Relative Agronomic Effectiveness of Phosphate Rock Compared With Triple Superphosphate for Initial Canola, Wheat, or Ryegrass, and Residual Wheat in Two Acid Soils

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Abstract: Direct application of phosphate rock (PR) may provide the essential phosphorus (P) nutrient for crop production in acid soils. However, the agronomic effectiveness of PR depends on several factors including PR reactivity, soil properties, and crop species. This greenhouse study investigated the effects of PR reactivity, soil pH, Al saturation, and crop species on the initial and residual relative agronomic effectiveness (RAE) of PR compared with water-soluble triple superphosphate (TSP) in two acid soils (Hartsells pH 4.8 and Hiwassee pH 5.4). Three PR sources, Tunisia, Mali, and Togo, representing high, medium, and low PR reactivity, respectively, were used. The soils were treated with P sources at 0, 25, 50, 100, 200, and 500 mg P kg^{-1} soil. Wheat, ryegrass, and canola were the test crops in the first season, and wheat was used as a residual crop after all three initial crops in the second season. Soil samples were collected for chemical analyses at 0 and 500 mg P kg^{-1} soil after the first crops. The initial RAE of PR for crop species followed: canola > ryegrass = wheat in the Hartsells soil and canola > ryegrass > wheat in the Hiwassee soil. However, the residual crop of wheat after wheat, wheat after ryegrass, and wheat after canola did not show any significant effect of previous crop. Among P sources, both initial and residual RAE followed: TSP > Tunisia PR > Mali PR ≥ Togo PR for all the crops and soils except for the initial canola crop grown in Hiwassee soil where all PR sources were as effective as TSP. In general, the RAE of PR in Hiwassee soil was higher than that of Hartsells because of the negative effects of soil acidity and Al saturation on crop growth in the Hartsells soil. A significant relationship between available P after first crops and residual wheat grain yield was found in the Hiwassee soil.

Key words: Acid soils, crop species, phosphate rock, Pi soil test, relative agronomic effectiveness, triple superphosphate.

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Phosphorus (P) is an essential plant nutrient, and the deficiency of P severely restricts crop yields. Tropical and subtropical soils are predominantly acidic and often extremely P deficient with high P fixation (sorption) capacity. Direct application of phosphate rock (PR) can be an effective alternative to the use of more expensive water-soluble P (WSP) fertilizers to provide P nutrition in adequate amounts for crop production under certain soil and crop conditions. The agronomic effectiveness of PR depends on several factors involving PR reactivity, soil properties, crop species, and climate (Hammond et al., 1986; Chien and Menon, 1995; Rajan et al., 1996). In contrast to WSP fertilizers (e.g., TSP) that dissolve rapidly and completely in soils, PR is insoluble in water, and the driving force for its dissolution in soils is mainly dependent on the proton supply and the gradient of P and Ca concentrations in soil solution (Robinson et al., 1994). The reactivity of PR is generally characterized by its solubility of PR with neutral ammonium citrate (NAC), 2% citric acid, or 2% formic acid. It should be pointed out that the solubility is only an index that is related to plant-available P from PR in soils, not the actual amount of P available to the plant (Chien and Hammond, 1978).

Crop species also vary greatly in PR use efficiency. For example, crops can modify the pH at the root-soil interface or rhizosphere so that it differs from that of bulk soil (Mengel and Kirkby, 1987). Crops such as canola (the Cruciferae family in general), pigeon pea, and lupin are known to exude organic acids, for example, malic, oxalic, and citric acid, which reduce pH around the roots, thereby increasing the use of PR. The cation-anion imbalance caused by plant uptake of some crop species, including legume crops, can result in changes of the rhizosphere pH that can in turn affect PR dissolution and agronomic effectiveness (Bekele et al., 1983). The density or structure of crop roots also varies, and thus, the total contact area with PR for P uptake varies among crops. Crops with longer growth duration, for example, perennials versus annuals, provide more time for PR dissolution, and hence, perennial crops in general have higher relative agronomic effectiveness (RAE) of PR with respect to WSP compared with annual crops (Khasawneh and Doll, 1978; Rajan et al., 1996).

Solubility of PR is one of the main factors influencing the agronomic effectiveness of a PR (Truong et al., 1978; Rajan et al., 1996). The dissolution of PR is influenced by soil acidity and by the secretion of organic acids by crops such as canola and pigeon pea (Jones, 1998; Montenegro and Zapata, 2002). High rates of PR application have been reported to release greater P quantity with time for less reactive PR than with highly reactive rocks (Chien and Hammond, 1978). The integrated effect of these factors was evaluated in this study.

