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Development and Validation of a Phosphate Rock Decision Support System

Suzette A. Smalberger, Upendra Singh,* Sen H. Chien, Julio Henao, and Paul W. Wilkens

ABSTRACT

Although some mathematical models exist to assist in deciding whether or not to apply phosphate rock (PR) to soils as a source of P, these models focused either on the use of highly soluble PR sources, mainly for pastures, or were too impractical for field use. There was, therefore, a need to develop a Phosphate Rock Decision Support System (PRDSS) with more comprehensive capabilities to predict the relative agronomic effectiveness (RAE) of PR with respect to water-soluble phosphorus (WSP) fertilizers at field and farm level. The PRDSS includes PR sources varying widely in solubility and different crop species grown on variable soil properties and rainfall conditions. In this paper, we describe the development and use of the mathematical model, PRDSS, to estimate RAE of PR sources with respect to WSP fertilizers and to calculate a simple index to be used for preliminary economic comparison of these two types of P sources. The PRDSS is able to function with a minimum input of only soil pH, the name of the mine that is the source of the phosphate rock, and the species of crop to be grown. A more accurate prediction of RAE is obtained from the PRDSS when more detailed data describing the soil, crop, and weather are included as inputs.

INCREASED human population pressure, reduced length of fallow, and inherently low soil fertility are causing soil degradation that is resulting in food shortages in developing countries, especially in countries of tropical, sub-Saharan Africa (SSA). Many soils used for agriculture in this large region are infertile with low levels of essential plant nutrients, especially N and P. Deficiency of P is so extreme in many soils that without adequate application of this element, investments in other agricultural technologies (e.g., use of N fertilizer and legumes for biological N fixation) may not be effective to increase crop productivity and to contribute to food security.

Applications of water-soluble P (WSP) such as single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), or diammonium phosphate (DAP) can meet the P requirement application for annual crops in developing countries. However, the lack of a well-developed, domestic P fertilizer industry and limited availability of foreign exchange for fertilizer imports have kept the application of P fertilizers by the poor farmers in SSA very low (1.0 kg P ha^{-1} vs. 14.3 kg P ha^{-1} in Asia, for example) (FAO, 2002). For certain crops, the direct application of suitable sources of phosphate rock (PR) can be an agronomically and economically attractive alternative practice, compared with the use of more expensive WSP fertilizers in tropical and subtropical acid soils (Leon et al., 1986; Chien and Menon, 1995).

Many developing countries possess PR deposits (Fig. 1). If these PR sources could be economically used alone or in conjunction with WSP fertilizers, countries with PR deposits could save much-needed foreign exchange and some poor farmers in these countries might be able to profitably apply PR to their P-deficient soils. The use of PR for direct application has also gained attention worldwide because PR as a natural raw material is the only nutrient-rich P source for organic farming. Interest in PR as a "natural" fertilizer could open future markets to exports of PR from developing countries. Direct application of reactive PR will also reduce P eutrophication in vulnerable regions compared with the current use of WSP (Hart et al., 2004).

The PRDSS is a mathematical model developed through an iterative process based on verification of the model by data from experiments conducted by collaborating scientists in a number of developing countries. This mathematical model is a practical, decision-making tool resulting from international, collaborative research of many scientists supported by several funding institutions. The PRDSS is now a practical tool for researchers, extension services, farmers, planners, agribusiness dealers, and policymakers. The principal purpose of the PRDSS is to help decide, based on RAE, whether a given PR at a specific site is a good agronomic substitute for WSP fertilizers. The most important factors affecting the agronomic effectiveness of PR for direct application are the source of PR (solubility of PR differs among sources), soil properties, and crop species. Other factors that can influence the effectiveness of PR are management practices and agro-climatic conditions (Leon et al., 1986). These features distinguish PRDSS from models that have emphasized the use of highly reactive PR sources mainly for pastures (Gillard et al., 1997; Metherell and Perrott, 2003) and from models requiring homogeneous conditions and complex inputs (Watkinson, 1994; Nye and Kirk, 1987).

The PRDSS is also capable of using farm-gate prices of WSP and PR to determine whether PR may be an economically better choice than WSP. Based on RAE, the PRDSS can also generate a substitution value index (SVI) to determine the relative amount of PR needed to

Research and Market Development Division, IFDC, P.O. Box 2040, Muscle Shoals, AL 35662. Received 23 Aug. 2005. *Corresponding author (usingh@ifdc.org).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AlC, crop species variance in tolerance to Al saturation; AlFC, free carbonate and Al saturation effect on relative agronomic effectiveness; CA, citric acid; DAP, diammonium phosphate; DSSAT, Decision Support System for Agro-Technology Transfer; EAlS, effective Al saturation; FA, formic acid; FC, free carbonate; MAP, monoammonium phosphate; NAC, neutral ammonium citrate; NAC$_1$, first extraction; NAC$_2$, NAC second extraction; PDSS, Phosphorus Decision Support System; PR, phosphate rock; PRDSS, Phosphate Rock Decision Support System; RAE, relative agronomic effectiveness; REE, relative economic effectiveness; REL, rainfall effect on leaching; SSA, sub-Saharan Africa; SSP, single superphosphate; SVI, substitution value index; TSP, triple superphosphate; WSP, water-soluble phosphorus.

Fig. 1. Important and potentially important phosphate rock deposits (Van Kauwenbergh, 2003).

achieve the same target yield as with WSP. The PRDSS is an effective approach to integrate both biophysical and economic factors to assess the feasibility of using either PR or WSP as a P source for crops.

DEVELOPMENT OF THE PHOSPHATE ROCK DECISION SUPPORT SYSTEM

The initial response of a crop to PR application is very important for both agronomic and socioeconomic reasons. The RAE is an output and an index that estimates the initial response of a crop to P application as PR or WSP. A version of the PRDSS by Singh et al. (2003) has been expanded from an initial version where PR solubility, soil pH, and crop species were the only inputs to one that now allows the user to take into account other factors that affect PR dissolution such as rainfall, soil texture; organic C; Al saturation; P fixation, and additional crop species coefficient related to P fixation; Al toxicity; and duration of crop growth.

In our development of the PRDSS, RAE values of PR were calculated from the collected, published, and unpublished agronomic data based on fitting response functions of crop response to PR and WSP.

Process of Phosphate Rock Decision Support System

The basic outline of the PRDSS structure presented in Fig. 2 consists of all the main components influencing the RAE predictions. Figure 3 gives in detail all the factors to calculate the main components and includes a database composed of data for the following variables: PR sources, soil characteristics, crop species, and climatic factors. The minimum input data required for PRDSS to do a first and basic RAE prediction are the PR source, crop species (due to its influences on the rhizosphere) and soil pH. If the user can supply input data for the following variables, the first approximation of the RAE is then multiplied by factors for organic C, moisture, P fixation, and leaching. After the second approximation, the RAE is adjusted, based on effective Al saturation and free carbonate content of the PR source to predict the final RAE.

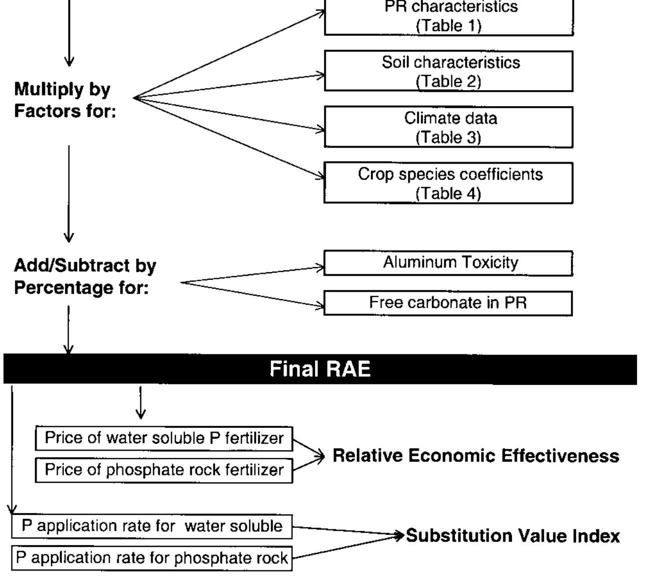

Fig. 2. Schematic representation of the main components in the phosphate rock decision support system (PRDSS).

