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A discussion of the methods for comparing the relative effectiveness of phosphate fertilizers varying in solubility

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Abstract

Because various phosphate (P) fertilizers differ widely in their solubility, it is commonly observed that crop response to P fertilizers varies under the same soil and crop conditions. Furthermore, a major problem encountered in the methods for determining the relative effectiveness (RE) of water-insoluble P fertilizer (e.g., phosphate rock) with respect to water-soluble P fertilizers, e.g., single superphosphate (SSP) and triple superphosphate (TSP), is that their growth response curves are usually nonlinear and often do not share a common maximum yield. In this paper, we review and discuss the advantages and disadvantages of the three most commonly used methods for calculating the RE of phosphate rock with respect to TSP (or SSP). The three methods are vertical comparison, horizontal (substitution rate) comparison, and linear-response comparison.

Introduction

Phosphate (P) fertilizers differ widely in their solubility in water and citrate solution. On the basis of their solubility, Chien et al. [10] grouped P fertilizer sources as follows:

1. Water-soluble, e.g., triple superphosphate (TSP) and single superphosphate (SSP) and ammoniated phosphates (DAP and MAP).
2. Partially water-soluble but almost completely citrate-soluble, e.g., nitrophosphate, ammoniated TSP.
3. Partially water-soluble and partially citrate-soluble, e.g., partially acidulated phosphate rock (PAPR).
4. Water-insoluble but almost completely citrate-soluble, e.g., fused Ca-Mg phosphates, basic slag.
5. Water-insoluble and partially citrate-soluble, e.g., phosphate rock (PR).

Because P fertilizers differ in solubility, it is commonly observed that crop response to these fertilizers varies widely under the same soil and crop conditions. Furthermore, direct comparisons of the effectiveness of various P fertilizers are complicated by interactions between P fertilizer properties (i.e., solubility) and soil properties (pH, P-sorption capacity, etc.) as well as by the influence of fertilizer management practices and crop species [9]. Nevertheless, several methods have been used in the literature to compare various alternative P fertilizers with respect to standard, normally water-soluble P sources such as SSP and TSP. A number of terminologies, not necessarily unique to each particular method, have been used to describe these comparisons. In this paper we shall use the term 'relative effectiveness' (RE) in a general way to refer to the comparison of two or more P sources. Specific terminologies associated with particular methods will be defined as they arise in the text.

The purpose of this paper is to review the advantages and disadvantages of the various methods for determining the RE of P fertilizers. We will emphasize two P sources, namely, PR and TSP (or SSP), because these P sources represent the calcium phosphates with the lowest and highest solubility, respectively.

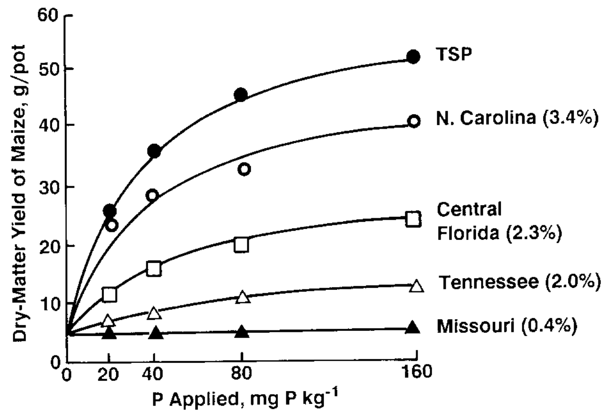

Fig. 1. Dry-matter yield of maize obtained with TSP and various phosphate rocks. Values in parentheses are citrate-soluble P contents in phosphate rocks. Data from [14].

