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Comparison of models for describing weed: crop competition

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Abstract

In order to predict sugar beet yield reduction from weeds, obtained data was fitted to some non-linear regression functions. Two independent variables were selected for validating these functions: time and thermal time. The hypotheses of normality, homoscedasticity, independence of residuals, predictive capacity or goodness of fit with respect of the model, and diagnosis of the model, have been verified by means of residuals analysis for both independent variables. In early competition, a hyperbolic function was rejected due to the fact that some parameters seemed insignificant. However, the goodness of fit was similar to other functions. In late competition, some parameters were insignificant, but this hyperbolic function reaches the best goodness of fit. Comparing the validated functions, the logistical equation that includes the inflection point with independent variable time is the one that reaches the best results. The high flexibility of the model may allow the detection of special cases, and thus minimize risk. This study could be done anywhere in the world, as long as the mathematical model is adapted to the climate study area.

Keywords: sugar beet; yield description; competition models; model discrimination.

Practical Application: The high flexibility of the model may allow the detection of special cases, and thus minimize risk

1 Introduction

Weeds generally reduce crop yields by competing for limited resources such as light, water, and nutrients, although in some cases, they may also release chemicals which can suppress germination or crop cultivation (allelopathy) (Aldrich 1987). Knowing the composition of weeds and its progression under environmental and cropping factors are necessary for improving weed management.

Nowadays, weeds are considered to be a critical problem for sugar beet cultivation. The use of herbicides is a common way to control weeds. However, economic and environmental considerations are putting pressure on this practice in order to decrease the application of these products. For this reason, a greater knowledge of the weeds affecting the crop is important (composition, assessment, phenology and competition).

Weed species affecting sugar beets in Spain were studied by several authors. In the South: Saavedra et al. (1989) and Omaña et al. (2004). In the North: Viruega & Pujadas (1993a, b, c), Velasco & Rico (1993), Omaña et al. (2004). However, neither of these studies was carried out in Castilla-La Mancha (in the middle of Spain).

Mathematical models have been used for describing, analysing, and predicting biological and agricultural processes (Penning de Vries, 1983). Models of weed: crop competition should be an essential part of cost-effective decisions in weed management (Vitta, 1992). The study of the dynamics in relations of competition has led to the use of static and dynamic predictive models, and dynamic and mechanistic simulation models (Dew 1972; Spitters & Aerts 1983; Cousens et al., 1984; Cousens, 1988; Kropff & Spitters, 1991, 1992; Kropff & Lotz, 1992; Lotz et al., 1992, 1995; González-Andujar et al., 1993; Satorre, 1995; Kropff et al., 1995; Chikoye & Swanton 1995; Aibar & Zaragoza 1997). These models could be used anywhere in the world, as long as they are adapted to a corresponding mathematical model. Some of these models have been applied to the relations of interspecific competition in multispecific weed populations, but most of them have been applied to the competitive relationships between one cultivable species and one weed species. Progress in modelling crop-weed interactions has been slow, partly due to the difficulty in designing experiments to clarify the mechanisms involved. For example, it has not been easy to separate the relative effects of competition and allelopathy, or to determine whether above-ground or below-ground interference is the more important (Teng et al., 1998).

Most yield description models use either simple linear equations (Dew 1972), hyperbolic equations (Cousens et al., 1984; Cousens, 1985a, b; Cousens et al., 1987; Kropff & Spitters, 1991; Kropff & Lotz, 1992; Lotz et al., 1992, 1995; Kropff et al., 1995) or sigmoidal function (Pardo 1990). However, there is no consensus in the literature whether the relationship between weed infestation and crop yield is best described by a hyperbolic or a sigmoidal function (Cousens et al., 1984, 1987; Cousens 1985a, b, 1991; Swinton & Lyford, 1996). The main limitation of weed models so far is that they include only a small subset of all of the factors that affect crop yield loss through weeds. For example, crop variety (Aldrich, 1987), planting date (Scott et al., 1979),

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weed density (Dew, 1972; Cousens et al., 1984; Cousens 1985a), weed density and relative to the time of emergence compared with the crop (Cousens et al., 1987; Knezevic et al., 1997), weed and crop densities (Cousens 1985b) or the relative leaf area of weeds (Kropff & Spitters, 1991; Kropff & Lotz, 1992; Lotz et al., 1992, 1995), but quantifying these effects through field experimentation alone is difficult, due to the large numbers of weed species that can occur in a field. Moreover, extrapolation of field results from one location to another is complicated by the fact that many weed species are photoperiod-sensitive. A second limitation of most of the models described above is that they assume a homogenous horizontal distribution of crop and weed leaf area. Under field conditions, weeds often emerge in successive flushes, making it difficult to apply a descriptive model that accounts for the effect of both weed density and relative time of weed emergence for every weed flush.

