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REVIEW

Modeling in Legumes, with Emphasis on Beans Crop

La modelación en las leguminosas, con énfasis en el cultivo del frijol

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ABSTRACT: The most widely produced grain legume for human consumption in the world is the common bean (*Phaseolus vulgaris* L.). This plant is native to the Americas, where it plays an important role in the daily diet. The environment where beans are grown is varied, from tropical zones to high mountains, with different growth habits and production systems, from highly technical to traditional. Therefore, efforts in bean crop modeling should start from identifying the type of bean and the target system. Beans are very sensitive to abiotic stress, a fact that has encouraged the modeling of their possible response under climate change scenarios. For this, a literature review was carried out to identify modeling exercises carried out in Latin America, which include growth studies (node production rates and leaf area), phenology and yield. The models used in these studies include EcoCrop, CROPGRO-DRYBEAN (implemented on the DSSAT platform), and in one case of each, Maxent and CLIMEX. Four studies are described in detail: in the two countries with the highest production in the world (Brazil and Mexico), and in Central America as a region highly vulnerable to climate change. Studies agree that bean productivity could suffer serious negative effects in the course of the 21st century because of climate change. Finally, a recent exercise to collect historical data from bean trials in Latin America is reported to feed future modeling efforts.

Keywords: Estimation, Simulation Models, Crop Yield.

RESUMEN: La leguminosa de grano para consumo humano de mayor producción en el mundo es el frijol común (*Phaseolus vulgaris* L.). Esta planta es nativa de las Américas, donde juega un importante papel en nuestra dieta cotidiana. El ambiente donde se cultiva el frijol es variado, desde zonas tropicales hasta alta montaña, con distintos hábitos de crecimiento y en sistemas de producción, desde los altamente tecnificados hasta los tradicionales. Por tanto, los esfuerzos en la modelación del cultivo del frijol deben empezar desde, identificar el tipo de frijol y el sistema objetivo. El frijol es muy sensible al estrés abiótico, hecho que ha animado el modelaje de su posible respuesta bajo escenarios de cambio climático. Para ello, se realizó una revisión de literatura para identificar ejercicios de modelación ejecutados en América Latina, que incluyen estudios de crecimiento (tazas de producción de nudos y área foliar), fenología, y de rendimiento. Los modelos empleados en dichos estudios incluyen EcoCrop, CROPGRO-DRYBEAN (implementado en la plataforma DSSAT), y en un caso cada uno, Maxent y CLIMEX. Se describen cuatro estudios en detalle: en los dos países de mayor producción en el mundo (Brasil y México), y en Centroamérica como región altamente vulnerable al cambio climático. Los estudios concuerdan que la productividad del frijol podría sufrir serios efectos negativos en el transcurso del Siglo XXI, a raíz del cambio climático. Finalmente, se informa sobre un ejercicio reciente de recopilar datos históricos de ensayos de frijol en Latinoamérica para alimentar futuros esfuerzos de modelaje.

Palabras clave: estimación, modelos de simulación, rendimiento de cultivos.

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INTRODUCTION

The consumption of grain legumes is valuable as a supplement in diets based on cereals or tubers, especially in regions where the population has limited access to protein of animal origin.

Legumes, by themselves, are a good source of protein, vitamins and minerals. However, they contain anti-nutritional factors such as trypsin inhibitors, hemagglutinins, saponins and phytic acid among others, many of which, fortunately, are destroyed, at least in part, by applying traditional culinary techniques. These factors modify the nutritional use of its nutrients (Serrano y Goñi, 2004).

Legumes include the genus *Phaseolus*, which is of Neotropical origin and the wild ancestor of the common bean. This plant grows as an annual vine, from northwestern Mexico to northern Argentina, in an environment classified as pre-montane sub-humid forest. This environment is typically between 1,500 and 2,200 m above sea level, characterized by its moderate temperatures, with marked periods of abundant rain alternating annually with drought (Freytag & Debouck, 2002).

The soil, in this environment, is not of the best quality, but it does not present major problems since it has a good organic matter content. Therefore, the ancestor of the cultivated bean evolved without major climatic or soil limitations; it is most probable that, due to the competition of the existing vegetation in a pre-montane forest environment, the greatest limitation could have been solar radiation available, thus forcing the wild to climb vigorously to compete with shrubs and small trees. Given this pattern of evolution, the species is not adapted to the abiotic stress of drought, high temperatures, acid soils or low fertility. For this reason, when man took the bean to other environments to cultivate it as a food source, the species was subjected to stress factors different from those present in the wild environment (indeterminate, determined and voluble shrubs).

