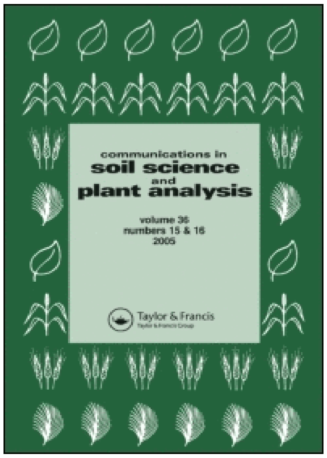

Communications in Soil Science and Plant Analysis
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597241

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Online Publication Date: 01 April 2008
To cite this Article: Alvarez, R. (2008) 'Analysis of Yield Response Variability to Nitrogen Fertilization in Experiments Performed in the Argentine Pampas', Communications in Soil Science and Plant Analysis, 39:7, 1235 - 1244
To link to this article: DOI: 10.1080/00103620801925943
URL: http://dx.doi.org/10.1080/00103620801925943

Communications in Soil Science and Plant Analysis, 39: 1235–1244, 2008

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620801925943

Analysis of Yield Response Variability to Nitrogen Fertilization in Experiments Performed in the Argentine Pampas

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Abstract: Nitrogen (N) fertilization has become a common practice in corn and wheat crops in the Argentine Pampas during the past decade. In this region, great environmental variability determines erratic responses to fertilization. The quantity of data necessary for defining yield response models to N has not been investigated, and the relative yield transformation, combined with the total nutrient approach, has been widespread when analyzing fertilizer response results. The objectives were to determine the minimum data set necessary for fitting average yield functions suitable for fertilizer recommendation at regional scale and to investigate the consequences of using relative yield on N response functions when the total nutrient approach is used. Published results from two extensive fertilization networks, one with corn and the other with wheat, were used. Data were aggregated at different levels, because one single experiment to the entire network results, and yield response functions to N were fitted. Yield models tended to stability when a set of around 100 or more data points, generated in experiments performed across different sites and years, were used for fitting models with both crops. This amount of data was generated by performing 20 experiments in the corn network and 35 in the wheat network. Relative yield transformation allowed us to obtain models with lower dispersion than yield, but in the case of corn a biased model was generated that leads to underestimating fertilizer requirements. In wheat, similar fertilizer recommendations were produced from yield or relative yield functions. Response variability to fertilization must be addressed in the experimental area by increasing the amount of data used, rather than by applying the relative yield transformation.

Keywords: Corn, relative yield, nitrogen fertilization, wheat

Received 14 September 2006, Accepted 16 March 2007
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INTRODUCTION

Yield response variability to fertilizers is generally very great when taking into account experiments performed across different sites and years. Consequently, it is necessary to perform many experiments to establish yield functions suitable for fertilizer recommendation at a regional scale (Nelson 1999). Two steps may be distinguished when planning fertilizer experimentation: the number of experiments to perform and the number of treatments in each experiment. Because between-site variability is much higher than within-site variability, many experiments must be performed with some treatments for each (Nelson, Voss, and Pesek 1985). The number of experiments (scenarios) must be planned according to environmental variability to select sites that represent possible production conditions. Climatic variability is evaluated by conducting experiments during various growing seasons. The fertilizer rates are a consequence of previous knowledge about crop response to fertilizer (Colwell 1994).

The Pampas region is considered one of the most suitable areas for grain crop production in the world (Satorre and Slafer 1999). Since 1990, an exponential increase in the use of nitrogen (N) and phosphorus (P) fertilizers has occurred, mainly in corn and wheat crops (FAO 2004). Numerous examples of fertilizer recommendation strategies developed in the Pampas show that the previously mentioned criteria had not been adopted commonly (Alvarez 2005), because of economic limitations on extensive experimentation, as in other developing countries. The number of experiments and the quantity of yield data necessary for obtaining average yield response curves to nutrients had not been investigated. Conversely, a strategy used many times for counteracting the great environmental variability effects on fertilizer responses is the transformation of yield data to relative yield, both for N and P fertilizers. Relative yield had been used in the literature generally for nonmobile nutrients, such as P and potassium (K), but not for mobile nutrients such as N (Black 1993; Stelly 1984). There is no experience on how the relative yield transformation may affect N response functions, especially when this transformation is applied to the total nutrient approach used in the Pampas (sum of soil and fertilizer N).

