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COMPARISON OF TWO MODELS OF RESPONSE TO NITROGEN DOSES IN CORN AND COFFEE

Comparación de dos modelos de respuesta a dosis de nitrógeno en maíz y cafeto

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ABSTRACT. The common method to generate fertilizer recommendations is by fitting yield data for each crop separately through mathematical models. This work was carried out with the objective of comparing two response equation models to nitrogen rates in two economically important crops, corn and coffee, besides defining the most appropriate criteria to select the model that offers an adequate optimal fertilization rate. Thus, N doses from 0 to 200 kg ha^{-1} for corn (*Zea mays*) were studied along with different types of crop rotation: fallow followed by corn; fallow-corn inoculated with arbuscular mycorrhizal fungi (AMF); jackbean-corn and jackbean-corn inoculated with AMF, in experiments performed during 2003 and 2006. In the case of coffee crop, N doses from 0 to 400 kg ha^{-1} were studied depending on plant age, within the first two productive cycles of a *Coffea canephora* plantation, during 1996 and 2007. The rectilinear discontinuous model with lineal equations and the curvilinear continuous model with second degree equations were compared. Maximum yield, optimum economic rate and partial productivity factor were estimated by the equations obtained from each model. In both crops studied, the rectilinear discontinuous model offered lower fertilizer dose estimations than the one obtained by the curvilinear model, so that together with the partial productivity factor, they constitute effective methods to estimate the amount of nutriments to be applied, avoiding N overdoses..

Key words: *Coffea canephora*, application rates, maize, linear models

RESUMEN. El método común para generar recomendaciones de fertilización, es ajustar los datos de rendimiento en forma independiente para cada cultivo, a través de modelos matemáticos. El trabajo se realizó con el objetivo de comparar dos modelos de ecuaciones de respuesta a dosis de nitrógeno, en dos cultivos de importancia económica: maíz y cafeto y definir los criterios más adecuados para seleccionar el modelo que ofrezca una dosis óptima de fertilización. Se estudiaron dosis de nitrógeno que oscilaron desde 0 hasta 200 kg ha^{-1} para el cultivo del maíz (*Zea mays*) en presencia de diferentes tipos de rotación: barbecho seguido de maíz; barbecho maíz inoculado con hongos micorrízicos arbusculares (HMA); canavalia maíz y canavalia maíz inoculado con HMA, en experimentos ejecutados durante los años 2003 y 2006. En el caso del cafeto, se estudiaron dosis que oscilaron entre 0 a 400 kg ha^{-1}, en dependencia de la edad de la planta, durante los dos primeros ciclos productivos de un cafetal de *Coffea canephora*, entre los años 1996 y 2007. Se compararon el modelo discontinuo rectilíneo con ecuaciones lineales y el curvilíneo continuo, con ecuaciones de segundo grado. Con las ecuaciones obtenidas en cada modelo se estimó el rendimiento máximo, la dosis óptima económica y el factor parcial de productividad. El modelo discontinuo rectilíneo, en los dos cultivos estudiados, ofreció estimados de la dosis óptima de fertilizante a aplicar inferiores al que el que se obtiene mediante el modelo curvilíneo, por lo que de conjunto con el factor parcial de productividad, constituyen métodos efectivos para estimar la cantidad de nutrimentos a aplicar en un cultivo, evitando aplicaciones excesivas de nitrógeno.

Palabras clave: *Coffea canephora*, dosis de aplicación, maíz, modelos lineales

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INTRODUCTION

An updated United Nation projection on the world population growth states the current estimate of 7 000 million will rise to one billion over the next 12 years[A]; consequently, it involves the need to increase crop yield and agricultural production efficiency to meet food demand of an ever-growing population (1).

Nitrogen (N) has been a determining factor in rising agricultural production within the latest 50 years. Different studies showed that a third portion of the world agricultural production increment in the 70s and 80s of the XX century was due to a greater use of fertilizers. However, when N is not properly applied, it may have negative effects on the environment; the most important problems it provokes are due to losses by washing, volatilization and denitrification (2).

The application of adequate amounts of nutrients is a key aspect to improve agricultural production. At present, fertilization rates recommended to farmers are very general and, in some cases, are not related to required nutrients for the crop and its availability in the soil, resulting in an unbalanced and inefficient use of fertilizers and high production costs.