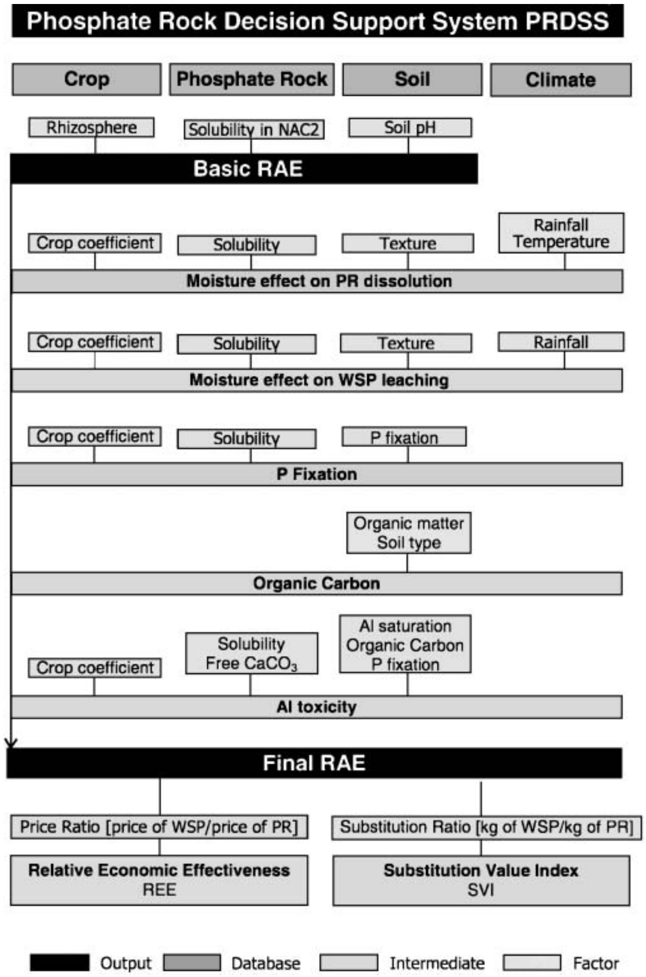

Fig. 3. Schematic representation of all the components, factors, and processes in phosphate rock decision support system (PRDSS).

Based on the fertilizer price supplied by the user and the predicted RAE, relative economic effectiveness (REE) of a PR can be estimated. Based on relative amount of P application, an SVI for PR can be calculated. The PRDSS is programmed in Delphi (Borland Delphi Version 5.0). Factors used by PRDSS to predict RAE are detailed as follows.

Definition of Relative Agronomic Effectiveness

The RAE (%) of PR sources compared with a selected WSP fertilizer is defined as follows (Chien et al., 1990):

$$\mathrm{RAE}\ (\%) = \left[\frac{Y_{\mathrm{PR}} - Y_{\mathrm{o}}}{Y_{\mathrm{WSP}} - Y_{\mathrm{o}}}\right] \times 100 \qquad [1]$$

where

Y_{PR} = yield of PR obtained at a P rate
Y_{WSP} = yield of WSP obtained at the same P rate
Y_{o} = yield obtained with no application of P

Chien et al. (1990) 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 PR and WSP could be used to represent RAE. The advantage of using the ratio of the two regression coefficients to express RAE as defined by Eq. [1] is that the ratio is independent of the rate of P applied since the RAE, as defined by substitution ratio (Gillard et al., 1997), varies with targeted crop yield and P rate (Chien et al., 1990). 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 (Chien et al., 1990) as follows:

$$Y_i = \alpha + \beta \ln (x_i),\ x_i \geq 1 \qquad [2]$$

and

$$Y_i = \alpha + \beta\, (x_i)^{0.5} \qquad [3]$$

where

Y = yield obtained with PR or WSP
α = yield obtained with zero P or intercept
β = regression coefficient of PR or WSP
x_i = rate of P applied

Thus, as defined by Eq. [1], the RAE of PR with respect to WSP is constant at any rate of P applied and can be expressed as follows:

$$\mathrm{RAE} = (\beta_{\mathrm{PR}}/\beta_{\mathrm{WSP}}) \times 100 \qquad [4]$$

where

β_{PR} and β_{WSP} = regression estimates of β in Eq. [2] or [3].

In the development of our current PRDSS, RAE values of PR were calculated from the collected published and unpublished field and greenhouse data based on Eq. [1] or Eq. [4].

Phosphate Rock Solubility and Reactivity

The solubility of PR is determined by chemical analysis using neutral ammonium citrate (NAC), 2% citric acid (CA), or 2% formic acid (FA) (Chien and Hammond, 1978). The PRDSS uses the NAC second extraction (NAC_2) for its estimations. This method extracts the residual PR sample after the first extraction (NAC_1) to eliminate the possible effect of free carbonates (calcite and dolomite) on apatite solubility in NAC (Chien and Hammond, 1978; Chien, 1979, 1993). Phosphate rock solubility is only an index of the rate of dissolution and not the quantity of actual plant-available P. The reactivity of PR is an intrinsic property as determined by the degree of carbonate substitution for phosphate in the apatite structure. In this paper PR reactivity is considered a qualitative term (high, medium, low) while PR solubility is quantitative and its value will depend on the extracting reagent (NAC, CA, FA, water, etc.).

The PRDSS allows users to input PR solubility as determined by either 2% CA or 2% FA, and the PRDSS uses the following equations to calculate the equivalent Y_{NAC2}.

$$\mathrm{Y}_{\mathrm{NAC2}} = 0.133 + 0.302\, x_{\mathrm{FA}},\ n = 50, R^2 = 0.92 \qquad [5]$$

$$\mathrm{Y}_{\mathrm{NAC2}} = 0.294 + 0.649\, x_{\mathrm{CA}},\ n = 70, R^2 = 0.92 \qquad [6]$$

where

Y_{NAC2} = PR solibility by NAC_2 as % P of rock
x_{FA} = PR solibility measured by 2% FA as % P of rock
x_{CA} = PR solibility measured by 2% CA as % P of rock

The system uses the PR solubility of finely ground rock to estimate the agronomic effectiveness. Several highly reactive PR sources are being marketed in "as-received, unground" form. Although the solubility of a highly reactive PR in unground form is lower than that of finely ground form, they give similar crop response, but for medium and low reactive PR, the unground source gives much lower yields than the ground form of PR (Chien and Friesen, 1992; Chien, 1993, 1998). If the users have the solubility data of highly reactive PR in the unground form, the following equation is used to convert the solubility from ungound to finely ground form and PRDSS will then use this ground value for predictions:

$$Y_{\text{G}} = 0.320 + 1.210x_{\text{UG}}, n = 10, R^2 = 0.91 \quad [7]$$

where

Y_{G} = NAC_2 solubility for finely ground PR in % P of rock
x_{UG} = NAC_2 solubility for unground PR in % P of rock

Some PR sources contain significant amounts of free carbonates. In these cases, the amount of P extracted with NAC_2 will be higher than the amount of P extracted with NAC_1, because free carbonates are not present during the second extraction. Therefore, extraction of P using NAC_2 more realistically represents the actual solubility of PR. Figure 4 gives the relationship between NAC_1 and NAC_2 solubility of seven PR sources that includes Huila PR from Colombia to illustrate the influence of free carbonate on PR solubility as determined by NAC_1 and NAC_2 (Chien and Hammond, 1978). Data of selected PR sources stored in the PR database are shown in Table 1.

