gera 2015/16 (E5) showed average response to all genotypes, while Agaro 2015/16 (E7) exhibited non-additive behavior. Therefore, this study clearly indicated the possibility of exploiting the yield potential of Limmu coffee genotypes under its growing conditions either by using wider adaptable coffee types or location specific high yielder genotype under favorable environmental condition.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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