Artículo Científico **Rev. Fitotec. Mex. Vol. 30 (3): 311 – 319, 2007**

AN EMPIRICAL MODEL TO PREDICT YIELD OF RAINFED DRY BEAN WITH MULTI-YEAR DATA

UN MODELO EMPÍRICO PARA PREDECIR EL RENDIMIENTO DE FRIJOL DE SECANO CON DATOS DE VARIOS AÑOS

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SUMMARY

The prediction of crop yield and harvest volume of about 700 thousand ha planted to dry bean in Zacatecas State will enable the implementation of strategies to decrease the degree of uncertainty of decisions pertaining to agriculture. The purpose of the present study was to predict bean yield under rainfed conditions using leaf area index (LAI), light interception (LI) by the canopy, and rainfall. LAI and LI of both black-grain and light-colored grain beans were determined at the beginning of flowering, at pod formation, at the beginning of pod filling, and at intermediate pod filling. The relationship yield: LAI/LI/rainfall as well as the verification of a model were examined by linear least-square regression. Maximal LI and its LAI for the various years were 70 % and 1.6 for 2002 and 75 % and 2.5 in 2003. For these years, LI as a function of LAI could be described by an exponential model. LAI and LI at pod formation and the beginning of pod filling were the phenological stages that better explained bean yield for all varieties. The empirical model relating bean yield: LAI/LI/rainfall accounted for 71 % of the variability of light-colored grain bean yield. The corresponding percentages of the variability in measured yields for black-grain beans were 68 % for Emiliano Zapata and Progreso and 74 % for Zaragoza and Miguel Auza. Even though the relationship LAI/LI/rainfall was affected due to the low plant population density, the many varieties employed, and the agroecological sites, the information from this kind of studies will be useful to decision makers and farmers to make decisions.

Index words: *Phaseolus vulgaris*, linear regression, crop modeling, photosynthetically active radiation (PAR), rainfed cropping systems.

RESUMEN

La predicción del rendimiento y el volumen de cosecha de aproximadamente 700 000 ha sembradas con frijol en el Estado de Zacatecas permitirá implementar estrategias que disminuyan el grado de incertidumbre en decisiones relativas a la agricultura. El objetivo del presente estudio fue estimar, mediante el uso de los índices de área foliar (IAF) y la luz interceptada (LI) así como la lluvia, los rendimientos de frijol. El IAF y la LI por el dosel fueron determinados al inicio de la floración, a la formación de vainas, al inicio y llenado intermedio de vainas en frijoles de grano negro y grano claro. La relación de rendimiento: LAI/LI/lluvia, así como la verificación del modelo fueron examinados mediante regresión lineal; los valores de LI máximo e IAF correspondiente fueron 70 % y 1.6 para el 2002 y 75 % y 2.5 para el año 2003. En los dos años, la LI como una función del IAF pudo ser descrita por un modelo exponencial. Las etapas fenológicas que mejor explicaron los rendimientos correspondieron a formación de vainas e inicio de llenado de vainas para todas las variedades. El modelo de la relación rendimiento: LAI/LI/lluvia explicó 71 % de la variabilidad en los rendimientos de frijol de grano claro. En el frijol negro, los valores en cuestión fueron de 68 % en las localidades de Emiliano Zapata y Progreso y 74 % en las localidades de Zaragoza y Miguel Auza. Aún cuando la relación LAI/LI/precipitación resultó afectada, debido a la baja densidad de población, las muchas variedades empleadas y los variados sitios agroecológicos, la información de este tipo de estudios será útil a los tomadores de decisiones y agricultores en la toma de decisiones.

Palabras clave: *Phaseolus vulgaris*, regresión lineal, modelaje de cultivos, radiación fotosinteticamente activa, sistemas de cultivo de secano.

INTRODUCTION

Dry bean (*Phaseolus vulgaris* L.) is the most important crop in the State of Zacatecas, México. About 700 000 hectares are planted each year with beans and 85 % of the cultivated area is under rainfed conditions. Therefore, dry bean production is affected by a high frequency of droughts, early or late occurrence of frosts, and strong winds. Weather conditions, along with fluctuations in the planted area, lead to year-to-year variation in the production of this basic crop, thus affecting decision making for ensuring an adequate food production. Recently, harvest forecasting technology has been developed to decrease the degree of uncertainty in agricultural decisions (Lobell *et al*, 2007; Baez-Gonzalez *et al*., 2002).

In an effort to predict crop yields, researchers have been using mechanistic and empirical models. Empirical models,

Recibido: 13 de Febrero del 2006.
Aceptado: 27 de Enero del 2007.

once developed and validated, can be used to predict crop yield or they can be incorporated into subroutines of mechanistic models. Empirical models have been developed by using linear regression to examine the relationship between yield and either rainfall, dry matter, leaf area index or row spacing (Sangoi *et al*., 2001), among other factors. For instance, dry matter quantified at the beginning of seed filling was used as a criterion for yield optimization in soybean (*Glycine max* L.) (Modali, 2004, Personal comm.[1]).