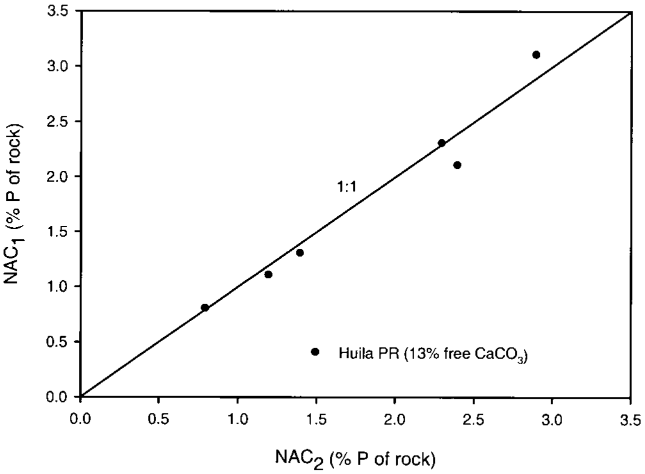

Fig. 4. Relationship between the percentage of P extracted by the first (NAC_1) and second (NAC_2) neutral ammonium citrate extractions of seven PR sources that includes Huila PR from Colombia, which has a high free carbonate content of 13% (data from Chien and Hammond, 1978).

Soil Characteristics

Different soil characteristics influence the dissolution of PR. An example of all the related soil factors included in PRDSS is given in Table 2. In general, the most important soil-related factors that influence the dissolution of PR in soils are soil pH, pH buffering capacity, P-fixing capacity, soil CEC, and exchangeable Ca (Robinson et al., 1994). The model does not include the effect of plant-available P. The status of plant-avaiable P has little influence on the dissolution of PR because soil solution P concentration is usually very low (between 0.05 and 0.5 mg L^{-1}) (Rajan et al., 1996).

Soil pH

The agronomic performance of PR for direct application is most dependent on the solubility of PR and soil pH (Singh et al., 2003; Chu et al., 1962; Chien et al., 1980; Robinson et al., 1994). The relationship and the effect of PR solubility and soil pH (ranging from pH 4.0 to 8.5) on RAE as presented in Fig. 5 is based on regression models and the interpolative function from the Delphi program.

Data from Leon et al. (1986) and Singh (1985) were used to develop the following relationship to convert soil pH (KCl) to pH (H_2O) for PRDSS use:

$$Y_{\text{H2O}} = -0.783 + 1.69x - 0.064x^2, n = 85, R^2 = 0.96 \quad [8]$$

where Y_{H2O} = soil pH (H_2O) and x = soil pH measured in KCl.

Phosphorus Fixation

The minimum value and degree or the effect of P fixation on PR dissolution are both functions of PR solubility. Phosphate rock sources with low to medium reactivity are relatively more prone to a higher reduction in RAE than the highly reactive PR sources. The agronomic performance of PR sources is decreased in soils that have relatively high P fixation (Fig. 6). The relationship between the effect of soil P-fixing capacity and the solubility of PR on RAE is as follows:

$$\text{Y}_{\text{PFM}} = 90/\{1.0 + \exp - [(x_{\text{NAC2}} - 2.578)/0.7217]\}, \quad n = 17, R^2 = 0.92 \quad [9]$$

where Y_{PFM} = minimum P fixation in (%) influencing reduction of RAE and x_{NAC2} = PR solubility as determined by NAC_2 expressed as % P of rock.

The effect of P fixation on the RAE changes based on the solubility of the rock. The impact of the effect of soil P-fixing capacity on a PR is less for a low solubility PR, more for a medium soluble rock, and less again for a highly soluble PR. Data from IFDC greenhouse experiments, Leon et al. (1986) and Mokwunye and Hammond (1992), were used to determine slope of the P fixation based on PR solubility (PFS).

$$Y_{\text{PFS}} = 0.2643 + 0.552x_{\text{NAC2}} + 0.0238x^2_{\text{NAC2}} - 0.0219x^3_{\text{NAC2}}, n = 9, R^2 = 0.89 \quad [10]$$

Table 1. Characteristics of several samples of phosphate rock showing differing solubility of P in the first (NAC_1) and second (NAC_2) extracts of neutral ammonium citrate, 2% citric acid (2% CA), 2% formic acid (2% FA), total P content, and free $CaCO_3$.

			NAC_1		NAC_2		2% CA			
Country	Location	Total P	Ground	Unground	Ground	Unground	Ground	Unground	2% FA ground	Free $CaCO_3$
			% P of rock							% of rock
Algeria	Bled El-Hadba	13.1	3.1	2.1	3.1	2.0	4.8	4.0		
Algeria	Btita	12.3	3.2	2.3	3.1	2.5	4.8	4.2		
Algeria	Djebel Onk	12.7	3.5	2.4	3.5	2.3	5.3	4.0		
Algeria	Kef Essenoun	13.0	2.9	2.1	2.6	2.1	4.0	3.8		
Algeria	Noir	12.6	3.0	2.3	3.0	2.2	4.5	4.0		
Algeria	Quest Beige	12.3	2.9	2.3	2.6	2.2	4.0	4.1		
Australia	Christmas Islan	15.0	1.9		2.3		4.2			
Australia	Duchess	13.6	1.5		1.7		3.2			
Benin	Mekrou	12.7	1.7		1.4		2.7			
Bolivia	Capinota	8.7	0.8		1.4		2.7			8.8
Brazil	Araxa	16.1	1.4		1.2		2.5			
Brazil	Catalao	16.0	0.8		0.8		1.8			
Brazil	Jacupiran	16.2	0.5		0.8		1.8			
Brazil	Potas de Minas	11.0	1.1		1.1		2.3			
Brazil	Tapiara	13.9	0.9		0.8		1.8			
Burkina Faso	Kodjari	11.0	0.9		1.1		2.3			
Burundi	Montongo	6.0	0.5		0.5		1.3			
Chile	Bahia Inglese	8.2	3.4		3.0		5.2			
China	Jiangxian	12.6	0.4		0.5		1.3			
China	Kaiyan	14.0	1.4		1.5		2.8			
China	Onfu	16.2	1.6		1.6		3.1			
China	Quanyang	13.8	1.3		1.4		2.7			
Colombia	Huila	8.8	0.6		1.9		3.5		2.7	13.4
Colombia	Media Luna	13.1	1.5		2.0		3.7			
Colombia	Pesca	9.7	1.6		1.5		2.9		2.3	
Colombia	Sardinata	16.1	1.6		1.6		3.0			
Colombia	Tolima	8.7	1.1		1.9		3.5			
Ecuador	Napo	12.1	0.6		2.2		4.0			11.4
Egypt	Abu Tatur	13.6	3.0		2.9		5.2			
Egypt	Hanawen	9.7	2.5		2.5		4.4			
India	Jhamarkotra-1	7.8	0.2		0.3		0.9			38.4
India	Jhamarkotra-2	10.9	0.1		0.2		0.8			
India	Mussoorie	10.9	0.3		1.0		2.1			
India	Sangar	13.9	0.9		0.9		1.9			
Iran	Elburz	10.4	1.5		1.8		3.3			
Israel	Arad	14.1	3.3		4.4		5.7			
Jordan	El Hassa-1	12.8	2.4		2.9		5.2			
Jordan	El Hassa-2	13.9	2.6		2.8		5.0			
Jordan	Eshidiya-1	15.0	3.2		3.1		5.4			
Jordan	Eshidiya-2	14.8	2.5		2.6		4.6			
Kazakstan	Chelesai	7.4	2.6		2.4		4.3			
Kazakstan	Chulaktau	8.4	1.2		1.6		3.0			
Mali	Tilemsi Valley	12.4	2.4		2.5		4.5		5.3	
Morocco	Khouribga	14.5	2.9		3.1		5.4			
New Zealand	Cathathan Rise	7.5	0.8		3.5		6.1			34.8
Niger	Parc W	14.6	1.4		1.4		2.7			
Niger	Tahoua-1	12.1	1.3		1.3		2.6			
Niger	Tahoua-2	12.1	1.7		1.8		3.4			
Nigeria	Sokoto	14.7	1.7		1.7		3.2			
Pakistan	Hazara	12.3	1.1		1.0		2.2			
Peru	Sechura	13.6	3.6	3.0	3.9	3.3	6.3	5.6	9.5	
Philippines	Leyte	15.1	1.9		2.3		4.2			
Russia	Kengessepp	13.0	1.9		2.0		3.7			
Senegal	Matam	12.5	2.6		2.4		4.3		6.7	
Senegal	Taiba	15.7	1.7		1.9		3.5			
South Africa	Phalabora	16.1	0.3		0.7		1.6			
Sri Lanka	Eppawala	15.8	1.2		1.1		2.2			
Syria	Ain Layloan	12.2	3.5		3.4		5.8			
Syria	Kheifiss	13.9	2.2		2.9		5.0			
Syria	Sharkich	13.3	2.8		2.6		4.7			
Tanzania	Minjingu	13.0	3.4		3.7		6.3			
Tanzania	Panda Hills	10.8	0.2		0.2		0.8			
Thailand	Lumphun	14.9	3.6		3.7		6.4			
Togo	Hahotoe	15.9	1.8		1.8		3.3			
Tunisia	Gafsa 1	12.7	3.6	2.6	3.8	2.8	5.5	4.7		
Tunisia	Gafsa 2	12.7	3.5	2.6	3.8	2.8	5.2	4.3	9.7	
Uganda	Sukulu Hills	16.5	0.7		0.7		1.6			
USA	Central Florida	13.5	2.6		2.3		4.2		3.6	
USA	Idaho	14.2	1.2		1.5		2.9			
USA	Missouri	15.0	0.3		0.6		1.5			
USA	North Carolina	13.0	4.0		4.2		6.9		11.2	
USA	Tennessee	13.5	1.5		1.6		3.1		3.0	
Venezuela	Lobatera	6.0	0.1		1.1		2.3			31.2
Venezuela	Monte Fresco	10.4	0.3		1.3		2.6			23.8
Venezuela	Riecite	11.9	1.9		2.1		3.9			
Zambia	Chilembwe	8.7	0.8		0.7		1.6			
Zimbabwe	Dorowa	14.4	0.4		0.8		1.8			