The objectives were (1) to analyze results from fertilizer experiments to assess the variability of yield response to N in corn and wheat in the Pampas and the minimum quantity of experiments and data necessary to obtain average yield functions, and (2) to asses the effect of using relative yields on data variability and N fertilizer recommendations.

MATERIALS AND METHODS

The Pampas is a vast plain of around 50 Mha, which runs from 28° to 40° S in Argentina (Alvarez and Lavado 1998). Agriculture is performed in the semi-arid and humid portions of the region on well-drained soils, mainly Mollisols, formed on loess-like materials under graminaceous vegetation and a warm temperate climate (Hall et al. 1992). Nearly 50% of the area is dedicated to agriculture, with soybean (*Glycine max*), corn (*Zea mays*), and wheat (*Triticum aestivum*) being the main crops (Hall et al. 1992). The most important cropping portion of the Pampas is the Rolling Pampa, a northern area of around 10 Mha with rolling relief, where corn and wheat have been cropped for decades. Agricultural soils in this area are predominantly Argiudolls and Hapludolls, with textures in the top 20 cm varying from loamy to silty clay loam and organic matter contents ranging from 40 to 120 Mg C ha^{-1} yr^{-1}. During corn and wheat growing seasons, rainfall may vary from 200 to 900 mm and from 200 to 600 mm, respectively.

Published results from field experimental networks performed in the Rolling Pampa for corn (Senigagliesi, García, and Galetto 1984) and wheat (Barberis et al. 1983) were used. In both cases, experiments were performed under scenarios similar to production plots. Tillage systems were as farmers' practices and sowing and harvest were performed by commercial machinery. The corn network was composed of 33 experiments at different sites along four growing seasons. Five N rates were applied to all experiments (0, 30, 60, 90, and 120 kg N ha^{-1} as urea). Combination of year × site × management conditions generated 165 data points. The wheat network was composed of 43 experiments at different sites along five growing seasons. Three N rates were applied to 29 experiments and only two to the rest, changing N rates between years (0, 50, and 100 kg N ha^{-1} or 0, 35, and 70 kg N ha^{-1} as urea). Combination of year × site × management conditions generated 115 data points. Soil nitrate contents, fertilizer rates, and average crop yields from three to four replications were reported for all treatments of both networks. When nitrates were determined only in the 0 to 20-cm soil layer, nitrates in the 0 to 60-cm soil layer were estimated using equations developed locally (Alvarez, Alvarez, and Steinbach 2001). Phosphorus was a nonlimiting nutrient in these soils (average P Bray of the networks greater than the local deficiency threshold of 17 ppm).

A procedure was developed to study the relationship between the stability of the yield function and the quantity of data used for its development by integration of data in different levels (Table 1). It was simulated the work of a researcher when developing a yield model. In the first stage, results from individual experiments were analyzed (1 sample = 1 experiment = 3–5 data points). In a second stage, results from a small group of experiments (3–5) were analyzed using data from experiments performed at different sites and years (1 sample = 3–5 experiments = 13–15 data points). In the third stage, a bigger sample was used, integrating data from more experiments and so on, until all experiments were analyzed as a sample (1 sample = 33–43 experiments = 115–165 data points). All samples were independent of each other. Consequently, in each stage of integration, an experiment was part of only one sample. The integration process was repeated three times, allowing different combinations of data.