Generally speaking, there is not any analytical method to measure N availability in the soil that can be daily employed by laboratories, largely due to its transformations in the soil, which are influenced by environmental conditions. Therefore, N recommendations should be based on response curves obtained under different soil and climatic conditions (3).

With this respect, mathematical models has been particularly focused on predicting crop productive response to fertilizers, since they enable to provide information about the possible maximum yield reached, carrier expenses, as well as to measure optimum economic fertilizer rates for each agro-ecosystem and other useful variables to make decisions[B].

The common method to generate fertilizer recommendations is by fitting data for each crop separately through mathematical models. The quadratic model is usually proposed, which has the disadvantage of overestimating optimal rates. Thus, it is advisable to adjust and compare several models before recommending fertilization doses (4).

Among the models suggested to be analyzed are: quadratic with plateau; logistic used as a growth model; exponential or Mitscherlich; sinuous wave; polynomial models with different exponents in the predicting variable, such as the value 0,5 (for square root model); 0,75; 1,5 or another suitable value to model response curvature (5).

The rectilinear discontinuous model (6) is among the ones having a starting response point with minimum nutrient (limiting factor) and a final point, which is the maximum steady yield. Logical estimates of nutrient requirements are given by interpreting discontinuous model. Curvilinear interpretation of the same data provides unreasonable predictions of nutrient requirements.

Consequently, this research study was conducted, with the objective of comparing two response equation models to N rates in two economically important crops, corn and coffee, besides defining the most appropriate criteria to select the model that offers an optimal fertilization rate.

MATERIALS AND METHODS

Corn

The influence of *Canavalia ensiformis* (L.) D.C., used as succeeding green manure, and mycorrhizal inoculation of corn (*Zea mays* L.) with an efficient AMF strain on N fertilizer requirements of this crop was evaluated in an Eutric Rhodic Nitisol (7). The experiment was carried out in plots located at 23º01' N latitude and 82º08' W longitude, 138 m above sea level, from the National Institute of Agricultural Sciences (INCA), San José de las Lajas municipality, Mayabeque province, in Western Cuba, during the period from May to October (rainy season) in 2003 and 2006.

[A]Servicio de Noticias de las Naciones Unidas. *Centro de noticias de la ONU en español - La población mundial crecerá en mil millones en la próxima década* [en línea]. cod. Servicio de Noticias de las Naciones Unidas, [Consultado: 15 de enero de 2016], Disponible en: <http://www.un.org/spanish/News/story.asp?newsID=26703#.VphCeU9BcYt>.

[B]Rodríguez, de la T. E. *Bases de conocimientos para generar modelos predictivos de respuesta a los fertilizantes nitrogenados en agroecosistemas cañeros* [en línea]. [Tesis de Maestría], Universidad Agraria de La Habana, La Habana, Cuba, 2002, 86 p., [Consultado: 26 de junio de 2014], Disponible en: <http://www.monografias.com/trabajos-pdf/conocimientos-modelos-fertilizantes-nitrogenados-agroecosistemas/conocimientos-modelos-fertilizantes-nitrogenados-agroecosistemas.pdf>.

A split plot design with four repetitions was used. During the first year (2003), the following sequences were established as main plots: 1) fallow for two months and subsequent corn seeding; 2) canavalia as green manure preceding corn crop and 3) canavalia as precedent crop and corn inoculated with AMF strain *Glomus cubense* INCAM 4 (8), coming from INCA's strain collection through seed coating technique, using a guaranteed inoculant of minimum quality, 20 spores g^{-1} inoculant at an equivalent dose to 10 % seed weight.

In each sequence, five mineral N fertilizer rates (0; 50; 100; 150 and 200 kg ha^{-1}) were evaluated as subplots, with the corn variety "Francisco mejorado" that is sponsored by "Alejandro de Humboldt" Fundamental Research Institute in Tropical Agriculture (INIFAT) of Cuba.

During the second year (2006), the same sequences described were studied, besides adding a more consistent sequence of fallow for two months and a subsequent seeding of corn inoculated with the same AMF strain.

The canavalia preceding corn was sown in May of both years studied, using two seeds per nest at plant spacing of 0,45 m x 0,30 m. Each plot had 12 canavalia rows 7 m long. The eight central rows of each plot were considered as calculus area.

Green manure was cut and included 60 days after its germination, at flowering initiation, to the soil through a whole three-disk plough at 20 cm deep. Ammonium nitrate (NH_4NO_3) was employed as carrier, splitting 50 % rate at sowing time and 50 % 30 days after corn germination (Table I).