The bean is a plant of tropical origin, it develops better at temperatures between 18 and 24 °C and the highest yields are obtained at the indicated average temperatures. In addition, it is reported that beans can be produced satisfactorily in hot areas, as long as night temperatures are not very high, since hot nights commonly induce flower drop to the detriment of production (Faure Alvarez *et al.*, 2014). Low temperatures (below 15 °C) can cause yield decreases, since they affect vegetative development because growth is very slow and cause delays in flowering, which considerably lengthens the growth cycle (Rosas, 2003).

Beebe (2012) defines that the factors that influence bean yields are pests and diseases, especially fungus. Even so, other important factors in many production areas are those for which the species was not prepared in its wild state: drought, high temperatures, phosphorus deficiency and, in some areas, aluminum and/or manganese toxicity. For this reason, these aspects are considered in research programs on the modeling of bean crop, which contribute to the yields estimation, in different Latin American countries.

The objective of this work is to provide the state of the art of the main simulation models in legumes, specifically in the bean crop, with the results of its application in the Latin American environment.

MODEL DEFINITION

It can be said that a model is the ideal representation of a system, the way it operates, in which relevant characteristics of the object under study are highlighted and whose objective is to analyze or predict future behavior. (Jay, 2012).

It is the main tool used by statisticians to symbolize life problems or situations. Mathematical models constitute a particular case.

THE STATE OF ART OF BEAN MODELING IN LATIN AMERICA

Since the 1980s, crop simulation models have been developed to be used by academics and scientists, extension agents, educators and agricultural policy makers. Among the best known and used systems in Latin America is the set of modeling computer programs known as DSSAT (Decision Support System for Agrotechnology Transfer), which has been adapted and modified numerous times for specific purposes and crops (Jones *et al.*, 2003). The first model developed specifically for beans was BEANGRO, a model written in FORTRAN and developed with the active participation of a CIAT physiologist in Cali, Colombia, ensuring that it included production perspectives in tropical zones (Hoogenboom *et al.*, 1993). BEANGRO was designed with the same philosophy as other models in DSSAT: it simulates crop growth at the farm level from planting to maturity under different scenarios of agronomic practices, soils and climate variability. The model responds to environmental variables of solar radiation, temperature, precipitation, wind speed, relative humidity and the capacity of the soil to retain moisture. It allows defining crop characters to estimate their contribution to productivity-function that can be used by breeders, to design crops for specific production environments.

Subsequently, the CROPGRO computer program was introduced by the same BEANGRO authors, as a more generic module for legumes within the DSSAT modular system, based on routines not only for beans, but also for soybeans (*Glycine max* L) and peanuts (*Arachis hypogaea* L) (Boote *et al.*, 1998). Currently, the CROPGRO module can simulate the growth of 7 legumes, including pigeon pea (*Cajanus cajan* L), chickpea (*Cicer arietinum* L), cowpea (*Vigna unguiculata* L Walp), broad bean (*Vicia faba* L), as well as soybeans, peanuts and beans. As in BEANGRO, the CROPGRO code is in FORTRAN, with parameters of the species, ecotype and cultivar of interest compiled into separate files (species or SPE file, ecotype or ECO file and culture or CUL file). Compared to previous versions, CROPGRO calculates photosynthesis every hour with estimates more precise of light interception and with options to vary evapotranspiration based on vapor pressure deficit (VPD) and CO_2 concentration. It also adds more options for nitrogen (N) including N balance, effects of N deficiency on photosynthesis and growth and symbiotic N fixation and its interaction with carbon (C) availability. CROPGRO uses the DSSAT SPAM (Soil-Plant-Atmosphere) module, which is based on several options for calculating evapotranspiration (Penmann, 1965; Priestley-Taylor, 1972; Penmann-Monteith, 1981) and on the *tipping-bucket* model of water balance (Ritchie, 1998). In this sense, it is an advance with modifications focused on the physiology of legumes. In addition, CROPGRO incorporates the possibility of estimating the environmental effects at different times of the crop cycle.

CROPGRO has been widely used in many Latin American countries. Uses include calibration and evaluation in defined environments by Acosta-Gallegos *et al.* (1996) and Chaves de Oliveira (2007) and environmental characterization as a tool for genetic improvement (Heinemann *et al.*, 2016). Furthermore, evaluation of the impact of climate change (Eitzinger *et al.*, 2017; Álvarez *et al.*, 2016) and the link between genetic and eco-physiological information (Hoogenboom *et al.*, 1997; Hwang *et al.*, 2017). Acosta-Gallegos *et al.* (1996) used the CROPGRO model to understand the different variations in yield in highland environments in Mexico. These authors were able to associate the reductions in performance observed in the experiments with the results of the simulation model in a satisfactory way.