Despite the abundance of empirical models proposed for determining the interspecific competition period between crop and weeds (temporal structure of competition), and the knowledge of the critical period during which the presence of weeds involves a measurable loss in yield, these models have seldom been compared with each other and even less so for Spanish conditions. It is necessary to validate the most favourable conditions in different geographical areas to create a general competition model between the yield of sugar beet (*Beta vulgaris* L. var. *altissima* Döll) and its accompanying natural weeds. This model not only indicates the period of the most intense competition, but also the optimal time for weeding and loss prevention.

The experiments reported here compared the effects of controlling the natural weed flora by hand weeding, or allowing it to grow, for different periods in the life of the crop. The objective of this study was to validate and evaluate through sensitivity analysis of four descriptive models of weed: crop competition with field data collected on sugar beet grown in competition with various species of weeds under the conditions specific to Castilla – La Mancha, Spain.

2 Materials and methods

Two farms located in Albacete province were selected for the testing process. Weeds of eight experimental plots irrigated by a central pivot were evaluated during two consecutive years. Soil fertility is similar to agricultural middle area of Albacete province. According to "Keys to Soil Taxonomy" (United States Department of Agriculture, 2003), the land from "Los Llanos" farm was classified such as: Order, Aridsols; Suborder, Calcids; Great group, Haplocalcids; Subgroup, Xeric Haplocalcids. On the other hand, the land from "Casablanca" farm was classified such as: Order, Aridsols; Suborder, Argids; Great group, Petroargids; Subgroup, Xeric Petroargids.

In both years and farms, the seeding date was in March and harvesting was in October. The seeding dose was between 140,000 and 150,000 seeds/ha. Every year and farm, two simultaneous and complementary tests were carried out. The experimental design was a randomized complete block with four replications for each test. Plots were weeded by hand or overgrown with weeds after a fixed date (T_1 to T_8 treatments). Each individual plot consisted of eight rows 305 cm long and 51 cm apart (12 m^2, of which six centre rows were harvested).

Weeds were allowed to enter test plots named as "With Weeds Until" (WWU) from 50% sugar beet emergence until a fixed date. Then, plots were weeded by hand and kept free of weeds until harvest. Treatment T_1 was free of weeds from emergence until harvest. Treatments T_2 to T_7 were overgrown with weeds from emergence until a date fixed for each T_i. Treatment T_8 was overgrown with weeds from emergence until harvest. Plots named as "Free of Weeds Until" (FWU) were free of weeds from 50% sugar beet emergence until a fixed date. Then, plots were allowed to be overgrown with weeds until harvest. Treatment T_1 was overgrown from emergence until harvest. Treatments T_2 to T_7 were kept free of weeds from emergence until a date fixed for each T_i. Treatment T_8 was kept free of weeds from emergence until harvest.

In order to study composition and to assess overgrowth parameters, multiple measurements on several samples were carried out during the growing period. Overgrowth was assessed through: density or abundance (D); specific density (D_s); sampling relative frequency (F_r); and specific relative frequency (F_{rs}) (Pujadas 1986; Saavedra 1987; Recasens 1994). Non-linear regression models used in competition studies are shown in Table 1 (Pardo 1990). Apart from purely statistical considerations, discussed below, the following initial conditions that are considered important have been established: i) the model should describe the losses in the harvest in relation to the weed competition period, ii) their parameters should preferably have an agronomic sense, and iii) there should not be insurmountable difficulties at the time of observations.

Yield at harvest (dry biomass of sugar beet root) was selected as the dependent variable. On the other hand, competition period duration was selected as the independent variable. Competition period duration was measured in two ways. In the first way, we measured competition period duration in terms of the number of days after 50% sugar beet emergence (t). In the second, we

Table 1. Models used in competition studies.

