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Regional Maize Grain Yield Response to Applied Phosphorus in Central America

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ABSTRACT

Maize (*Zea mays* L.) in Central America is commonly grown under continuous cultivation and on marginal lands where restricted use of conservation practices and fertilizers limit productivity. Maize grain yield response to P source, rate, and method of application was evaluated at 33 locations in Central America. Soil orders included Andisols, Inceptisols, and Ultisols. Treatments included rock phosphate (RP) applied broadcast preplant without incorporation at rates of 13 and 26 kg P ha^{-1}, triple superphosphate (TSP) band-applied at planting at rates of 13 and 26 kg P ha^{-1}, TSP broadcast preplant at 26 kg P ha^{-1}, and a check where no P was applied. All treatments received 100 kg of N ha^{-1} as urea applied in split applications and 30 kg S ha^{-1} as $CaSO_4 \cdot 2H_2O$. Averaged over locations, maize grain yield increased 0.38 and 0.74 Mg ha^{-1} when 13 and 26 kg P ha^{-1} was band-applied as TSP and increased 0.21 and 0.16 Mg ha^{-1} when RP was broadcast at the same rates. All P treatments had a probability (PR) >0.61 of outperforming the unfertilized check. Triple superphosphate band-applied at 26 kg P ha^{-1} offered the greatest probability (0.69) of an economic response to P fertilizer across environments. Stability analyses and analyses of yield differences suggest that response to applied P was independent of environment for the sites evaluated. The consistent response to applied P across a wide range of environments demonstrates that P is a limiting element for maize production on marginal lands in Central America and that the probability for economic response to applied P is high.

Extensive areas of Central America have been subjected to additions of allophane and other amorphous materials capable of adsorbing phosphate. Acidity and the presence of amorphous materials such as allophane on the exchange complex are often associated with high P-fixation capacities and reduced P-use efficiencies (Sanchez, 1976). Weathered tropical soils generally have lower pH and higher anion exchange capacity than temperate soils (Blair and Lefroy, 1987). In many tropical soils, leaching of bases and silica has left the soil exchange complex dominated by Al and Fe, as well as reactive Al and Fe oxides (Blair, 1988). Consequently, localized placement of P is considered necessary to reduce the surface area of the soil in contact with water-soluble fertilizer sources. Alternatively, low soil solution pH and increased contact with soil enhance P availability from insoluble P fertilizer sources such as finely ground rock (Joos and Black, 1950; Lindsay and Moreno, 1960; Chu et al., 1962; Gichuru and Sanchez, 1988; Chien et al., 1987).

Methods of evaluating long-term experiments and/or multilocation experiments have been addressed by Cady (1991). The use of regression on the environment mean to assess stability of genotypes as affected by fertilizer treatment has been presented by Hildebrand (1984). Eskridge and Mumm (1992) suggested that pairwise cultivar evaluation could be enhanced by a decision-making tool that quantifies the probability that a test cultivar outperforms the check over a broad range of environments. They introduced a test for determining reliability of test cultivars that can be useful to breeders in identifying superior cultivars when the major risk is selecting a cultivar that outperforms a check.

Determining the probability of crop yield response to P fertilization using calibrated soil tests in Central America has been limited by the high costs of soil testing and a lack of specific calibrated responses for each cropping system. Past efforts have concentrated on selecting the ideal soil P test, rather than on establishing field calibration of crop response to fertilizer source, rate, and application method. Since most Central American farmers apply P in localized bands, the value of the soil test remains limited by the large sampling error (i.e., the number of subsamples required to obtain reliable estimates of soil P status). Very little published work exists in this region concerning P fertilization in maize.

There are many common characteristics in maize growing regions throughout Central America, including influence of volcanic ash, highly sloped terrain, and a history of continuous cultivation on marginal lands. Determining the probability of yield response to applications of P under uniform management across a range of environments is an alternative for improving recommendations. Treatments can be described by the magnitude and variability of response compared with a check at each location. Observed responses can then be related to specific soil and environmental properties. The objectives of this research were to use regional evaluations that would (i) identify combinations of P source, rate, and method that have a high probability of increasing maize grain yield compared with no P fertilization and (ii) quantify the magnitude and variability of treatment response as affected by maize grain yield potential and soil characteristics of experimental sites.

