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Interpretations of field fertility research on Solanaceae in Puerto Rico[1]

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ABSTRACT

One approach for the development of fertilizer recommendations is based on field-measured yield response to added fertilizer. The crop nutrient requirement (CNR) is the total amount of that element needed by the crop during the production season to produce optimum economic yield, and is equivalent to the fertilizer rate above which no significant increase in yield occurs. Published and unpublished fertilization research done in Solanaceae, tomato (*Lycopersicon esculentum*), eggplant (*Solanum melongena*), and sweet pepper (*Capsicum annuum*), in Puerto Rico over the past 25 years was used to calculate CNR values for nitrogen (N), phosphorus (P) and potassium (K). The mean yields obtained from each fertilizer treatment were converted from a unit area basis (ton/ha or kg/ha) to percentage relative yield (RY). The RYs were then plotted against rates of nutrient applied and fitted to linear, quadratic, linear-plateau, quadratic-plateau, exponential, and Cate-Nelson models to determine CNR values. Plant response to K was not observed in soils dominated by 2:1 clays (2:1 clay soils). Large variability and few experimental data points precluded fitting equations to the data in soils dominated by 1:1 clays (1:1 clay soils). For P and N, predicted CNR values varied widely, depending on the selected model. The best model was selected on the basis of coefficients of determination, standardized residual plots, and was corroborated with economic returns. For 1:1 clay soils, predicted CNR values were 113 and 255 kg P_2O_5/ha and 150 and 207 kg N/ha for the Cate-Nelson and quadratic models, respectively. For 2:1 clay soils, predicted CNR values were 50 and 148 kg P_2O_5/ha for the Cate-Nelson and linear-plateau models, respectively, and 50 and 120 kg N/ha for the Cate-Nelson and exponential models, respectively.

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Key words: Crop nutrient requirement, Solanacea, P fertilization, N fertilization, K fertilization

RESUMEN

Interpretaciones de trabajos de fertilización con Solanaceae en Puerto Rico

Una metodología para realizar recomendaciones de fertilización se basa en relaciones entre niveles de fertilización y medidas correspondientes de rendimiento. El requisito nutricional del cultivo (RNC) es la totalidad del elemento que requiere el cultivo durante el ciclo de producción para producir rendimientos económicos óptimos, y es equivalente al nivel de fertilización (cuando el suelo suple poca o ninguna cantidad del nutrimento) por encima del cual no existe un aumento significativo en rendimiento. Investigaciones realizadas con la familia Solanaceae: tomate (*Lycopersicon esculentum*), berenjena (*Solanum melongena*), y pimiento (*Capsicum annuum*) en Puerto Rico se utilizaron para calcular valores de RNC para nitrógeno (N), fósforo (P) y potasio (K). Los valores promedios obtenidos de cada nivel de fertilización fueron convertidos de unidad por área (ton/ha, kg/ha, cajas/acre) a rendimiento relativo (RR). Los valores de RR fueron graficados contra niveles de aplicación de nutrimentos y se ajustaron diferentes modelos (lineal, cuadrático, lineal-meseta, cuadrático-meseta, exponencial y Cate-Nelson) para determinar los valores de RNC. No se observó respuesta a la aplicación de K en suelos dominados por arcillas 2:1 (suelos 2:1). En suelos dominados por arcillas 1:1 (suelos 1:1) ninguna de las ecuaciones se ajustó adecuadamente a los datos porque había pocos datos experimentales y alta variabilidad entre los valores de rendimiento. Para P y N, los valores de RNC predichos variaron según el modelo utilizado. El mejor modelo se escogió basándose en los coeficientes de determinación y gráficos de residuales estandarizados, y corroborados con retornos económicos. En los suelos 1:1, los valores de RNC predichos fueron 113 y 255 kg P_2O_5/ha y 150 y 207 kg N/ha para los modelos Cate-Nelson y cuadrático, respectivamente. En los suelos 2:1, los valores predichos fueron 50 y 148 kg P_2O_5/ha para los modelos Cate-Nelson y lineal-meseta, respectivamente, y 50 y 120 kg N/ha para los modelos Cate-Nelson y exponencial, respectivamente.

INTRODUCTION

Several strategies are possible for the development of fertilizer application rates for major agronomic and horticultural crops. In Puerto Rico, for example, development of fertilizer recommendations for bananas (Irizarry et al., 1988), plantains (Irizarry et al., 1980), yams (Irizarry and Rivera, 1985), tannier (Vicente-Chandler et al., 1982), cassava (Irizarry and Rivera, 1983), and forages (Vicente-Chandler et al., 1983) has been based on the crop nutrient uptake approach:

$$N_f = \frac{N_u - N_s}{E_f} \qquad [1]$$

where N_f is the amount of fertilizer of the particular nutrient to be applied; N_u is the quantity of the particular nutrient that is accumulated in the aboveground dry matter to attain desired yield; N_s is the amount of particular nutrient supplied by the soil; and E_f is the efficiency of fertilization of the specific nutrient. The application of this technique is described by Grove (1979).

Positive aspects of the use of this technique deal with the ease in which the numeric values for calculating N_f can be obtained. For example, estimates for all three terms can easily be obtained from the scientific literature and substituted into the equation. When values for N_u are not available, field experiments that measured crop uptake of various nutrients simultaneously were performed, and estimates of N_s and E_f for each of the nutrients were determined from the literature. Balanced formulations of complete fertilizers for particular crops were thus established.

Although there are practical merits associated with the use of the crop nutrient uptake approach, there are potential limitations. One is that N_s estimated by a soil test does not indicate an absolute amount of nutrient available to the crop but rather is an index of availability, and values of N_s estimated by crop nutrient uptake for a particular soil cannot be extrapolated to other sites, because soil management and fertilizer application history have a marked influence on soil nutrient availability. Values for the term E_f do not exist for the majority of crops and soils, and reported values in the literature can vary two- to fourfold. The amounts of nutrient extracted by a crop can vary because of expected yield, nutrient concentration variability, changes in nutrient distribution in vegetative parts, and luxury consumption among other variables that sometimes cannot be assessed. Thus, any given estimation of nutrient application rate is subject to the inherent limitations associated with each of the terms in equation 1, as well as to the bias imposed by the individual when choosing the appropriate values from the wide range in values reported in the literature.

