PARAMETERIZATION OF ALMANAC CROP SIMULATION MODEL FOR NON-IRRIGATED DRY BEAN IN SEMI-ARID TEMPERATE AREAS IN MEXICO

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SUMMARY

Dry bean simulation models can be used to make management decisions when properly parameterized. This study aimed to parameterize the ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) crop simulation model for dry bean in the semi-arid temperate areas of Mexico. The parameterization process was based on data from two important non-irrigated dry bean fields in Mexico. The parameters were potential heat units (PHU), leaf area index (LAI) and harvest index (HI) for both adapted improved cultivars and native cultivars. Model performance with the parameters was evaluated by comparing simulated and measured yields. The model described much of the variability in measured yields; it had a root mean square error (RMSE) of 0.26 Mg·ha^{-1}. The mean squared deviation (MSD) was 0.11, and the values of its three components were 0.01 for squared bias (SB), 0.10 for lack of correlation weighted by standard deviation (LCS) and 0.001 for squared difference between standard deviations (SDSD). The derived crop parameters for native cultivars (1000 PHU, 0.3 HI and 0.6 LAI) and for improved cultivars (850-900 PHU, 0.46-0.50 HI and 0.7-1.5 LAI) have potential use for simulating dry bean in semi-arid temperate areas in Mexico.

Dry bean (*Phaseolus vulgaris* L.) is grown in a wide range of latitudes, soils and climatic conditions, making the crop vulnerable to late-spring freezes, intermittent or terminal drought, and high temperatures during grain growth (Padilla-Ramirez *et al*., 2004; Acosta-Diaz *et al*., 2008, 2011; Osuna-Ceja *et al*., 2013). Producers need to make effective decisions regarding sowing date, maturity type, sowing rate, and fertilizer rate to maximize profit and minimize risks associated with unpredictable weather conditions. Simulation models are tools that help optimize management practices for this important crop. Robust crop models can provide a quantitative means to predict crop yields under different environmental and climatic conditions (Evans *et al.* 2013; Monteiro and Sentelhas 2013). With accurate soil information and updated weather data, they can provide producers with realistic predictions on the outcome of various management alternatives.

KEYWORDS: Dry Bean / Harvest Index / Leaf Area Index / Parameterization / Potential Heat Units / Simulation Models /

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The ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model (Kiniry *et al*., 1992, 2007; Surendran Nair *et al.*, 2012; Timmons, 2013; Woli and Paz, 2013) is designed to simulate critical growth processes that reflect the impact of various field-level management practices on the soil and water environment and on crop yields. While ALMANAC has been demonstrated to be an accurate model for maize and grain sorghum in diverse temperate sites in the USA (Kiniry *et al*., 1997; Kiniry and Bockholt, 1998; Xi *et al*., 2001), the extension of the model to simulate dry bean in more tropical, low latitude regions, such as in Mexico, offers new challenges.

The widespread application of models is often restricted by the lack of accurate parameters for their different components (Ahuja and Ma, 2002; Surendran Nair *et al*., 2012). Parameterization is a difficult process, but the possible utility of ALMANAC in Mexico, once meaningful dry bean parameters have been developed, makes the effort worthwhile. Such a model, if it can make realistic yield predictions of this crop, could be used in Mexico and similar low latitude areas for large-area yield forecasts as well as for evaluating field management scenarios for single production fields. Hence, the objective of this study was to derive dry bean parameters for the ALMANAC model to enable it to simulate yield in semi-arid temperate areas in Mexico.

Materials and Methods

Model description

The ALMANAC model (Kiniry *et al*., 2007; Johnson *et al*., 2011; Surendran Nair *et al*., 2012; Behrman *et al*., 2013) simulates processes of crop growth and soil water balance, including light interception by leaves, dry matter production, and partitioning of biomass into grain. The model simulates grain yield based on harvest index (HI), which is grain yield as a fraction of total aboveground dry matter at maturity.

For the model, extinction coefficients are linear functions of row spacing (Flénet *et al.* 1996). The equation is:

$$k= \alpha + \beta \text{ ROWS} \quad (1)$$

where ROWS: row spacing in meters, and k: light extinction coefficient. For dry bean, the intercept and slope are -0.57 and -0.22, respectively.