Corn was seeded by hand in August, 20 days after incorporating green manure, in six rows per plot at plant spacing of 0,90 m x 0,30 m, considering the four central rows as calculus area. Yield (t ha^{-1}) was determined when green corn was harvested. Soil and climatic characteristics, as well as agronomic results are detailed and discussed (9).

Coffee

With the purpose of determining the effect of N fertilization on *Coffea canephora* yield, this experiment was performed in Cruce de los Baños town, Tercer Frente municipality, Sierra Maestra mountainous area, located at 20º09' N latitude and 76º16' W longitude, 35 km WNW far from Santiago de Cuba city, 150 m above sea level, on a haplic Cambisol (10) as well as in La Alcarraza town, Sagua de Tánamo municipality, Nipe-Sagua-Baracoa mountainous area, located at 20º35' N latitude and 75º15' W longitude, 118 km ESE far from Holguin city, 300 m above sea level, on a stagnic Cambisol (7), in Eastern Cuba.

Seedlings were planted in May, 1996, at plant spacing of 3 m x 15 m, making up a population of 2,222 plants ha^{-1}. The response to five N fertilization systems was studied in a randomized block design (Table II) with four replications during two productive cycles. Experimental plots were composed by three rows of seven plants each; five central plants of each row were considered as calculus area.

Table I. Treatments studied in corn experiment

Doses	Sequences			
	Fallow–corn (kg N ha^{-1})	Jackbean–corn (kg N ha^{-1})	Jackbean–corn+AMF (kg N ha^{-1})	Fallow–corn+AMF (kg N ha^{-1})
Mineral fertilizer rates	0	0	0	0
	50	50	50	50
	100	100	100	100
	150	150	150	150
	200	200	200	200

Fallow: idle soil for two months Green manure: *Canavalia ensiformis* Mineral fertilizer: NH_4NO_3
Inoculation with AMF: EcoMic® based on *Glomus cubense*

Table II. N rates (kg ha^{-1}) used for fertilization schemes studied in coffee crop

Treatments	First productive cycle			Second productive cycle		
	1996	1997	1998-2002	2003	2004	2005-2007
N_0	0	0	0	0	0	0
N_1	30	45	50	50	75	100
N_2	60	90	100	100	150	200
N_3	90	135	150	150	225	300
N_4	120	180	200	200	300	400

Within the first cycle, N rate in 1996, 2000, 2001 and 2002 was split to 50 %, with two annual applications (April and early October), whereas in 1997, 1998 and 1999, it was split into three equal parts (April, July and October) in both locations.

Within the second cycle, N rate was split to 33 % and applied three times every year (April, June and early October). Urea was used as carrier. Fertilizers were applied at half-moon shape about 50 cm around the stem.

Every year, ripe fruits from each plot were harvested, weighed (kg) and extrapolated first to t ha^{-1} coffee cherries and subsequently to t ha^{-1} coffee berries. Soil and climatic characteristics, as well as agronomic effects of this experiment are detailed (11, 12).

Statistical analysis

For interpreting response data to fertilizer of each experiment, they were adjusted through rectilinear discontinuous model (6). Thus, agricultural yield results were gathered and arranged depending on growing nutrient rates, establishing the maximum steady yield, response slope and yield turning point.

Finally, the mathematical interpretation of response to the nutrient was performed as follows:

y= a x + b (where max y is obtained by rec x)

y: yield
a: yield with minimum nutrient
x: amount of nutrient applied
b: response slope
y max: maximum steady yield
rec x: optimal rate recommended

Curvilinear model was used as a traditional fitting model and second-degree quadratic equations; critical point [N rates (x) to achieve maximum yield (y)] was determined through the first equation derivative.

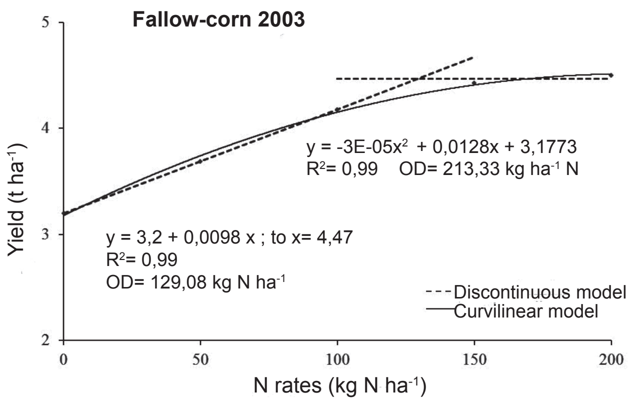
Partial productivity factor (PPF) was determined on yield estimated by calculating each model and obtaining an optimal mineral N fertilizer rate, using the following equation (13):