One alternative approach is based on the sufficiency concept, in which fertilizer recommendations are based on yield response curves from the level of nutrient applied. Yield response diminishes with increasing rate of fertilization as optimum yield is approached. *Hochmuth and Hanlon (1995) refer to this philosophical approach as* the crop nutrient requirement (CNR) system and define it as the total amount of that element needed by the crop (which can come from soil, air, water or fertilizer) during the production season to produce optimum economic yield. Nutrient rate recommendations from fertilizers are made to supplement nutrients already present in the soil which can contribute to optimum crop response previously indexed by a soil test. The totality of the CNR should be applied when the soil supplies little or no nutrients to the growing crop. Only when the soil test for a particular nutrient has been adequately calibrated can the soil test value be used as an index for making such fertilizer recommendations (Kidder, 1993; Mitchell, 1993).

Environmental and economic constraints imposed by modern agriculture as well as recent technological advances such as drip irrigation and fertigation, have changed the focus from applying complete fertilizer formulations to specific nutrient management strategies for supplying crop nutrient needs. In Puerto Rico (although not exclusive to the island), it is common for farmers who grow high-value horticultural crops to fertilize with single or binary fertilizer raw materials at rates many times exceeding the crop nutrient requirements. This practice might be common because of the risks associated with growing such crops, yet it results in unwanted nutrient losses from agricultural fields leading to potential ground- and surface-water contamination. Within modern specific nutrient management strategies, it is important to quantify optimum fertilizer rates to optimize crop yield and quality, maximize profitability, and reduce the risk of environmental pollution.

Field fertility research performed with Solanaceae, such as tomato (*Lycopersicon esculentum*), eggplant (*Solanum melongena*), and pepper (*Capsicum annuum*) in Puerto Rico, has produced a large database of research results that documents yield response to varying rates of fertilizer application. Individual interpretation of the results from each of the studies leads to slightly different CNR estimates because of the wide range in yield variability obtained. Objective optimum fertilizer application rates are thus difficult to ascertain unless data from various field experiments are combined and fitted to several statistical models to determine CNR values. Since in many areas similar fertilizer recommendations are given for the solanaceaus crops (Tyler and Lorenz, 1999; Hochmuth and Hanlon, 1995), it is appropriate to group results from the fertilizer studies to obtain CNR values for the three crops combined. The objective of this study was to improve nitrogen (N), phosphorus (P), and potassium (K) fertilizer recommendations for Solanaceae in Puerto Rico by (i) performing a quantitative summary of fertilization research performed over the past 25 years, (ii) fitting the data to published statistical models, (iii) comparing various statistical models, and (iv) estimating CNR values.

MATERIALS AND METHODS

The experimental data used in this study were obtained from field fertility research performed in Puerto Rico over the past 25 years dealing specifically with crop yield response to fertilizer applied N, P and K (Table 1). Most of the data were obtained from studies that were pub-

TABLE 1.—*Summary of fertilizer research in Puerto Rico from 1975 to 2001, which evaluated Solanaceae (tomato, pepper, and eggplant) response to applied N, P, and K.*

Reference	Study No.	Nutrient evaluated	Method of nutrient application	Nutrient rates evaluated	Maximum yield	Maximum nutrient rate[1]	Crop	Cultivar	Soil[2]
				------------	kg/ha	------------			
Abrams et al., 1975	1	N	Soil	0, 112, 224, 448	21,800	224	Tomato	Floradel	Coto clay (Oxisol)
Abrams et al., 1975	1	P_2O_5	Soil	0, 112, 224, 448	20,760	224	Tomato	Floradel	Coto clay (Oxisol)
Abrams et al., 1975	1	K_2O	Soil	0, 112, 224, 448	17,390	NR[3]	Tomato	Floradel	Coto clay (Oxisol)
Gonzalez and Beale, 1987	7	N	Soil	0, 75, 150, 225, 300, 375	22,110	75	Sweet Pepper	Blanco del País	Coto clay (Oxisol)
Gonzalez and Beale, 1987	7	P_2O_5	Soil	0, 75, 150, 225, 300, 375	19,840	NR	Sweet Pepper	Blanco del País	Coto clay (Oxisol)
Mangual-Crespo, 1981	9b	N	Soil applied, incorporated into bed	0, 113, 225, 338, 450	38,100	338	Eggplant	Rosita	Coto clay (Oxisol)
Mangual-Crespo, 1981	9a	N	Soil applied, incorporated into bed	0, 113, 225, 338, 450	36,900	450	Eggplant	Rosita	Coto clay (Oxisol)
Mangual-Crespo, 1981	9b	P_2O_5	Soil applied, incorporated into bed	0, 113, 225, 338, 450	27,270	NR	Eggplant	Rosita	Coto clay (Oxisol)
Mangual-Crespo, 1981	9a	P_2O_5	Soil applied, incorporated into bed	0, 113, 225, 338, 450	25,400	NR	Eggplant	Rosita	Coto clay (Oxisol)
Mangual-Crespo, 1981	9b	K_2O	Soil applied, incorporated into bed	0, 113, 225, 338, 450	28,067	225	Eggplant	Rosita	Coto clay (Oxisol)
Mangual-Crespo, 1981	9a	K_2O	Soil applied, incorporated into bed	0, 113, 225, 338, 450	27,750	225	Eggplant	Rosita	Coto clay (Oxisol)

[1] Maximum nutrient rate applied at which optimum plant response was obtained.

[2] Soil series where the research was performed with the soil order in parenthesis.

[3] NR indicates that a value for this parameter was not reported.

TABLE 1.—(CONTINUED) *Summary of fertilizer research in Puerto Rico from 1975 to 2001, which evaluated Solanaceae (tomato, pepper, and eggplant) response to applied N, P, and K.*