The objective of the study was to investigate the effect of different crop species, TSP and three PR sources on the yield, P uptake, and RAE for the initial and residual crop using two acid soils with different P rates. It should be pointed out that the intention was not to translate the results from the current greenhouse studies to the field trials because the rooting systems and rates of P used in greenhouse pots differ from field plots. It was intended to integrate the effect of PR reactivity, soil properties, crop species, and P rates on the initial and residual P effects. Such information is also relevant to the application of a recently developed PR decision support system (Smalberger et al., 2006).

MATERIALS AND METHODS

Three greenhouse experiments were conducted, with wheat (*Triticum aestivum* L.), ryegrass (*Lolium multiforum* L.), and canola (*Brassica napus* L.) as test crops. The treatments to all

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TABLE 1. Selected Soil Properties of the Two Soils Used

Soil	pH	Organic Matter, %	Available P		Exchangeable					Al Saturation	P-fixing Capacity‡	Sand	Clay
			Bray-1	Pi-P†	Mg	Na	Ca	K	Al				
			mg P kg^{-1}		--------cmol kg^{-1}--------					-------------%-------------			
Hartsells	4.8	1.5	0.76	1.9	0.07	0.14	1.55	0.09	1.54	45	38	47	21
Hiwassee	5.4	2.3	0.36	1.7	0.82	0.12	1.15	0.22	0.04	2	31	41	34

†Method by Habib et al. (1998).

‡Method by Fassbender and Ingue (1976).

three crop experiments were the same. In each experiment, two soils—Hartsells (*Typic Halpuldult*) and Hiwassee (*Rhodic Kanhapludult*)—were used. Some characteristics of these two soils are shown in Table 1. In addition to Bray-1 P, available P was measured by the Pi strip method as described by Habib et al. (1998). As evident from both Bray-1 and Pi strip values, available P in both soils was very low.

Four P sources were used: Hahotoe PR from Togo, Tilemsi Valley PR from Mali, Gafsa PR from Tunisia, and granulated TSP. The moderately reactive PR sources such as Togo PR and Mali PR were finely ground to 0.15 mm (or 100 mesh) to improve their agronomic effectiveness. The highly reactive Tunisia PR was used in the unground as-received form because its agronomic effectiveness is not improved by finely ground product. The solubility of PR was determined by NAC second extraction (NAC_2) (Chien and Hammond, 1978). This method reextracts the PR sample after the first extraction with NAC to eliminate the possible effect of free calcium carbonate (calcite and dolomite) on apatite solubility in NAC. Chemical and crystallographic properties of the P sources are shown in Table 2. In general, the lower the α value of apatite minerals, the greater their reactivity; hence, Tunisia PR is more reactive than Togo PR and Mali PR.

Both N and K in the forms of urea and KCl, respectively, were applied at 200 mg N kg^{-1} soil and 200 mg K kg^{-1} soil. A nutrient solution containing Mg, Zn, Cu, B, Mo, and S was also applied at adequate levels. All P sources were applied at rates of 25, 50, 100, 200, and 500 mg total P kg^{-1} soil. The P materials were thoroughly mixed with 4 kg of soil. A control (no P) was also included in the treatments. Five canola seeds were planted and thinned to three plants per pot after germination. Nine wheat seeds were planted and thinned to five plants after germination. Ryegrass seeds were planted with 0.2 g of seed (~70 seeds) per pot. The soil moisture was kept at approximately 80% of field capacity by daily watering during the plant growth. The field capacity soil moisture content was determined for each soil by the soil column free-drainage method (Coleman, 1947).

Wheat and canola plants were harvested at maturity. Depending on the P treatments, up to six cuts were made during the ryegrass growth. Soil samples treated with 500 mg P kg^{-1} soil were collected, air-dried, and ground to 2-mm size for chemical analyses. Roots of all crops were reincorporated in the soil, and wheat was planted as a residual crop after the initial three crops. The grains of wheat and canola and the aboveground ryegrass were dried at 60 °C, weighed, and ground to 0.5 mm. Plant samples were digested with an H_2SO_4-H_2O_2 mixture (Parkinson and Allen, 1975). Concentrations of P in the plant digests were measured by the method of Murphy and Riley (1962).

TABLE 2. Total and Soluble P Content of the P Sources Used

P Source	P Content			α
	Total	Water Soluble	NAC_2†	
	-----------%----------			A
Togo (ground)	15.9	0	1.3	9.351
Mali (ground)	12.4	0	1.6	9.350
Tunisia (unground)	13.0	0	2.3	9.322
TSP	20.1	16.7	3.4	—

†NAC_2: second extraction with NAC (Chien and Hammond, 1978).