Table 1. Levels of integration of data from corn and wheat fertilization experiments performed in the Pampas

Corn			Wheat		
Number of samples	Experiments in sample	Data in sample	Number of samples	Experiments in sample	Data in sample
33	1	5	29	1	3
11	3	15	8	5	13
5	6	30	4	10	26
3	11	55	3	14	38
2	16	80	2	21	56
1	21	105	1	28	74
1	27	135	1	35	92
1	33	165	1	43	115

The total nutrient approach (sum of soil nitrate and fertilizer nitrogen = SFN) was used for characterization of N availability to the crops. Similar agronomic efficiencies for soil and fertilizer N have been observed in the Rolling Pampa for corn in a very wide range of nitrate N and fertilizer rates. For wheat, similar agronomic efficiencies were also observed for both nutrient sources in the medium range of nitrates and fertilizer rates (Alvarez and Grigera 2005). The relationship between SFN and yield was analyzed by the transformed polynomial quadratic model (Colwell 1994):

$$\text{Yield} = a + b\,\text{SFN}^{0.5} - c\,\text{SFN} \qquad (1)$$

where *a, b,* and *c* are fitted coefficients and SFN is the sum of nitrate N and N fertilizer rate.

This model is equivalent to the common quadratic model used in fertilizer response evaluation but appeared to be more suited to our data because the linear term ($\text{SFN}^{0.5}$) allowed the function to curve and the quadratic term (SFN) contributed with additional curvature. The model was fitted by the minimum square method using the F test for significance evaluation ($P = 0.05$). When the quadratic term was not significant, it was excluded from the model. The model was fitted to the different data samples, the determination coefficient (R^2) calculated and, when significant, the targeted N supply was estimated for optimum economic rates. Economic optimums were estimated as the levels of SFN, where the slope of the yield function became equal to the fertilizer N/grain price ratio (Bock, Sikora, and Hergert 1991). Average fertilizer N/grain price ratios in the Pampas rounded to 10 for corn and 7 for wheat (Alvarez 2005).

The yield functions obtained at each level of data integration were compared with the functions fitted to the entire network data, contrasting the estimated economic optimums by the following expression:

$$D = \left(\frac{|X_i - \overline{X}|}{\overline{X}}\right)100 \qquad (2)$$

where D = difference between economic optimum of sample i and economic optimum of the network (%), X_i = economic optimum of sample i, and $\overline{X}$ = economic optimum of the network.

At each level of integration maximum differences between sample optimums and network optimums were fitted to different functions. The significant model (F test, P = 0.05), which was better fitted as judged by the R^2 criterion, was used for estimating the amount of data necessary to produce a targeted N supply no more than 10% biased from the network targeted N supply.

Relative yield was calculated for each experiment as the ratio between treatment yield and maximum yield of the experiment (Black 1993). Three response functions were tested: the modified polynomial quadratic model [Eq. (1)] and two nonlinear functions, the Mitscherlich model (Black 1993) [Eq. (3)] and the linear-plateau model (Colwell 1994) [Eq. (4)]:

$$Y = Y_{\max}(1 - e^{-b\,\mathrm{SFN}}) \qquad (3)$$

$$\begin{array}{ll} Y = a + b\,\mathrm{SFN} & \text{if SFN} < \mathrm{SFN}_{opt} \\ Y = Y_{\max} & \text{if SFN} \geq \mathrm{SFN}_{opt} \end{array} \qquad (4)$$

where Y = yield or relative yield, $Y_{\max}$ = maximum yield or maximum relative yield, a and b = fitted coefficients, SFN = sum of nitrate N and N fertilizer rate, and SFN_{opt} = optimum level of SFN for obtaining $Y_{\max}$.

Models were fitted to yield data by the least squares method. Because relative yield is a variable usually not normally distributed and with heterogeneous variance (Black 1993; Colwell 1994), an alternative procedure was employed for fitting models to relative yield: weighed least squares method (Neter, Wasserman, and Kutner 1990). Normality of residual distributions was tested by visual inspection of normal probability plots of the residuals. Model performance was compared by the root mean square error (RMSE):

$$\mathrm{RMSE} = \left(\frac{\sqrt{(1/n)\sum_{i=1}^{n}(Y_{pi} - Y_{oi})^2}}{\overline{Y}_o}\right)100 \qquad (5)$$

where RMSE = root mean square error (expressed as percentage of the mean of the observed dependent variable), n = number of observations, Y_{pi} = predicted value for the dependent variable, Y_{oi} = observed value for the dependent variable, $\overline{Y}_o$ = mean of the observed dependent variable.