Table 2. Characteristics of selected soils included in the phosphate rock decision support system (PRDSS) that are used to evaluate the relative agronomic effectiveness (RAE) of phosphate rock.

												Exchangeable					
Locality	Country	Organic C	pH H_2O	pH KCl	P	Method	Sand	Clay	Latitude	Longitude	CEC	Ca	Al	P fixation	Method	Texture	Soil order
		%			mg/kg		—— % ——			$cmol_c$/kg				%			
Quilichao	Colombia	4.1	4.1	–	1.8	Bray-II	4	71	3.1	−76.5	4.2	0.7	2.7	22	Fassbender	clay	Ultisol
Nakau	Indonesia	4.0	4.9	4.5	1.4	Pi	14	60	−5	105	4.5	2.2		350	Fox and Kamprath	clay	Typic Peleudult
Sadore	Niger	0.2	5.7	4.3	2.8	Bray-1	94	2	13.25	2.30	0.9	0.4	0.0	55	Fox and Kamprath	sand	Psammentic Paleustalf
Panicuasan	Philippines	9.03	5.2	4.6	0.2	Pi	60	40	13.67	123.30	4.8	3.5	1.3	2650	Fox and Kamprath	clay	Hydric Dystrandept
Greytown	South Africa	3.9	4.3	3.9	5.7	Ambic	25	61	−29.33	30.67	5.9	0.9	3.1	600	Fox and Kamprath	clay	Typic Haplorthox
Hartsells	USA	1.9	4.6	4.0	10	Bray-II	46	35	33.95	−83.32	2.6	0.2	1.9	–	–	sandy clay loam	Typic Hapludult

where Y_{PFS} = slope of RAE reduction for P fixation based on PR solubility and x_{NAC2} = PR solubility as determine by NAC_2 expressed as % P of rock.

The system uses soil P fixation values developed by the Fassbender method (Fassbender and Ingue, 1976), although it is also commonly determined by the Fox and Kamprath (1970) method. The PRDSS transforms the Fox and Kamprath (1970) values to Fassbender using the following equation based on the data of Leon et al. (1986):

$$Y_{PFF} = 0.390 + 0.0284x_{PF}, n = 21, R^2 = 0.83 \qquad [11]$$

where Y_{PFF} = P fixation (%) by using Fassbender method and x_{PFK} = P fixation (mg/kg) by the Fox and Kamprath method—P added to reach the equilibrium solution concentration of 0.2 mg P L^{-1}.

Organic Carbon

Soil organic C can increase the dissolution of PR by increasing soil CEC and thus remove dissolved Ca^{2+} from the dissolution zone. Additionally, organic C may chelate Ca^{2+} from the dissolved PR and thus enhance PR dissolution (Chien, 1979). The chemical formula of apatite (fluoroapatite) is $Ca_{10}(PO_4)_6F_2$, which explains why Ca also plays a role in the dissolution of PR. Organic C consists of organic acids that promote PR dissolution. The PRDSS uses a factor ranging from 0.8 to 1.1 to modify the RAE of a given PR; for volcanic ash soils (Andisols), where the organic C is more tightly bound, the effect on RAE is less significant and ranges from 0.8 to 1.03 (Alvarez et al., 2003; Gatiboni et al., 2003). Figure 7 describes the effect of soil organic C on the factor for organic C effect (that is then used to calculate the RAE).

Aluminum

The best crop response to PR use is obtained on soils with low pH. However, soils with low pH (pH < 5.2) may also be associated with high exchangeable Al that results in poor crop growth and reduction in yield due to Al toxicity. The RAE for these soils estimated by the PRDSS would be higher than the observed RAE. In soils with significant amounts of exchangeable Al, the P fixation capacity may increase with Al saturation, while organic C tends to ameliorate the Al toxicity effect on crops (Haynes, 1982; Helyar and Anderson, 1974; McLean and Logan, 1970; Smyth and Sanchez, 1982; Chien et al., 1980). The PRDSS corrects for the double accounting of P fixation effect and ameliorative effect of organic C to give an effective Al saturation (EAlS) as follows:

$$Y_{EAlS} = \text{Al saturation} \times (x_{PF}/x_{OC}) \qquad [12]$$

$$x_{PF} = 1.1 - 0.0001\ (z_{PF})^2 \qquad [13]$$

$$x_{OC} = 1.0 + 0.1 \times \ln\ (z_{OC}) \qquad [14]$$

where

Y_{EAlS} = effective Al saturation (%)
x_{PF} = influence of P fixation on effective Al saturation (%)