MATERIALS AND METHODS

Thirty-three experiments were conducted in maize growing regions of six Central American countries from 1989 to 1990 (Table 1). Most experiments were conducted on-farm and under the predominant maize-based cropping system at each location where fertilization, planting, and harvest are all accomplished by hand. With few exceptions, tillage operations in these trials were not performed on the hillsides. Soil orders included were Ultisols (Panama), Inceptisols (Guatemala and Nicaragua), and Andisols (El Salvador, Costa Rica, and Honduras). A randomized complete block design with three replications was used at each location. Individual plots consisted of four to six maize rows, 5.5 m in length. Plant densities ranged from 45 000 to 65 000 plants ha^{-1}, because of differences in row width across locations. Weeds were controlled with preemergence herbicides and manual weeding.

Treatments were rock phosphate, 0–13.3–0 N–P–K, applied broadcast preplant without incorporation at rates of 13 and 26 kg P ha^{-1}; TSP, 0–20–0 N–P–K, applied in localized bands (spot placement, P applied 4 to 6 cm deep and 4 to 6 cm to the side of individual hills containing two to three planted seeds) at rates of 13 and 26 kg P ha^{-1}; TSP applied broadcast preplant

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Abbreviations: RP, rock phosphate; TSP, triple superphosphate.

Table 1. Locations where phosphorus method–source–rate experiments were conducted in maize growing regions of Central America, 1989–1990.

Country	1989	1990
Panama	Las Tablas	Las Tablas
	La Honda	La Honda
	Parita	Parita
	–	Las Comadres
Costa Rica	Esparza	–
Nicaragua	–	Nindiri
	–	Posoltega
El Salvador	Metalio Guaymango	Metalio Guaymango
	Sacacoyo	Opico Quezaltepeque
Honduras	Caguira	Siguatepeque
	El Tejar	–
	Esperanza	–
	Ologosi	–
Guatemala	La Maquina	Jutiapa
	Zacapa	La Maquina C-16
	Retalhuleu	La Maquina B-6
	Jutiapa PC	San Geronimo
	Jutiapa AM	Chimaltenango 1
	Jutiapa VT	Chimaltenango 2
	Cuyuta	Zacapa

without incorporation at 26 kg P ha^{-1}; and a check where no P was applied (0P). North Carolina rock phosphate (apatite high in francolite, 62.7% citric acid soluble) was used at all locations. Potential effectiveness of rock phosphate was expected to be reduced by the lack of incorporation (no-tillage). Because of this, a factorial arrangement of treatments (method, source, and rate) was not used—and also because band-applied rock phosphate (spot placement) was not a viable alternative given the necessity of hand application (the material is too fine). For all six treatments, 50 kg N ha^{-1} was applied in a localized band at planting and 50 kg N ha^{-1} 30 to 35 d following planting (both as urea, 46-0-0 N-P-K). Gypsum ($CaSO_4 \cdot 2H_2O$) was applied at an average rate of 30 kg S ha^{-1} to all treatments.

Ears were hand harvested from the center two to four rows (5 m in length) and shelled for determination of grain moisture and yield. Slope, rainfall, elevation, soil chemical characteristics, and tillage method were recorded at each site. Soil test P was determined using a 0.05 *M* HCl and 0.0125 *M* H_2SO_4 extracting solution (Nelson et al., 1953) and soil organic matter was determined as described by Walkley and Black (1934). The maize genotype planted at each location (mostly hybrids, except at Chimaltenango in Guatemala and all Honduras sites, where varieties were used) was selected based on past performance from regional variety trials.

Average estimates of treatment effects and associated standard errors were obtained using a combined analysis of variance model accounting for missing data. Location and treatment were considered as random and fixed effects, respectively. Nonorthogonal single-degree-of-freedom contrasts were used to estimate the effect of P rate for the two sources. Stability analysis as described by Finlay and Wilkinson (1963), without data transformations, was performed to evaluate treatment performance as a function of the environment mean. Environment means were determined by calculating the average yield for all replicated treatments at each location. Estimated probabilities (normal reliabilities, RN_i) of P treatment response (*P*) compared with the 0P check for the sample of treatment differences were determined as defined by Eskridge and Mumm (1992), where $RN_i = P(Z > -y_{di}/s_{di})$, such that Z is a standard normal random variable and y_{di} and s_{di} are estimates of the sample mean difference and standard deviation, respectively, for treatment *i*. A modified reliability estimate (economic reliability, RE_i) was calculated by subtracting the costs (in yield units) of the fertilizer and its application from the mean difference for the *i*th treatment (d_i) against the 0P check: $RE_i = P[Z > -(y_{di} - c_i)/s_{di}]$, where c_i represents the equivalent yield necessary to pay for the fertilizer and its application for a given price ratio. These values were then substituted in the equation to calculate reliability for normally distributed differences. The recalculated reliability represents the normal probability that a treatment will outperform the 0P check in a quantity superior to c_i, therefore, providing an estimate of the economic feasibility of the practice as well as allowing direct comparisons of net benefits among calculated reliabilities for a given price ratio.