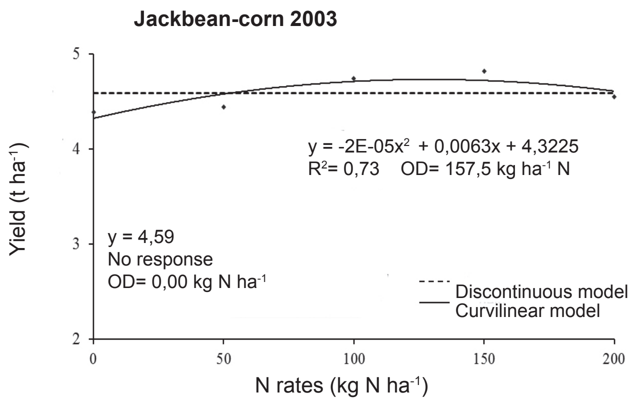
$$PPF = \text{crop yield (kg ha}^{-1}) / \text{nutrient rate applied (kg ha}^{-1})$$

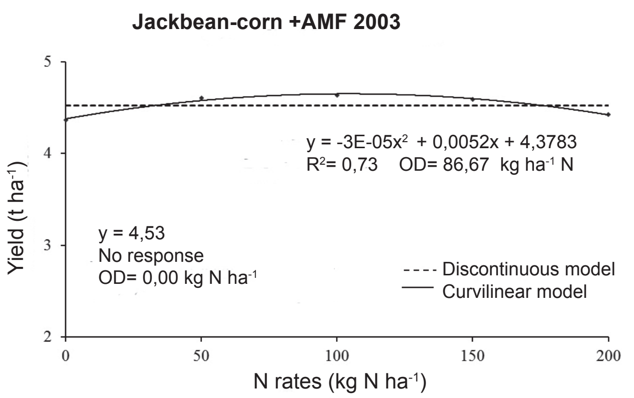
RESULTS

Corn

Figures 1 and 2 show response fittings to mineral N fertilizer rates through curvilinear and discontinuous models over different sequences and years studied in corn crop.