Problems associated with the comparison

The major problem encountered in the methods for determining the RE of PR and TSP (or SSP) is that the growth response curves for these P sources are usually nonlinear and often do not share a common maximum yield. Figure 1 shows an example in which four PR sources were compared with TSP in terms of their effectiveness in increasing dry-matter yield of maize. Because of differences in the mineralogical composition of PRs due to differences in the degree of carbonate substitution for phosphate in the apatite (francolite) lattice, a given PR has its own characteristic ion-activity product constant. As a result, each PR has its own solubility in soil solution, which will not be exceeded regardless of how much PR fertilizer might be applied to the soil [7, 6]. Because factors controlling soil solution P concentration determine crop response to P, the agronomic effectiveness of PRs follows their order of solubility or reactivity, as shown in Figure 1 (i.e., North Carolina > Central Florida > Tennessee > Missouri). Furthermore, differences in maximum solubility account for the fact that the maximum yield differed for each PR and that all PRs were less effective than TSP.

When the standard (e.g., TSP) and alternative P fertilizers (e.g, PR) differ in their influence on maximum corp yields, the ratio of the availability coefficients obtained from the classical Mitscherlich equation cannot be used to estimate the RE of various fertilizers. In other words, the effects on crop growth from those fertilizers are not simply due to the differences in content of the same available nutrient. Thus, the methods used by Plamer et al. [17] and Colwell and Goedert [11] are not applicable for determining the RE of PR with respect to TSP. In fact, Colwell and Goedert [11] only determined the RE of PAPR with respect to TSP. Because PAPR contains water-soluble P, the two P sources in that comparison [11] theoretically should have produced the same maximum yield if the P rates were increased to sufficiently high levels.

In the following sections, we will discuss the three most commonly used methods for calculating the RE of PR with respect to TSP (or SSP), namely, the methods of vertical comparison, horizontal comparison, and linear-response comparison.

The vertical comparison

Without considering the response function, the following two definitions have been used to compare the effectiveness of a test fertilizer with respect to a standard fertilizer at a single rate of applied nutrient [18]:

$$\text{Relative yield (RY)} = \frac{\text{Yield with test fertilizer}}{\text{Yield with the standard}} \times 100 \qquad (1)$$

Relative yield increase (RYI)

$$= \frac{\text{Yield increase for test fertilizer}}{\text{Yield increase for the standard}} \times 100 \quad (2)$$

Because, in a plot of yield against P rates, comparisons of P sources are made at the *vertical* axis for a given P rate, this method of calculating RE has been referred to as a 'vertical comparison' [10].

To calculate the RE of a PR with respect to TSP, the two definitions may be written as follows:

$$RY = \frac{Y_{PR}}{Y_{TSP}} \times 100 \quad (3)$$

$$RYI = \frac{Y_{PR} - Y_0}{Y_{TSP} - Y_0} \times 100 \quad (4)$$

where

Y_{PR} = Yield with PR

Y_{TSP} = Yield with TSP

Y_0 = Yield with check (no P added)

In our opinion, Eq. 4 is more appropriate than Eq. 3; by subtracting the yield with no P added, Eq. 4 reduces the effect of site, initial soil P content, weather, etc., from the response to P sources.

Equation 4, defining RYI, was used in a study of the response of flooded rice to various PRs and TSP [12] and in a comparison of bean response to PRs and TSP [8]. In the study by Engelstad et al. [12], the average of the yields obtained over all rates for a given P source was used in Eq. 4 to calculate the RYI value for that P source with respect to TSP. Chien and Hammond [8] calculated RYI values for the various PRs at each rate of P applied and then averaged the results to obtain a mean RYI for each PR source. [In both studies, RYI was referred to as relative agronomic effectiveness (RAE)]. As Barrow [1] pointed out, calculation of RE at a given P rate may depend on the P level chosen. If the levels are chosen mostly on the plateau region of a response curve, the result obtained will differ from that obtained with the levels are mostly on the ascending part of the curve.