Table 2. Mean squares for maize grain yield (Mg ha^{-1}) from the combined location analysis of variance, nonorthogonal contrasts, and combined treatment yield means from 33 regional agronomy trials, Central America, 1989–1990.

Source of variation	df	Mean squares
Location	32	30.60**
Rep(location) (Error *a*)	66	1.17
Treatment	5	5.27**
Location × treatment	160	0.51*
Error *b*	293	0.40
Contrast		Estimate
RP broadcast–linear†	1	0.1450
TSP band–linear†	1	0.7108**
TSP band vs. TSP broadcast, 26 kg P ha^{-1}	1	0.2315*

Source	Method	P rate	Overall yield mean
		kg ha^{-1}	Mg ha^{-1}
Check	Check	0	4.20
RP	Broadcast	13	4.41
RP	Broadcast	26	4.36
TSP	Band	13	4.59
TSP	Band	26	4.94
TSP	Broadcast	26	4.71

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† RP, rock phosphate; TSP, triple superphosphate.

RESULTS AND DISCUSSION

Grain Yield Response to Applied Phosphorus

Mean grain yields for the 33 locations ranged from 1.5 to 6.6 Mg ha^{-1}. Main effects of location and treatment and the location × treatment interaction were significant in the combined analysis of variance model (Table 2). Even though a slightly significant location × treatment interaction was observed in analysis of variance, interpretation of treatment main effects was accomplished, since stability analysis showed consistent response to applied P across locations. A significant linear grain yield response to applied P was observed when TSP was band-applied. Banding TSP increased yields by 0.23 Mg ha^{-1} compared with broadcast at the 26 kg P ha^{-1} rate (Table 2). Averaged over locations, TSP increased grain yields 0.38 ± 0.10 and 0.74 ± 0.09 Mg ha^{-1} at the 13 and 26 kg P ha^{-1} rates, respectively, compared with the check (0P). For the TSP source, 70 and 88% of the sites demonstrated a positive response to applied P at rates of 13 and 26 kg P ha^{-1}. No significant linear response in grain yield was observed when rock phosphate was applied broadcast (Table 2). Average grain yield gains when compared with the check were 0.21 ± 0.10 and 0.16 ± 0.10 Mg ha^{-1} at rates of 13 and 26 kg P ha^{-1}, respectively, as rock phosphate. At 61 and 70% of the sites, there was a positive response to rock phosphate at the same rates, respectively.

Stability Analyses

An important assumption in stability analysis is that the lack of consistency of treatment effects over locations (treatment × location interaction) can be interpreted in part as a linear function of the environment mean on the mean yield for a given treatment (Raun et al., 1993). Linear regression equations of grain yield on the environment mean (average of all treatments at a given location), indicate that grain yield response to applied P was consistently greater across environments for TSP than for rock phosphate (observed slopes and intercepts from stability analysis, Table 3). Slopes for P treatments were not statistically different, suggesting the lack of a location × treatment interaction. The significant location × treatment interaction observed in analysis of variance was considered to be a function of the large number of degrees of freedom used to test this effect (Table 2).

It is not understood why the yield increase from applied P was the same in both low- and high-yielding environments (TSP band-applied at 13 and 26 kg P ha^{-1}, Fig. 1). However, these results suggest that some homogeneous limiting production factor (e.g., presence of allophane from volcanic ash across the region) controlled the magnitude for which yield increases occurred as a result of applying P at the rates used in this study. This is not in agreement with the percent sufficiency concept, which would predict yield response as a percent of yield possibility (environment mean), as has been proposed by Bray (1954). It is also possible that the high P rate used was too low to observe increased yield in higher-yielding environments.