Statistical modeling developed for regional assessment of maize productivity, has used average rainfall through several months as an independent variable, obtaining a correlation coefficient of 77 % between maize (*Zea mays* L.) yield and rainfall (Alexander and Hoogenboom, 2000); in this study, the occurrence of drought brought about differences of nearly 20 % between calculated and measured maize grain yield. On the other hand, Jones (2002, Personal comm.[2]) pointed out that the relationship between soybean yield and LAI depends largely on developmental stage, location and year. In bean, the relationship between plant density and LAI, dry weight per plant and other variables was reported by Aguilar *et al.* (1977).

Leaf area index (LAI) is the ratio of unit leaf area of a crop to the unit ground area. Dry bean LAI will vary within and between fields due to cultivar selection and other agronomic practices. For instance, Díaz *et al*. (2001) found that the values and dates for maximum dry bean LAI varied among varieties and locations, thus implying that LAI depended on genotype, environment, and their interaction. LAI is a physiological parameter that allows estimating the capacity of the plant canopy to intercept photosynthetically active radiation (PAR). The rate of light interception (LI) depends on planting times, since it decreases as planting is delayed, indicating a positive correlation between fresh pod yield and plant light interception from red-podded bean varieties (Balkaya *et al*., 2004). Board (2004) pointed out that sufficient LAI must be maintained at the mid-seed filling stage to keep light interception (LI) at or above 95 %, since below this level plants show defoliation and yield losses.

In the Zacatecas High Plains region, dry bean is grown mainly under rainfed conditions in three areas, which vary in rainfall, temperature, evapotranspiration, first frost date, rainfall:evaporation ratio and altitude (Pérez and Galindo, 2003). In terms of yield potential, the black-grain beans are grown in the area with the highest annual rainfall (500 mm, approx.) whereas the light-colored grain bean is grown in areas with 300 to 400 mm rainfall (Medina and Ruiz, 2004).

Grain yield can be considered the overall expression in any cropping system. Van Oosterom *et al*. (2002) have indicated that grain number and grain mass are the yield components that contribute most to the final yield, although Reynolds *et al*. (2004) stated that light interception, radiation use efficiency and harvest index also contribute to the yield potential. Stability of these parameters would greatly contribute to the accuracy of grain yield estimates. Parameter stability for bean is important because of the diversity of climatic conditions in which this crop is grown.

The objective of this study was to build up empirical models to estimate grain yield for light-color grain and black-grain beans growing under rainfed conditions, based on LAI, LI, and rainfall data obtained at the middle of the growing season. This information about expected bean production would be helpful to growers from Zacatecas, México for obtaining grain trading supports, and also useful to decision makers for defining grain bean importation needs, but not necessarily for establishing a base price. Parameterization of the models from this study would not necessarily make them applicable to the entire High Plains region, but would demonstrate that similar simple regression models at specific locations within the region could be developed. The main challenge for the study was to determine the most appropriate empirical model to predict dry bean yields considering weather variation, since year-to-year variation in weather in a fixed location is generally perceived to be random to and unaffected by the farmer, as well as because the effects of weather depend on the weather itself and on the management practices of farmers, which in turn might also be influenced by weather (Schlenker, 2006).

MATERIALS AND METHODS

Site description

Two important dry bean regions were monitored throughout the growing season during the Summer and Autumn from 2002 to 2004, in the northwestern and central regions of the state of Zacatecas, México. The black-grain bean varieties 'Negro San Luis' and 'Negro Zacatecas' are predominant in the northwestern region, whereas light-colored grain varieties such as 'Flor de Mayo', 'Flor de Junio', 'Media Oreja' and 'Bayos', are mainly planted at the central region. For this study, bean was planted in rows spaced 76 cm apart at densities from 50 000 to 78 000 plants/ha for black-grain bean, and 57 000 to 83 000 plants/ha for light-colored grain beans.

All the varieties planted in the Zacatecas High Plains region were Type III of indeterminate growth habit, and each one has particular morphological traits. 'Negro San Luis' and 'Negro Zacatecas' have a short branched main stem with purple flowers; they flower 54 d after planting and their life cycle is 95 d to harvest. 'Flor de Mayo' and 'Flor

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[1] **Modali H (2004)** Dry matter accumulation by the start of seed filling as a criterion for yield optimization in soybean. Ph. D. Diss. Louisiana State University, USA. 114 p.