	Model	Function
[1]	General logistic equation	Y=a/(1+d.exp(-b.X))
[2]	Logistic equation including inflection point	Y=a/(1+exp(-b.(X-c)))
[3]	Gompertz's equation including inflection point	Y=a.exp(-exp(-b.(X-c)))
[4]	Hyperbolic equation	Y=a.(1-d/((exp(b.X)+g).100))

Y. yield of dry sugar beet root biomass (gm-2); X, sugar beet physiological age from 50% emergence (days or growing degree days); a, upper asymptotic value; b, curve slope or growth rate; c, abscissa value at inflection point; d, g and h are non-linear regression adjustment coefficients.

measured competition period duration as a function of the degree of growth days after 50% sugar beet emergence (GDD). A base temperature of 6 °C was considered.

Data were fitted to the models (Eqs. 1 to 4; Table 1) using the non-linear regression procedure of SPSS to Windows, version 10.0.6 (SPSS Inc. 1999) and STATGRAPHICS, version 5.0 (Statistical Graphics Corp. 2000). Validation of non-linear regression functions, used for fitting yield data under different years and test conditions, should verify the following hypothesis for independent variables t and GDD: normality (Shapiro and Wilk methodology; asymmetric coefficient and kurtosis); homoscedasticity (statistics of Cochran; Bartett; Hartley); and independence of residuals (test of Durbin Watson) (Cochran & Cox, 1980; Peña 1992). All statistical tests were conducted at 5% and 1% levels of probability. This study could be done anywhere in the world, provided there be a mathematical model adapted to the study area.

3 Results and discussion

Depending on the year and experimental farm, the sugar beet youth stage ranged from taking 71 to 85 days to be reach adequate maturation, which is equal to 825-842 GDD (°C). Duration of total marketable yield ranged from 160 to 184 days after emergence, which is equal to 2177-2287 GDD (°C). An example of weed composition for two specific situations is shown in Tables 2 and 3.

Under early competition conditions (WWU), most of the plots located in both experimental farms were overgrown with *Amaranthus retroflexus* L., *Chenopodium album* L., and *Setaria* spp. The presence of *Amaranthus retroflexus* L. decreases in year 2. Other species such as *Salsola kali* L. and *Solanum nigrum* L. appear in an isolated way (Table 4). Under late competition conditions (FWU) there are differences between years and farms. This way, during year 1, most of the plots located in both experimental farms were overgrown with *Solanum nigrum* L. and *Chenopodium album* L.. In addition, *Amaranthus retroflexus* L. was important in "Los Llanos" and *Setaria* spp. in "Casablanca". During year 2, *Solanum nigrum* L. and *Chenopodium album* L. were again the most abundant species in both farms (Table 4).

Results obtained in the hypothesis verification process of the models confirm that the data are independent, normal and with homogeneous variance. So, it is not necessary to transform them. However, different parameter results were obtained in the validation process of these equations. In addition, goodness of fit is slightly different depending on the equation used. For independent variable t, Equations 1 to 3 (Table 1) are valid for both WWU and FWU experiments. The independent variable GDD, mainly under WWU conditions, is not suitable for estimating parameters related with Equations 1 to 3. This variable presents higher problems than variable t for estimating the following parameters: c of Eq. [2] under WWU conditions; a, b, and c of Equation 3 under WWU conditions; and c of Equation 3 under FWU conditions in "Los Llanos". The results obtained estimating hyperbolic Equation 4 parameters are different compared with last equations. Only a parameter (asymptotic value) is significant every year for both t and GDD variables under WWU and FWU conditions. The b parameter is valid under FWU conditions in "Casablanca" and for the t variable as well. In the rest of the cases, parameter values are insignificant.

The fitting of non-linear regression models under WWU conditions is quite similar when using t and GDD independent variables (Equations 1 to 4; Table 1). In both cases, goodness of fit is around 93%. This value is represented by the coefficient of determination (R^2). The lack of adjustment is conditioned by internal variations of data. In this case, true error has a greater effect than the lack of adjustment. Under FWU conditions and t as the independent variable, the lack of adjustment due

Table 2. Weeds composition. Year 1; Farm: "Los Llanos"; Test: "With Weeds Until" (WWU); Treatments T1 to T8; Sampling date (day/month).