Yield Differences as a Function of the Environment Mean

Evaluation of yield differences between preplanned, pairwise treatment comparisons across locations offers a tool for the study of patterns of response and relationships with other variables such as soil, climate, and yield level. Treatment response expressed as the yield difference (P treatment minus the check) against the environment mean is presented in Fig. 2 for TSP and rock phosphate treatments. An additional comparison of TSP banded vs. TSP broadcast at the 26 kg P ha^{-1} rate is illustrated in Fig. 3. As in the results from stability analyses, grain yield response to applied P appeared to be independent of the environment mean for all P source and rate combinations (Fig. 2 and 3). Despite the large variability in response to applied

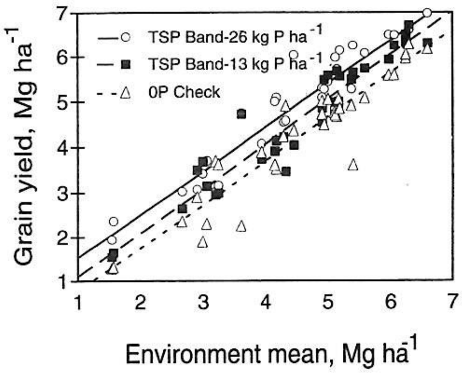

Fig. 1. Regression of maize grain yield on the environment mean for the check (0P) and treatments receiving triple superphosphate (TSP) band-applied, 1989 and 1990 regional trials, Central America.

P (all source and method combinations included), TSP showed more consistent positive increases in maize grain yield when compared with rock phosphate. Because rock phosphate was not incorporated with the underlying soil at any location, P reaction with the soil and subsequent availability was limited. The advantages of banding TSP compared with broadcast without incorporation at the 26 kg P ha^{-1} rate are illustrated in Fig. 3.

Relationship with Soil Characteristics

The largest yield increases as a result of applying P (>0.75 Mg ha^{-1}) were obtained at extractable P levels <5 mg kg^{-1} (Fig. 4). However, soil test P was not always a reliable indicator of a positive response to applied P, since significant yield increases were also observed at higher soil test P levels. Few sites had P levels >10 mg kg^{-1} extractable P, and a conclusive relationship could not be established between high soil-test P and response to P fertilizer. Fertilizer is spot-applied next to maize plants in Central America, causing heterogeneous distribution of fertilizer P in the field and making reliable soil sample estimation of available soil P difficult to obtain.

The relationship between soil organic matter and the yield difference due to P fertilization compared with the check from experiments conducted in 1990 (soil organic matter was not determined in 1989), demonstrated that 60% of the positive responses were obtained on soils with organic matter levels <2.5% (Fig. 5). However, most experiments in this study were conducted in maize growing regions of Central America where soil organic matter levels have been depleted through erosion and/or long-term cultivation. No linear or quadratic relationships (PR < 0.10) between maize grain yield and other soil chemical

Table 3. Linear regression equations of maize grain yield (Mg ha^{-1}) on the environment mean by treatment from the combined 33 regional agronomy trials, Central America, 1989–1990.

Source†	Method	P rate	Intercept	SE of estimate	Slope	SE of estimate	r	Root mean square error
		kg ha^{-1}						
–	Check	0	−0.1177	0.3128	0.9487	0.0659	0.93	0.5026
RP	Broadcast	13	−0.2286	0.2906	1.0179	0.0612	0.94	0.4669
RP	Broadcast	26	−0.2257	0.2358	1.0062	0.0497	0.96	0.3789
TSP	Band	13	0.1261	0.2525	0.9718	0.0532	0.95	0.4057
TSP	Band	26	0.6024	0.2538	0.9525	0.0535	0.95	0.4077
TSP	Broadcast	26	0.1248	0.2651	1.0065	0.0558	0.95	0.4259

† RP, rock phosphate; TSP, triple superphosphate.