[2] **Jones B (2002)** Determination and manipulation of leaf area index to facilitate site-specific management of double-crop soybean in the Mid-Atlantic. M. Sc. Thesis, Virginia Polytechnic Institute and State University, USA. 169 p.

de Junio' have a branched main stem and flower between 55 and 65 d after planting; their life cycle is 100 d to harvest. 'Bayos' has a long branched main stem (Pérez, 1998).

Experiments were carried out in homogeneous areas planted with beans in at least 80 % of the area, and polygons with a minimum of 300 ha were delimited within those areas. In 2002 and 2003, eight plots of 10 ha each, with bean plants at the same physiological stage were selected per polygon. Four sites were sampled in each plot amounting to 32 sites per polygon or location. Sampling was carried out in six locations in 2002 and seven in 2003. In both years, data from black-grain bean varieties came from Emiliano Zapata and the ExHacienda de Zaragoza in Sombrerete County, Progreso in Río Grande County, and Campo 1 in Miguel Auza County. Data from light-colored grain bean varieties were obtained from Ejido Nopales in Morelos County in both years, Ejido La Tesorera in Pánfilo Natera County in 2002, and Ejidos Carrillo and Rancho Grande in Fresnillo County in 2003. In 2004, three sampling plots of 10 ha each per location were selected in Fresnillo, Morelos and Pánfilo Natera, but one sampling plot in Morelos and two sampling plots in Pánfilo Natera were dropped out because they became weedy.

Field measurements

Photosynthetically active radiation (PAR) and leaf area index (LAI) were determined at the beginning of flowering, pod formation, beginning of pod filling, and intermediate pod filling stages, corresponding to a 15 d interval between sampling dates for both black- and light-colored grain beans. The first LAI and PAR sampling started after observing the first flower in bean plants. Collections of rainfall data started 15 d before the first LAI and PAR sampling. The PAR value was measured between 10:30 h and 14:30 h by taking one reading above the canopy and four below the canopy, with a 0.80-m-long Sunfleck ceptometer (Decagon; Pullman, WA, USA). The below-canopy readings were done by holding the ceptometer across two adjacent rows.

Light interception (LI) by plants was calculated as the percentage of the sunlight intercepted by the canopy and expressed in µmol m^{-2} s^{-1}, as suggested by Norsworthy and Oliver (2001):

$$LI = (a - b)/a \qquad \text{(Eq. 1)}$$

where *LI* represents light interception, *a* is the quantity of PAR above the dry bean canopy, and *b* is the average PAR at the ground level beneath the canopy. Basal PAR was assumed to be 45 % of the total solar radiation (Meek *et al.*, 1984). Leaf area index was calculated by using light measurements above and below the crop (Goudriaan and Van Laar, 1994) from the ceptometer (Decagon Devices, 2003).

Daily records of rainfall were obtained from automated meteorological stations located as near as possible to the study areas, consulting the net of agroclimatological stations from the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias in Zacatecas (CEZAC, 2005; Medina and Torres, 2004) and from the Comisión Nacional del Agua. Grain yield was estimated by harvesting two rows 5.0 m long around the sites used for leaf area and LI determinations. Harvest index was determined at harvest time; this index did not include the fallen leaves nor the root system. Yield measurements on a per site basis were transformed to g m^{-2}.

Statistical analysis

The relationship LAI to intercepted PAR was examined by a non-linear regression using PROC NLIN (SAS, 2004). Intercepted PAR in response to LAI is described by the following formulae (Landsberg, 1977):

$$Y = A \times (B - e^{-D \times LAI}) \qquad \text{(Eq. 2)}$$

where Y is the estimated intercepted PAR, A is the maximum intercepted PAR, B is the intercept, and D is the slope. The coefficient of determination R^2 was calculated as described by Vandepitte *et al*. (1995).

Multiple regressions using LAI, LI and rainfall as independent variables and dry bean yield as a dependent variable, were examined by linear regression using the procedure PROC REG from SAS (2004). The parameterization of the polynomial models were obtained by running programs with data from independent and dependent variables pooled across years, so that the empirical model for light-colored grain bean was developed with data from 2002 to 2004, whereas the models for black-grain bean were generated with data from 2002 to 2003. The multi-year data sets used in the calculations were elaborated in order to include the maximum rainfall variability, since failed results caused by differences in rainfall across years were obtained by attempting a cross-validation, using either 2002 data set to estimate the 2003 values for the polynomial model, or viceversa. For black-grain bean, field data from Emiliano Zapata and Progreso was included into the group 1 whereas the field data from Zaragoza and Miguel Auza constituted the group 2. The following three regression models were developed for predicting yield:

Light-colored grain predicted yield:

$$\text{Yield} = -40.9 + 59.1(\text{LAI}) + 185.3(\text{LI}) - 227.6(\text{LI}^2) + 0.65(\text{RAIN}) \qquad \text{(Eq. 3)}$$