The impact of the relative yield transformation on optimal nutrient level estimation was determined by comparison with optimal levels estimated using yield data. Yield transformation effects on scattering of data were assessed by the RMSE of the models fitted.

RESULTS AND DISCUSSION

The analysis of variability in yield response to N showed similar results for both crops. When samples used for yield response fits were constituted by 3–5 data points (one experiment at a time), only one third of the samples using the polynomial model could be significantly fitted (Figure 1). In these cases, the significant correlation coefficients of the regressions obtained were very high. As the number of data in samples increases, the proportion of samples in which the model could be significantly fitted also increases, but the correlation coefficient of the regressions decreases sharply. When samples were integrated by more than 50 data points, the polynomial model could be fitted to all samples tested and the determination coefficients tend to stabilize in values around 0.2–0.3.

Targeted N supplies estimated using only significant functions showed great variability if samples where constituted by data from only one experiment (Figure 2). A five to seven fold difference was observed between lower and higher targeted N supplies estimated for corn and wheat with a maximum bias of around 150–200% in relation to the entire network optimum. Bias decreased as data points in samples increased. With samples integrated by 92–97 data points, estimated differences between a sample's fit would not be more different than 10% from the entire network targeted N supply. Consequently, around 100 data points seemed to be necessary as a minimum data set for stable function predictions. This amount of data

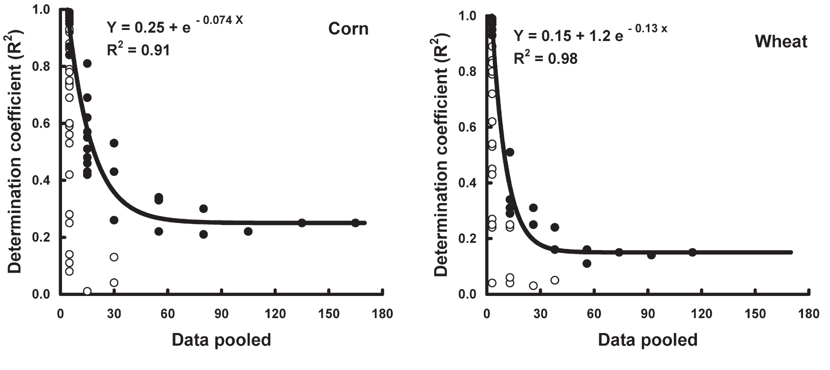

Figure 1. Determination coefficients of yield functions in relation to the amount of data pooled in the sample. Empty circles: not significant; full circles: significant. The exponential functions were fitted only to significant cases.

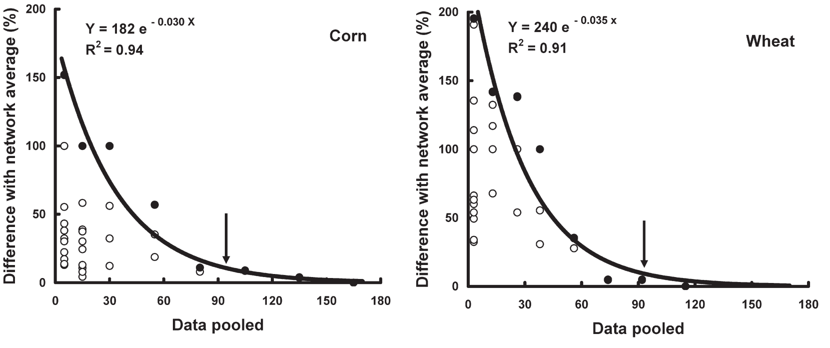

Figure 2. Targeted N supplies estimated using significant fitted functions in relation to the amount of data pooled in samples. Full circles: maximum bias from the network optimum at each level of data integration. The arrows indicate the amount of data where bias is 10%.

was attained by integrating results from 20 experiments in corn and 35 in wheat, selected across different sites and years. Similar results were obtained the three times the integration process was repeated.