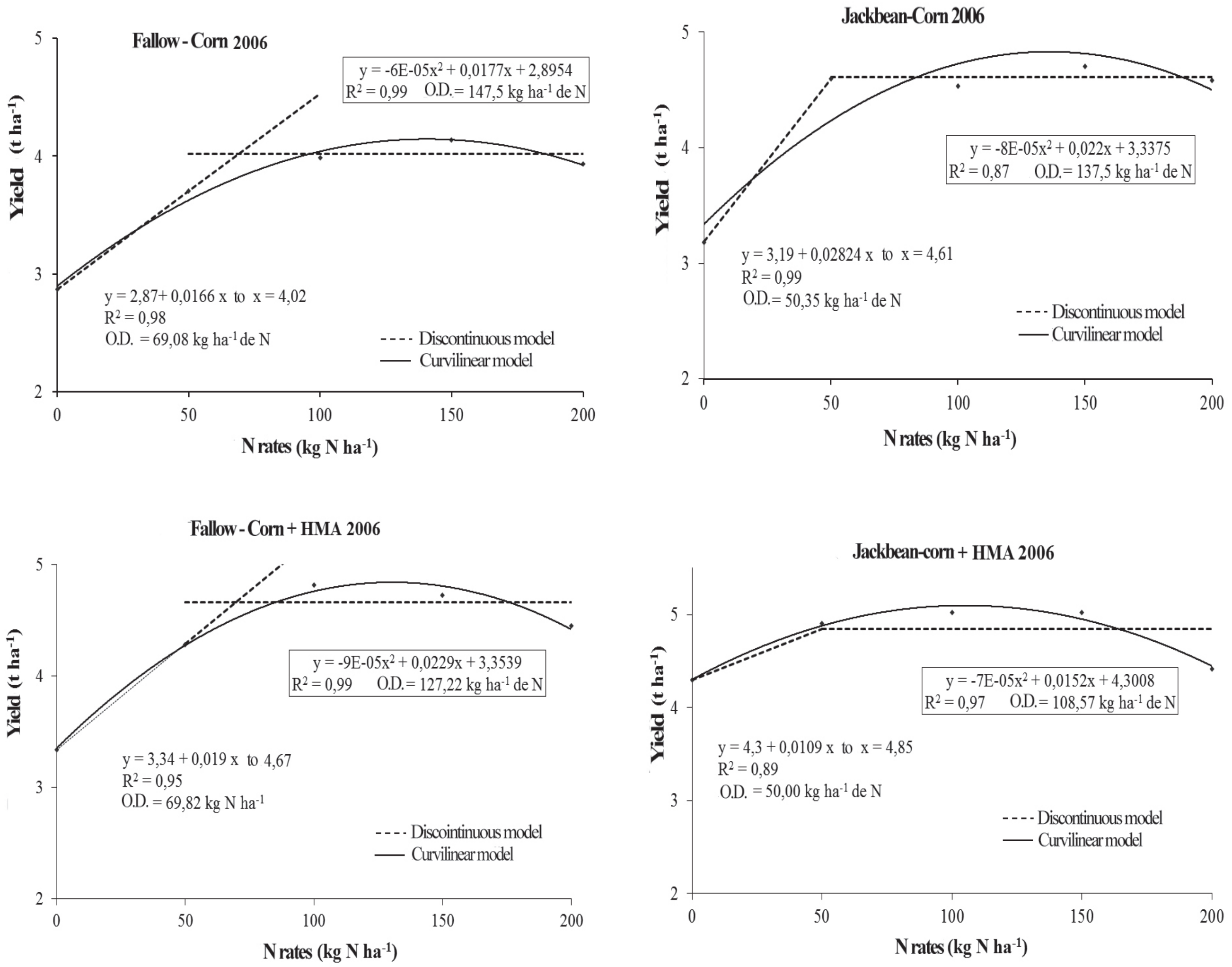
OD: Optimal dose recommended

AMF: based on *Glomus cubense*

Mineral fertilizer: NH_4NO_3

Fallow: Idle soil for two months

Figure 1. Comparison of curvilinear and rectilinear discontinuous models of corn response to mineral N fertilizer rates along with green manure and mycorrhizal inoculation. 2003



OD: Optimal dose recommended. AMF: based on *Glomus cubense.* Mineral fertilizer: NH_4NO_3. Fallow: Idle soil for two months

Figure 2. Comparison of curvilinear and rectilinear discontinuous models of corn response to mineral N fertilizer rates along with green manure and mycorrhizal inoculation. 2006

In all cases, there was a strong response predicting adjustment (high coefficients of determination, R^2); however, curvilinear model overestimated optimal rate values recommended, consequently, when calculating partial productivity factor, the values obtained by this model were less favorable than when doing the same analysis with fitting data by discontinuous model (Table III).

This result is basically due to the fact that partial productivity factor (PPF) is calculated not only based on yield, but also on the mineral fertilizer rate applied; in every case, the recommended rate was lower through discontinuous model, which leads to higher values of this variable, also implying money saving so as to achieve the highest yield with the lowest possible nutriment rate.

The evaluation of partial productivity factor as an indicator of a short-term efficient management of mineral N is important in agricultural systems, due to the transient nature of inorganic N in the soil.

Table III. Maximum yield and partial productivity factor summarized when using data obtained by corn crop in both response fitting models to N fertilizer

	Curvilinear model		Discontinuous model	
	Maximum yield ($t\ ha^{-1}$)	PPF	Maximum steady yield ($t\ ha^{-1}$)	PPF
2003				
Fallow–corn	4,54	21,29	4,47	34,59
Jackbean–corn	4,82	30,59	4,59	ND
Jackbean–corn+AMF	4,60	53,12	4,53	ND
2006				
Fallow–corn	4,20	28,48	4,02	58,15
Fallow–corn+AMF	4,81	37,81	4,67	93,33
Jackbean–corn	4,85	35,27	4,61	66,03
Jackbean–corn+AMF	5,13	47,21	4,85	96,23

FPP: Partial productivity factor (kg yield per each kg N applied)

ND: non-determined because in this model it is not necessary to supply mineral N fertilizer

Coffee

In all harvests, productive cycles and experimental sites, there was a positive coffee response to growing N rates applied. Figures 3 and 4 present response fitting to N rates studied, through curvilinear and discontinuous methods, in both experimental sites during both harvesting cycles.