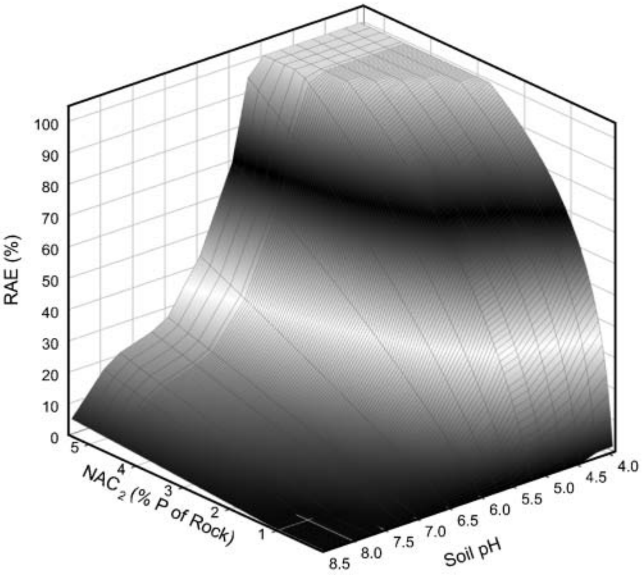

Fig. 5. The relative agronomic effectiveness (RAE) of phosphate rock as a function of soil pH and the solubility of phosphate rock as indicated by the % P removed in a second neutral ammonium citrate (NAC$_2$) extraction.

x_{OC} = influence of organic C on effective Al saturation (%)
z_{PF} = soil P fixation (%)
z_{OC} = soil organic C (%)

The x_{PF} value is not allowed to exceed 1.0 in the PRDSS, implying the EAlS will be either the same or, as in most cases, lower than Al saturation. The x_{OC} value, on the other hand, is not allowed to be lower than 1.0, implying the EAlS will be either the same or, as in most cases, lower than Al saturation due to beneficial effects of organic C. If EAlS is larger than 15%, then the model uses equations based on the crop species variance in tolerance to Al saturation to calculate the percentage reduction in RAE due to Al saturation (AlC). For highly soluble rocks, Al saturation has almost no significant influence on RAE for most crops, whereas the effect is more pronounced for PR sources with low solubility. Figure 8 summarizes the combined effects of crop species and PR solubility at an effective Al saturation of 45% on the relative reduction in RAE.

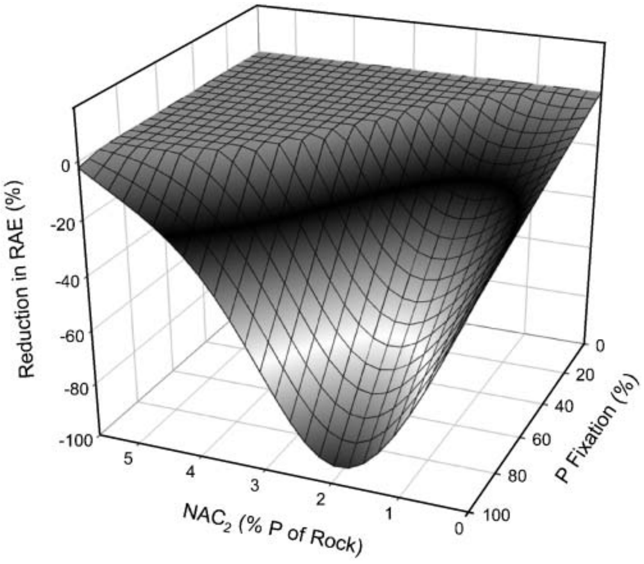

Fig. 6. Percentage reduction in relative agronomic effectiveness (RAE) as a function of soil P fixation and the solubility of phosphate rock indicated by % P removed in a second extraction using neutral ammonium citrate (NAC$_2$) extraction.

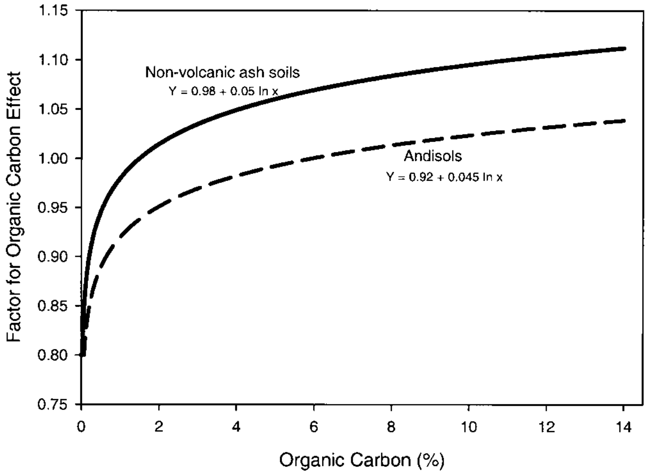

Fig. 7. Calculation of the factor for the effect of soil organic C on relative agronomic effectiveness (RAE) in volcanic ash soils (andisols) and all other soil orders in the PRDSS.

Some PR sources contain appreciable amounts of free carbonate (FC). Free carbonate content of a PR source reduces the Al toxicity effect on crop response and hence improves the RAE. Based on FC content of a PR and the reduction in RAE due to a specific EAlS and crop (AlC) the combined effect of soil Al, crop species, and free carbonate in PR (FC) will be expressed as follows:

$$Y_{AlFC} = a_{AlC} - [2.3x_{NAC2} \times z_{FC} \times (0.03 + 0.02985 \ln z_{FC})] \quad [15]$$

where

Y_{AlFC} = change in RAE based on EAlS and free carbonate content of PR (%)
a_{AlC} = change in RAE due to EAlS (soil and crop effect) (%)
z_{FC} = free carbonate of PR (%)
x_{NAC2} = PR solubility as determine by NAC$_2$ (% P of rock)

Hence, a PR source with substantial FC content will reduce the negative effect of EAlS on RAE.

The impact of PR solubility, free CaCO$_3$ content, and Al toxicity on the reduction in RAE is illustrated in Fig. 9. For example, if a soil with an Al saturation of 45% was treated with Jhamarkotra PR (NAC$_2$ solubility of 0.2% P), there would be no improvement in RAE despite high free CaCO$_3$ content (38%), whereas with Huila PR (NAC$_2$ solubility of 1.9% P and free CaCO$_3$ of 13%) the reduction in RAE due to Al is 50% less because of the higher reactivity of the PR and the high FC content.

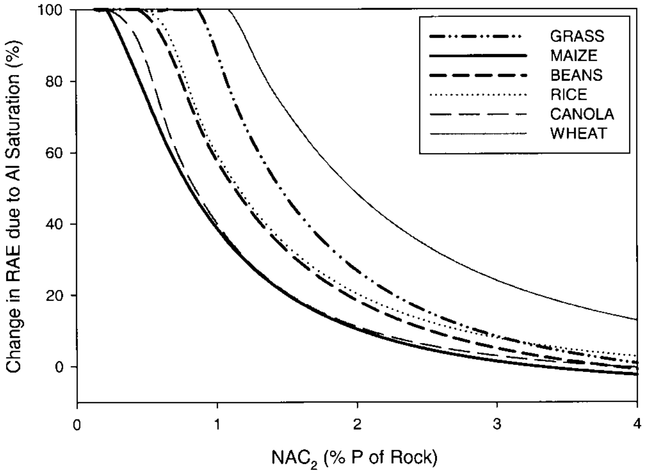

Fig. 8. An example of how the actual percentage value for a soil with an effective Al saturation of 45% is calculated based on the solubility of phosphate rock determined by second extraction neutral ammonium citrate (NAC_2) and crop species. This value is then subtracted from the basic RAE value in Fig. 2.

Climate Effect

The PRDSS will predict a lower RAE for a PR when soil moisture content is low for its dissolution compared with WSP. High rainfall causing leaching of WSP will result in higher RAE. The algorithm developed to incorporate the effect of soil moisture as a function of soil texture on PR dissolution and WSP leaching potential is based on relationships used for estimating water-holding capacity in the DSSAT model (Ritchie et al., 1987).