Black-grain predicted yield Group 1:

$$\text{Yield} = 147.5 - 101.5(\text{LAI}) - 330.1(\text{LI}) + 870.3(\text{LI}^2) - 0.14(\text{RAIN}) \qquad \text{(Eq. 4)}$$

Black-grain predicted yield Group 2:

$$\text{Yield} = 49.9 + 74.1(\text{LAI}) - 130.2(\text{LI}) + 193.6(\text{LI}^2) + 0.28(\text{RAIN}) \qquad \text{(Eq. 5)}$$

Model validation was done by regressing the estimated yields against the measured yields, and analyzing the data from each year. Accuracy of the polynomial models for yield estimation was related to assumptions such as: an appropriate R^2, slopes should not be significantly different from one, and intercepts should not be significantly different from zero. Optimal accuracy of the yield estimation model will occur as the slope reaches a value of one, implying that for each observed yield unit will correspond an estimated yield unit. Other models have been validated using this technique (Fritz *et al.*, 1997; Khorsandi *et al.*, 1997).

RESULTS

Light interception

Maximum LI achieved by the bean canopy was about 75 % in 2003 with a LAI of 2.5, while in 2002 it was 70 % with a LAI of 1.6 (Figure 1). In 2002, black-grain bean varieties grown in some plots at the locations E. Zapata and Zaragoza in the northwestern region showed the highest LI, whereas light-colored grain varieties grown in Carrillo intercepted more light than in Morelos in 2003. The response observed in 2003 depended on the crop foliage estimated at Carrillo rather than on plant population, because the mean plant density quantified at Carrillo was lower than that at Morelos (Table 1). Several studies have demonstrated the importance for crops of maintaining at least 95 % LI for obtaining optimum yields (Board and Boethel, 2001; Haile *et al*., 1998; Norsworthy and Oliver, 2001). However, LI values lower than 95 % quantified in this study can be related to the low crop foliage produced by the low crop density (6 plants/m^2 on average), as well as to soil moisture and rainfed conditions interacting with plant growth and development. Dapaah *et al*. (2000) pointed out that irrigated 'Pinto' bean yielded more than the unirrigated crop due to the interception of 84-95 % of incident radiation, 72 % higher maximum LAI, and other crop features. It has been stated that the lack of intraspecific interference allows plants to branch and compensate for reduced crop density (Norsworthy and Oliver, 2001). However, bean canopy structure in these locations only allowed a maximum of 75 %.

Light interception as a function of LAI could be described by an exponential model in all years. This curvilinear response has already been observed in the evaluation of correlations between PAR interception and LAI of monocrop and intercrop soybeans (Ali *et al*., 2003) and growth simulation of pearl millet *Pennisetum glaucum* (van Oosterom *et al*., 2002). LI rate was higher in 2003 than in 2002 as a response to a higher variation in LAI caused by the increased number of varieties.

Table 1. Some attributes for black-grain and light-colored grain in bean crop at Zacatecas, México.

Location	Plant density (plants/m^2)	Weight of 100 grains (g)	Harvest index
	2002		
	Black-grain		
Emiliano Zapata	5.0 (±1.61)	28.4 (±1.82)	55.6 (±2.32)
Zaragoza	6.9 (±2.06)	29.4 (±2.32)	45.7 (±8.03)
Progreso	3.8 (±1.04)	30.9 (±1.73)	41.0 (±3.42)
Miguel Auza	7.6 (±1.69)	30.8 (±1.90)	37.9 (±5.50)
	Light-colored grain		
Morelos	8.3 (±1.90)	31.1 (±2.18)	55.9 (±4.86)
Pánfilo Natera	5.7 (±2.29)	29.5 (±2.68)	54.3 (±4.98)
	2003		
	Black-grain		
Emiliano Zapata	4.2 (±0.72)	25.6 (±1.86)	41.3 (±8.77)
Zaragoza	6.1 (±1.38)	27.0 (±0.96)	44.6 (±6.00)
Progreso	4.5 (±1.44)	30.9 (±0.84)	46.0 (±3.68)
Miguel Auza	7.8 (±2.13)	31.3 (±3.10)	50.3 (±2.99)
	Light-colored grain		
Morelos	7.1 (±2.13)	30.5 (±1.80)	50.2 (±4.82)
Carrillo	5.8 (±1.12)	29.7 (±2.63)	48.5 (±5.15)
Rancho Grande	6.2 (±1.30)	28.9 (±1.71)	47.5 (±5.34)