Consequently, results from one to a few experiments were very unstable, in spite of the high correlation coefficient that yield functions showed, and a minimum of 100 data points, generated in many experiments along different years and sites, was necessary to obtain average yield functions. As data in samples increased, internal sample variability also increased and the determination coefficient of the yield function decreased, but the yield response function represented a wider spectrum of possible production scenarios. Larger data sets generated in other field fertilization networks are needed to confirm these estimations. The methodology used appeared useful in defining the minimum data necessary for fertilization recommendation.

The Mitscherlich model fitted poorly to the data. The RMSE doubled those from the polynomial and linear-plateau models and was discarded during the analysis. Similar tendencies were observed when using the polynomial and the linear-plateau models, and only results from the last are shown for simplicity. Transformation of yield to relative yield allowed reduction of scattering of data, decreasing the RMSE of fitted functions by two to three fold (Figs. 3 and 4). Relative yield transformation decreased crop response variability to N fertilizer as may be expected (Black 1993). In the case of corn, it also modified the nature of the response. In this crop, yield increased up to a SFN content of 180 kg N ha^{-1}, but the relative yield curve presented a maximum at a SFN of 110 kg N ha^{-1}. Conversely, in wheat similar tendencies were observed when comparing the curves of yield and relative yield. Both functions showed maximums around 60 kg N ha^{-1}. This phenomenon was the consequence of a displacement of the corn relative yield curve to the right upper quadrant of the figure in comparison to the yield function. A wide range of soil nitrate N contents

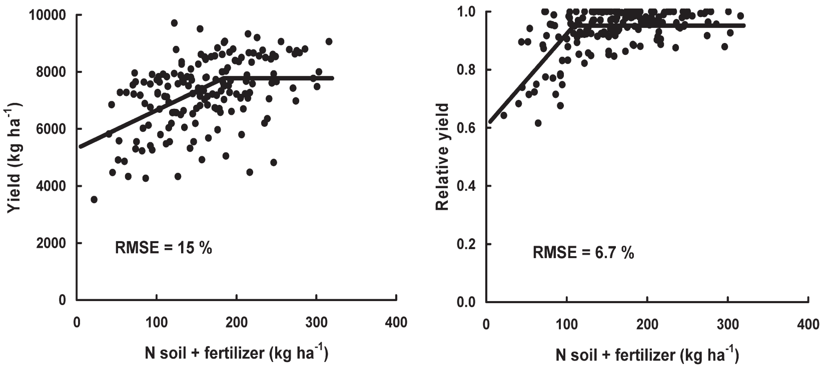

Figure 3. Relationships between yield and relative yield of corn with soil N content plus fertilizer nitrogen. Root mean square errors (RMSE) were calculated as percentages of average yield and relative yield.

between the corn experiments caused the function displacement. The bulk (80%) of soil nitrate N data in the corn network ranged from 44 to 176 kg N ha^{-1}, whereas in the wheat network the bulk data ranged from 16 to 55 kg N ha^{-1}. Consequently, in many corn experiments, the relative yield value of 1 was assigned to yield data from sites where SFN values were low, and this generated high relative yield values in scenarios where SFN was still a limiting factor to yield (Figure 5). Relative yield transformation produced a deformation of the true corn yield response to N. In the wheat experimental network, there were not large differences in soil N content between sites, and crop response to N was not deformed by the relative yield transformation. In corn, targeted N supply estimations