Phosphate Rock Dissolution

The model calculates a minimum rainfall needed for the dissolution of PR for each situation based on soil texture, percentage wet days, and the basic RAE. The rainfall/moisture requirement is based on a threshold concept as reported by Gillard et al. (1997) and Rajan et al. (1996). If the growing season rainfall is higher than this minimum rainfall, the model will make no change to the basic RAE prediction. The PRDSS uses 450 mm as absolute minimum rainfall for PR dissolution. The following equations are used to predict the minimum rainfall value, and if the growing season rainfall is less than this minimum rainfall, the model uses Eq. [16] to calculate the final moisture effect on PR dissolution:

$$Y_{\mathrm{M}} = x_{\mathrm{RT}}/x_{\mathrm{RM}} \quad [16]$$

$$x_{\mathrm{RT}} = 1.1\ z_{\mathrm{R}} \quad [17]$$

$$x_{\mathrm{RM}} = 600 \times x_{\mathrm{RS}} \times x_{\mathrm{WD}} \times x_{\mathrm{RAE}} \quad [18]$$

$$x_{\mathrm{RS}} = 0.46 + \exp - 0.032\ z_{\mathrm{S}} \quad [19]$$

$$x_{\mathrm{WD}} = 2 \times \exp - 0.0325\ z_{\mathrm{WD}} \quad [20]$$

where

Y_{M} = moisture effect on PR dissolution (0.0–1.0 value)
x_{RT} = total seasonal rainfall from time of PR application to harvest
1.1 = 10% increase of rainfall to account for time from P application to planting
x_{RM} x_{RM} = minimum rainfall value as in Eq. [18] or a value of 450 mm
x_{RS} = moisture index based on soil sand content
x_{WD} = moisture index based on percentage wet days in crops growing season
x_{RAE} = basic RAE estimation (%)
z_{R} = location specific growing season (planting to harvest) rainfall (mm)
z_{S} = soil sand content (%)
z_{WD} = percentage wet days in crops growing season (%) calculated as: (No. of wet days)/(No. of growing season days)

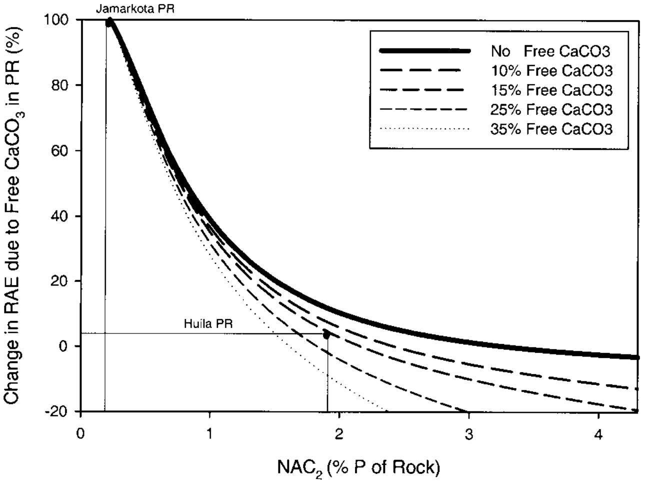

Fig. 9. The percentage reduction in RAE based on the free carbonate (CO_3) content of a phosphate rock (PR) and PR solubility as determined by second extraction neutral ammonium citrate (NAC_2). This example is for a soil with an effective Al saturation (EAlS) of 45%. The solid line represents the calculated line for reduction in RAE for a soil with EAlS of 45%, maize as crop in Fig. 8, and a PR that has no free $CaCO_3$. The high free CO_3 content of a rock and PR solubility both play a role in reducing the RAE due to EAlS.

If Y_{M} is larger than one, the model will only use a value of one to multiply Basic RAE, implying that rainfall will not have limiting effect on PR dissolution.

Some users, particularly when actual rainfall data are not available, may prefer MARKSIM (Jones et al., 2002) to generate location specific rainfall. It estimates the temperature and rainfall pattern of a given place with the user input of latitude, longitude, and planting date. An example of general rainfall data and climatic data generated by MARKSIM is given in Table 3.

Leaching

The PRDSS adapted the algorithm from the CERES–N model (D.C. Godwin and U. Singh, unpublished data, 1991) and P leaching in pasture system (Gillard et al., 1997) to determine the leaching of WSP compared with phosphate rock. The model uses the following equations based on rainfall, soil texture, and basic RAE estimation in its calculations for the rainfall effect on leaching (REL) in PRDSS (Fig. 2 and 3). Note that the basic

Table 3. Examples of entries in the climatic database of the phosphate rock decision support system (PRDSS) that are used to modify the effect of moisture on leaching and dissolution of phosphate rock from different sources.

Agroclimatic zone or country	Locality	Annual rainfall	Growing season rainfall	Latitude	Longitude	Elevation	Solar radiation	Max. temp.	Min. temp.
		mm				m	°C		
General	–	1200	800						
Guinea Savanna	low rainfall	1050	700						
Guinea Savanna	high rainfall	2100	1400						
Rain Forest	–	2267	691						
Sahel	–	700	500						
Colombia	Quilichao	1676	827	3.10	−76.5	1066	231.7	28.9	18.1
Indonesia	Nakau	2358	635	−5.00	105.0	56	196.9	31.4	23.1
Niger	Sadore	623	415	13.25	2.30	152	237.5	37.3	22.0
Philippines	Panicuasan	2490	1479	13.67	123.3	100	167.7	29.5	23.0
South Africa	Dundee	831	221	−28.15	30.32	−1	200.5	33.3	18.4

RAE approximation is based on soil pH, PR solubility, and crop rhizosphere effect (Fig. 2) as follows:

$$Y_{\mathrm{REL}} = 1.0 + \{x_{\mathrm{LR}}/[1.0 + \exp - ((x_{\mathrm{RT}} - x_{\mathrm{LT}})/300)]^{40}\} \qquad [21]$$

$$x_{\mathrm{LR}} = -0.008\, x_{\mathrm{RAE}} + 1 \qquad [22]$$

$$x_{\mathrm{LT}} = 1500 - 19\, z_{\mathrm{S}} \quad \text{or} \quad x_{\mathrm{LT}} = 50 + 16\, z_{\mathrm{C}} \qquad [23]$$

where

Y_{REL} = rainfall effect on leaching (≥ 1.0)
x_{LR} = effect of basic RAE (PR solubility, soil pH, crop) on PR dissolution
x_{RAE} = predicted basic RAE (%)
x_{LT} = factor for soil texture influence on leaching
x_{RT} = total seasonal rainfall from time of PR application to harvest (Eq. [17])
z_{S}, z_{C}, z_{R} = location specific soil values for sand (%) and clay (%), and rainfall (mm)

Crop Effect

The four processes that take place in the rhizosphere of crop species that influence PR dissolution are: (i) removal of Ca and P by plant uptake, (ii) H^+ release by exuding organic acids (especially in the case of canola), (iii) H^+ release by a cation–anion imbalance, and (iv) chelating of Ca by organics in the rhizosphere. The rhizosphere as modified by the root then determines the availability of nutrients for the plant and thus also the dissolution of PR. Lowering the rhizosphere pH and Ca^{2+} through these processes combined with the quantity and distribution of roots help crops to utilize PR more effectively (Gahoonia and Nielson, 1992; Rajan et al., 1996; Marschner, 1991; Hansinger, 2001; Bolan et al., 1997). Greenhouse data from IFDC trials and data from Jiang et al. (1990) were used to determine the values for the rhizosphere effect. The rhizosphere effect adjustment for each crop is given in Table 4. For example, maize (*Zea mays* L.) has a rhizosphere coefficient value of 0.05 and in contrast canola has a rhizosphere coeffi-

Table 4. Crop coefficients as used in the phosphate rock decision support system (PRDSS) for calculation based on rhizosphere pH, P-fixation, Al toxicity, and crop growth duration.