Like in corn crop, there were high fittings of yield predicting models; however, in every case, it is observed how curvilinear model overestimated the optimal rate recommended, compared to discontinuous model, which resulted that when predicting curvilinear model, partial productivity factor was much lower than the one obtained when fitting results by discontinuous model (Table IV).

In coffee crop, not only PPF was higher if it is calculated by discontinuous model fitting, but also, in some seasons and years, it reached more than twice its value, when it was compared with the variable obtained by using fitting data through curvilinear model.

DISCUSSION

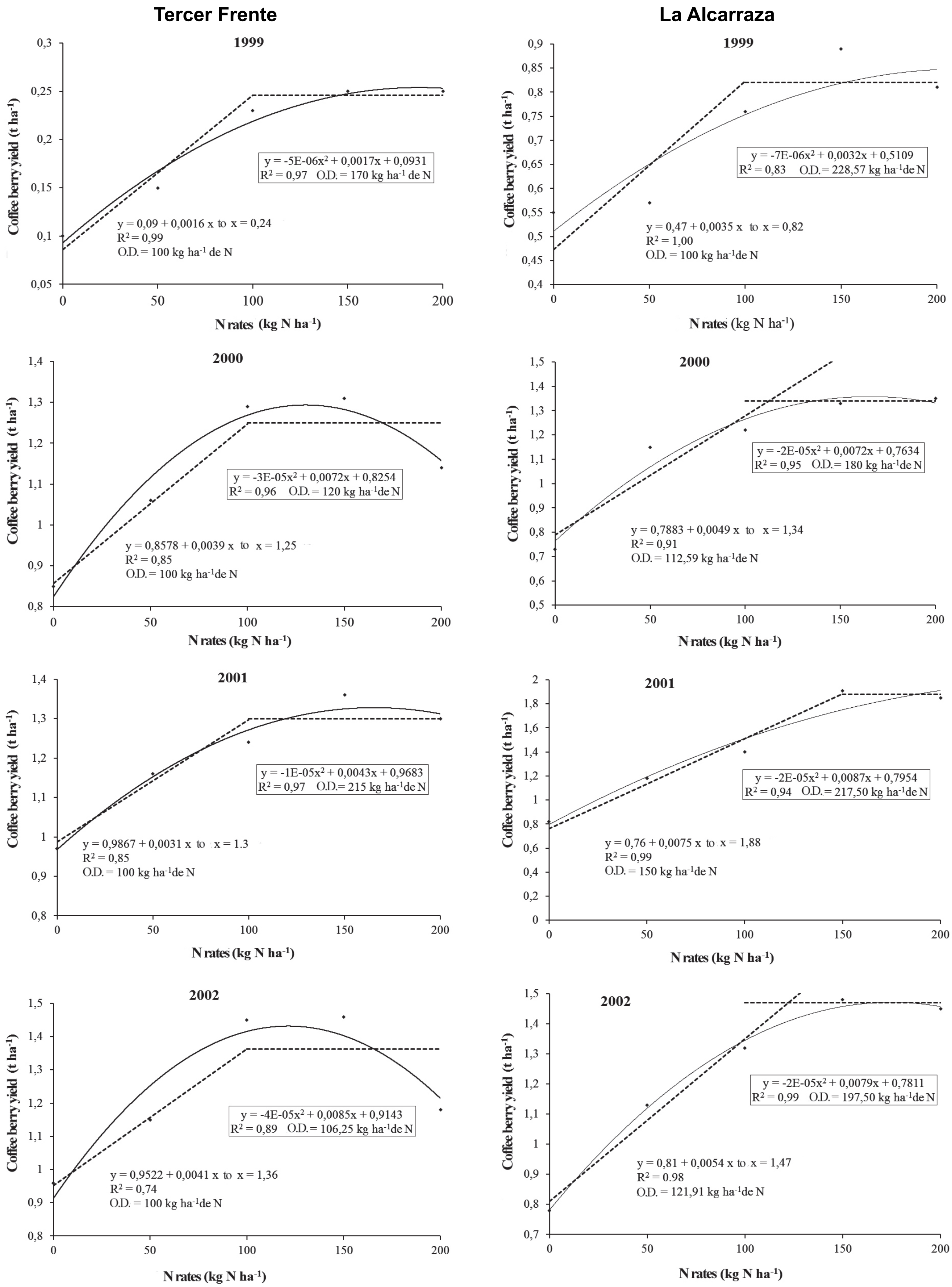
Generally, there is no consensus among researchers to select a statistical model for determining critical nutriment levels. Some of them prefer models to reach a discrete value, as the one used in this investigation, whereas others prefer curvilinear continuous models, such as quadratic, exponential (mainly Mitscherlich) and the reverse; in that case, an arbitrary value of relative yield (for instance, 90 %) or the inflection point of the curve is selected or even the economic optimum.