Statistical Analysis

The relationship between grain yield (wheat and canola), dry matter yield (ryegrass), or P uptake by crop and P rate applied for all P sources was tested using polynomial, power, exponential, and logarithmic functions. The relationship was best described by the following semi–log regression equation:

$$Y_i = \beta_0 + \beta_i \ \ln X + \varepsilon_i, X \geq 1 \qquad (1)$$

where Y_i is yield or P uptake of P_i source, β_0 is yield of check, β_i is the regression coefficient of P_i source, X is P rate, and ε_i is error term of P_i source. This model was also chosen because it results in the simplest way to determine the RAE for each PR source. A combined multiple regression analysis using a dummy variable as described by Chien et al. (1987a) was performed for all P sources. This resulted in a common intercept and a single value of $S_{RAEi1-RAEi2}$ and R^2 for all the P sources.

In this study, RAE was defined by the following equation:

$$\mathrm{RAE} = (\beta_{PR}/\beta_{TSP}) \text{ x } 100 \qquad (2)$$

$$\begin{aligned} \mathrm{VAR(RAE)} = {} & \mathrm{VAR}(\beta_{PR}/\beta_{TSP}) \\ & -(S^2/\beta_{TSP})(\beta^2_{TSP}C_{ij} - 2\beta_{TSP}C_{ij} + C_{ij}) \qquad (3) \end{aligned}$$

where β_{PR} and β_{TSP} are the regression coefficients of PR and TSP. This is the so-called *vertical comparison*, which produces a constant RAE value for a given PR source across all P rates, C are elements from the sum of squares matrix for P rates, and S^2 is the estimate of the residual mean square (Chien et al., 1990; Chien et al., 1987a). From the previously mentioned variance, the SE for RAE comparisons ($S_{RAEi1-RAEi2}$) is calculated.

RESULTS AND DISCUSSION

The yield data of initial wheat, ryegrass, and canola obtained with different P sources are shown in Fig. 1. The regression estimates (β) and the calculated RAE values of P sources are shown in Table 3. In both Hartsells and Hiwassee soil, TSP was more effective than Mali and Togo PR sources for wheat and ryegrass based on RAE. The RAE of TSP was also significantly higher than Tunisia PR in Hartsells soil for both wheat and ryegrass. However, in Hiwassee soil, TSP response was not significantly different from highly reactive Tunisia PR. The effectiveness of PR for wheat and ryegrass follows the order of Tunisia > Mali ≥ Togo PR (Table 3), an order similar to the solubility of PR (Table 2). In general, higher yields of wheat, ryegrass, and canola were obtained with all P sources in Hiwassee soil than in Hartsells soil, as evident from Fig. 1 and the higher slope, β values (Table 3). The lower pH and higher Al saturation of Hartsells soil than that of Hiwassee soil (Table 1) may be responsible for the lower yields and lower RAE of PR in Hartsells soil (Fig. 1; Table 3) because many crops are sensitive to soil acidity and Al toxicity (Foy, 1984). This occurred despite the fact that PR dissolution in the lower pH Hartsells soil is expected to be higher than in Hiwassee soil. If a crop is more tolerant to soil acidity and Al toxicity, PR effectiveness should be expected to increase with decreasing soil pH. For example, Habib et al. (1998) reported that with an Al-tolerant maize variety, North Carolina PR was as effective as TSP in the same Hartsells soil, whereas it was less effective than TSP in Hiwassee soil.

Canola used PR more effectively than did wheat and ryegrass in both Hartsells and Hiwassee soils. For example, the RAE of Togo PR increased from 19% for wheat and 18% for ryegrass to 63% for canola (Table 3). In Hiwassee soil, the corresponding increases in RAE were from 50% for wheat and 70% for ryegrass to 98% for canola. In Hartsells, the P effectiveness for canola follows TSP = Tunisia PR > Mali PR = Togo PR,