Crop	Rhizosphere coefficient	P fixation coefficient	Base temperature	Growing degree	Aluminum coefficient
			°C		
Barley	0.20	1.00	3.0	3000	2.91
Buckwheat	−0.90	1.00	5.0	3000	2.91
Canola	−2.30	1.00	5.0	3500	1.65
Cassava	−0.80	1.00	8.0	6000	1.96
Chickpea	−0.70	0.75	5.0	4500	2.01
Clover	−0.30	0.75	5.0	5000	1.87
Cowpea	−0.55	0.75	8.0	2000	2.01
Crotolaria	−0.40	0.75	8.0	2000	2.01
Drybean	−0.50	0.75	8.0	2000	2.01
Lowland rice	0.20	1.00	9.0	2200	1.87
Mucuna	−0.55	0.75	8.0	2500	2.01
Maize	0.05	1.00	9.0	3000	1.96
Millet	0.10	1.00	9.0	3000	1.96
Peanut	−0.40	0.75	8.0	3300	2.01
Potato	0.00	1.00	7.0	3300	2.91
Ryegrass	−1.80	0.25	0.0	3800	1.87
Sesame	0.05	1.00	5.0	2900	2.91
Sesbania	−0.40	0.75	8.0	3300	2.01
Sorghum	−0.10	1.00	9.0	3000	1.96
Soybean	−0.50	0.75	9.0	3300	2.01
Sugarcane	−0.90	1.00	8.0	8000	1.96
Sunflower	0.00	1.00	7.0	2800	1.84
Tomato	0.00	1.00	9.0	4000	2.91
Upland rice	−0.90	1.00	9.0	2350	1.84
Wheat	0.05	1.00	0.0	2900	2.91

cient of −2.3. Under identical conditions (soil pH = 5.8, PR = Gafsa, NAC_2 = 3.8, Table 1), the model would predict 64 and 100% basic RAE for maize and canola, respectively.

Crops differ in their ability to tolerate Al toxicity in the soil. When Al saturation is present in the soil, PRDSS will modify the RAE according to crop species (Table 4), Al saturation, and PR solubility as earlier mentioned (Fig. 8).

The effect of P fixation on plant-available P from PR is also influenced by crop species. Legumes are more effective in utilizing PR than nonlegume crops (Rao et al., 1998). The position of the P fixation equation is therefore a function of crop species. A value of 1 for nonlegumes and 0.75 for legumes was used to estimate the actual effect of P fixation (Table 4).

The combined effect of soil P fixations and PR solubility as earlier determined by Eq. [9] and [10] combine with the crop coefficient for P fixation to give the final P fixation factor as follows:

$$Y_{PF} = (x_{PFM} \times x_{PFS}) - (x_{PFS} \times z_{PFC}) \qquad [24]$$

where

Y_{PF} = P fixation factor
x_{PFM} = minimum P fixation where RAE reduction will take place (Eq. [9]) (%)
x_{PFS} = slope of RAE reduction for P fixation (Eq. [10])
z_{PFC} = crop coefficient for P fixation (Table 4)

The moisture effects on PR dissolution and WSP leaching are also influenced by the growing duration of a crop (Table 4). A long duration crop will provide more time for PR dissolution and may result in improved RAE. The PRDSS has 25 crops included in its database as shown in Table 4. Figure 3 gives a summary of how the crop database interacts with PR, soil, and climate database to predict final RAE.

Relative Economic Effectiveness

The RAE value predicted by the PRDSS is the agronomic or yield effectiveness of the various PR sources relative to WSP (e.g., TSP). This was supplemented by a one factor limited evaluation on the economic feasibility of PR. The PRDSS uses the RAE prediction and the farm gate price of PR and WSP to calculate the REE of a PR; this does not include more detailed expenses like labor or other costs associated with PR use compared with WSP application. The following calculation based on Engelstad et al. (1974) provided an estimate of REE:

$$\text{REE} = \text{RAE} \times \frac{\text{Price of WSP/kg P}}{\text{Price of PR/kg P}} \div 100 \qquad [25]$$

If REE exceeds 1 in this calculation, PR would be more preferable to WSP. These REE calculations were used to prepare an indifference curve where RAE values were plotted against price ratio of WSP: PR on P-cost basis (Fig. 10). The curve represents an isoline where the REE (=1.0) is independent of the P source. Based on a given price ratio in the market, one can evaluate whether PR or WSP should be used based on farm-gate prices. For example, the average 2004 price for Gafsa PR in Tunisia was US $0.23 per kg P and for TSP $0.46 per kg P. Assuming RAE of Gafsa as 90%, REE is 1.8 based on Eq. [25], which suggests that it will be more profitable to use Gafsa PR than WSP as shown in Fig. 10. If the predicted RAE were 40% for the same price ratio, then TSP would be more profitable than the PR (Fig. 10) because REE is less than 1.0. To conduct economic assessment, the users must enter the farm-gate prices of both P sources in accordance with the agronomic results. Also note that this is only for one-time application and first-year response.

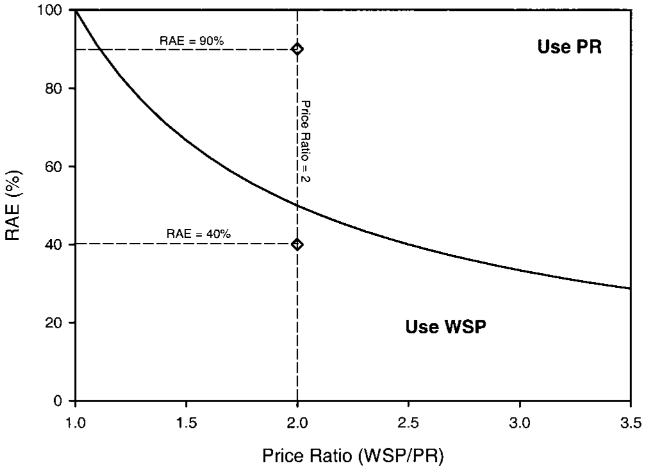

Fig. 10. Relative economic effectiveness (REE) of phosphate rock (PR) as indicated by a curve that is a function of the relative agronomic effectiveness (RAE) and the price ratio of P derived from water-soluble phosphorus (WSP) and PR. Values of RAE above the REE curve indicate that PR is more agronomically effective than WSP; below the curve, WSP is more agronomically effective than PR.

Substitution Value

Another method to expand PRDSS beyond agronomic effectiveness is the SVI (Gillard et al., 1997). The SVI compares the rate of PR with WSP needed to achieve the same relative target yield (Fig. 11). For example, if a PR with 80% RAE were used, the SVI for a 75% relative yield target would be 2.2 as shown in Fig. 11. This means that a 2.2 times higher P rate from PR than WSP is required to produce the same crop yield. As illustrated in Fig. 11, PRDSS uses a semi-logarithm response to relate P application rate to relative yields. Unlike the REE approach, the SVI at least offers users the choice of high or low relative target yield.