When selecting the model, it is necessary to prevent biased estimates from the optimal rate, which constitutes a more important criterion than R^2 size (coefficient of determination), since various models have similar R^2 values, but the optimal dose estimated by each one is very different (4); this approach was taken into account when analyzing the results of investigation, so as to select the most appropriate model under experimental conditions.

The mathematical fitting of data through quadratic, square root or Mitscherlich models overestimates the optimum amount of nutriments and estimated yield at the optimal point[B]. This phenomenon was observed at the mathematical analysis of data from the experiments evaluated, where optimal rates calculated through curvilinear model were much higher than those obtained by discontinuous model.

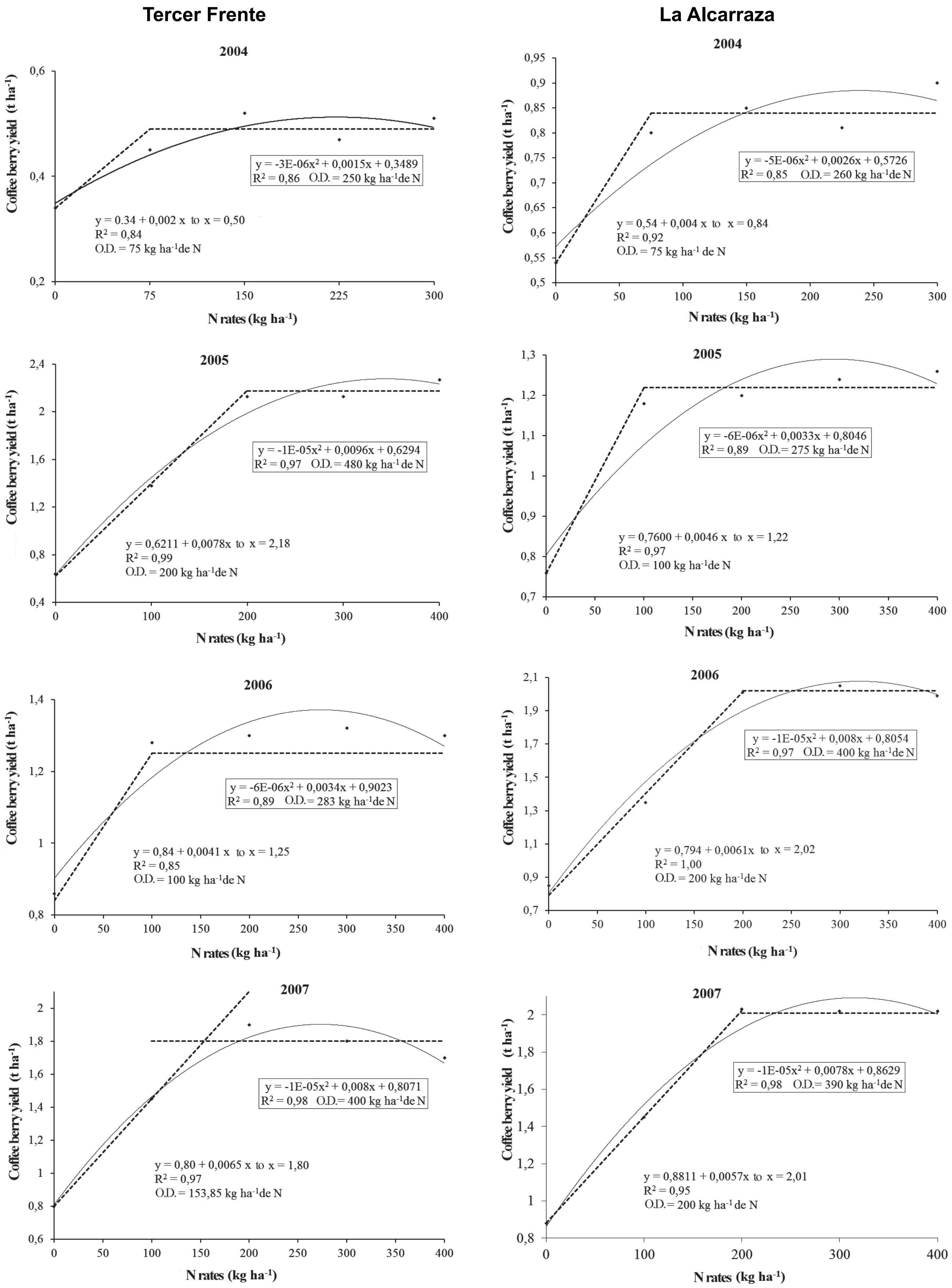
Several researchers, at different developing stages of agricultural sciences, have studied various curvilinear models, with the purpose of achieving an optimal nutrient dose; however, they mostly agree in recognizing the advantages of rectilinear discontinuous model facing asymptotic functions when defining optimal economic amounts, so avoiding bias to the right of curvilinear models[B].