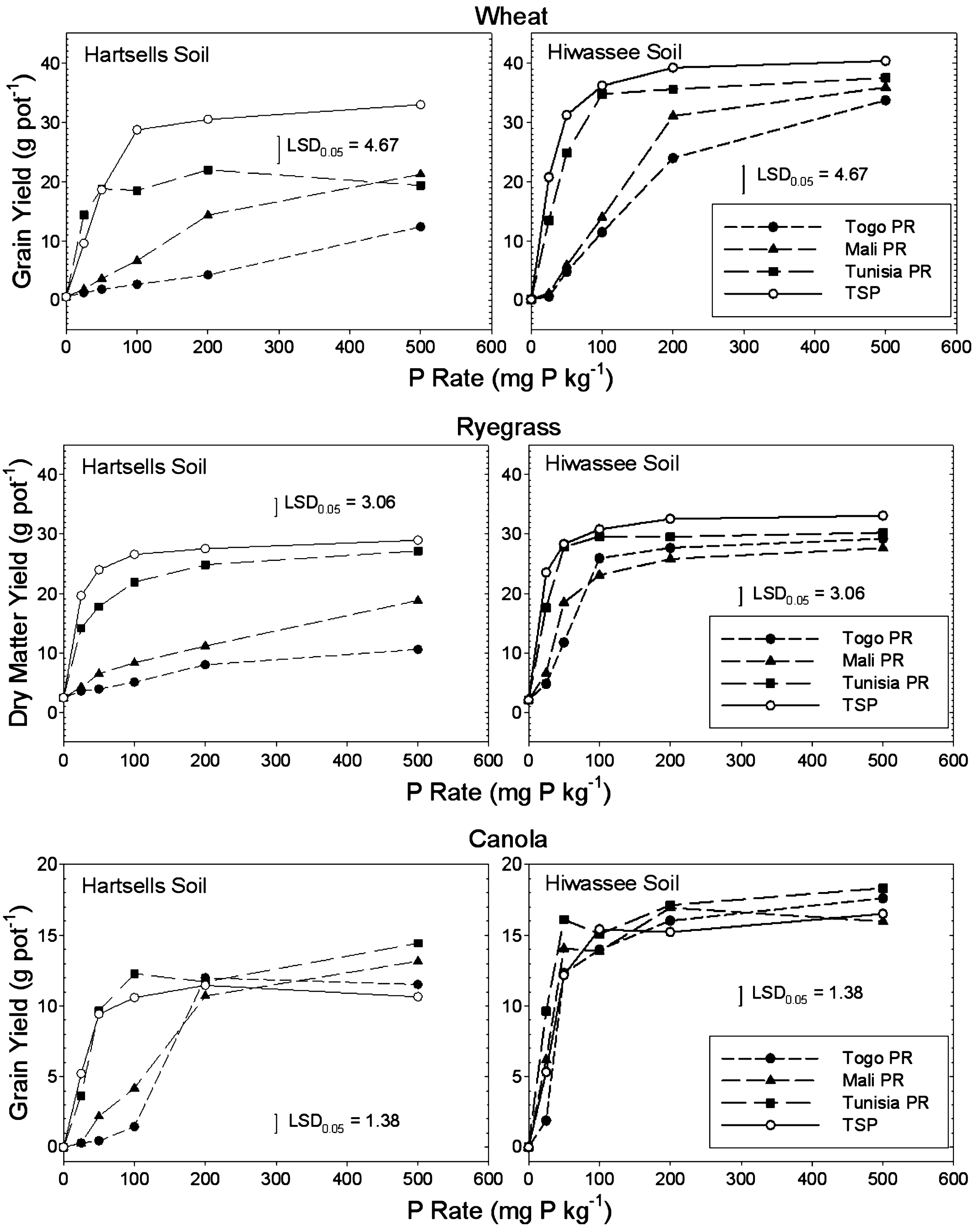

FIG. 1. Grain yield of wheat, dry matter yield of ryegrass, and grain yield of canola as influenced by soil, P rate, and P sources.

TABLE 3. Regression Estimates (β_0, β, $S\hat{y}$, and R^2) for the Semi–Log Response Function† and Initial RAE of P Sources in Two Soils

	Wheat		Ryegrass		Canola	
P Source	**Hartsells**	**Hiwassee**	**Hartsells**	**Hiwassee**	**Hartsells**	**Hiwassee**
	β					
Togo PR	0.96	3.57	0.89	4.04	1.26	2.74
Mali PR	2.15	4.16	1.73	4.04	1.46	2.88
Tunisia PR	3.76	6.48	4.04	5.25	2.26	3.23
TSP	5.17	7.12	4.82	5.79	2.01	2.80
	β_0					
	0.58	0.14	2.40	2.05	0.01	0.01
	$S_{\mathrm{RAEi1-RAEi2}}$					
	0.40	0.70	0.23	0.45	0.31	0.25
	R^2					
	0.93	0.92	0.98	0.96	0.86	0.96
	RAE,‡ %					
Togo PR	19D	50B	18C	70B	63B	98A
Mali PR	42C	58B	36C	70B	73B	103A
Tunisia PR	73B	91A	84B	91A	112A	115A
TSP	100A	100A	100A	100A	100A	100A

Values with the same letter in each column are not significantly different ($P = 0.05$).

† $Y = \beta_0 + \beta \ln X$.

‡ RAE, % = $(\beta_{PR}/\beta_{TSP}) \times 100$.

whereas all PR sources were equally effective as TSP in Hiwassee soil. This and lower yields in Hartsells soil suggest that canola was also sensitive to soil acidity and Al toxicity. The highly reactive Tunisia PR was effective in Hartsells soil because of its high available P for canola, which is known to be very effective in using PR because of strong organic acids released in the rhizosphere (Hoffland et al., 1989; Hoffland, 1992; Jones, 1998; Montenegro and Zapata, 2002) and the liming value of Tunisia PR on Al saturation (Table 4). Chien et al. (2003) reported that Tunisia PR was 88% as effective as TSP, even in an alkaline soil (pH 7.7), for canola, whereas it was totally ineffective for rice at soil pH 8.0 (Chien and Menon, 1995).