Chien et al. [10] suggested that if a suitable response function with a one-term coefficient for the independent variable (i.e., P rate) could be found to fit the experimental data, then the ratio of the two fitted coefficients obtained with the test and the standard P fertilizers could be used to represent the 'RE index' of the test P fertilizer. The advantage of using the ratio of the two regression coefficients to express the RE index as defined by Eq. 2 is that the ratio is independent of rate of P applied. Researchers have used the following two equations, which contain only a one-term coefficient in the independent variable X, to describe the curvilinear response to P fertilizers:

$$Y_i = Y_0 + b_i \ln X, X > 1 \quad (5)$$

and

$$Y_i = Y_0 + b_i X^{1/m} \quad (6)$$

where

Y_0 = Yield obtained with no P added (common to all P sources)
Y_i = Yield obtained with source (i)
b_i = Regression coefficient of source (i)
m = Constant
X = Rate of P applied

Equation 5 was used by Leon et al. [16] to compare P availability from various South American PRs with that from TSP and by Hellums et al. [13] to compare Ca availability of PRs with that of $CaCO_3$. Equation 6 was used by Kpomblekou [15] and Bationo et al. [2] with the value of m equal to 2.0 when various sources of PR or PAPR were tested against TSP. Thus, as defined by Eq. 2, the RE index of a PR with respect to TSP is constant at any rate of P applied and can be expressed as

$$\text{RE index } (\%) = \frac{b_{PR}}{b_{TSP}} \times 100 \quad (7)$$

The usefulness of Eq. 7 is in its ability to rank a series of of test fertilizers with respect to a

Table 1. Relative effectiveness (RE) index of phosphate rocks for Panicum maximum (three cuttings) [16]

P source	Dry-matter yield		P uptake	
	bi[a]	RE index[b] (%)	bi[c]	RE index[b] (%)
Highly effective				
TSP	3.65	100	4.18	100
N. Carolina PR	3.62	99	3.54	84
Bayovar PR	3.51	96	3.55	85
Gafsa PR	3.50	96	3.56	85
Arad PR	3.09	85	3.02	72
Medium effectiveness				
Central Florida PR	2.90	79	2.48	57
Huila PR	2.80	76	2.30	54
Pesca PR	2.71	74	2.26	54
Tennessee PR	2.71	74	2.20	52
Low effectiveness				
Lobatera PR	2.46	67	1.86	44
Sardinata PR	2.14	59	1.62	38
Patos de Minas PR	2.11	58	1.74	41
Araxa PR	1.74	48	1.44	34
Abaete PR	1.55	42	1.33	32
Very low effectiveness				
Jacupiranga PR	1.02	28	0.91	22
Catalao PR	0.81	22	0.72	17
Tapira PR	0.45	12	0.40	9
R^2	0.93		0.87	

[a] $Y = 0.80 + b_i\,5\ln X$.
[b] RE index $= b_i/b_{TSP} \times 100$.
[c] $Y = 0.41 + b_i \ln X$.

standard fertilizer according to their agronomic potential to produce a yield response at the same rate of P applied. For example, Leon et al. [16] used the semilog response function, i.e., Eq. 5, to calculate RE index values of various PRs with respect to TSP and used Eq. 7 to rank them as shown in Table 1. Furthermore, because the RE index as calculated with Eq. 7 is independent of rate, it can be considered an intrinsic property of a PR under a given set of agronomic conditions. Thus, the RE index of PRs should correlate well with chemical reactivity, which is also an intrinsic property of PRs. As shown in Figure 2, the RE index of the PRs used by Leon et al. [16] was found to be closely related to the citrate solubility of these PRs.

Another advantage of using the RE index as defined in Eq. 7 is the fact that the coefficient ratio appears to be independent of the form of one-term regression function used. Chien and