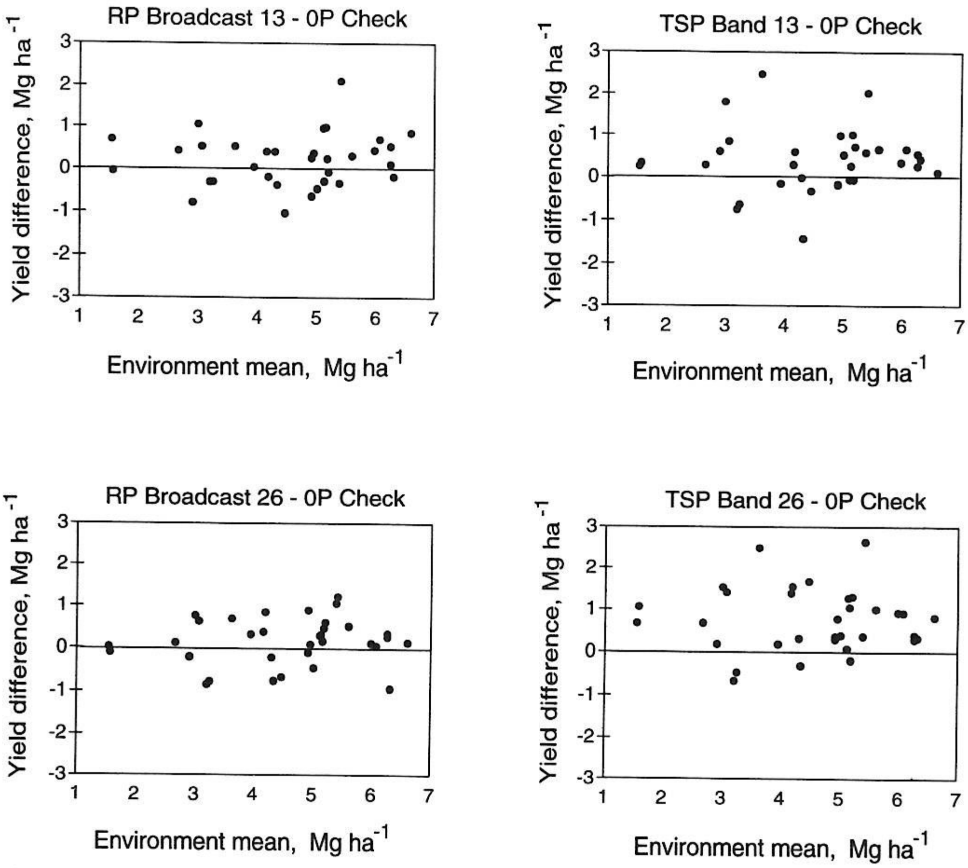

Fig. 2. Linear relationship of the environment mean vs. grain yield response to source and rate of applied P expressed as the yield difference (P − 0P), 1989 and 1990 regional trials, Central America. RP, rock phosphate; TSP, triple superphosphate.

properties (pH, Ca, Mg, Al, Fe) or environmental factors were observed (data not shown).

Probability of Yield Response to Phosphorus fertilization

Probability of outperforming check varieties (reliability) has been used to assist plant breeders in identifying promising cultivars (Eskridge and Mumm, 1992). It was also useful in this work where the main interest was to identify combinations of P source, rate, and method that have a high probability of increasing grain yield compared with no P fertilization across environments. Eskridge and Mumm (1992) cite two key assumptions for appropriate use of reliability as a decision tool: (i) the experimenter is primarily concerned with identifying treatments with a high probability of responding against a check and (ii) the experiments are conducted in environments that are

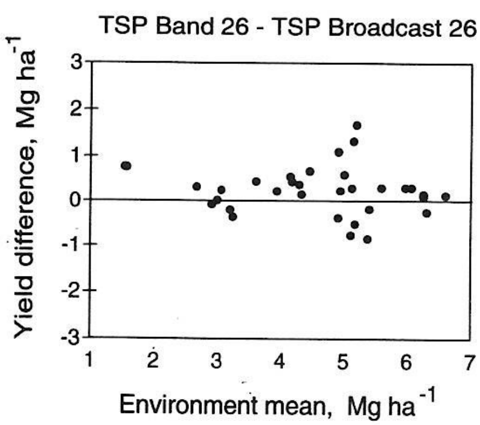

Fig. 3. Linear relationship of the environment mean vs. grain yield response to method of applied P as triple superphosphate (TSP) expressed as the yield difference (P − 0P), 1989 and 1990 regional trials, Central America.