Values within parentheses are standard deviations

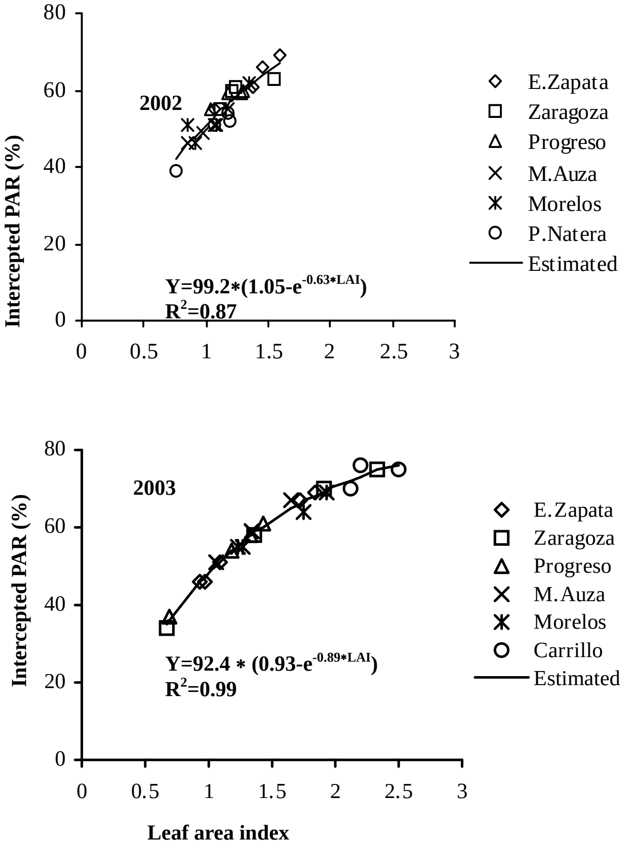

Figure 1. Relationship between intercepted PAR and LAI for light-colored grain (Morelos, Pánfilo Natera, and Carrillo) and black-grain (E. Zapata, Zaragoza, Progreso, and M. Auza) beans grown under rainfed conditions in 2002 and 2003, in Zacatecas, México.

Yield and LAI-LI-rainfall interaction

The LAI and LI determined either at the pod formation or at the beginning of pod filling, as well as the amount of rainfall accumulated before and between these development stages for the light-colored grain varieties and black-grain varieties closely explained bean yields (Table 2, Figures 2 and 3), than those determined at the beginning of flowering and at intermediate pod filling (data not shown).

Light-colored grain. According to the coefficient of determination, the estimated light-colored grain bean yields could be explained by the LAI, LI and rainfall interaction up to 71 % (Table 2). Results from regression analysis show how bean yields in 2003 were more accurately explained than those yields quantified in 2002 and 2004 (Figure 2), mainly due to differences among years in locations like Pánfilo Natera, which is located within a low yield potential region, whereas the Fresnillo and Morelos sites were located in a middle-yield potential region (Medina and Ruiz, 2004; Pérez and Galindo, 2003).

Table 2. Relationship between dry bean yields and LAI-LI-rainfall interaction for light-colored grain varieties at pod formation, as well as for black-grain-color varieties at the beginning of pod filling (Group 1) and pod formation (Group 2) developmental stages at the northwestern and central regions of Zacatecas, México, respectively. Group 1 was constituted by Emiliano Zapata and Progreso, and Group 2 was constituted by Zaragoza and Miguel Auza locations.

	Light-colored-grain varieties	Black-grain varieties	
		Group 1	Group 2
Intercept	-40.9	147.5	49.9
LAI (ß$_1$)	59.1*	-101.5*	74.1
LI (ß$_2$)	185.3	-330.1	-130.2
LI^2 (ß$_3$)	227.6	870.3	193.6
RAINFALL (ß$_4$)	0.65**	-0.14	0.28
R^2	0.71	0.68	0.74
Prob. > F	<0.0001	<0.0001	<0.0001
CV[†]	26.4	17.5	16.2

*Parameter estimates significantly different from zero ($P \leq 0.05$).
[†] CV = Coefficient of variation (%).

The yields estimated by the regression model increased at a rate of 59.1 g per LAI unit or 0.65 g per millimeter of rainfall, and amounted to approximately 225 g m^{-2}, because the negative relationship showed by the quadratic form of LI reduced the effect of the linear LI variable (Table 2). In spite of the use of the same empirical model, estimated bean yield values varied among years due to differences in rainfall and plant canopy values.

In 2002, the lowest estimated light-colored grain bean yields occurred in the location of Pánfilo Natera with 0.56 LAI, 0.32 LI and 77.4 mm of rainfall accumulated during 14 d prior to pod formation, whereas the highest yields were estimated in the location of Morelos with 1.51 LAI, 0.65 LI and 121.6 mm of rainfall accumulated at the same developmental stage. In 2003, the highest estimated yield was quantified with 3.86 LAI, 0.88 LI and 78.4 mm of rainfall accumulated 14 d previous to pod formation; afterwards, crop yield decreased on a curvilinear way at a rate of 227.6 g per square LI unit (Table 2). The lowest estimated bean yield occurred in the location of Rancho Grande, was obtained with 0.69 LAI, 0.37 LI and 7.0 mm of rainfall.