Chaves de Oliveira (2007) relied on the CROPGRO model using adjustments in the genetic parameters derived from experimental data of the Pérola, Ouro Preto and Ouro Vermelho varieties to estimate the sowing date under local rainfall and productivity conditions. Data were obtained from two experiments under irrigation conditions and one under rain fed conditions. After the calibration of the model, it was applied to the estimation of phenology and yields for 31 years, between 1975 and 2006. The results suggest that the model is highly sensitive to differences in genetic coefficients between the three varieties. The model satisfactorily estimated the crop phenology under soil and climate conditions. It also satisfactorily estimated the productivity of Pérola and Ouro Preto with mean square error less than 5%, and 12.6% for Ouro Vermelho.

A more recent study in the state of Goiás in Brazil used the CROPGRO-DRYBEAN model to classify environments according to the intensity and synchrony of the drought, with the aim of providing information on sites and typical stresses in the area to define breeding genetic objectives (Heinemann *et al.*, 2016). The study developed parameterizations for two bean cultivars (Pérola and BRS Radiante) under various drought environments. The analysis of Heinemann *et al.* (2016) reported that the model well represents the behavior of the crop under moderate drought (less than 20 days), but that it presents limitations when simulating the behavior under severe drought (more than 1 month). The study concluded that the conditions of the state of Goiás deserve the consideration of drought within the selection criteria of the bean improvement program.

Another study used DSSAT-CROPGRO in an ex ante analysis to isolate the effect of drought on yield losses in 18 countries in Latin America, 23 in Africa, and two in the Middle East. That study estimated that the benefits of drought tolerance varied greatly from country to country, but in 72% of countries, there would be a positive and significant effect. On average, drought tolerance could provide an increase in yield of 24.7 % (Álvarez *et al.*, 2016).

The study by Eitzinger *et al.* (2017) used the CROPGRO-DRYBEAN model to simulate the impact of climate change on bean production systems in Central America, a region reported by the literature as highly vulnerable (Beebe *et al.*, 2011). These authors simulated the growth and development of beans in three different periods (first, last and early sowing) that follow the typical management of the region. Observations suggest that, in the absence of adaptability, climate change could lower bean yield between 10 and 50 % depending on the site and the planting period.

Although models offer general breeding guidance on trait value, it is even more useful if a model can be applied to predict the value of specific genes. This is because by linking directly with the eco-physiological behavior of a variety, it is possible to determine the behavior of "virtual" varieties (with the presence or absence of certain genes) in different environments or under particular management conditions. This allows estimating in advance the potential effect of breeding efforts.

A creative effort to model bean characters based on known genes utilized a seven-gene model for flowering, growth habit and grain size (Ppd, Hr, Fin, Fd, Ssz-1, Ssz-2, and Ssz- 3). The model allowed explaining 75 % of the variance in days to flowering, 68 % in days to maturity, but only 11 % in yield (Hoogenboom *et al.*, 1997).The science of genomics advances, the manipulation of regions of the genome for complex characters is much more feasible as a tool for genetic improvement, without the need to know the genes involved. The concept was extended to genes defined by "quantitative trait loci" (QTL) for bean growth traits in the field. Analyzing 187 recombinant lines derived from the cross of two bean cultivars, Jamapa x Calima, Hwang *et al.* (2017) developed a model that managed to combine the date to flowering, rate of producing nodes and nodes in the main stem. Through genetic analysis using linear mixed models, they were able to relate (QTL) with characters that reflect the establishment of the crop in the field. The prediction of the time to flowering presented high accuracy (R^2=0.75), as well as the total number of nodes in the linear growth phase (R^2=0.93). The performance was lower in the final number of nodes (R^2=0.27). Using the same data from the 187 recombinant lines, Clavijo Michelangeli *et al.* (2014) used CROPGRO to characterize the growth pattern of the two parents (Jamapa and Calima) and three of the progenies through serial sampling and combined with predictions based on genotypes. The parameter values reflected the genetic differences of the lines and produced satisfactory estimates of growth. Interestingly, some genotypes reached the same final biomass, but with different growth patterns. These studies offer evidence on the potential of CROPGRO to simulate genotypic differences and therefore, contribute important tools to establish concrete directions in bean improvement programs. Along the same lines of understanding the dynamics of bean leaf area production for photosynthesis, a study was carried out at two sites in Colombia. It considered six genotypes using three growth habits: determinate shrubby (Type I), indeterminate shrubby (Type II) and indeterminate prostrate (Type III) with two genotypes of each habit; and planted in six densities, of 5, 10, 15, 20, 25 and 35 plants per m^{-2}. Destructive samplings were taken starting at 14 days, initially every week, and then every two weeks until the end of the cycle. Significant effects were found both for genotype and for densities in leaf area production, but no genotype x density interaction was detected. The models were able to predict adequately the formation of leaf area