Reference	Study No.	Nutrient evaluated	Method of nutrient application	Nutrient rates evaluated	Maximum yield	Maximum nutrient rate[1]	Crop	Cultivar	Soil[2]
Rivera and Irizarry, 1984	12	P_2O_5	Soil applied	0, 50, 100	29,525	NR	Sweet Pepper		Santa Isabel clay (Mollisol)
Alers-Alers and Orengo Santiago, 1977	2	P_2O_5	Soil applied	0, 448	38,560	NR	Sweet Pepper	Blanco del País	San Antón (Mollisol)
Crespo-Ruiz et al., 1988	6	N	Fertigation split in 11 applications	0, 150, 300, 500	51,251	300	Sweet Pepper	Cubannelle	San Antón (Mollisol)
O'Hallorans et al., 1993	11	N	Fertigation	0, 56, 112, 168	85,200	NR	Tomato	Capitan	San Antón (Mollisol)
Muñoz and Colberg, 1990	10a	N	Fertigation split in 9 applications	0, 112, 224	60,894	112	Pepper	Key Largo	San Antón (Mollisol)
Muñoz and Colberg, 1990	10b	N	Fertigation split in 9 applications	0, 112, 224	50,168	112	Pepper	Key Largo	San Antón (Mollisol)
Velez-Ramos et al., 1991	14a	K_2O	Soil applied banded	0, 84, 168, 252, 336	42,932	NR	Tomato	Duke	San Antón (Mollisol)
Velez-Ramos et al., 1991	14b	K_2O	Fertigation	0, 56, 112, 168	43,455	NR	Tomato	Duke	San Antón (Mollisol)
Beale and Rivera, 1989	4a	N	Banded + Fertigation	0, 84, 168, 252, 336	45,720	168	Sweet Pepper	Key Largo	San Antón loam (Mollisol)
Beale and Rivera, 1989	4b	N	Banded + Fertigation	0, 84, 168, 252, 336	34,840	168	Sweet Pepper	Cubannelle	San Antón loam (Mollisol)
Beale and Rivera, 1987	3	N	Soil, split in 2 applications at planting and after 6 wk	0, 100, 200, 300	27,520	100	Sweet Pepper	Cubannelle	San Antón (Mollisol)

[1] Maximum nutrient rate applied at which optimum plant response was obtained.

[2] Soil series where the research was performed with the soil order in parenthesis.

[3] NR indicates that a value for this parameter was not reported.

TABLE 1.—(CONTINUED) *Summary of fertilizer research in Puerto Rico from 1975 to 2001, which evaluated Solanaceae (tomato, pepper, and eggplant) response to applied N, P, and K.*

Reference	Study No.	Nutrient evaluated	Method of nutrient application	Nutrient rates evaluated	Maximum yield	Maximum nutrient rate[1]	Crop	Cultivar	Soil[2]
Beale and Rivera, 1987	3	P_2O_5	Soil, split in 2 applications at planting and after 6 wk	0, 100, 200	28,600	NR	Sweet Pepper	Cubannelle	San Antón (Mollisol)
Beale and Rivera, 1987	3	K_2O	Soil, split in 2 applications at planting and after 6 wk	0, 125, 250, 375	27,370	NR	Sweet Pepper	Cubannelle	San Antón (Mollisol)
Beale et al., 1990	5a	N	Banded + Fertigation	0, 50, 84, 100, 134, 168, 185, 218, 269	36,680	269	Sweet Pepper	Key Largo	San Antón (Mollisol)
Beale et al., 1990	5b	N	Banded + Fertigation	0, 50, 84, 100, 134, 168, 185, 218, 269	25,280	269	Sweet Pepper	Cubannelle	San Antón (Mollisol)
Lugo et al., 1987	8	P_2O_5		0, 56, 112, 168, 224, 280	28,610	NR	Sweet Pepper	Cubannelle	San Antón clay loam (Mollisol)
Lugo et al., 1987	8	K_2O		0, 45, 90, 134, 224	28,430	NR	Sweet Pepper	Cubannelle	San Antón clay loam (Mollisol)
Sotomayor et al., 2000	13	N	Fertigation split in 4 applications	0, 65, 130, 195, 260	55,074	130	Tomato	Bonanza	Fraternidad clay (Vertisol)
Sotomayor et al., 2000	14	N	Fertigation split in 4 applications	0, 65, 130, 195, 260	74,096	NR	Tomato	Bonanza	San Antón clay loam (Mollisol)

[1] Maximum nutrient rate applied at which optimum plant response was obtained.

[2] Soil series where the research was performed with the soil order in parenthesis.

[3] NR indicates that a value for this parameter was not reported.

lished in peer-reviewed journals; other data were obtained from annual research progress reports to the University of Puerto Rico, Agricultural Experiment Station, and others were obtained from proceedings of scientific meetings and forums. When possible, the data were cross checked with progress reports that dealt with particular experiments. Most studies reported results from one experiment, whereas others reported results from two or more experiments performed either simultaneously within the same field, simultaneously in different fields, or concurrently at different seasons.

Soils dominated by 1:1 clays and 2:1 clays differ in their chemical properties thus influencing N, P and K availability to crops. For example, 1:1 clay soils may contain similar total N values as compared to those of 2:1 clay soils but may differ in terms of potentially mineralizable pools and rate constants (Sierra and Marbán, 2000; Greenland et al., 1992). Soil P buffering capacity will be greater in 1:1 clay soils, so the soils will fix greater amounts of applied P (Havlin et al., 1999; Fox, 1982). Potassium buffering capacity is expected to be greater in 2:1 clay soils because of higher cation exchange capacity; therefore, greater amounts of plant available K will exist in solution at given soil test values. For these reasons, relationships between crop yield and fertilizer applied N, P and K were studied separately in 1:1 clay soils and 2:1 clay soils.

For each reported experiment, the mean yields obtained from each fertilizer treatment were converted from a unit area basis (boxes/acre, ton/ha or kg/ha) to percentage relative yield (RY). The maximum response was established as 100 maximum yield (MY) and taken as the highest yielding experimental unit in a particular experiment, or when no significant differences were observed, as the average of the highest yielding experimental treatments. The RY for each nutrient level applied was taken as the ratio of the yield for each treatment and MY on a percentage basis. The RYs were then plotted against rates of nutrient applied to determine the optimum yield response to fertilizer. This methodology allowed the inclusion of data from diverse locations throughout the island, representing various crops and cultivars, planting dates, and growing conditions in a graphical summary.

Net economic returns for P and N fertilizer were calculated for each P and N treatment by subtracting the cost of fertilization from the value of additional fruit produced. We used the 2001 mean price of triple superphosphate (TSP) ($1.04/kg P_2O_5 as TSP) and urea ($0.85/kg N as urea). An on-farm produce price of $0.36/kg, $0.87/kg, and $0.73/kg for tomato, pepper, and eggplants, respectively, was used corresponding to mean prices during 1998-2000 (Commonwealth of Puerto Rico, 2000). We assumed similar production costs among the three crops. Values were plotted as a function of fertilizer P and N applied.