Species	T_1(07/04)		T_2(25/04)		T_3(10/05)		T_4(25/05)		T_5(07/06)		T_6(21/06)		T_7(12/07)		T_8(09/08)	
	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}
Am. r.	-	-	23.5	16.3	18.5	9	23	10.7	25	13.1	33	21	13	12	12.5	21.5
Am. b.							18	8.3	9.5	5	5.5	3.5	4	3.7	3.5	6.3
Ch. a.	-	-	4.5	3.1	58	22.2	64.5	20.9	100	52.6	109	69.4	67.5	62.5	34.5	59.5
St. spp.			113	78.8	90.5	44	100	46.6	53	27.7	7.5	4.8	21.5	19.9	-	-
Kch. s.			2	1.4	1.5	0.7	1	0.5	0.5	0.3	-	-	-	-	-	-
Ss. k.			0.5	0.3	-	-	-	-	1	0.5	-	-	-	-	-	-
Sl. n.			-	-	34	16.5	-	-	-	-	2	1.3	2	1.8	6.5	11.2
Pg. a.			-	-	3	1.5	4.5	2	1.5	0.8	-	-	-	-	-	-
Fm. o.			-	-	-	-	0.5	0.2	-	-	-	-	-	-	-	-
Ht. a.			-	-	-	-	0.5	0.2	-	-	-	-	-	-	-	-
Sb. i.			-	-	-	-	0.5	0.2	-	-	-	-	-	-	-	-
Sg. h.			-	-	-	-	-	-	-	-	-	-	-	-	1	1.7

Ds, specific density (plants m-2); Frs, specific relative frequency or percentage of one species compared with the total amount of species present in a plot (%); Am. r., Amaranthus retroflexus L.; Am. b., Amaranthus blitoides Watson; Ch. a., Chenopodium album L.; St. spp., Setaria spp.; Kch. s., Kochia scoparia Schrader.; Ss. k., Salsola kali L.; Sl. n., Solanum nigrum L.; Pg.a., Poligonum aviculare L.; Fm. o., Fumaria officinalis L.; Ht. a., Helianthum annus L.; Sb. i., Sisymbrium irio L.; Sg. h., Sorghum halepense (L.) Pers.

to the model is similar to true error, and slightly lower when using GDD as the independent variable. Under WWU and FWU conditions, the equations which reach the best fitting are logistic and include an inflection point (Equation 2; Table 1), with t as the independent variable. Using the same independent variable t, Gompertz's equation including an inflection point (Equation 3; Table 1) reaches a good result but the fitting is the worst. Under FWU conditions and GDD as the independent variable, it is possible to apply Equation 2 and 3 (Table 1). In this case, Equation 2 reaches the best fitting.

Under WWU and FWU conditions, yield curves (referred to 100%) are shown in Figure 1. All the estimated parameters are significant (Table 5). In addition, R^2 is higher than 97% but under FWU in "Los Llanos" year 2 (R^2=84.39%; Table 5).

Table 3. Weeds composition. Year 1; Farm: "Casablanca"; Test: "Free of Weeds Until" (FWU); Treatments T1 to T8; Sampling date (day/month).

Species	T_1(22/04)		T_2(13/05)		T_3(27/05)		T_4(13/06)		T_5(27/06)		T_6(10/07)		T_7(06/08)		T_8(16/09)	
	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}	D_s	F_{rs}
Am. r.	-	-	0.6	0.7	-	-	-	-	-	-	0.62	6.67	-	-	-	-
Am. b.	8.1	5.7	2.5	2.9	0.6	3.4	4.4	21.2	2.5	17.6	1.9	20	1.2	16.7	0.6	20
Ch. a.	88.7	62.8	37.5	44.1	8.1	46.4	15	72.7	3.75	35.3	1.25	13.3	1.25	16.7	1.9	60
St. spp.	38.7	27.4	39.4	46.3	3.7	21.4	4.38	21.2	3.12	29.3	3.7	40	16.7	33.3	-	-
Kch. s.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ss. k.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sl. n.	-	-	4.3	5.1	4.4	25	3.8	18.1	1.88	17.6	19	20	1.2	16.7	0.6	20
Pg. a.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fm. o.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ht. a.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sb. i.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sg. h.	5.6	4	0.6	0.7	0.6	3.6	-	-	-	-	-	-	1.2	16.7	-	-