The combined analyses for all three crops on both the soils showed that the effectiveness of crop species to use PR as observed in the present study thus follows: canola > ryegrass ≥ wheat. On the Hartsells soil, wheat and ryegrass performance was similar; both crops showed significantly higher yield with Mali PR than Togo PR. In general, the better performance of ryegrass, compared with wheat, was probably caused by its denser rooting system, which results in a wider contact with PR particles (Khasawneh and Doll, 1978; Hocking et al., 1997; Hinsinger, 1998).

The RAE for P uptake by crops was also calculated according to Eq. (2). The results of P uptake by different crop species from P sources in general follow the same trends as RAE calculated for crop yield, except that the RAE values for P uptake were lower than that for crop yield for PR (data not shown). For example, the RAE of Mali PR was 44% based on P uptake by canola seed in Hartsells soil versus 73% based on canola seed yield. Chien et al. (1987b) reported that the internal efficiency, that is, P uptake per unit of yield increase, was greater with PR than with TSP. This result may be caused by the differences in P uptake during early plant growth when solution P concentration was much higher from TSP than from PR. Consequently, the RAE of PR would be lower based on P uptake than the RAE based on crop yield.

Soil data after the first three crops show that the pH of Hartsells soil with 0 P (control) significantly decreased from 4.8 (Table 1) to 4.6 after wheat, 4.3 after ryegrass, and 4.4 after canola (Table 4). The decrease was probably caused by acidification of N fertilizer added at a high rate (200 mg N kg^{-1}). Treatments with highly reactive Tunisia PR and TSP did not decrease soil pH of Hartsells soils after all first crops, whereas less reactive Mali PR and Togo PR showed a slight decrease in soil pH, especially when cropped with ryegrass. Tunisia PR, compared with Mali PR and Togo PR, dissolved more rapidly and was able to more effectively counteract the acidification effects of N fertilizer as evidenced by its higher values of Pi-P and exchangeable Ca that resulted in its higher pH and lower Al saturation in Hartsells soil (Table 4). For TSP, the mechanism for pH increase was probably caused by OH^- release from hydrous Al oxides during P surface adsorption, especially at a high P rate such as 500 mg P kg^{-1} soil used in the present study (Rajan et al., 1974). This increase in pH may counteract the soil acidification induced by nitrification; thus, TSP treatment did not show a decreased soil pH in Hartsells soil compared with the soil pH before cropping. Similar trends of the effect of P treatments on soil properties after first cropping were also observed in Hiwassee soil but at a lesser degree because of the relatively high initial soil pH. A significant change was soil pH associated with the 0 P (control) treatments that decreased from 5.4 (Table 1) to 4.6 for wheat, 4.4 for ryegrass and canola, whereas all P treatments maintained soil pH ≥5.0 (Table 4). Similar to the results in Hartsells soil, Tunisia PR dissolved more than Mali PR and Togo PR did in Hiwassee soil.

The yield data of residual wheat after wheat, ryegrass, and canola obtained with different P sources are given in Fig. 2. The residual wheat yields after the initial three crops were consistently lower compared with the initial wheat yields with all P sources in both soils (Fig. 1). The average residual wheat yield after wheat ranged from 0.2 g pot^{-1} with Togo PR to 14.2 g pot^{-1} with TSP compared with initial wheat yield from

TABLE 4. Chemical Properties of Hartsells and Hiwassee Soils for 0 P (Control) and 500 mg P kg^{-1} Pots After First Cropping