Statistical analysis

In order to combine results from different experiments carried out under different conditions, it is important to consider the following statistical aspects: (i) the number of replicates for each experiment (the larger the number, the more reliable the results); (ii) the coefficient of variation (CV) of each experiment (the smaller the CV, the more reliable the results), (iii) the correlation among observations from the same experiment, and (iv) the possibility of "publishing" bias, since only experiments with significant differences tend to be published.

These problems need to be taken into account in order to make valid inferences. The first two items can be addressed by using weighting techniques (like weighted regression). The weights to be used are the reciprocal of the coefficient of variation of the mean ($w = \sqrt{n}/(CV)$). This coefficient combines the two aspects of reliability in a field experiment (number of replicates and coefficient of variation of the experiment). The third problem can be accounted for if the model includes a random term for the effect of each experiment, although this aspect was not included in the analysis because there were too few experiments for this method to be used.

Model selection

Six statistical models (linear, quadratic, linear plateau, quadratic plateau, exponential, and Cate and Nelson) were selected to describe tomato, pepper, and eggplant yield to field applied N, P, and K fertilizer. For the models used, Y is the relative yield, and X is the fertilization rate (kg/ha). The CNR values were obtained by solving the linear, quadratic and exponential models at 95% maximum yield. For linear-plateau and quadratic-plateau models the CNR value is the value of x at which the curve reached the plateau. The linear model is:

$$Y = a + bX \qquad [2]$$

and CNR is calculated as:

$$\mathrm{CNR} = \frac{0.95 - a}{b} \qquad [3]$$

The quadratic model is:

$$Y = a + b\mathrm{X} + c\mathrm{X}^2 \qquad [4]$$

and CNR is calculated by using one of the solutions as:

$$CNR = \frac{-b \pm \sqrt{b^2 - 4(a - 0.95)c}}{2c} \qquad [5]$$

The exponential model (i.e., the Mitscherlich model) is

$$Y = a - b\exp(-cX) \qquad [6]$$

and CNR is calculated as:

$$\text{CNR} = \frac{1}{c}\log_e\frac{(a-0.95)}{b} \qquad [7]$$

For the linear-plateau model the equation used to estimate the linear portion of the model was:

$$Y = \begin{cases} a + bX & \text{if } X < \text{CNR} \\ c & \text{if } X \geq \text{CNR} \end{cases} \qquad [8]$$

where a is the yield at the intercept or where fertilizer value is 0, b is the slope of the line from the intercept to the point where the plateau yield and critical level intercept, c is the plateau, and CNR is the point of intersection of the two lines calculated as:

$$\text{CNR} = \frac{c-a}{b} \qquad [9]$$

For the quadratic plateau model the equation used to estimate the quadratic portion of the model was:

$$Y = \begin{cases} a + bX + dX^2 & \text{if } X < \text{CNR} \\ c & \text{if } X \geq \text{CNR} \end{cases} \qquad [10]$$

and the CNR value determined as:

$$\text{CNR} = -\frac{b}{2d} \qquad [11]$$

For the above mentioned models, the R^2 values were computed from the analysis of variance table as:

$$R^2 = 1 - \frac{\text{residual sum of squares}}{\text{corrected total sum of squares}} \qquad [12]$$

The Cate-Nelson model assumes there are two mean yield levels; one for values of X smaller than the critical level of X_o, and another for values of X larger than X_o. The critical level X_o is determined so that the R^2 value is maximized (Cate and Nelson, 1971). The R^2 values were computed from the analysis of variance table as in [12]. All procedures were performed using SAS (SAS Institute, 1996).

RESULTS AND DISCUSSION

Yield response to potassium application

The experimental data which describe the relative yield response to applied K for 1:1 clay and 2:1 clay soils are shown in Figure 1. In neither group did the tested models significantly describe the yield response to applied K. Although higher variability appears to be associated with the results obtained in the 1:1 clay soils (Figure 1A) as compared to 2:1 clay soils (Figure 1B), the graphs suggest that no response to K application may have occurred in the studies as the slopes of the lines do not differ significantly from zero ($P > 0.05$).

Yield response to phosphorus application

The experimental data which describe the relative yield response to applied P for 1:1 clay and 2:1 clay soils are shown in Figure 2. Differing response to P application rates is expected because of varying soil test P levels where the studies were conducted. In 1:1 clay soils (Figure 2A), only the quadratic and the Cate-Nelson models significantly described the yield response to applied P (Table 2). Predicted CNR values were 255 and 113 kg P_2O_5/ha for the quadratic and Cate-Nelson models, respectively. Considerable scatter is observed in the data, especially with regards to the study by Mangual-Crespo (1981) (study 9b), which evaluated eggplant response to applied P (Table 1). This particular study may have contributed to low R^2 values and the failure of the models to fit the experimental data.

In 2:1 soils (Figure 2B), there was little variation among R^2 values obtained by the tested models (Table 2). Values ranging from 0.31 to 0.34 were obtained for all significant models. With similar R^2 values, however, a large variation in predicted CNR values was obtained. Predicted CNR values for the quadratic, linear-plateau, and quadratic plateau models were at least three times higher than CNR values predicted by the Cate-Nelson model, with values of 237, 148, and 172 kg P_2O_5/ha, respectively. The fact that the quadratic models yield the highest CNR values is in agreement with other studies (Bélanger et al., 2000; Cerrato and Blackmer, 1990). The high variability in predicted CNR values may be due to the low R^2 values obtained with each of the models, as each model adjusts to different features of the data set. Higher R^2 values obtained with the Cate-Nelson model for both soil groups are in agreement with those of other studies (Cate and Nelson, 1971; Mallarino and Blackmer, 1992).