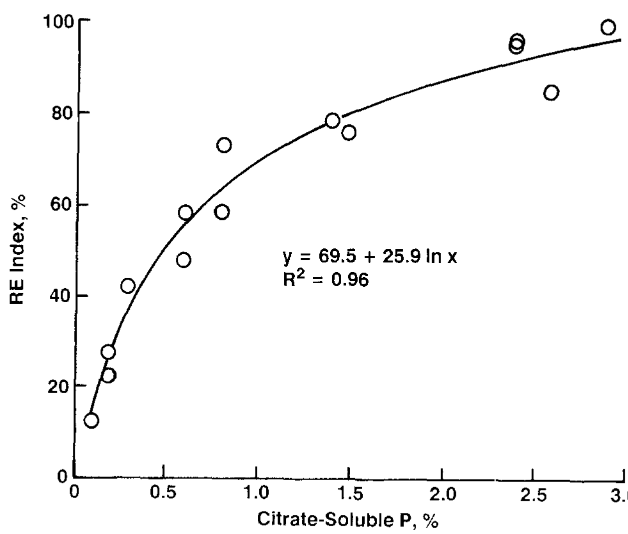

Fig. 2. Relationship between relative effectiveness (RE) index of various phosphate rocks and their citrate-soluble P content. Data from [16].

Table 2. Relative effectiveness (RE) index of partially acidulated Huila phosphate rock (PAPR–50% H_2SO_4) with respect to SSP [9]

Response function[a]	Soil	P-fixing capacity (%)	P source	b_i	RE index (%)
$Y = Y_0 + b_i \ln X$	Savannah T	5.6	PAPR	4.33	84
			SSP	5.17	100
	Guthrie	14.7	PAPR	5.81	91
			SSP	6.42	100
	Savannah S/A	20.7	PAPR	7.27	101
			SSP	7.19	100
	Vanago A	26.2	PAPR	6.44	92
			SSP	7.02	100
$Y = Y_0 + b_i X$	Savannah S/B	37.3	PAPR	0.135	106
			SSP	0.128	100
	Venago B	57.1	PAPR	0.112	123
			SSP	0.091	100

[a] Y = Dry-matter yield of maize.
X = Rate of P applied.

Hammond [9] studied the RE index of a PAPR (Huila PR partially acidulated with H_2SO_4 at 50% acidulation level) with respect to SSP on six soils varying widely in P-fixing capacity. The semilog response function was most suitable for four soils, whereas the linear response function was needed for the two soils with highest P-fixing capacity (Table 2). A significant linear relationship was found between the RE index of PAPR and the soil P-fixing capacity using RE index values based on both semilog and linear response functions (Fig. 3). This shows that the RE index

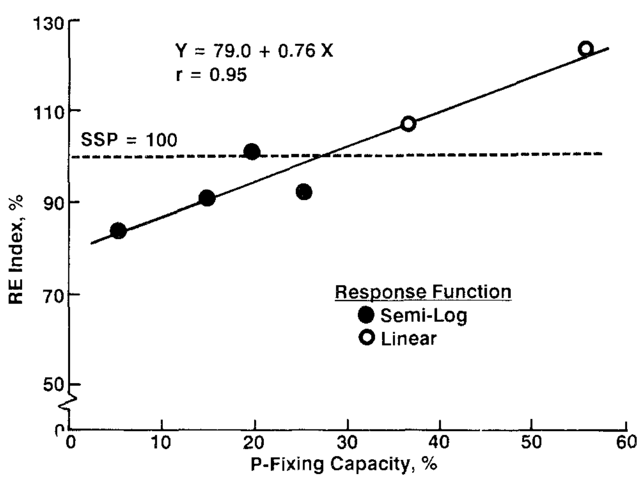

Fig. 3. Relationship between relative effectiveness (RE) index of a partially acidulated phosphate rock (Huila PAPR–50% H_2SO_4) and soil P-fixing capacity. Data from [9].

value of a P fertilizer with respect to another fertilizer as calculated from the coefficient ratio can be used to correlate with soil properties such as P-fixing capacity.