In 2004, dry bean measured yields were more affected by the rainfall accumulated during 14 d previous to pod formation than by any other independent variables. The lowest measured yield occurred at Fresnillo County (40.7 g m^{-2}), and was estimated with 1.14 LAI, 0.55 LI and 21.4 mm of rainfall, whereas the highest yield occurred at Morelos (108.2 g m^{-2}) and was measured with 1.49 LAI, 0.59 LI, and accumulated rainfall of 48.8 mm.

Based on the 1:1 line (Figure 2) and determination coefficients (Tables 2 and 3), the measured and estimated yield variables were not closely related in every year. The overall relationship between these two variables could be explained

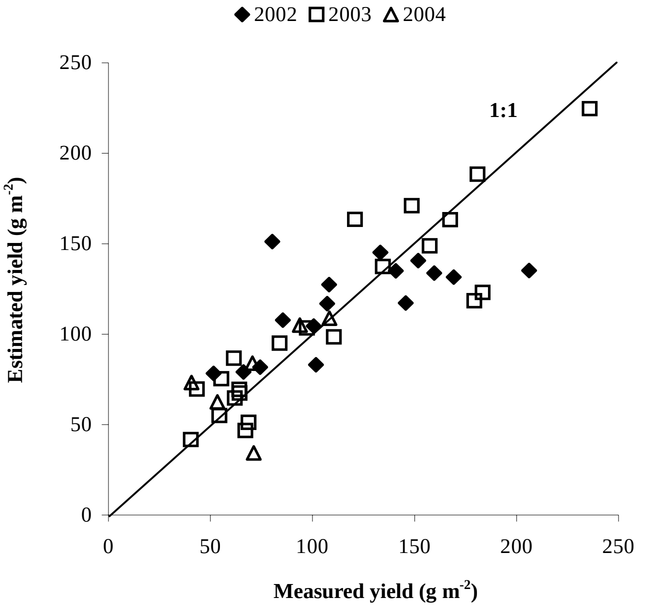

Figure 2. Relationship of estimated yield and measured yield based on LAI, LI, and accumulated rainfall data for light-colored grain bean varieties at pod formation developmental stage from 2002 to 2004 at the central region of Zacatecas, México.

up to 71 %, although the multi-year regression model explained better the relationship estimated-measured yield for light-colored grain bean in 2003 than in 2002 or 2004, due to the low variation in field sampling conditions showed in 2003 respect to the other years. The multi-year regression model, which explains the estimated-measured yield relationship, was not as accurate as expected because the model showed a good fit of 81 % in only one out of three years (Table 3), implying that this empirical model requires more work before being proposed.

According to the validation process of the regression model for the 2003 estimated-measured yields, the linear model showed an appropriate R^2 (0.81), but the slope was significantly different from 1.0 and the intercept was significantly different from zero (Table 3). In contrast, the validation process for the 2002 and 2004 estimated-measured yields showed how the regression model did not appropriately fit the data (0.43 and 0.39). Therefore, this model for light-colored grain should not be used for prediction because of its heterogeneous response, attributed to the year-to-year rainfall variation, as suggested by Schlenker (2006) for weather conditions.

Black-grain. For black-grain bean, crop measured yields were explained 68 and 74 % for the group constituted by Emiliano Zapata and Progreso (Group 1) and the group formed by Zaragoza and Miguel Auza (Group 2), respectively (Table 2). For Group 1, LAI and LI measured at the beginning of pod filling, as well as the rainfall accumulated during 14 d before reaching this phenological stage, were the best data for predicting bean yields. According to the regression model, the estimated yields varied from 68 to 188.4 g m^{-2} in response to variable LI^2, which was partially reduced by its linear form of LI (Table 2). Except for LAI, the regression coefficients for LI (P = 0.68), LI^2 (P = 0.21) and rainfall (P = 0.14) were not significantly different from zero. However, a new regression analysis with LAI as the only independent variable was not possible because all independent variables were correlated, so dropping any of these variables included in this study would affect the regression estimates and the hypothesis test (Cody and Smith, 1997). By holding constant LAI, LI and rainfall values, bean yields showed a slightly quadratic behavior in response to intercepted light, thus indicating that bean plants from Emiliano Zapata or Progreso yielded well even though they did not reached the maximum light interception as stated by Board (2004).

Based on the 1:1 line (Figure 3, Group 1) and determination coefficients (Table 2), both multi-year measured and estimated yields were closely related. The overall linear relationship between these two variables was explained up to 68 %, although according to the validation process the empirical model explained 71 and 70 % of the relationship estimated-measured yield for black-grain bean in 2002 and 2003, respectively, due to the similar variation in field sampling conditions between these two years.