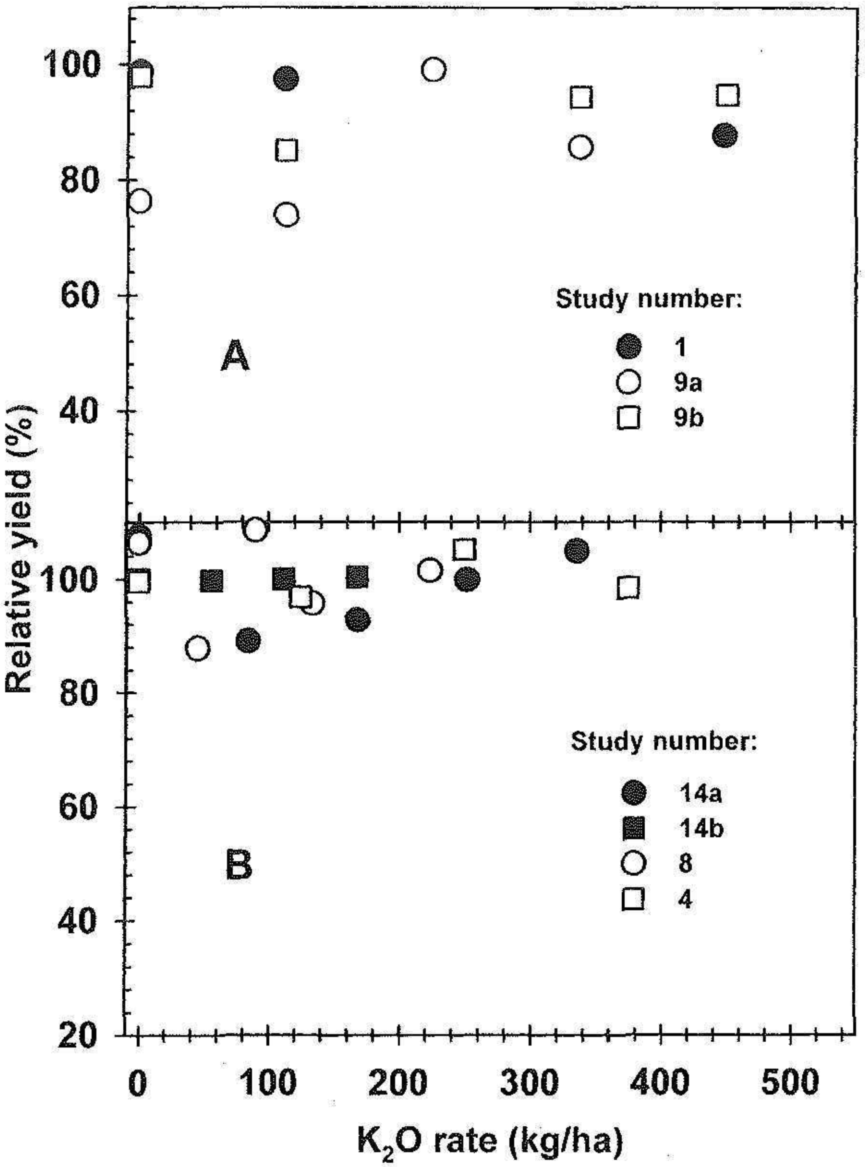

FIGURE 1. Relative yield of tomato, pepper and eggplant as a function of applied K in (a) 1:1 red clay soils and (b) 2:1 clay soils of the semiarid southern coast of Puerto Rico. Study numbers correspond to the references described in Table 1.

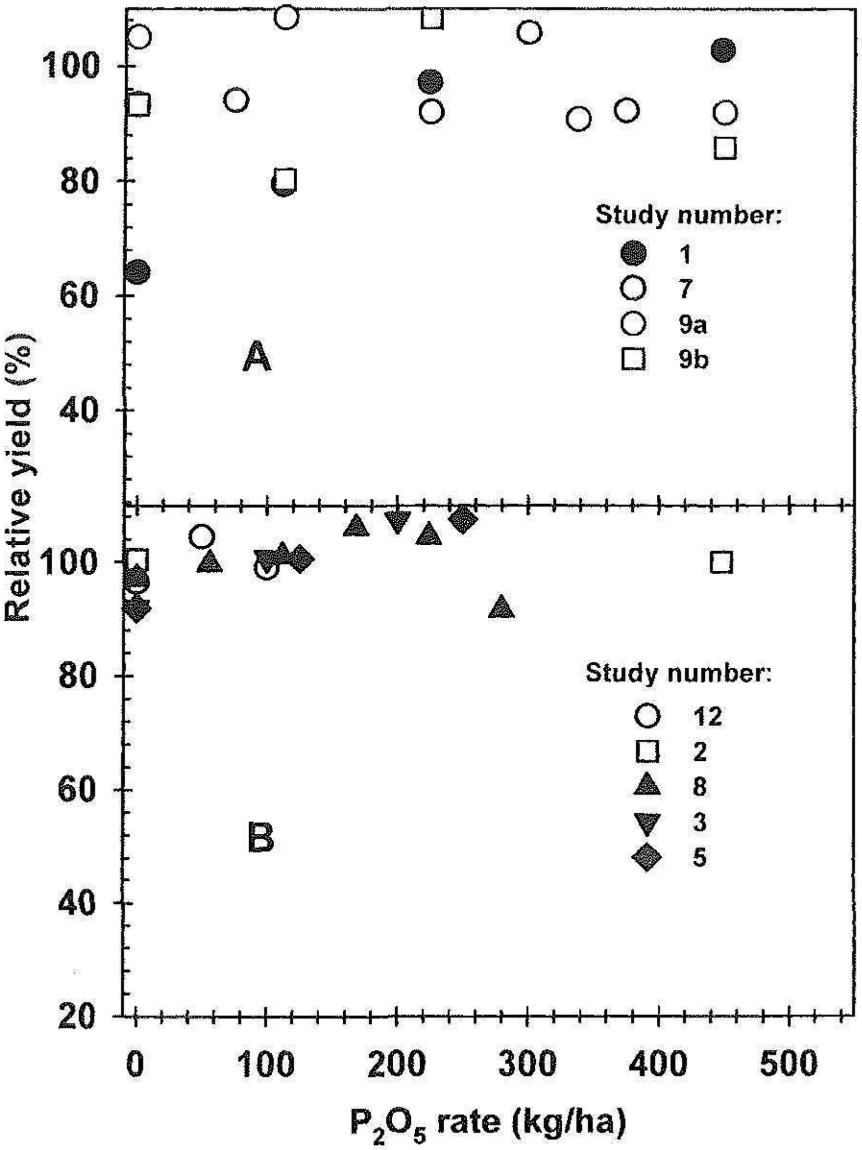

FIGURE 2. Relative yield of tomato, pepper and eggplant as a function of applied P in (a) 1:1 red clay soils and (b) 2:1 clay soils of the semiarid southern coast of Puerto Rico. Study numbers correspond to the references described in Table 1.

