Estimation of the optimal nitrogen dose in a *Brachiaria humidicola*-corn rotation system in the Colombian Eastern Plains

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Abstract

Improving nitrogen (N) use efficiency by optimizing the N fertilizer application dose is one way to reduce greenhouse gas (GHG) emissions in agriculture and livestock production, especially in higher demanding crops such as corn. Taking a *Brachiaria humidicola* (*Bh*)-corn rotation system in the Colombian Eastern Plains, we seek to determine both the optimal economic dose (OED) and the optimal technical dose (OTD) of N, which allow to maximize income at producer level and minimize environmental impacts. This particular rotation system was chosen as research subject given the presence of the residual effect of Biological Nitrogen Inhibition (BNI) in permanent lots of *Bh*, which has positive impacts on corn production such as increased yields and better N efficiency. The data for this study was obtained from trials conducted between 2013 and 2017, where corn production in a *Bh*-corn rotation system (with residual BNI effect) was compared with conventional corn production (without residual BNI effect). For determining the OED and OTD of N, three response models were applied: a pseudo-quadratic model (PQM), a quadratic model (QM) and a discontinuous-rectilinear model (DRM). The results show that the PQM and DRM models turn out to be the most suitable for estimating the OTD producing a better fit for the data, thus the required N doses are not overestimated. *Bh*-corn treatments require lower OTD and OED compared to the control scenario, which results from the residual BNI effect. The OED is lower than the OTD in the QM and PQM models for the three treatments. Thus, for maximizing profits a lower N dose is required. Both N input and corn sales price variables determine the optimum dose for maximizing the producer's profits. In general, estimating the correct doses of N in a *Bh*-corn rotation system contributes to improving both efficiency in production and profitability, helping to avoid excessive application of N fertilizers and its associated negative effects on the environment.

1. Introduction

Among the essential macro elements, N is a critical element for the growth and yield of crops (Baligar et al., 2001). Specifically, N is a key factor in the formation of amino acids, proteins, and enzymes in plants (Ohyama, 2010). Thus, the contribution of N in optimal quantities leads to obtaining forages and grains with higher protein content, while a deficiency significantly affects plant development. In order to maintain desired production levels, large amounts of N are applied to the soil, obtained mainly from N fertilizers (Baligar et al., 2001). However, it is estimated that around 70% of the applied N is lost through nitrification and denitrification processes in the soil (Subbarao et al., 2017; Coskun et al., 2017). Fertilizer, which is not used by the crop, produces considerable environmental damage (e.g. water pollution, GHG emissions, nitrous oxide) and generates economic loss for the producer (Subbarao et al. 2013).

In this sense, it is important to improve the N use efficiency through the optimization of application rates. Apart from economic savings, this also contributes to reducing GHG emissions, especially in crops with high demand for N such as corn. Against this background, CIAT and its partner institutions have carried out studies on the Biological Nitrification Inhibition (BNI) capacity of the grass *Brachiaria humidicola* (CIAT 679) (*Bh*), which allows for a higher NUE in a rotation system with corn (Subbarao et al., 2017). A better NUE reduces fertilizer costs, decreases the rate of nutrient loss and improves crop yields. However, in addition to identifying strategies that assure better NUE, it is necessary to determine the optimal N levels that maximize the economic return for the producer, considering key market variables such as input and sales prices.

In this sense, and based on technical data derived from previous BNI research in a *Bh*-corn rotation system, the present study aims at determining both the OTD and OED doses of N that allow to maximize income at the producer level and minimize environmental impacts. This was done by applying three response models: (i) a pseudo-quadratic model (PQM), (ii) a quadratic model (QM), and (iii) a discontinuous-rectilinear model (DRM). We also compare these models, in order to determine the one with the best fit.

2. Methods and Study Site

2.1 Data source and study area

The data used in this study were derived from a technical evaluation carried out by Karwat et al. (2017). This study measured the residual BNI effect in permanent pastures of *Brachiaria humidicola* (CIAT 679) on the subsequent production of corn (Monsanto Dekalb 1596 hybrid). These effects include an increase in corn yields and higher NUE. The compilation of technical data was carried out at the facilities of Agrosavia (formerly Corpoica) in La Libertad, located in the foothills of the Eastern Plains in Colombia (4°03′46″N, 73°27′47″W), during an evaluation period of five years (2013-2017). Average annual precipitation is approximately 3685 mm with an average temperature of 21.4 °C. The elevation is 338 m.a.s.l.. The data related to costs were collected during the establishment of the trials, and updated to market prices according to the Colombian Price Information System for the Agricultural Sector (SIPSA) and the Colombian Cattle Producer Federation's (FEDEGAN) databases.