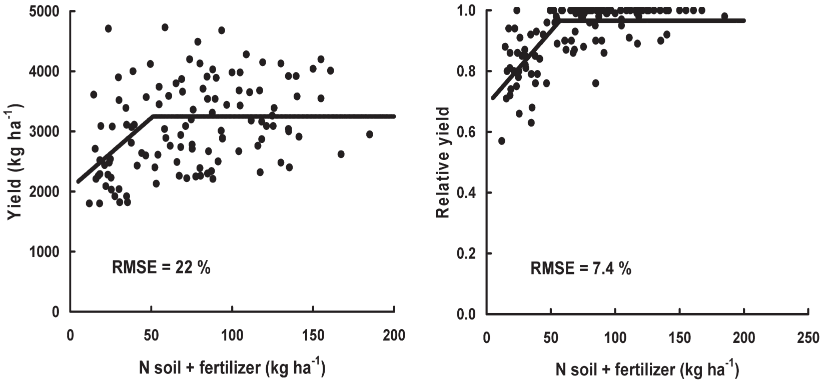

Figure 4. Relationships between yield and relative yield of wheat with soil N content plus fertilizer N. Root mean square errors (RMSE) were calculated as percentages of average yield and relative yield.

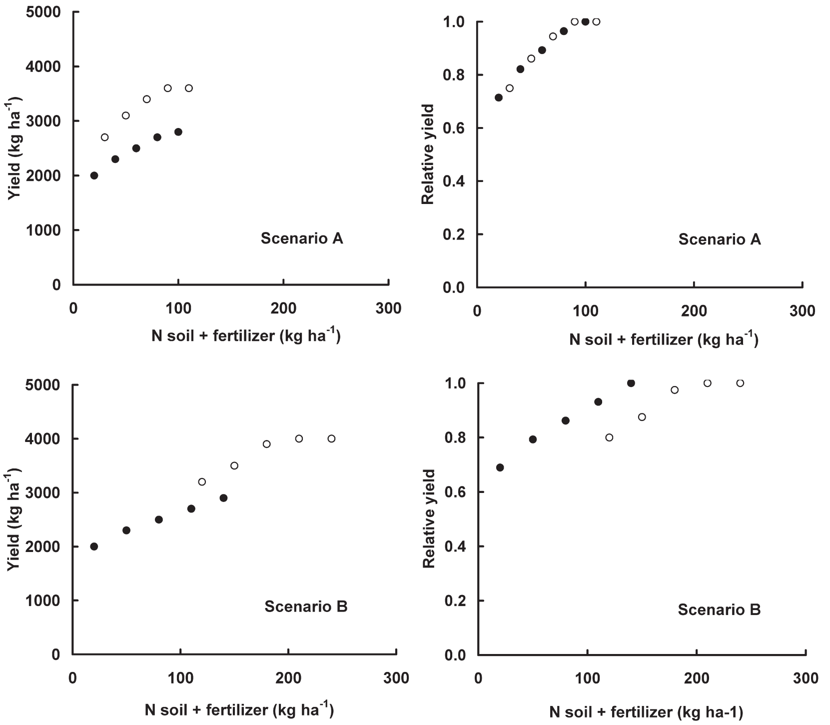

Figure 5. Hypothetical effect of the transformation of yield data to relative yield under two different scenarios when the total nutrient approach is employed. (A) Results from two fertilization experiments with similar soil nitrate content (full circles: exp. 1; empty circles: exp. 2). (B) Results from two fertilization experiments with very different soil nitrate content (full circles: exp. 1; empty circles: exp. 2).

using the relative yield function produced a biased estimation of fertilizer requirement.

Some authors had previously stated, when analyzing the effect of relative yield on P responses, that relative yield may lead to erroneous interpretation of fertilization results (Black 1993; Colwell 1994). In our case, the use of relative yield did not improve fertilizer recommendation when using the total nutrient approach for N. In corn, relative yield function produced a biased relationship with N availability. In wheat, despite the fact that relative yield improves adjustments to the response models, the same targeted N supply was estimated when using the yield model.

Relative yield was not a useful strategy to reduce response variability of corn and wheat yield to N fertilization. Response variability to fertilization must be faced in the experimental area, performing experiments enough to produce 100 or more data points generated from different combinations of year $\times$ site $\times$ management conditions in 20–30 different experiments. This estimation must be confirmed by future work.

ACKNOWLEDGMENTS

This research was granted by the University of Buenos Aires (UBACYT G 033).

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