P Source	Pi-P, mg P kg^{-1}	pH	Exchangeable					Al saturation, %
			Mg	Na	Ca	K	Al	
			-cmol kg^{-1}-					
Hartsells soil after wheat								
Control	2.4	4.6	0.3	0.0	2.0	0.6	1.5	34.0
Togo	7.5	4.6	0.3	0.0	2.1	0.4	1.4	33.1
Mali	5.7	4.8	0.2	0.0	2.3	0.4	1.3	30.1
Tunisia	11.1	5.1	0.2	0.1	2.5	0.2	1.0	26.5
TSP	34.4	5.0	0.2	0.0	2.1	0.2	1.3	35.2
Hartsells soil after ryegrass								
Control	2.3	4.3	0.3	0.0	1.9	0.7	1.9	40.0
Togo	8.6	4.4	0.2	0.0	2.0	0.7	1.8	37.3
Mali	7.7	4.4	0.2	0.0	2.2	0.5	1.7	36.7
Tunisia	11.1	4.9	0.2	0.0	2.5	0.3	1.2	29.1
TSP	32.7	4.8	0.2	0.0	2.1	0.2	1.5	37.3
Hartsells soil after canola								
Control	2.4	4.4	0.2	0.1	1.9	0.6	1.3	32.0
Togo	7.4	4.5	0.2	0.1	1.7	0.4	1.5	40.6
Mali	6.9	4.6	0.2	0.1	1.6	0.3	1.4	40.2
Tunisia	12.1	5.0	0.1	0.1	1.9	0.1	1.3	36.9
TSP	30.0	4.9	0.1	0.1	1.5	0.1	1.6	46.9
Hiwassee soil after wheat								
Control	2.3	4.6	1.0	0.0	1.2	0.7	0.1	5.0
Togo	10.9	5.1	0.9	0.0	1.6	0.4	0.1	2.5
Mali	8.7	5.2	0.9	0.0	1.6	0.3	0.1	2.4
Tunisia	17.1	5.5	0.9	0.1	1.9	0.2	0.1	1.9
TSP	21.9	5.3	0.8	0.1	1.4	0.1	0.1	4.6
Hiwassee soil after ryegrass								
Control	2.4	4.4	0.9	0.0	1.1	0.8	0.2	8.0
Togo	11.1	5.0	0.8	0.0	1.6	0.4	0.1	3.4
Mali	8.9	5.1	0.8	0.0	1.6	0.3	0.1	3.3
Tunisia	16.9	5.4	0.9	0.1	2.1	0.2	0.1	1.9
TSP	24.0	5.2	0.8	0.1	1.5	0.2	0.1	4.4
Hiwassee soil after canola								
Control	2.5	4.4	1.0	0.1	1.2	0.7	0.1	5.0
Togo	10.5	5.2	0.6	0.1	1.3	0.2	0.1	6.0
Mali	9.9	5.2	0.5	0.1	1.2	0.1	0.1	7.5
Tunisia	15.2	5.4	0.6	0.1	1.6	0.1	0.1	5.1
TSP	22.4	5.2	0.6	0.1	1.0	0.1	0.2	9.9

4.5 g pot^{-1} with Togo PR to 24.1 g pot^{-1} with TSP in Hartsells soil. In Hiwassee soil, the same comparisons were from 8.8 g pot^{-1} with Togo PR to 17.7 g pot^{-1} with TSP for residual wheat yield compared with initial wheat yield from 14.9 g pot^{-1} with Togo PR to 33.5 g pot^{-1} with TSP.

At 500 mg P kg^{-1} rate, the residual wheat yield for Togo PR and Mali PR was significantly lower than initial wheat yield in Hartsells soil (Table 5). The initial and residual wheat yield for Tunisia PR and TSP were similar at 500 mg P kg^{-1} rate. At this P rate, soil pH did not significantly change before and after the first wheat crop (4.8 before vs. 4.6–5.1 after), and Al saturation actually decreased after the first wheat crop in Hartsells soil (45% before vs. 27%–35% after) for all P sources (Tables 1 and 4). Therefore, the lower residual wheat yield with Togo PR and Mali PR was probably caused by lower reactivity of these P sources that resulted in less available P to the second wheat crop. Residual yield in Hiwassee soil, although higher than residual yield in Hartsells soil, was significantly lower than initial wheat yield for all P sources (Table 5). The P uptake (mg P pot^{-1}) for the following P sources in Hartsells soil Togo, Mali, Tunisia, and TSP were 19.1, 33.1, 34.8, and 128, respectively, compared with 59.1, 77.5, 115, and 158 in Hiwassee soil. Higher yield and P uptake by the first wheat crop at 500 mg P kg^{-1} rate in low Al-saturation Hiwassee soil resulted in less available P for the second crop.

The regression estimates and the calculated RAE values of P sources for residual wheat after initial wheat, ryegrass, and canola are shown in Table 6. In general, residual RAE values of PR were higher in Hiwassee soil than Hartsells soil, similar to the result for the initial RAE of PR for wheat (Table 3), again probably caused by a lower Al saturation of Hiwassee soil than Hartsells soil (Table 4). The high Al saturation of Hartsells soil impedes wheat growth that, in turn, may counteract the benefit of soil acidity on PR dissolution. Further evidence to support this