In this sense, when comparing two mathematical models of response curve to N fertilization in corn crop, it was shown that although there were not any differences among optimal doses recommended by the models studied under the experimental conditions, the linear discontinuous model proved to be more easily agronomically explained and practically applied, so it is recommended to be used in fertilization systems of corn growing over large areas (14).



OD: Optimal dose recommended. MSY: Maximum steady yield - - - - Discontinuous model —— Curvilinear model

Figure 3. Effect of N fertilization on *C. canephora* yield during its first cycle



OD: Optimal dose recommended. MSY: Maximum steady yield - - - - Discontinuous model —— Curvilinear model

Figure 4. Effect of N fertilization on *C. canephora* yield during its second cycle

Table IV. Maximum yield and partial productivity factor summarized when using data obtained by corn crop in both response fitting models to N fertilizer

Year	Curvilinear model Maximum yield (t ha^{-1})	FPP	Discontinuous model Maximum steady yield (t ha^{-1})	PPF
		Tercer Frente		
1999	0,24	1,40	0,24	2,40
2000	1,26	10,48	1,25	12,50
2001	1,43	6,65	1,3	13,00
2002	1,37	12,86	1,36	13,60
2004	0,54	2,15	0,5	6,67
2005	2,93	6,11	2,18	10,90
2006	1,38	4,88	1,25	12,50
2007	2,41	6,02	1,8	11,70
		La Alcarraza		
1999	0,88	3,84	0,82	8,20
2000	1,41	7,84	1,34	11,90
2001	1,74	8,01	1,88	12,53
2002	1,56	7,90	1,47	12,06
2004	0,91	3,50	0,84	11,20
2005	1,26	4,58	1,22	12,20
2006	2,41	6,01	2,02	10,10
2007	2,38	6,11	2,01	10,05

In general, a model with a limited number of parameters that is easily adjusted and does not cause bias when estimating the optimal is preferable. In this sense, discontinuous model produces conservative estimates of the optimal (4), which is advantageous for recommending optimal nutriment rates, from the economic and environmental point of view.

In this research, not only two models of response curves were compared, but also a parameter was used to evaluate the amount of fertilizer recommended by the model that is recovered by the crop, based on the expected yield, which is known as fertilizer use efficiency or partial productivity factor (15).

In other research studies, it was found that partial productivity factor may increase along with an adequate management of different nutritional choices. This result showed a higher nutriment use efficiency, which leads to a lower potential of its losses from the environment (16).

Partial productivity factor gets higher values of the recommended fertilizer systems with the lowest optimal rates, in both crops studied, indicating the increased efficiency of N fertilizer used by corn and coffee crops, which should be considered when selecting a response model to fertilization that avoids mineral N fertilizer overdoses.

Therefore, the last step before recommendations is to apply economic criteria for determining if the procedure will be profitable for the producer. In this regard, discontinuous model indicates the optimal dose to achieve maximum yield with the lowest nutriment application, so as to reach an economically feasible yield level (6).

Consequently, it is advisable to be based not only on a plant response model or another to nutriment source addition, but also the selection of optimum rates should take into account other indexes, such as the efficiency of converting the amounts of nutriments applied into yield obtained; in this way, the economic and environmental impact of recommended agricultural practices can be also assessed.

CONCLUSIONS

Rectilinear discontinuous model is more appropriate in the recommendation system of optimal N fertilizer rates for corn and coffee crops, compared to curvilinear model, which provides higher optimal rates, which involves a lower partial productivity factor of the recommended dose.

Partial productivity factor, together with rectilinear discontinuous model, constitute appropriate criteria for establishing the response model to fertilizers that recommend the optimum economic dose of mineral N fertilizer for coffee and corn crops.

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