It should be reiterated that the RE index defined in Eq. 7 is based on a vertical comparison of yields from two P sources at a given P rate. Results therefore can be misleading if the researcher attempts a horizontal comparison of sources (to be discussed below) without recognizing the curvilinear nature of the response functions. Suppose the crop response to a source of PR and TSP follows a semilog function (i.e., Eq. 5) and the RE index of the PR with respect to TSP, as calculated with Eq. 7, is 0.5; this result simply means that the effectiveness of PR, in terms of increasing crop yield per unit of P applied, is half of that of TSP whether the P rate applied from both P sources is 30 kg P ha^{-1} or 60 kg P ha^{-1}. However, it *does not* mean that PR applied at 60 kg P ha^{-1} would result in the same yield as TSP applied at 30 kg P ha^{-1}. To compare RE of P fertilizers in terms of the amount of P required to produce a given crop yield, a horizontal comparison should be used, as discussed below.

The horizontal comparison

In the horizontal method, the effectiveness of two P fertilizers is compared on the basis of the relative amounts of each that are required to give the same yield in the responsive region of the yield/P rate curve [18, 17]. Thus, the comparison is made along the *horizontal* axis, and the RE value is calculated by dividing the rate of the reference fertilizer (e.g., TSP) for a particular yield by the rate of the test fertilizer (e.g., PR) that gives the same yield according to the response curve. The 'horizontal comparison' has also been referred to as the 'substitution rate (SR)' of fertilizers because it compares the amount of one source that will substitute for another in producing a selected common yield [1, 11, 4]. For example, as shown in Figure 1, approximately 30 g pot kg^{-1} of TSP or 55 mg P kg^{-1} of North Carolina PR was required to produce 30 g pot kg^{-1} of maize dry-matter. Thus, the RE or SR value of North Carolina PR with respect to TSP is 30/55 = 0.55. In contrast, the other PRs shown in Figure 1 have SR values of zero since the data show that, regardless of how high the P rates may be, they will never produce a dry-matter yield of 30 g/pot.

One advantage of using the SR (horizontal comparison) method is that it enables a fertilizer used to make a simple descision as to which fertilizer should be most profitable to use. For example, if the SR value of a PR with respect to TSP is 0.5 (Fig. 4), the application of P from PR

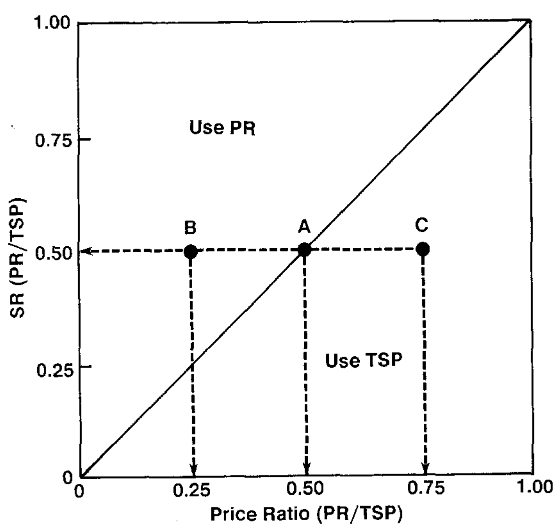

Fig. 4. Use of phosphate rock (PR) or TSP based on price ratio and substitution rate (SR) of PR to TSP.

must be twice the amount from TSP to produce the same crop yield. If the price ratio of PR/TSP is 0.5, use of PR or TSP would be economically the same (point A). However, if the price ratio is less than 0.5 (point B), then use of PR would be more profitable. On the other hand, TSP should be used if the price ratio is more than 0.5 (point C).

If crop response to P rates is curvilinear and is described by a semilog function (Eq. 5), the SR value, unlike the RE value based on vertical comparisons (Eq. 7), is not a constant and generally declines with increasing P rates of the less soluble P fertilizer [4]. Consider two fertilizers, PR and TSP:

$$Y_{PR} = Y_0 + b_{PR} \ln X_{PR} \tag{8}$$

$$Y_{TSP} = Y_0 + b_{TSP} \ln X_{TSP} \tag{9}$$

At a given common yield, the following equality is true:

$$b_{PR} \ln X_{PR} = b_{TSP} \ln X_{TSP} \tag{10}$$

and, by definition and substitution,

$$SR = \frac{X_{TSP}}{X_{PR}} = X_{PR}^{[(b_{PR}/b_{TSP})-1]} \tag{11}$$

In general, because $b_{PR} < b_{TSP}$, SR decreases as X_{PR} increases. In other words, the SR value of PR with respect to TSP decreases as the PR rate increases. This is demonstrated in Figure 5 with the data extracted from Table 1. The data also indicate that SR declines more rapidly with the less reactive PR than with the more reactive PR. Thus, for low-reactivity PR, the relative agronomic effectiveness with respect to TSP decreases with increasing rate of P applied. Because the SR value of PR with respect to TSP is not constant, Bolland et al. [3] suggested that the SR of PR be defined as the ratio of the amount of PR to that of TSP required to produce 50% of the maximum yield that was achieved with TSP. However, it must be recognized that the relative profitability of two P sources based on SR values determined at an arbitrarily selected common yield will change when a different yield goal is selected.

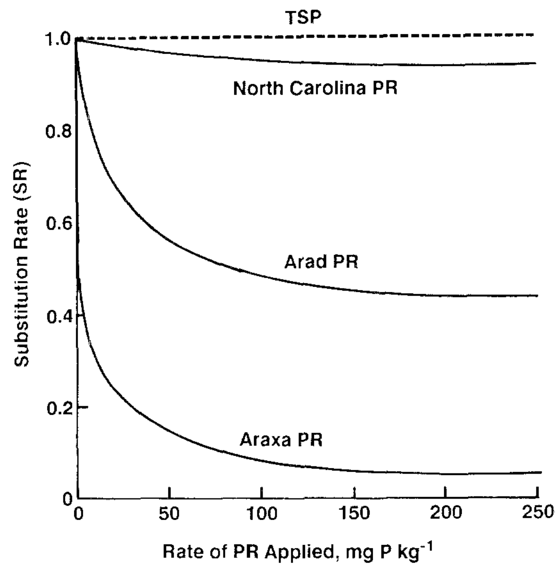

Fig. 5. Substitution rate (SR) of phosphate rocks (PR) to TSP in relation to rate of PR applied. Data from [16].

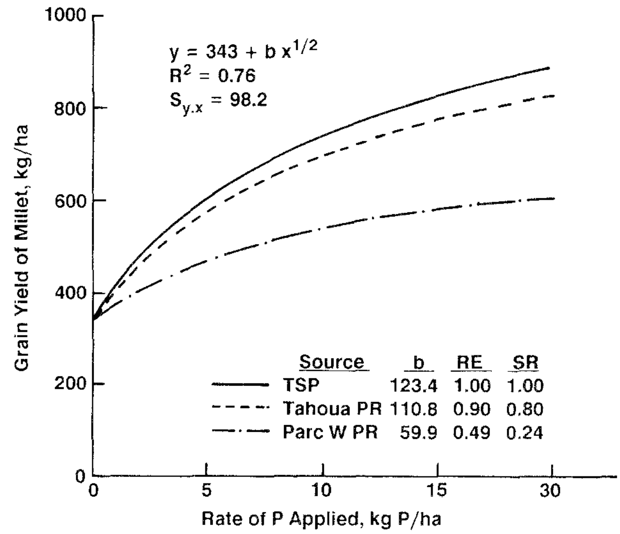

Fig. 6. Millet yield obtained with TSP and phosphate rocks (PR) in Niger (1985). Data from [2].