Ds. specific density (plants m-2); Frs. specific relative frequency or percentage of one species compared with the total amount of species present in a plot (%); Am. r.. Amaranthus retroflexus L.; Am. b.. Amaranthus blitoides Watson; Ch. a., Chenopodium album L.; St. spp., Setaria spp.; Kch. s., Kochia scoparia Schrader.; Ss. k., Salsola kali L.; Sl. n., Solanum nigrum L.; Pg.a., Poligonum aviculare L.; Fm. o., Fumaria officinalis L.; Ht. a., Helianthum annus L.; Sb. i., Sisymbrium irio L.; Sg. h., Sorghum halepense (L.) Pers.

Table 4. Species of weeds present in treatments T1 to T8.

Species	Sampling relative frequency (F_r)							
	With Weeds Until (WWU)				Free of Weeds Until (FWU)			
	Los Llanos		Casablanca		Los Llanos		Casablanca	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Am. r.	93.7	75.5	61.4	21	84.4	60	6.3	50
Am. b.	40.6	28.1	64.5	22	15.6	25	46.8	45
Ch. a.	87.5	59.4	96.9	100	81.2	55	75	35
St. spp.	71.9	62.5	96.9	53	-	30	62.5	45
Kch. s.	34.4	-	-	-	-	-	-	-
Ss. k.	9.4	50	12.5	22	3.1	10	-	-
Sl. n.	25	21.9	-	19	100	25	71.8	45
Pg. a.	21.9	-	-	-	6.2	-	-	-
Fm. o.	3.1	15.6	-	-	-	-	-	-
Ht. a.	3.1	3.1	-	16	-	-	-	10
Sb. i.	3.1	-	-	-	-	-	-	-
Sg. h.	3.1	-	3.1	-	62.6	45	9.4	-

Fr, sampling relative frequency or percentage of plots where that weed species was present (%); Am. r., Amaranthus retroflexus L.; Am. b., Amaranthus blitoides Watson; Ch. a., Chenopodium album L.; St. spp., Setaria spp.; Kch. s., Kochia scoparia Schrader.; Ss. k., Salsola kali L.; Sl. n., Solanum nigrum L.; Pg.a., Poligonum aviculare L.; Fm. o., Fumaria officinalis L.; Ht. a., Helianthum annus L.; Sb. i., Sisymbrium irio L.; Sg. h., Sorghum halepense (L.) Pers.