Critical for yield simulation in water-limited conditions is the simulated water demand. Potential evaporation (E_o) is calculated first. Then, potential soil water evaporation (E_S) and potential plant water transpiration (E_P) are derived from potential evaporation and leaf area index (LAI). Based on the soil water supply and crop water demand, the water stress factor is estimated to decrease daily crop growth and yield. For this study, E_o was estimated by the Priestley Taylor (1972) method.

Water stress factor is the ratio of water use to water demand calculated from potential plant transpiration in the model, and water use is a function of plant extractable water and root depth (Schilling and Kiniry 2007). If available water in the current rooting zone is sufficient to meet demand, then water use equals E_P. Otherwise, water use is restricted to the water available in the current rooting zone.

Field data

The study used four years (2000-2003) of data from the location of Sandovales, Aguascalientes State, and two years (2002-2003) of data from that of C. Progreso, Zacatecas State. Aguascalientes and Zacatecas are two important bean-growing states in central Mexico. The climate of the two locations is semi-arid temperate (BS1kw), according to the Köppen climatic classification as modified by Garcia (1973). Additional geographical and climatic data on the areas are found in Table I.

At the end of the growing season, dry bean grain yield was measured in the field by destructive methods. At least $4m^2$ for each replication was harvested on each location. Harvest yield was determined in $g \cdot m^2$ and expressed in $Mg \cdot ha^{-1}$.

When deriving plant parameters for models such as ALMANAC, it is important to have sites without drought or nutrient stress. In the present study ALMANAC was run with six years of data, so it was possible to test the model under different rainfall scenarios: a dry year, normal years, and a wet year. The dry bean plots in this study received varying amounts of fertilizer during the growing season each year based on the agronomic recommendation for each zone. Plots in Aguascalientes received $40kg \cdot ha^{-1}$ N and $40kg \cdot ha^{-1}$ P one month after sowing. In Zacatecas, $20kg \cdot ha^{-1}$N and $27kg \cdot ha^{-1}$P were applied 20 days after sowing.

Data on daily maximum and minimum air temperatures and precipitation were from the nearest available weather station for each data set. The weather station in C. Progreso was on the site (at the research station), while that in Sandovales was at a distance of 2km. The data for daily solar radiation were obtained from the National Oceanic and Atmospheric Administration-World Meteorological Organization (NOAA-WMO) database.

Soil parameters were important because they determined the capacity to store fall and winter rainfall for plant use when growing season rainfall was limited. The soil type was determined from measurements taken at each location. The soils in C. Progreso in Zacatecas were Xerosols with sandy-loam texture and without salinity problems. Those at the experimental site of Sandovales in Aguascalientes were Calcisol and Planosol, with sandy-loam texture, alkaline pH (7.9) and <1% of organic matter content (Osuna-Ceja *et al.* 2013).

Soil parameters were derived from the soil texture data for each soil layer (Table II). Total soil depth ranged from 0.4 to 0.95m. Plant available water at field capacity ranged from 9.2 to 12.5cm (Table II). In order to obtain reasonable values for initial soil water for the year that we wanted to simulate, the model was run beginning with the previous year's weather data.

Parameterization and statistical approach

Parameterization involves finding parameters that provide the best correlation between a model and the reality it is simulating (Skrehota, 2010). It is a general procedure to calibrate a crop model to explore the best fit for a certain regional environment of interest (Ko *et al*., 2009).

Calibration refers to the refining of the initial selection of parameters used to run the model by comparing

TABLE I

State/location	Latitude N	Longitude W	Elevation (m)	Mean annual rainfall (mm)	Mean annual solar radiation ($MJ \cdot m^{-2}$)	Average maximum temperature (ºC)	Average minimum temperature (ºC)
Aguascalientes, Sandovales	21.88861	-102.10722	2045	491	24.72	25.8	9.0
Zacatecas, C. Progreso	23.81556	-103.33972	2172	469	23.98	26.6	7.7

For dry bean simulations, geographic and climate data for two non-irrigated locations in Central Mexico.

TABLE II
SOIL DATA SETS FOR DRY BEAN AT TWO NON-IRRIGATED LOCATIONS IN CENTRAL MEXICO

State/location	Soil texture	Runoff curve number	pH	Slope (%)	Soil depth (m)	Available water for plant (cm)
Aguascalientes, Sandovales	Sandy loam	81	6.2	0.02	0.40	9.2
Zacatecas, C. Progreso	Sandy loam	78	8.0	2.0	0.95	12.5

the model results with a set of observed data (Ahuja and Ma, 2002). This process is widely used to derive parameters that are not available for important agricultural areas or crops (Driessen and Konijn, 1992; Monteiro and Sentelhas, 2013; Odongo *et al*., 2013).