A group of additional studies reports the use of various other models applied to beans. These studies use empirical models both to predict productivity and to predict the geographic distribution of beans. Cota Oliveira *et al.* (2011) made a comparison with five different empirical models (Blackman equation, rectangular hyperbole, negative exponential, non-rectangular hyperbole and efficient use of radiation), to explain variation in bean and corn yields in different regions of the state of Minas Gerais, calculating the carbon balance and thus estimating yields. These authors found more than 100% difference between models (i.e. the standard deviation is at least twice the mean) and concluded that certain criteria are required to choose the appropriate model.

The EcoCrop model has been used for various analyzes of beans related to habitat suitability and climate change (Beebe *et al.*, 2011). EcoCrop is a niche model that works empirically with a known distribution of a crop, the optimal ranges of temperature and precipitation and the extremes in which the species does not develop satisfactorily (Ramirez-Villegas *et al.*, 2013). The model assumes that, in an environment that presents rainfall or temperatures outside the optimum, it is marginal, while environments with the two parameters that are within the optimal range are acceptable for the species. Like other models, EcoCrop is of special relevance as a model to estimate the areas in which, depending on climatic conditions, the crop can grow satisfactorily. In this sense, the results of the model can be used to define vulnerable areas for adaptation interventions, to estimate potential changes in geographic niches and their potential implications for food and economic security. Beebe *et al.* (2011) used EcoCrop to determine current and future suitable areas for beans globally. The analysis indicated that, in the absence of adaptation or mitigation, many areas would no longer be conducive to bean production in the coming decades. The same study, however, found that breeding for drought tolerance could expand bean area by 35 %, and that an improvement in tolerating 2.5 ^{o} C more temperature could expand bean area by 60 %. Medina-García *et al.* (2016) and Delgado Assad *et al.* (2016) adopted a similar methodology for Mexico and Brazil, respectively, finding large reductions in arable areas for beans in these countries. Although not focused on Latin America, a study carried out at CIAT on climbing beans compared the EcoCrop model with another niche model called MaxEnt (Taba *et al.*, 2016). The purpose of this study was to identify other favorable environments for climbing beans using both models. The climbing bean is native to the highlands of Mesoamerica and the Andes and is gaining wide acceptance in Africa. Although climbing beans have been cultivated in the mountains of East Africa for many generations, CIAT introduced climbing beans adapted to elevations of 1,400 to 1,800 m above sea level in the 1980s. These beans have found wide acceptance in Rwanda, Burundi, in western Uganda and in central Kenya. Compared to EcoCrop, MaxEnt predicted a more restricted area but more in accordance with local knowledge about areas for climbing bean production. Ramirez-Cabral *et al.* (2016) carried out a study similar to that of Taba *et al.* (2016) and Beebe *et al.* (2011), but with the CLIMEX model. The findings of that study suggest important changes in the distribution of beans globally, especially in Africa and Latin America.

In recent years, increased attention has been devoted to breeding for drought tolerance in programs in Mexico (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias -INIFAP), Honduras

(Escuela Agrícola Panamericana), Brazil (Empresa Brasileira de Pesquisa Agropecuaria - EMBRAPA-CNPAF; Agronomic Institute -IAC) and at the International Center for Tropical Agriculture (CIAT). At least fourteen drought-tolerant varieties have been released in Latin America.

CONCLUSIONS

Beans (*Phaseolus vulgaris* L) is the most important legume in the Latin American diet and is cultivated in very diverse systems, from traditional agriculture with minimal inputs, to highly technical systems.

It is subject to multiple biotic and abiotic factors that limit its yield and all studies to date suggest that climatic changes will have strong and negative effects on the crop.

The use of modeling can predict the behavior of crops under specific conditions and whether it will be profitable or not, in terms of yield.

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