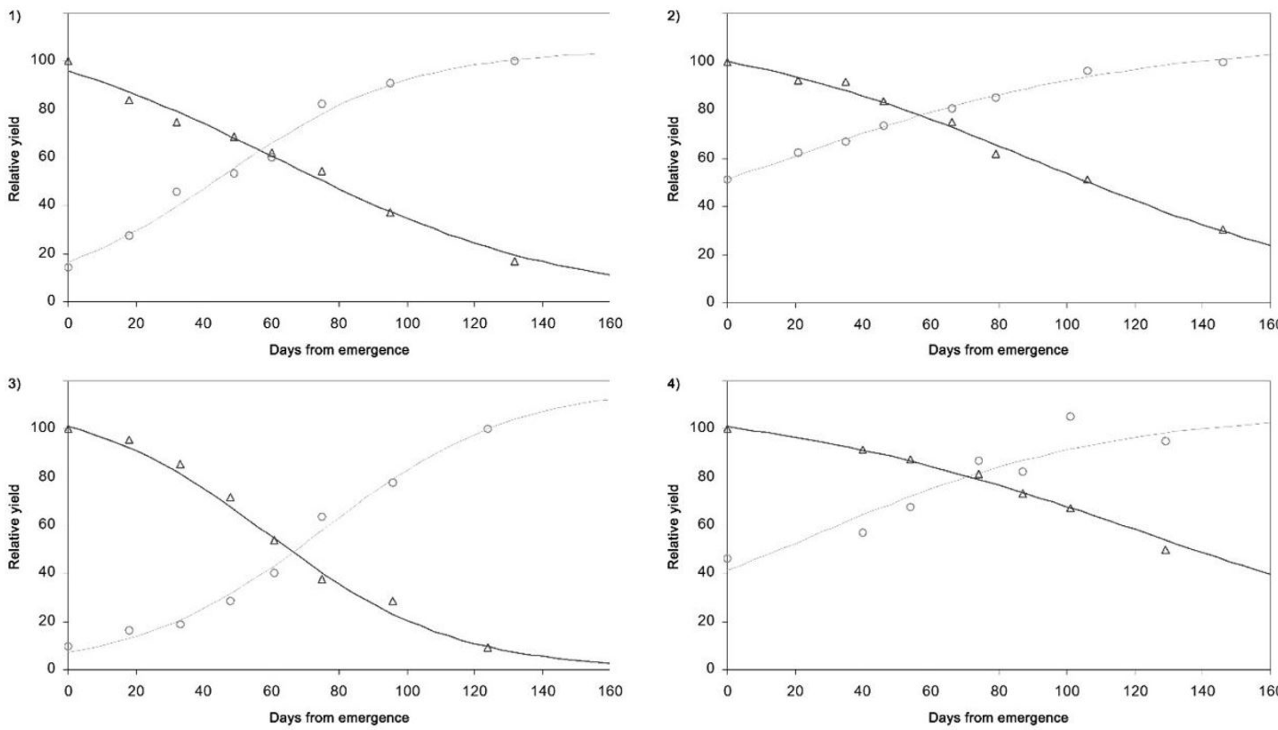

Figure 1. Logistic function corresponding to test "With Weeds Until" (WWU) and "Free of Weeds Until". Δ, Observed WWU; O, Observed FWU; 1), WWW and FWU "Casablanca". Year 1; 2), WWU and FWU "Casablanca". Year 2; 3), WWU and FWU "Los Llanos". Year 1; 4), WWU and FWU "Los Llanos". Year 2.

Table 5. Parameters (a, b and c), coefficient of determination (R2), standard error of estimate (SE), and mean absolute error (MAE), fitting Y=a/(1+exp(-b.(t-c))) under both "With Weeds Until" (WWU) and "Free of Weeds Until" (FWU).

	"Casablanca"		"Los Llanos"	
	Year 1	Year 2	Year 1	Year 2
Model "WWU"				
a	118.69*	116.59*	112.79*	113.39*
b	-0.02324*	-0.01989*	-0.03681*	-0.01701*
c	61.89*	92.24*	58.99*	123*
R^2	97.73	92.24	99.08	98.52
SE	3.96	2.80	3.15	2.51
MAE	2.74	1.71	2.07	1.42
Model "FWU"				
a	105.01*	109.48*	118.03*	107.70*
b	0.03666*	0.01803*	0.03500*	0.02200*
c	45.69*	7.51*	76.00*	22.00*
R^2	97.76	99.22	98.57	84.39
SE	4.53	1.47	3.91	8.35
MAE	2.85	0.94	2.65	5.84

Y, yield of dry sugar beet root biomass (gm-2); t, sugar beet physiological age from 50% emergence (days); a, b and c, mathematical models coefficients; *: $p < 0.05$.

4 Conclusions

In this study, after having ruled out the use of hyperbolic-type models due to both their statistical significance and their distance from the phenomenon of competition, the sigmoidal-type models are more acceptable, because they have a behavior more in line with reality.

To conclude, one can say that the prediction of damage, using mathematical models with few parameters can be a simple and effective tool for the establishment of economic thresholds for treatment, but these models must be validated by sufficient testing and, especially, by damage. In light of the experimental data presented in this manuscript, the dispersion of the data, due to no fault of competition, may affect the prediction and the goodness of the adjustments. At times like this, experimental data for several years can not be handled together because they lack the necessary homogeneity, despite being obtained in an identical way. The model most in line with reality that performed well for two years in two nearby farms may not be acceptable when applied to other crop campaigns, complicating the obtainment of extrapolated conclusions.

Given the heterogeneity that is sometimes present in data, it is essential to work with rates of production or loss in the annual theoretical maximum production level, which are rarely the same across campaigns. Additionally, the total harvest also varies due to it being rarely independent of the yearly climatic and the physical-chemical nature of the soil.

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