TABLE 2.—*Equations describing yield response of Solanaceae and crop nutrient requirements (CNR) as affected by P application in 1:1 clay soils and 2:1 clay soils of Puerto Rico.*

Model	Estimated equation	R^2[3]	CNR[4] (x units)
	1:1 clay soils		
Linear	NS[1]		
Quadratic	$86.7 + 14.3\ X - 2.78\ X^2$	0.18*	2.55
Linear-plateau	NS		
Quadratic-plateau	$88.0 + 11.0\ X - 2.21\ X^3; X < 2.50$ $102; X \geq 2.50$	0.12*	2.50
Exponential	$102 - 13.5 \exp(-1.17X)$	0.11*	0.59
Cate and Nelson	NA	0.19*	1.13
	2:1 clay soils		
Linear	NS		
Quadratic	$96.4 + 6.04\ X - 1.27\ X^2$	0.33*	2.37
Linear-plateau	$96.3 + 4.4\ X; X < 1.49$ $103; X \geq 1.49$	0.31*	1.48
Quadratic-plateau	$95.9 + 7.7\ X - 2.23\ X^2; X < 1.72$ $103; X \geq 1.72$	0.32*	1.72
Exponential	NS[1]	—	—
Cate and Nelson	NA[2]	0.34*	0.5

[1] NS = The global model is not significant at $P < 0.1$.

[2] NA = In the Cate and Nelson model, no equation nor significance level is associated with the model.

[3] *, **, ***; significant at 0.1, 0.05 and 0.01, respectively.

[4] CNR = Crop nutrient requirement; x = level of application (kg P_2O_5/ha * 0.01).

The fact that different predicted CNR values were obtained with similar coefficients of determination using different models is not unusual, as it has been reported in other studies (Belanger, 2000; Mallarino and Blackmer, 1992). In many instances, the choice of which model is most appropriate is rarely explained. In 2:1 soils, visual evaluation of standardized residual distribution plots showed that the most symmetrical distribution of data corresponded to the linear-plateau model as compared to the quadratic and quadratic-plateau models (data not shown). In 1:1 clay soils, the quadratic model had the most symmetrical distribution of data. The Cate-Nelson model could not be included in the comparison, as standardized residual plots cannot be obtained.

Current P recommendations by the College of Agricultural Sciences (CAS) (EEA, 1992) are to apply 106 kg P_2O_5/ha as triple superphosphate (TSP) when soil test P is less than 40 mg/kg Olsen extractable P in soils of the semiarid southern coast of Puerto Rico, which are dominated by 2:1 clays. Continuing the practice of adding the recommended amount of P may not result in significant economic investment for the farmer when compared to the suggested range of predicted CNR values of 50 and 148 kg P_2O_5/ha with the Cate-Nelson and linear-plateau models, respectively. In fact, the CAS recommendations are within the range of predicted CNR values in this study. If 50 kg P_2O_5/ha is taken as the optimum application rate, the additional 56 kg P_2O_5/ha results in an additional economic investment of $57.98/ha ($476/mt, current market price of TSP) for the farmer, which is a small amount compared to the potential economic fixed costs (excluding P fertilizer). Calculated maximum net economic returns from P fertilization for 2:1 clay soils were obtained with P applications < 148 kg P_2O_5/ha (Figure 3A). Nevertheless, application of additional P beyond crop nutrient requirement will result in soil P buildup, and potential P contamination of surface water when the field characteristics for off-site transport are favorable (Sharpley et al., 2000).

Yield response to nitrogen application

The experimental data which describe the relative yield response to applied N for 1:1 clay and 2:1 clay soils are shown in Figure 4. For 1:1 clay soils (Figure 4A), predicted CNR values ranged from 150 to 338 kg N/ha (Table 3). The lowest R^2 value was obtained for the Cate-Nelson model with all other models tested having values between 0.53 and 0.57. For 2:1 clay soils, all models tested adjusted significantly to the experimental data. The lowest R^2 value was obtained for the linear model, with all other models having R^2 values between 0.40 and 0.43. For models with the highest R^2 values, predicted CNR values ranged from 50 to 144 kg N/ha.

As shown previously for P, coefficients of determination determined for the varying models can be only partially used as criteria for selecting the best model for CNR prediction. The study by Crespo-Ruiz et al. (1988) showed a dramatic response to addition of 150 kg N/ha, and is reflected in the large economic return obtained (Figure 3B). Observation of the standardized residual plots shows that this data point significantly altered the fit of the models to the experimental data as the studentized residual for this data point had a value of -5. Comparison of the quadratic, quadratic-plateau, and exponential models showed that the exponential model had the most symmetric distribution of data with a predicted CNR value of 120 kg N/ha. For 1:1 clay soils, the most symmetric distribution of data occurred for the quadratic and quadratic-plateau models both of which predicted CNR values of 307 kg N/ha.

Figure 3B shows that maximum economic returns for 2:1 clay soils are obtained with values ranging from 50 to 150 kg N/ha. These values approximate the predicted CNR values obtained with the Cate-Nelson