Table 3. Modeled yield as a function of observed yield for dry bean varieties at the central and northwestern regions of Zacatecas, México. Group 1: Emiliano Zapata and Progreso; Group 2: Zaragoza and Miguel Auza locations.

		Slope		Intercept		
Dry bean	Year	Estimate	SE	Estimate	SE	R^2
Light-colored grain	2002	0.38**	0.10	71.37**	14.7	0.43
	2003	0.81	0.10	18.98	10.7	0.81
	2004	0.69	0.40	27.32	33.3	0.39
Black-grain (Group 1)	2002	0.73*	0.12	33.79	18.2	0.71
	2003	0.65**	0.11	45.27**	14.2	0.70
Black-grain (Group 2)	2002	0.74	0.12	32.60	16.1	0.71
	2003	0.67*	0.13	49.52*	20.9	0.65

*Slope not significantly different from 1.0 or intercept not significantly different from zero ($P \leq 0.05$).
SE = Standard error of the estimates.

On the other hand, LAI and LI measured at pod formation, as well as the rainfall accumulated during 14 d before reaching this phenological stage, were the data that better predicted bean yields for Group 2 (Table 2). According to the regression model, the estimated yields varied from 81 to 238 g m^{-2} in response to LAI, rainfall and LI^{2}, which was partially reduced by its linear form of LI. In this group, variation in estimated yields was recorded in response to all independent variables, since their regression coefficients were not significantly different from zero (Table 2), but none of them could be dropped because they were correlated. The lowest values of LAI, LI and rainfall, which were observed in the location of Miguel Auza, resulted in the lowest measured yields (74.5 g m^{-2}), but were increased to 228.1 g m^{-2} in the Zaragoza site as a response to increases up to 206, 10 and 971 % in LAI, LI, and rainfall values, respectively.

Based on the 1:1 line (Figure 3, Group 2) and determination coefficients (Table 3), both multi-years measured and estimated yields were closely related. The relationship between these two variables was explained up to 74 %, but with the validation process the regression model explained only 71 and 65 % of the relationship estimated-measured yield for black-grain bean in 2002 and 2003, respectively (Table 3). The empirical model was accurate enough in explaining the relationship estimated-measured yield for 2003 data, because the linear model showed an appropriate R^2, the slope was not significantly different from 1.0 and the intercept was not significantly different from zero (Table 3). In contrast, this same empirical model was not as accurate in explaining the relationship estimated-measured yield for 2002 data, because even though the linear model showed an appropriate R^2 the slope was not significantly different from 1.0 and intercept was not significantly different from zero (Table 3).

DISCUSSION

Despite the high correlations between LAI and yield reported for other crops such as maize (Bavec and Bavec, 2002; Baez-Gonzalez *et al*., 2005), the use of LAI alone as a criterion for bean yield estimation in the present study was not accurate (data not shown). Jones (2002; *Op. cited*) stated that the LAI-yield relationship studied in soybean was inconsistent because it is also affected by soil, genotype or a critical LAI level that interrelates with yield, so that a LAI alone measured at a specific development stage is not the only factor controlling yield. Likewise, dry matter accumulation measured at the start of seed filling was used as a criterion for yield optimization in soybean (Modali, 2004; *Op. cited*). On the other hand, because LI was lower than that reported as minimum (95 % or higher) for obtaining optimal yields, a poor relationship between LAI and yield in this study could be expected. Hence, the generated models in this study may help to understand how the interaction LAI-LI-cumulative rainfall at certain development stages could explain the variation in crop yields.