2.2 Description of the treatments

Corn production was measured in the following three treatments: (i) productive *Brachiaria humidicola* (*Bh*Prod), after 15 years of establishment and with high BNI potential; (ii) degraded *Brachiaria humidicola* (*Bh*Deg), after 15 years of establishment and with low BNI potential; and (iii) conventional corn (corn) production (control scenario), without residual BNI effect. Four doses of N were applied in each treatment: 0 (control), 60, 120 and 240 kg N/ha-1, respectively. Corn was harvested in the last months of the rainy season of each year (July 2013, June 2014 and in May 2015, 2016 and 2017, respectively).

2.3 Response models

Table 1 describes the main characteristics and equations of each response model.

Table 1. Description of the response models

Response models	***Model logic***	***Equation***
QM	Determines the critical point (dose of the nutrient (x) with which the yield (y) is maximized) by using the first derivative of equation 1.	$y = \beta_0 + \beta_1 x + \beta_2 x^2 \quad (1)$ where: y: corn yield. β_0: threshold yield (average yield obtained without nutrient application) x: applied nutrient dose β_1: linear coefficient β_2: quadratic coefficient
PQM	In this model, the critical point was determined by using the first derivative of equation 2.	$y = \beta_0 + \beta_1 x^{\alpha} + \beta_2 x^{2\alpha} \quad (2)$ where: y: corn yield. β_0: threshold yield (average yield obtained without nutrient application) x: applied nutrient dose β_1 y β_2: coefficients α: adjustment to the model
DRM	In this model, the results of the yields were taken and ordered according to the increasing doses of the nutrient. The maximum stable yield, the slope of the response and the turning point of the yield were established.	$y = \beta_0 + \beta_1 x \quad si\ x < rec\ x$ $y = y\ max \quad si\ x \geq rec\ x \quad (3)$ where: y: corn yield. β_0: threshold yield (average yield obtained without nutrient application) x: applied nutrient dose β_1: amount of product obtained with each dose of nutrient applied until reaching the stable yield plateau = slope $y\ max$: stable yield plateau or stable yield peak $rec\ x$: minimum amount of nutrient required to achieve stable yield plateau

2.4 OTD and OED estimations

OTD refers to the N dose that leads to a maximum physical or biological production and OED to the dose that leads to a maximum economic return. Table 2 shows the respective equations.

Table 2. Determination of OTD and OED in each response model

Model	Equation OTD	Equation OED*
QM	$x^* = -\frac{\beta_1}{2\beta_2}$ (4)	$x^\circ = \frac{PxPy^{-1} - \beta_1}{2\beta_2}$ (7)
PQM	$x^* = -(\frac{\beta_1}{2\beta_2})^{\frac{1}{\alpha}}$ (5)	$\frac{\delta y}{\delta x} = \alpha\beta_1 x^{\alpha-1} + 2\alpha\beta_2 x^{2\alpha-1} = \frac{Px}{Py}$ (8)
DRM	$N = \frac{y\,max - \beta_0}{\beta_1}$ (6)	N/A

*****Px: N price (kg); Py: corn price (kg)

3. Results

Figure 1 shows the adjustment of the models for 2016. Each point represents the average performance (of at least three repetitions) corresponding to each N dose applied in the different treatments. The three estimated models proved to have a good fit according to the R^2 indicator. Between 34% and 92% of the corn yield variation is explained by variations in the N fertilizer dose. Furthermore, the analysis of variance shows that the models are significant, with F values of <1%. The OTD and OED estimates are presented in Table 3.

In most cases, the OTD estimate shows higher values in the QM and PQM models for the three treatments than in the DRM model. The OTD values are different in each of the three models which results from the fact that each model obtains its best fit depending on the distribution of the data. In the case of QM, an alpha equal to 1 is used for all cases, while PQM adjusts a different alpha for each year and treatment depending on the distributions. DRM shows a very flat trend due to its linear fit in the first leg and a stable plateau for the second, so it only considers the lowest possible doses to achieve this plateau. Considering the fit of the three models during the four years of evaluation, the QM model tends to overestimate the maximum yield and the level of fertilizer required. The PQM model presents, in most cases, the best fit in the data distribution. Therefore, the values obtained from the PQM model for both OTD and OED are used. Results show that the *Bh*Prod treatment is the most efficient in both technical and economic terms. In other words, although the ODT and OED are 12% and 20% higher than the values of these indicators for the control scenario (Corn), the maximum expected return is 32% and 40% higher, respectively. In terms of efficiency, *Bh*Deg ranks second and corn third.

When comparing the OTD and OED values, we can see that the OED is lower than the OTD in both the QM and PQM models and for all treatments. This means that in order to maximize profits, the optimal N dose needs to be lower than the optimal dose for maximizing the yields, since the additional cost of fertilization does not justify the additional corn yield. This makes evident that both the price of N and corn are definitive factors that determine the optimal N dose for maximizing producer profits. On the other hand, both *Bh*-corn rotation treatments present lower OTD and OED values than those estimated for the corn treatment, which is a direct result of the residual BNI capacity of *Bh*. This shows that the rotation system is a potential alternative to improve both production efficiency and profitability compared to a conventional production system.