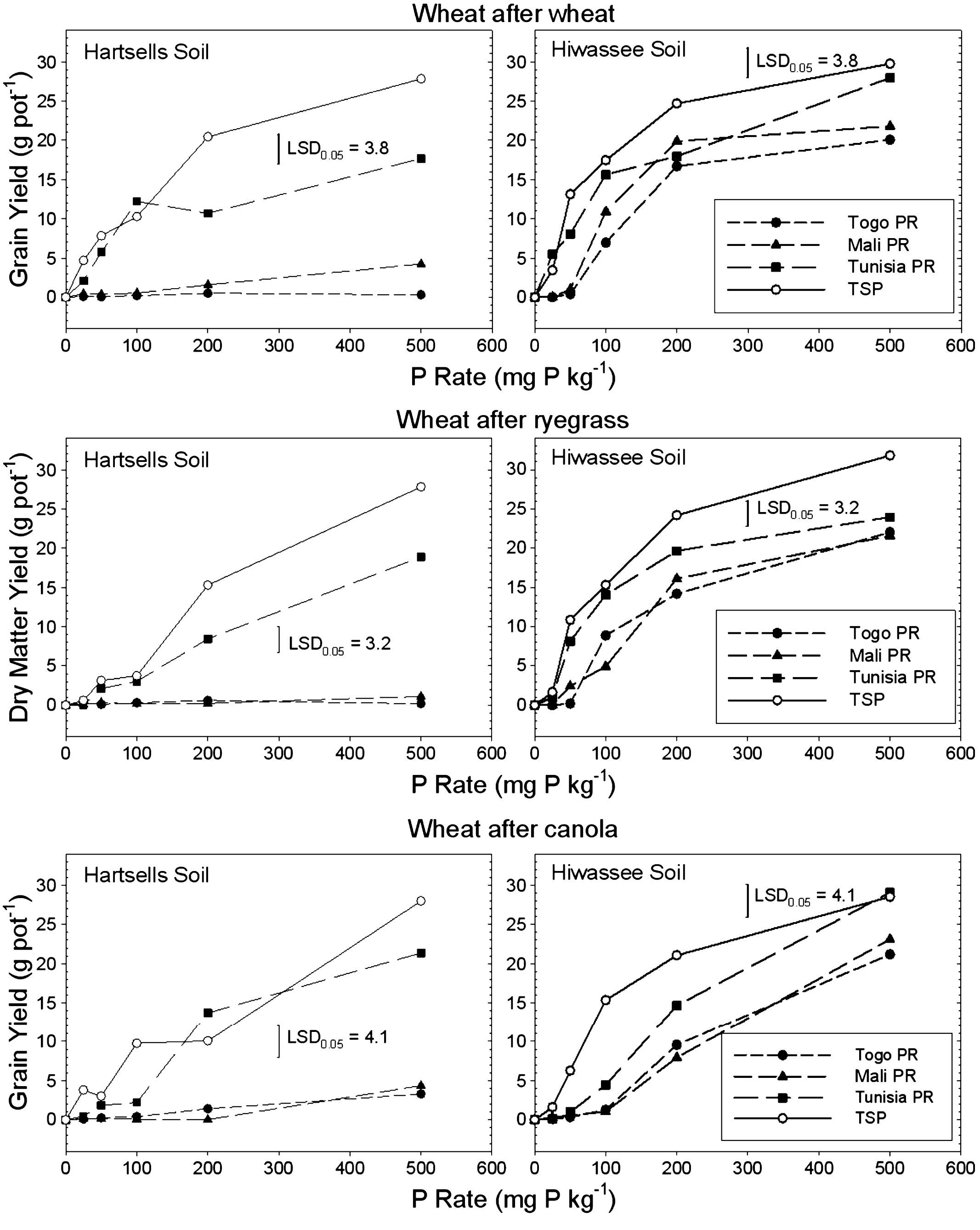

FIG. 2. Residual grain yield of wheat after wheat, wheat after ryegrass, and wheat after canola as influenced by soil, P rate, and P sources.

possible explanation can be seen in the significant relationship between available P (Pi-P) from all P sources after first crops and the residual wheat grain yield in Hiwassee soil (Fig. 3). There were no residual wheat grain yields from all 0 P (control) pots with soil Pi values of 2.3 to 2.4 mg P kg^{-1}. In Hartsells soil, no significant relationship could be found between soil P and yield (data not shown) because soil-available P was not the only factor affecting residual wheat growth. The negative effect of Al toxicity on wheat growth would be more critical than available P.

It is interesting to note that the residual RAE of Togo PR and Mali PR for wheat after wheat, ryegrass, and canola was very low, only 2% to 11%, in Hartsells soil (Table 6), whereas their initial RAE for wheat was 19% to 42% (Table 3). On the other hand, there seemed to be no significant decrease in RAE from initial wheat (73%) to residual RAE of wheat after wheat, ryegrass, and canola for Tunisia PR in Hartsells (64%–76%, with an average of 70%). Soil data in Table 4 clearly show that Tunisia PR maintained higher pH than Togo PR and Mali PR after first crops (4.9–5.1 vs. 4.4–4.8) in Hartsells soil. Furthermore, available P as extracted by Pi test showed that Tunisia PR was also higher than the other two PR (11.1–12.1 vs. 5.7–8.6 mg P kg^{-1} soil) after first crops in Hartsells soil. Therefore, the residual RAE of Tunisia PR for wheat was much higher than that of Togo PR and Mali PR in Hartsells soil.