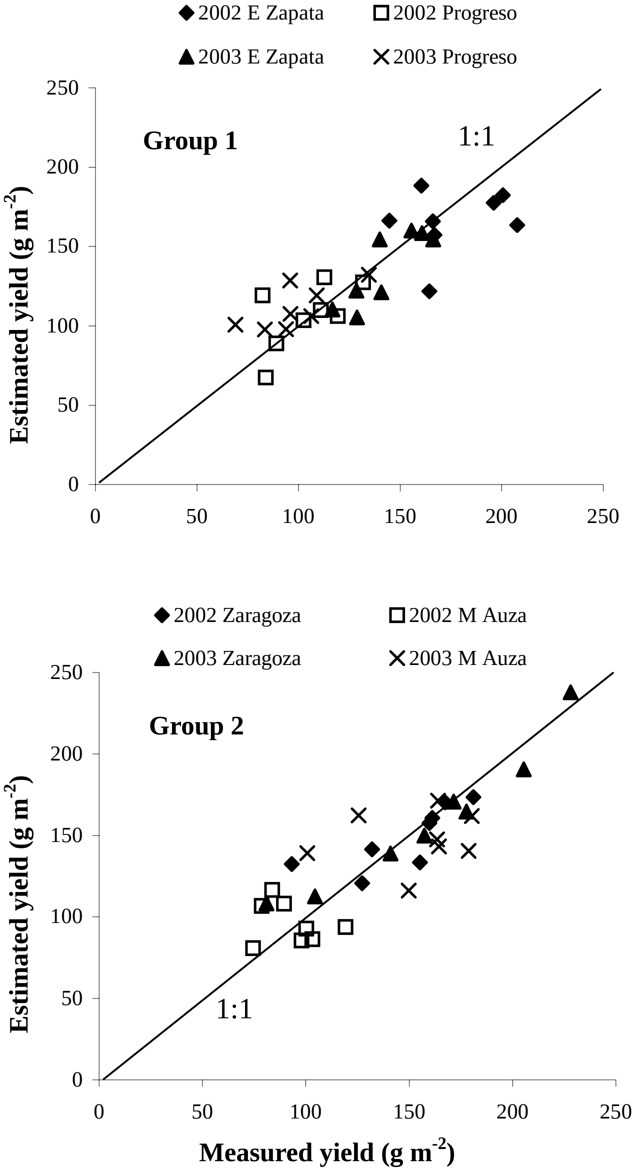

Figure 3. Relationship of estimated yield and measured yield based on LAI, LI, and accumulated rainfall data for black grain bean varieties at the beginning of pod filling (Group 1) and pod formation (Group 2) developmental stages, at the northwestern region of Zacatecas, México.

Weather is one of the key components controlling agricultural production. For rainfed production systems, weather plays a key role because 80 % of the variability in crop production is caused by the weather variability (Hoogenboom, 2000). According to the determination coefficients observed between bean yield and the LAI-LI-rainfall interaction, this relationship could have been affected by rainfall variation. Alexander and Hoogenboom (2000) observed a close correlation between rainfall and yield for maize and wheat (*Triticum aestivum* L.). In addition to rainfall, other factors increasing yield variation could have been a low and variable plant population, as observed in all locations (Table 1), which reduced LAI and affected the interception of light, as was observed by Haile *et al*. (1998) who pointed out that the apparent canopy photosynthesis is dependent on LI.

The goodness of the empirical models determined in this study to account for crop yields is confirmed by the 1:1 lines, as well as by the closeness between measured and estimated average data, demonstrating that through empirical modeling the estimation of light-colored and black-grain bean yields is feasible. This feasibility is given on that yields may be estimated 30 to 35 d before bean harvesting, which is enough time for decision makers, such as the Ministry of Agriculture (SAGARPA) and the State Government of Zacatecas, in order to define grain needs, pricing, etc. Attempts were made in this study to predict yields of subsequent seasons using only one empirical model, but failed results were obtained because of the rainfall variability across seasons. However, failing is not exclusive of the empirical models since the crop growth and yield models that use rainfall data as a primary input into the model structure are also sensitive to rainfall variations.

The lack of confidence of empirical modeling to predict bean yield does not imply that empirical models are poor, because in terms of crop yields each location has particular features, such as environmental conditions, crop population density, and crop management. Dourado-Neto *et al*. (1998) pointed out that there is not a right or wrong model, but models with variable degrees of suitability. In addition, Park *et al*. (2005) stated that empirical crop growth models can play an important role in identifying hidden structures of crop growth process relating to a wide range of land management options.

Therefore, whatever the model be, empirical or mechanistic, there is a necessity to aid predicting dry bean yields in order for farmers in obtaining supports for grain commercialization, and also for decision makers to predict yield potential, and hence to define possible needs of grain importations, rather than pricing as was stated by Modali (2004; *Op. cited*). An option to increase accuracy in yield prediction might be the addition of other factors such as dry matter (Board and Modali, 2005) or pod number per plant (Singer *et al*., 2004), which were not considered in this study.

CONCLUSIONS

The results depicted in this study indicate that bean yields observed at the highlands of Zacatecas are influenced by a set of factors, such as a maximum LI of 76% on average as a result of a low LAI, as well as to the variable rainfall across years and locations. The LAI-LI-rainfall interaction measured either at the pod formation or at the beginning of pod filling stage, explained dry bean yields better than at other reproductive stages. The yield to LAI-LI-rainfall relationship was influenced by a high regional variation in the use of varieties and agrometeorological sites where dry bean is usually grown.

ACKNOWLEDGEMENTS

The authors wish to thank the Fundación Produce Zacatecas, A. C. for financial support of this study during 2002 and 2003, and to Laboratorio Nacional de Modelaje y Sensores Remotos (INIFAP) for supporting this study in 2004.

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