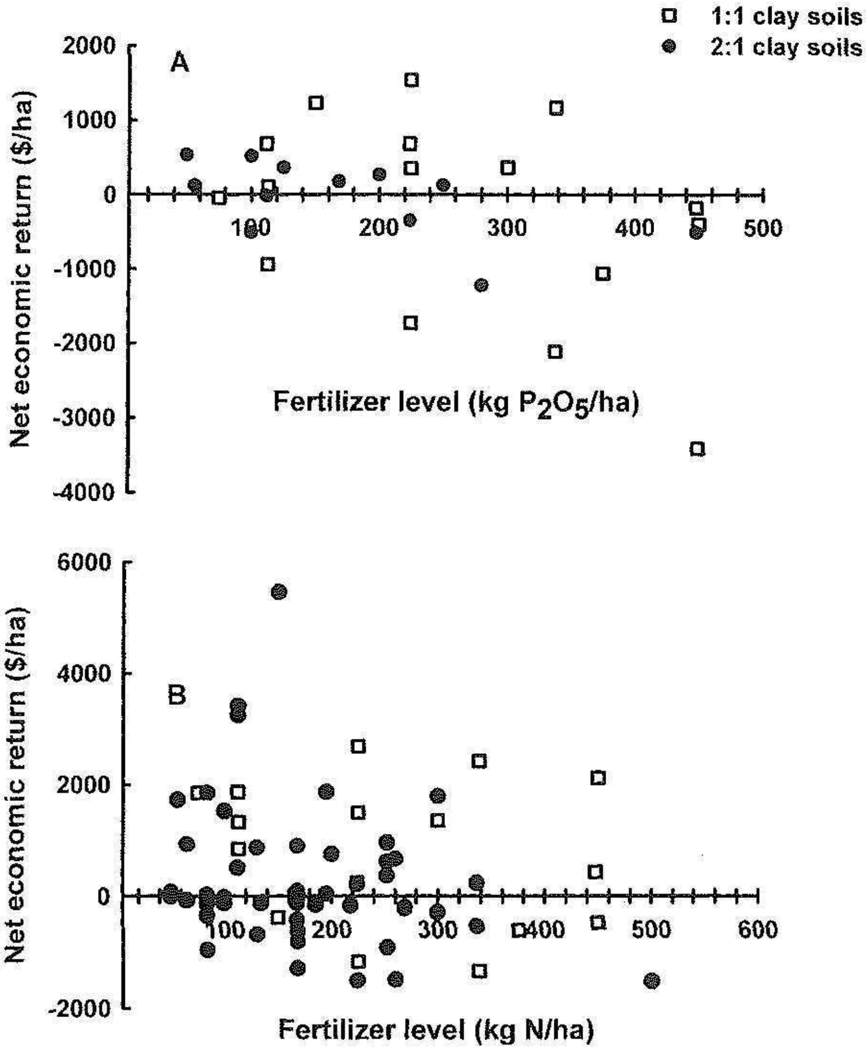

FIGURE 3. Net economic returns for Solanaceae as influenced by (a) P fertilizer applications and (b) N fertilizer applications in 1:1 clay soils and 2:1 clay soils of Puerto Rico.

and exponential models. For 1:1 clay soils, considerable scatter is observed in the maximum economic return values, as both positive and large negative values were obtained at high levels of fertilizer N application. Predicted CNR values were 150 and 107 kg N/ha for the Cate-Nelson and quadratic models, respectively. The analyses suggest that maximum economic returns can be obtained with fertilization levels as

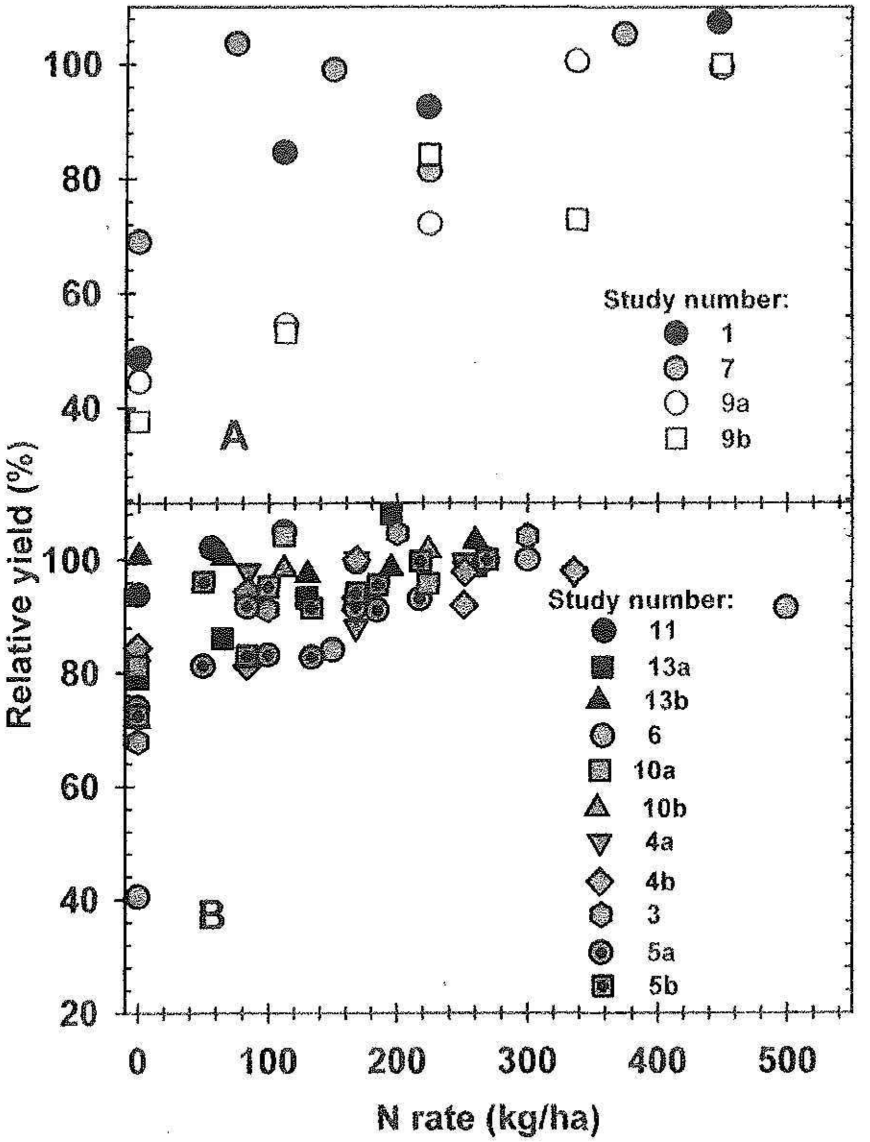

FIGURE 4. Relative yield of tomato, pepper and eggplant as a function of applied N in (a) 1:1 red clay soils from northeastern and (b) 2:1 clay soils of the semiarid southern coast of Puerto Rico. Study numbers correspond to the references described in Table 1.

high as 150 kg N/ha, with the Cate-Nelson and exponential models predicting optimum fertilization levels of 50 and 120 kg N/ha. Additional N (in excess of suggested values obtained in this study) does not result

TABLE 3.—*Equations describing yield response of Solanaceae and crop nutrient requirements (CNR) as affected by N application in 1:1 clay soils and 2:1 clay soils of Puerto Rico.*

Model	Equation	R^2[3]	CNR[4] (x units)
	1:1 clay soils		
Linear	$58.6 + 10.8 X$	0.53***	3.38
Quadratic	$53.6 + 19.7 - 2.04 X^2$	0.56***	3.07
Linear-plateau	NS[1]		
Quadratic-plateau	$53.6 + 19.7 X - 2.04 X^2$; $X < 3.07$ 95; $X \geq 3.07$	0.56***	3.07
Exponential	$107 - 55.0 \exp(-0.472 X)$	0.57***	3.18
Cate and Nelson	NA[2]	0.47	1.50
	2:1 clay soils		
Linear	$84.2 + 5.58 X$	0.27***	1.94
Quadratic	$79.3 + 14.6 X - 2.55 X^2$	0.41***	1.44
Linear-plateau	NS		
Quadratic-plateau	$77.2 + 27.5 X - 9.68 X^2$; $X < 1.00$ 95; $X \geq 1.00$	0.42***	1.00
Exponential	$98.0 - 20.8 \exp(-1.61X)$	0.43***	1.20
Cate and Nelson	NA	0.40	0.50

[1] NS = The global model is not significant at $P < 0.1$.