It is interesting to note that, if the curvilinear crop response is described by Eq. 6, the SR value of PR with respect to TSP is constant as shown in the following:

$$Y_{PR} = Y_0 + b_{PR} X_{PR}^{1/m} \tag{12}$$

and

$$Y_{TSP} = Y_0 + b_{TSP} X_{TSP}^{1/m} \tag{13}$$

Again, at a given common yield with PR and TSP,

$$b_{PR} X_{PR}^{1/m} = b_{TSP} X_{TSP}^{1/m} \tag{14}$$

and

$$SR = \frac{X_{TSP}}{X_{PR}} = \left(\frac{b_{PR}}{b_{TSP}}\right)^m \tag{15}$$

Because all coefficients (b and m) are constant, the SR is independent of the rate of P applied. In Niger, for example, Bationo et al. [2] used Eq. 6 with $m = 2$ to describe millet response to TSP and two indigenous PRs (Tahoua and Parc W) on an acid (pH 4.2, 1 N KCl) sandy soil. The calculated b coefficients were 123.4, 110.8, and 59.9 for TSP, Tahoua PR, and Parc W PR, respectively (Fig. 6). Based on Eq. 15, the SR values for Tahoua PR and parc W PR were calculated as 0.80 and 0.24, respectively. Based on Eq. 7 (vertical comparison), however, the RE index values of Tahoua PR and Parc W PR were calculated as 0.90 and 0.49, respectively. Thus, the vertical comparison and the horizontal comparison provide different RE values for PR with respect to TSP, even when both comparisons are independent of rate of P application.

The linear-response comparison

Often the region of primary interest in fertilizer performance is that of the most responsive part of the response curve. This region represents the level of response at which a farmer with limited resources will be applying fertilizer. Moreover, in this region the response to added P is often linear or nearly so. In this situation, a comparison of the slopes of the linear portions of the response curves is a simple means of arriving at a rate-independent estimate of RE. For example, Bolland et al. [5] calculated the initial linear slope of each fertilizer tested (Christmas Island C-grade, Duchess PR, and SSP) using yields for the check treatment and the first two levels of P applied. The RE of the fertilizers was calculated by dividing the initial slopes determined for each fertilizer each year by the intial slope determined for freshly applied SSP.

One difficulty with the procedure of the linear-response comparison is deciding on the number of levels of fertilizer input to include in the linear regression. A comparison of R^2 values for regressions using different levels of input is misleading because R^2 value is influenced by the degrees of freedom. An objective solution to this problem is to successively fit first- and second-order polynomial regressions to the data set, each time including the data for an additional fertilizer rate. The number of fertilizer rates selected to define the linear regression would be one less than the number used for the regression where the quadratic coefficient becomes significant ($P < 0.05$). It should be pointed out that the RE index of a test fertilizer determined by the linear-response comparison method is the same whether it is compared vertically or horizontally. However, the RE index is valid only within the region in which a limited number of P rates is used for linear regression.

Summary and conclusions

In view of the overall advantages and disadvantages associated with each method for comparing the effectiveness of various P fertilizers, the choice of method used should depend on the objective of the researcher. If the goal is to make an economic evaluation of different fertilizers on the basis of the amount of P required to give a particular yield, then the method of horizontal comparison should be used. On the other hand, if the objective is to rank a series of test fertilizers, relative to standard fertilizer, in their ability to produce a yield response or if the objective is to study the effect of environmental factors on the yield responses of different fertilizers, then an effectiveness index derived from the ratios of coefficients (vertical comparison) from fitted response functions has merit. However, the use of such an index in making an economic assessment of the test fertilizer can be misleading if the researcher does not recognize the curvilinear nature of the response function. A problem here is that not all field workers may be aware of the subtleties of these curvilinear effects.

Misleading results can be avoided by using a terminology other than the RE index. Confusion can arise because this one index is used in both vertical and horizontal comparisons, which produce different results (see Fig. 6). We therefore recommend that substitution rate (SR), the index derived from the horizontal comparison, be used in making economic assessments of different fertilizer products. Alternatively, when using the vertical comparison method to rank fertilizers or to study environmental effects or yield responses, then the index should be called the relative yield response (RYR) index.

A third method for comparing fertilizers is the linear-response comparison. If the goal is to provide resource-poor farmers with cheaper alternative P sources at low rates of P application, then the ratio of slopes of the linear responses in the most responsive region of the response curve will give a simple measure of substitution rate.

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