Using the calibration approach, we derived the potential heat units (PHU), leaf area index (LAI) and harvest index (HI) for dry bean. Values for radiation use efficiency and plant height were those that had been derived for this crop and were already in the model.

The ALMANAC model was run using the crop parameters and the management and climatic data of each location. A regression analysis was done to measure grain yield as a function of simulated grain yield and to see if the regression model was significant. Bias values and root mean square error (RMSE) values were calculated as described by Retta *et al.* (1996).

The agreement between measured and simulated values was further evaluated by calculating the mean squared deviation (MSD= $RMSD^2$) and its three components, i.e. the squared bias (SB), the lack of correlation weighted by the standard deviation (LCS) and the squared difference between standard deviations (SDSD; Kobayashi and Salam, 2000). This approach is useful in quantifying the deviation of the calculated values obtained with the model from those of field measurements.

Results and Discussion

Derived crop parameters

Crop parameters were descriptive of the cultivars and hybrids at each location (Table III). The sums of degree days (base 10ºC) from sowing to maturity, or potential heath units (PHU), ranged from 850 to 1000, based on field measurements at the locations. A possible explanation for this range is the duration of the cycle of the evaluated bean genotypes. Late genotypes require more accumulated heat units than the early genotypes. For instance, a genotype that matures 10 days later may require 120 to 150 heat units (HU) more than an early genotype, considering an average of 12 to 15 HU/day.

As for harvest index (HI), previous research at Veracruz State and Texcoco in Mexico State (Rosales-Serna *et al*., 2004) showed that dry bean HI could be reduced from 0.33 or 0.34 with no stress to 0.26 or 0.29 with stress (drought). In the present study, the input potential HI values for dry bean were 0.30 for native cultivars and 0.46-0.50 for improved cultivars. Simulated HI for dry bean under environmental stress was 0.24 to 0.30 for native cultivars and 0.23 to 0.50 for improved cultivars (Table III).

The wider range of simulated HI shown by improved cultivars may have been a result of the varying water stress days during the crop cycles. Table IV shows that the improved cultivars had 21.5, 10.3, and 1.6 days of stress and simulated HI values of 0.23, 0.44, and 0.46, respectively. The simulated HI of improved cultivars was 0.50 when there was no stress. For native cultivars, the simulated HI was 0.30 without water stress.

The input potential leaf area index (LAI) values, also derived through indirect field measurements at the locations, were 0.6 to 1.4. Similar LAI values were reported by Padilla-Ramirez *et al.* (2005) and Medina Garcia *et al.* (2003) for bean genotypes grown in the semi-arid highlands of Mexico under non-irrigated conditions. In contrast, Kamudini *et al.* (2001) reported a range of 3.0 to 4.0 as critical values of the LAI in soybean (*Glycine max* L.) to achieve 95% interception of radiation. The same percentage of interception with a value of 4.0 LAI for bean was reported by Immer

TABLE III

State, location	Plant material*	Planting date**	Harvest date**	Plants /m^2	Mean PHU (^{0}C)	Potential LAI (m m^{-2})	Potential HI	Simulated HI
Aguascalientes, Sandovales	N	182	289	10.0	1000	0.6	0.30	0.24
		178	285	10.0	1000	0.6	0.30	0.30
		189	296	10.0	1000	0.6	0.30	0.30
		195	302	10.0	1000	0.6	0.30	0.30
	I	182	274	10.0	850	0.7	0.50	0.44
		178	267	10.0	850	0.7	0.50	0.50
		189	281	10.0	850	0.7	0.50	0.50
		195	287	10.0	850	0.7	0.50	0.50
Zacatecas, C. Progreso,	I	171	271	5.0	900	1.4	0.46	0.23
		188	293	5.0	900	1.5	0.46	0.46

Data sets used in dry bean simulations for two non-irrigated locations in Central Mexico.
* N: native cultivars, I: improved dry bean cultivars.
** Julian date.
PHU: potential heat units, LAI: leaf area index, HI: simulated harvest index values that the ALMANAC model simulated based on input potential and simulated drought stress near anthesis.