[2] NA = In the Cate and Nelson model, no equation nor significance level is associated with the model.

[3] *, **, ***; significant at 0.1, 0.05 and 0.01, respectively.

[4] CNR = Crop nutrient requirement; x = level of application (kg N/ha*0.01).

in a large economic burden to the farmer as the net economic return for given fertilizer level is high. Nevertheless, excess N (that is not taken up by the plant during growth) in soil results in a potential source of NO_3^- to aquifers which can result in groundwater contamination.

Yield relationships to soil test values

Soil test P and K values for the soils in which the studies were conducted can be used to calibrate the soil tests for particular soils and crops. With regards to P, in the studies conducted in 1:1 soils, only two reported soil test P values of 4 and 27 mg/kg (Bray1 extractant) (Table 4). In 2:1 clay soils, values (Olsen extractant) were greater than 21 mg/kg, with one study reporting a soil test P value of 1.71 mg/kg. In the latter, plant response was evaluated with regards to N application; therefore, it cannot be determined whether there is plant response at this soil test P level. Reported critical soil test P values for Puerto Rico are 20 and 35 mg/kg for the Bray1 and Olsen tests, respectively (Muñiz-Torres, 1992). From the reported soil test P data, it cannot be quantitatively confirmed whether crop response to plant applied P is expected below the suggested critical soil test values.

TABLE 4.—*Summary of reported soil chemical characteristics for fertility research for Solanaceae in Puerto Rico.*

Soil	pH	O.M	N	P	Ca	Mg	K	Na	Σ Bases	CEC	Reference
		%		ppm	- - - - - - - - - - - cmolc/kg - - - - - - - - - - -						
Coto clay	6.01	3.41	0.21	27 (Bray1)	5.75	1.36	0.46	NR	10	NR	González and Beale, 1987
Coto clay[1]	4.02	2.44	NR	4 (Bray1)			0.12	NR	NR	6	Mangual-Crespo, 1981
Santa Isabel clay	8.0	NR	NR	31 (Olsen)	18.8	8.2	0.60	NR	NR	NR	Rivera and Irizarry, 1984
San Antón	7.4	NR	NR	60 (Olsen)	19	5	0.77	NR	NR	22	Alers-Alers and Santiago, 1977
San Antón	7.0	NR	NR	1.71	26.9	4.2	1.78	NR	NR	NR	Crespo-Ruiz et. al., 1988
San Antón	NR[2]	NR	NR	58	15.7	2.54	0.99	NR	NR	NR	O'Hallorans et. al., 1993
San Antón	7.47	NR	NR	40	13.35	5.5	0.94	NR	NR	22	Vélez-Ramos et. al., 1991
San Antón clay	7.4-8.1	1.7-2.1	NR	42-82 (Olsen)	21.5-37.4	2.8-4.1	1.68	NR	NR	NR	Beale and Rivera, 1987
San Antón loam	NR	1.0-3.1	NR	35-47 (Olsen)	12.8-16.9	2.23-3.1	0.78-1.0	NR	NR	NR	Beale and Rivera, 1989
San Antón loam	7.55-7.64	1.9-2.8	NR	21-29 (Olsen)	17.1-17.7	2.71-2.8	0.64-0.77	NR	NR	NR	Beale et al., 1990
San Antón clay-loam	7.05-7.34	NR	NR	30.5 (Olsen)	15.2	4.9	0.98	NR	NR	NR	Lugo et al., 1987

[1] The soil was limed with 7.5 ton/ha prior to experiment. The P extractant was assumed to be Bray 1.

[2] NR indicates that a value for this parameter was not reported.

Soil test values were reported in four studies which evaluated plant response to applied K (Table 4). A value of 0.12 cmol$_c$/kg was reported in a 1:1 clay soil where plant response was reported, and values ranged from 0.94 to 1.68 in 2:1 clay soils where no plant response was reported. Muñiz-Torres (1992) suggests that no response is expected at values greater than 0.4 cmol$_c$/kg. More data are needed to ascertain soil test critical values for K.

Summary

A quantitative attempt was performed to improve fertilizer recommendations for Solanaceae in Puerto Rico with statistical models and economic analyses of historical experimental data sets. Interpretations of the results should be taken cautiously and under the scope of the present study. Plant response to K was not observed in 2:1 clay soils. Large variability in conjunction with few experimental data points precluded fitting equations to the data in 1:1 soils. For P and N, predicted CNR values varied widely depending on the selected model. The best model was selected on the basis of coefficients of determination, and standardized residual plots, and corroborated with economic returns. For 1:1 clay soils, predicted CNR values were 113 and 255 kg P_2O_5/ha for the Cate-Nelson and quadratic models, respectively, and 150 and 207 kg N/ha for the Cate-Nelson and quadratic models, respectively. For 2:1 clay soils, predicted CNR values were 50 and 148 kg P_2O_5/ha for the Cate-Nelson and linear-plateau models, respectively, and 50 and 120 kg N/ha for the Cate-Nelson and exponential models, respectively.

To improve the reliability of the results, a larger pool of data may be needed because of the large variation in soil chemical and physical properties influencing nutrient availability within soil types, and external factors influencing plant growth. In order to improve fertilizer recommendations for Solanaceae in Puerto Rico, we encourage researchers to follow the proposed experimental scheme:

1. Perform yield response experiments in Solanaceae which test the addition of single element levels (e.g., P levels only or K levels only) on crop yield in soils differing in initial soil nutrient contents.

2. Report soil test values for P and K including extractant methodology.

3. Report soil test characteristics including pH, organic matter, texture, and cation exchange capacity which can aid in further grouping of soils.

Adequate development and implementation of the suggested calibrated soil testing procedures should result in more efficient use of fertilizers and possibly lower production costs to vegetable farmers in Puerto Rico. This technique should also be applicable for other crops grown on similar soils.

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