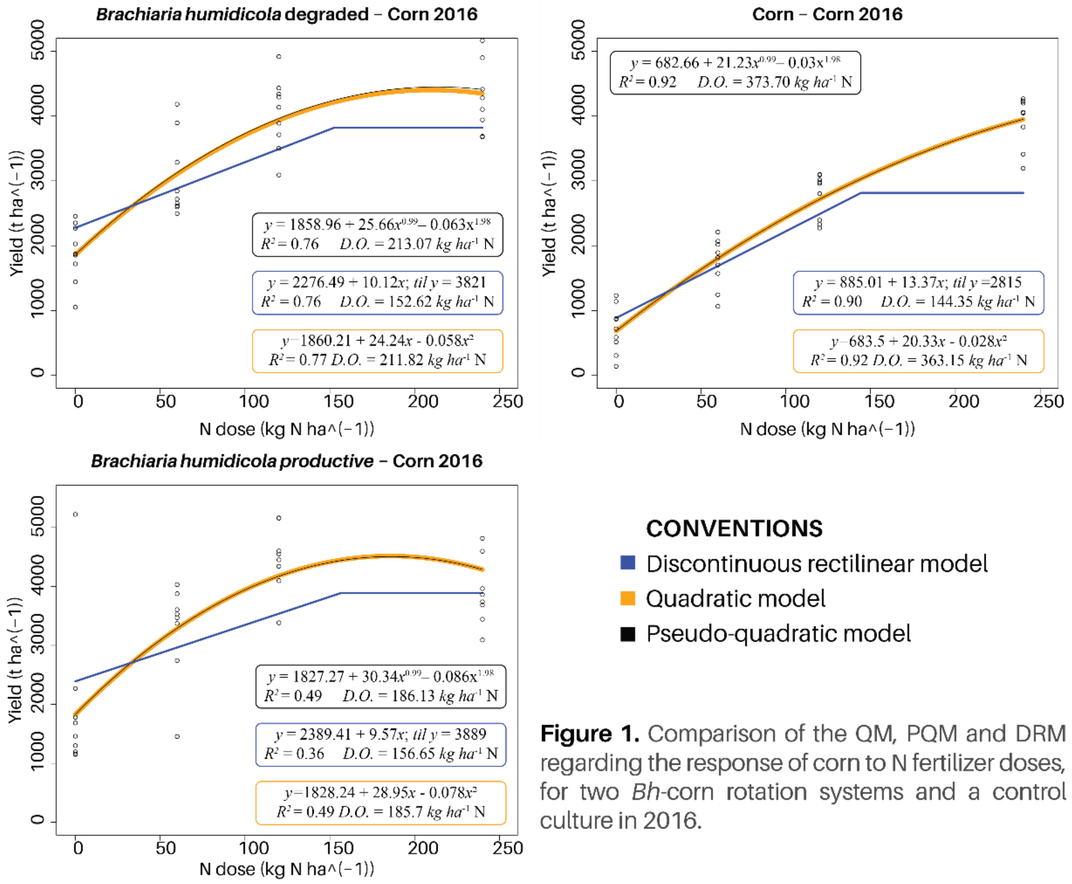

Figure 1. Comparison of the QM, PQM and DRM regarding the response of corn to N fertilizer doses, for two *Bh*-corn rotation systems and a control culture in 2016.

Table 3. OTD, OED and maximum average production 2013-2017

Variables/ Treatment	QM Model			PQM Model			DRM Model		
	Corn	*Bh*Deg	*Bh*Prod	Corn	*Bh*Deg	*Bh*Prod	Corn	*Bh*Deg	*Bh*Prod
OTD (N/ha)	286	232	251	172	245	197	156	149	153
MPOTD (kg/corn/ha)	11419	10602	12125	3433	5328	5116	3032	4445	4583
OED (N/ha)	229	183	186	126	189	158	NA	NA	NA
MPOED (kg/corn/ha)	8839	8516	9897	3209	5196	5439	NA	NA	NA

MP: Maximum average production

4. Conclusions

Both the PQM and DRM models turn out to be the most suitable for estimating the OTD. Given the best fit of the data distribution, required N doses are not being overestimated. The *Bh*Prod treatment proved to be the most efficient in terms of N use both at technical and economic level since the optimal N level results in the highest expected yield, compared to the other treatments. The OED is lower than the OTD in both the QM and PQM models and for all treatments, indicating that for maximizing profits, a lower N dose is required than for maximizing yields since additional fertilization costs do not justify higher N doses. Both N input and corn sales prices are definitive factors in determining the optimal N dose for maximizing producer profits. The results of this study are key for providing recommendations to primary producers on the correct N doses to apply in a *Bh*-corn rotation system. This contributes to improving both efficiency in production and profitability, and help to avoid the excessive and unnecessary application of nitrogen fertilizer and its associated negative effects on the environment. The results are also important for other actors (e.g. extension workers, policy and decision makers) who offer recommendations on fertilization or work on guidelines and policies for fertilizer use.

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