TABLE 5. Grain Yield of Initial Wheat and Residual Wheat After Wheat, Ryegrass, and Canola as Influenced by Soil and P Source at P Rate of 500 mg P kg^{-1}

	Hartsells				Hiwassee			
Crop	**Togo PR**	**Mali PR**	**Tunisia PR**	**TSP**	**Togo PR**	**Mali PR**	**Tunisia PR**	**TSP**
	-g pot^{-1}-							
Wheat	12.4A[†]	21.2A	19.3A	33.0A	33.7A	35.9A	37.4A	40.3A
Wheat after wheat	0.31B	4.24B	17.7A	27.8A	20.1B	21.8B	28.0B	29.7B
Wheat after ryegrass	0.20B	1.11B	18.9A	27.8A	22.0B	21.6B	24.0B	31.8B
Wheat after canola	3.31B	4.35B	21.4A	28.0A	21.2B	23.1B	29.1B	28.5B

[†]Values with the same letter in each column are not significantly different (P = 0.05).

TABLE 6. Regression Estimates (β) for the Semi–log Response Function and Residual RAE for Wheat After Wheat, Ryegrass, and Canola of P Sources in Two Soils

	Wheat After Wheat		Wheat After Ryegrass		Wheat After Canola	
P Source	**Hartsells**	**Hiwassee**	**Hartsells**	**Hiwassee**	**Hartsells**	**Hiwassee**
Intercept	0	0	0	0	0	0
Togo PR	0.053	2.162	0.065	2.225	0.274	1.664
Mali PR	0.352	2.586	0.094	2.205	0.251	1.698
Tunisia PR	2.211	3.424	1.619	3.095	1.969	2.482
TSP	3.284	4.021	2.511	3.896	2.600	3.415
$S_{\mathrm{RAEi1-RAEi2}}$	0.33	0.58	0.49	0.62	0.49	0.74
R^2	0.87	0.84	0.62	0.80	0.66	0.65
			RAE			
Togo PR, %	2C[†]	54C	3B	57B	11B	60B
Mali PR, %	11C	64BC	4B	57B	10B	62B
Tunisia PR, %	67B	85AB	64AB	79AB	76A	86AB
TSP, %	100A	100A	100A	100A	100A	100A

[†]Values with the same letter in each column are not significantly different (P = 0.05).

In Hiwassee soil, this difference was less pronounced (79%–86% for Tunisia PR with an average of 83% vs. 54%–64% and with an average of 60% for Togo PR and Mali PR). The superiority of Tunisia PR over the other two PR on residual RAE in Hiwassee soil was influenced by available P and not by the negative effect of Al saturation on residual wheat growth. For the highly reactive Tunisia PR, the RAE values for the three initial crops and residual wheat after first crops were statistically not different from the RAE values of TSP (Tables 3 and 6). However, Tunisia PR was less effective than TSP for initial and residual effects in the more acidic Hartsells soil, with at least 30% less yield (Table 5). This suggests that although PR dissolution increases as soil acidity increases, there can also be a negative effect of soil acidity, that is, Al saturation, which can inhibit crop growth. Proper management of soil acidity, in addition to PR reactivity and crop species, thus needs to be considered for the agronomic use of PR for crop production.

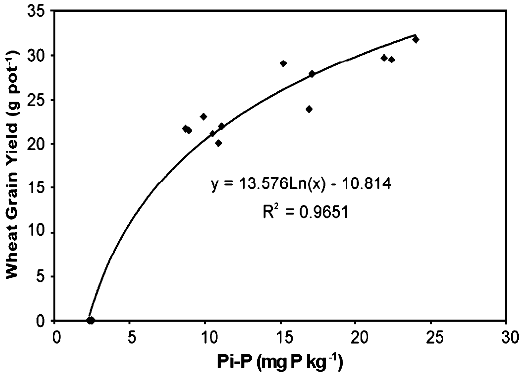

FIG. 3. Relationship between Pi-P after first crops and residual wheat grain yield when 500 mg P kg^{-1} was applied to the Hiwassee soil.

The effectiveness of crop species in using PR was evident from initial crop yield and RAE, where canola > ryegrass ≥ wheat. However, the residual crop of wheat after wheat, ryegrass, and canola did not show any significant effect of previous crop (Tables 5 and 6). The additional PR dissolution and available P (Table 4) caused by crop species effect was probably used by that crop, thus having no significant carryover effect on the yield, RAE, and P uptake of the residual crop.

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