VALIDATION OF THE PHOSPHATE ROCK DECISION SUPPORT SYSTEM

Testing of Phosphate Rock Decision Support System

We have tested PRDSS with data from previously conducted field and greenhouse trials. Due to the diversity of the studies conducted, some of the information is not complete, particularly on crop duration, rainfall, and some of the soil properties. One needs to be cautious

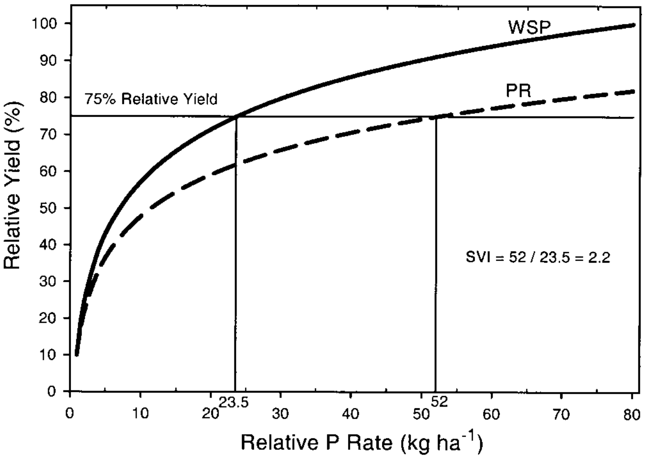

Fig. 11. The substitution value index (SVI) is the relative amount of P as phosphate rock (PR) compared to water soluble phosphorus (WSP) fertilizer needed to give the same relative yield. An example of this would be if a phosphate rock (PR) with 80% relative agronomic effectiveness (RAE) is used. To get a 75% of the maximum yield (75% relative yield), 52 kg P ha^{-1} of PR compared with 23.5 kg P ha^{-1} of WSP is needed. The SVI is thus 52/23.5 = 2.2.

with the predicted results if errors are introduced due to estimation of missing inputs. The model equations may also have some errors because they are based on regression, empirical, and functional relationships. A summary of all the model tests conducted is included in Fig. 12. As evident, the overall performance of the PRDSS is promising with more than 85% of the predicted results from a wide range of experimental conditions falling within ±10% of the observed results.

Additionally PRDSS validation field trials are being conducted in several countries in sub-Saharan Africa (Togo, Burkina Faso, and Tanzania), Asia (Malaysia and Vietnam), and South America (Argentina and Brazil). When the field data are available, the current PRDSS version may need to be adjusted to improve its precision.

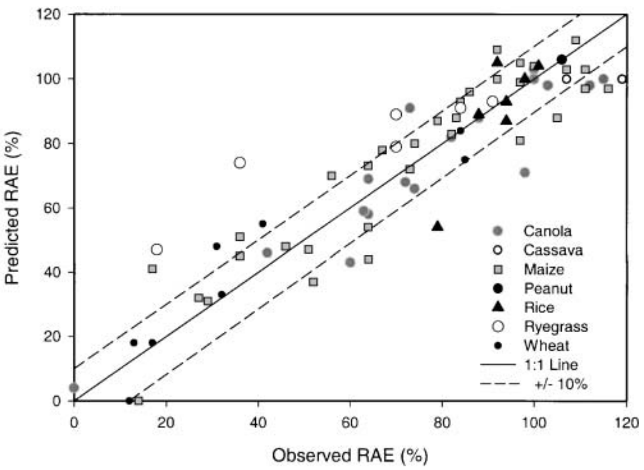

Fig. 12. Relationship of relative agronomic effectiveness (RAE) estimated by the phosphate rock decision support system (PRDSS) and observed RAE calculated using data from field and greenhouse experiments. Observed results include all factors (e.g., climate, soil pH) except liming.

Sensitivity Analyses

A sensitivity analysis provides a quick means to identify the most influential factors affecting the agronomic effectiveness of PR while keeping all other factors constant. Thus, a user will know which management inputs and soil–crop–climate factors will affect the RAE of a PR.

For example, for a soil with pH 6.5, sensitivity analyses will show that more soluble rocks will not improve RAE; however, switching crops, for example, growing canola instead of maize, will definitely improve the RAE. Figure 13 illustrates the importance of sensitivity analysis for model testing and verification as well as for field application.

The standard sensitivity run (standard input multiplication factor = 1.0 in Fig. 13) used maize as a test crop, a PR source with 2.0% P of rock (NAC_2 method), soil pH (H_2O) of 5.5, sand content of 33%, organic C of 2.0%, P fixation of 20%, Al saturation of 20%, and a growing season rainfall of 800 mm. The changes in any of these inputs resulted in rapid or slow changes in RAE, thus pointing out the sensitivity of the inputs/factors with respect to the standard conditions.

Soil pH and PR solubility are key factors influencing RAE for the maize crop. In general, sand content has little influence, except at very high levels where P leaching may become a factor. The leaching of WSP is dependent on soil texture, rainfall, and PR solubility. Impact of P fixation is minimum up to 30%; however, at 40% P-fixing capacity (standard input multiplication factor of 2.0), it becomes a critical factor. If one uses a more reactive PR than used here (NAC_2 of 2.0% P), 40% P fixation will not affect the RAE (Fig. 5). As Al saturation increases it also becomes an important factor in reducing the RAE of the PR. One must be cautious when interpreting results from sensitivity analysis; for

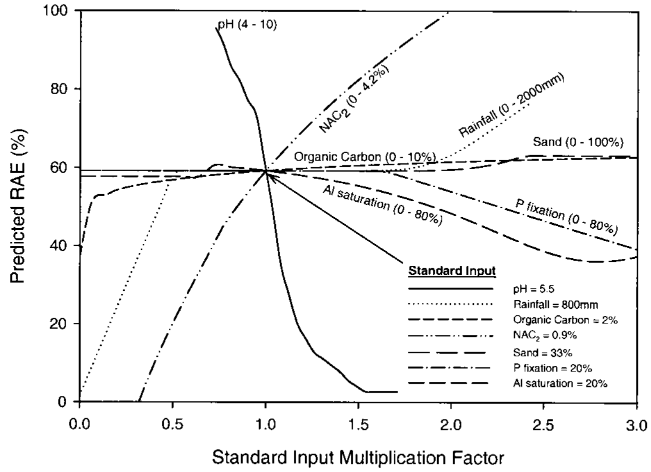

Fig. 13. A sensitivity analysis of the estimated relative agronomic effectiveness (RAE) as calculated by the phosphate rock decision support system (PRDSS). Factors affecting RAE include phosphate rock solubility measured by a second extraction using neutral ammonium citrate (NAC_2), soil pH, organic C (%), sand (%), P fixation (%), Al saturation (%), and rainfall (mm). Values in brackets are the range of values for each factor in the PRDSS.

example, as we increase the Al saturation, the soil pH remains at pH 5.5.

Application of Phosphate Rock Decision Support System

It should be pointed out that the current version of PRDSS only predicts the relative initial effectiveness of PR with respect to WSP in agronomic performance and economic analysis. It provides a tool to help the users make a decision about whether to use PR or WSP as a P source for crop production. However, it does not predict the actual crop yield or allow for a complete economic analysis. One of the future goals is to link PRDSS to the Decision Support System for Agro-Technology Transfer (DSSAT) model (Tsuji et al., 1994) or the Phosphorus Decision Support System (PDSS) model (Osmond et al., 2002) that has been developed to predict the actual crop yield from WSP fertilizers. The PRDSS can then be used to predict the actual crop yield and P requirement with PR vs. WSP fertilizers.

Work on PRDSS will continue to expand the model to include the long-term response to one-time application or annual application of PR and WSP for different crops and soils. Additional work on PRDSS may also include mixing small amounts of WSP as a starter effect to improve the effectiveness of PR sources with low to medium solubility. Several studies have shown this approach is agronomically and economically feasible (Chien and Menon, 1995).

CONCLUSIONS

The PRDSS use is still limited to first-year PR application; however, the next version will include residual and long-term effect of PR application and the possible lime effect of PR sources. The capability of PRDSS has been expanded from the initial version where PR solubility, soil pH, and crop species were key inputs for RAE. Users now have the option to include more specific factors that affect PR dissolution, P fixation, P leaching, and Al toxicity. The PRDSS also includes a simple economic evaluation that could help decide whether a given PR at a specific site is a good substitute for WSP fertilizers based on farm-gate prices. The PRDSS also generates a SVI to determine the relative amount of PR needed to achieve the same target yield as with WSP.

Field trials are currently being conducted in the following countries—Argentina, Brazil, Burkina Faso, Malaysia, Tanzania, Togo, and Vietnam—to validate the PRDSS, which has been mounted on the FAO/IAEA website for public use (www.IAEA.org; verified 29 Dec. 2005). The long-term goal is also to link PRDSS to DSSAT or PDSS to predict crop yields and P requirements.

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