TABLE IV
MEAN SIMULATED AND MEASURED YIELD OF ANNUAL RAINFALL AND AVERAGE STRESS DAYS FOR DRY BEAN IN TWO NON-IRRIGATED LOCATIONS IN CENTRAL MEXICO

State, location	Plant material*	Amount of rainfall ingrowing season (mm)	Ave. stress (days)	Mean sim. yield (Mg·ha^{-1})	Mean msrd yield (Mg·ha^{-1})	Bias
Aguascalientes, Sandovales	N	379.0	17.7	0.29	0.25	0.04
		421.0	0.0	0.44	0.56	-0.12
		467.8	0.0	0.36	0.42	-0.06
		578.6	0.0	0.32	0.55	-0.23
	I	369.0	10.3	0.60	0.58	0.02
		408.0	0.0	0.80	0.78	0.02
		438.0	0.0	0.63	0.63	0.00
		571.6	0.0	0.58	1.25	-0.67
Zacatecas, C. Progreso	I	376.0	21.5	0.49	0.79	-0.30
		660.4	1.6	1.39	0.98	0.41

* N: native cultivars, I: improved dry bean cultivars.

et al, (1977). However these values corresponded to a crop without water stress.

The low LAI values observed in this study indicate that the conditions under which the bean plants were developed, mainly water stress, did not allow higher values, a typical situation in the semi-arid areas of Mexico.

Dry bean yield estimation

The model realistically simulated dry bean grain yield under non-irrigated conditions during dry, normal and wet climatic conditions. The root mean square error (RMSE) of ALMANAC, considering the pooled data, was 0.28Mg·ha^{-1} (Figure 1).

The reasonable agreement between simulated and measured yields is also shown in the low value (0.11) of the mean squared deviation (MSD) and each of its three components: 0.01 for squared bias (SB), 0.10 for lack of correlation weighted by standard deviation (LCS) and 0.001 for squared difference between standard deviations (SDSD).

The SB value of 0.01 indicates that the use of the derived parameters in the model did not affect the accuracy of the model. The low values of LCS (0.10) and SDSD (0.001) signify that the model simulated in a similar way the pattern and magnitude of yield fluctuations across measurements in the two study areas in the years of the study.

A comparison of model simulations of native and improved cultivars showed an RMSE of 0.15Mg·ha^{-1} for native cultivars and 0.38Mg·ha^{-1} for improved cultivars. For native cultivars, the MSD was 0.05 with 0.01 SB, 0.04 LCS and 0.002 SDSD; for improved cultivars, the MSD was 0.16 with 0.01 SB, 0.14 LCS and 0.01 SDSD. These values indicate that the model had similar accuracy in

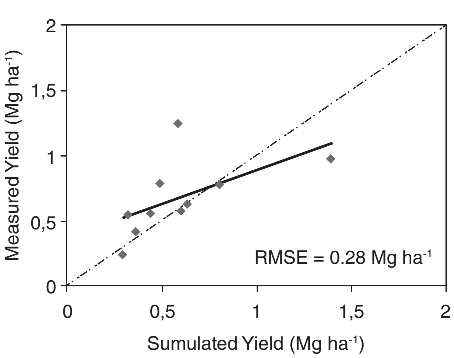

Figure 1. Non-irrigated dry bean simulations in Aguascalientes and Zacatecas, Mexico. The solid line is the regression and the dashed line is the 1:1 line through the origin. Each point is for one cultivar at a location.

simulating native and improved cultivars (SB with similar values); however, the pattern and magnitude of yield fluctuations were better simulated in native cultivars (low values of LCS and SDSD). The overall deviation of model simulations (MDS) was lower in native cultivars than in improved cultivars (0.05 *vs* 0.16).

The results showed best agreement between simulated and measured yields in the dry and normal years of precipitation. Similar results were obtained by Balkovic *et al*. (2013), who reported better performance of the EPIC model (on which the ALMANAC model was based) in dry compared to wet years for winter wheat, rainfed and irrigated maize, spring barley and winter rye. In our study, the bias in the wet year was as large as -0.67Mg·ha-^{1}. This underestimation of yield could be attributed to the potential LAI simulated by the model (Table III). Padilla-Ramirez *et al.* (2001) and Acosta-Diaz *et al.* (2011) mention that the accurate simulation of LAI and the fraction of the growing season when the maximum LAI occurs are some of the major factors to be considered for dry bean growing under non-irrigated conditions in Mexico.