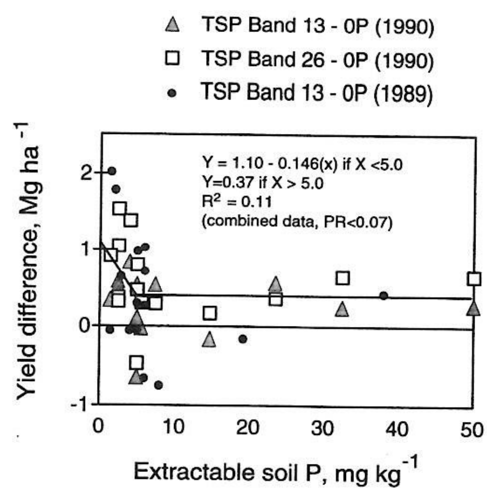

Fig. 4. Extractable soil P vs. grain yield response to applied P expressed as the yield difference (P − 0P), 1989 and 1990 regional trials, Central America. TSP, triple superphosphate.

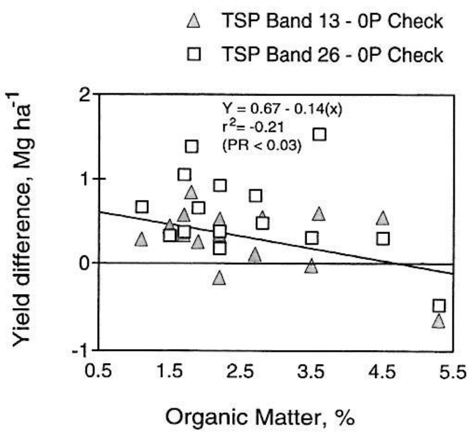

Fig. 5. Soil organic matter (%) vs. grain yield response to applied P expressed as the yield difference (P − 0P), 1990 regional trials, Central America. TSP, triple superphosphate.

representative of the population of environments where the practice is well adapted. These two conditions were applicable to this work, since all of the experiments were conducted in common maize growing environments in Central America.

For each sample of differences among P treatments vs. the 0P check, normal reliabilities (RN_i) were calculated as described by Eskridge and Mumm (1992). Estimated normal reliabilities for all treatments were >0.61, indicating that all treatments had >61% chance of outperforming the unfertilized check (Table 4). Although there are a range of soil and environmental parameters that could be affecting response to applied P, obtaining a response probability of 84% for TSP band-applied at 26 kg P ha^{-1} indicates that P was limiting for the vast majority of the locations. It was equally important to note that the apparent P-availability of sources, methods and rates was reflected in the differences between reliabilities (Table 4). Reliability of response was greater when P was band-applied as TSP compared with broadcast at the same P rate. Moreover, these reliabilities demonstrate the importance of P fertilization as a critical input for maize production in a region where P fertilizers are not commonly applied. In this regard, it is unlikely that any controllable agronomic factor other than weed control and/or applied N could result in regional probabilities of response as great as P.

An extension of the reliability concept adds some insight into the economical feasibility of applying P for maize production in Central America. Central American farmers must produce an average of 14 and 10 kg maize to pay for 1 kg of P as TSP and rock phosphate, respectively. To compensate for these costs, the magnitude of treatment response must be greater than the costs of P fertilizer. Taking these costs into consideration, the recalculated normal reliabilities (RE_i) for rock phosphate treatments were <0.55, while for TSP applied in bands at 13 and 26 kg P ha^{-1}, reliabilities were 0.61 and 0.69, respectively. These results indicate that TSP applied in bands at 26 kg P ha^{-1} offered the highest probability of an economic response across environments. Given that application and P source costs were considered, long-term benefits of P fertilization for maize production in Central America are expected to be high.

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Table 4. Reliabilities for mean grain yield differences (MD, P treatment yield minus the 0P check) from 33 regional agronomy trials, Central America, 1989–1990.

Source†	Method	P rate	Mean yield	MD	SD of difference	RN_i‡	RE_i§
		kg ha^{-1}	Mg ha^{-1}				
RP	Broadcast	13	4.41	0.20	0.624	0.63	0.55
RP	Broadcast	26	4.36	0.15	0.552	0.61	0.42
TSP	Band	13	4.59	0.38	0.752	0.70	0.61
TSP	Band	26	4.94	0.74	0.758	0.84	0.69
TSP	Broadcast	26	4.71	0.51	0.541	0.75	0.58

† RP, rock phosphate; TSP, triple superphosphate.
‡ RN_i, normal reliability: normal probability of treatment *i* outperforming the 0P check.
§ RE_i, economic reliability: economic probabilities calculated assuming a price ratio of 14 for TSP (0–20–0, N–P–K) and 10 for RP (0–13.3–0).

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