Conclusions

Over-all, the results suggest that the derived crop parameters for native cultivars (1000 potential heat units, harvest index of 0.3 and leaf area index of 0.6) and for improved cultivars (850-900 PHU, 0.46-0.50 HI and 0.7-1.5 for LAI) have potential use for simulating dry bean in semi-arid temperate areas in Mexico. These parameters can be useful in extending the use of simulation models such as the ALMANAC to these areas.

Results of this study provide exciting possibilities for future field research, investigating differences between improved varieties and native cultivars. Additional research on plant characteristics, such as LAI values during wet years, may help increase model accuracy in the simulation of non-irrigated dry bean in semi-arid regions of Mexico. It will be vital to determine potential LAI in these regions in relation to cultivars grown and planting density. Such findings will be important to realistically simulate yields in wet years when drought stress does not decrease the LAI values. Work investigating HI differences with and without stress will also greatly aid simulation model accuracy and increase the understanding of yield limitations in these regions.

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PARAMETRIZACIÓN DEL MODELO DE SIMULACIÓN DE CULTIVOS ALMANAC PARA FRIJOL EN ÁREAS SEMIÁRIDAS TEMPLADAS DE MÉXICO

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RESUMEN

Los modelos de simulación para frijol pueden ser usados para tomar decisiones de manejo cuando estos son parametrizados adecuadamente. El presente estudio tiene como objetivo parametrizar el modelo de simulación de cultivos ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) *para el cultivo de frijol en áreas semiáridas templadas de México. El proceso de parametrización se basó en información de dos importantes áreas de frijol de temporal en México. Los parámetros fueron unidades calor potenciales (UCP), índice de área foliar (IAF) y índice de cosecha (IC) para cultivares mejorados y nativos. Se evaluó el comportamiento del modelo cuando se le incluyó los parámetros comparando la producción simulada y medida. El modelo describe mucha de la variabilidad de la producción medida; tuvo un error cuadrado medio (RMSE) de 0,26Mg·ha^{-1}. El cuadrado medio de desviación (MSD) fue 0,11 y los valores de sus tres componentes fueron 0,01 para desviación cuadrada (SB), 0,10 para perdida de correlación dada por la desviación estándar (LCS) y 0,001 por la diferencia cuadrada entre la desviación estándar (SDSD). Los parámetros derivados para cultivares nativos (1000 UCP, 0,3 IC y 0,6 IAF) y para los cultivares mejorados (850-900 UCP, 0,46-0,50 IC y 0,7-1,5 IAF) tienen un uso potencial para la simulación de frijol en áreas semiáridas templadas de México.*

PARAMETRIZAÇÃO DO MODELO DE SIMULAÇÃO DE CULTIVOS ALMANAC PARA FEIJÃO EM ÁREAS SEMIÁRIDAS TEMPERADAS DE MÉXICO

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RESUMO

Os modelos de simulação para feijão podem ser usados para tomar decisões de manejo quando estes são parametrizados adequadamente. O presente estudo tem como objetivo parametrizar o modelo de simulação de cultivos ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) para o cultivo de feijão em áreas semiáridas temperadas do México. O processo de parametrização se baseou em informação de duas importantes áreas de feijão de temporal no México. Os parâmetros foram unidades calor potenciais (UCP), índice de área foliar (IAF) e índice de colheita (IC) para cultivares melhorados e nativos. Avaliou-se o comportamento do modelo quando foram incluidos os parâmetros comparando a produção simulada e medida. O modelo descreve muita da variabilidade da produção medida; teve um erro quadrado medio (RMSE) de 0,26Mg·ha-1. O quadrado medio de desviação (MSD) foi 0,11 e os valores de seus tres componentes foram 0,01 para desviação quadrada (SB), 0,10 para perda de correlação devida pela desviação estándar (LCS) e 0,001 pela diferença quadrada entre a desviação estándar (SDSD). Os parâmetros derivados para cultivares nativos (1000 UCP, 0,3 IC e 0,6 IAF) e para os cultivares melhorados (850-900 UCP, 0,46-0,50 IC e 0,7-1,5 IAF) têm um uso potencial para a simulação de feijão em áreas semiáridas temperadas do México.