Influence of Landscape Position, Soil Series, and Phosphorus Fertilizer on Cotton Lint Yield

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) response to P fertilizer can vary within fields, making P recommendations difficult. Phosphorus response may be more predictable with variable-rate fertilization, which matches soil test P and P fertilizer rate on a site-specific basis. Our first objective was to determine the effect of landscape position and soil series on cotton P accumulation, lint yields, and P fertilizer response on two irrigated cotton sites in the Southern High Plains of Texas. The second objective was to compare variable-rate P, blanket-rate P, and zero P applications. Mehlich-3 P levels ranged from 8 to 25 mg P kg^{-1} at Lamesa, and from 12 to 23 mg P kg^{-1} at Ropesville. Phosphorus fertilizer was not recommended when Mehlich-3 P >33 mg P kg^{-1}. In both years at Lamesa, P accumulation at early squaring and lint yields were greater in the bottomslope than in the south-facing sideslope. Phosphorus fertilizer did not affect lint yields at Lamesa in 2000. In 2001, Lamesa lint yields responded to variable-rate and blanket-rate P in the south-facing sideslope only, which had just 8 mg P kg^{-1}. At Ropesville in 2000, early P accumulation, biomass and lint yields responded to P on a calcareous soil but not on a noncalcareous soil. In all cases, yields were similar between variable-rate and blanket-rate P. Thirty-eight percent less P was applied with variable-rate than blanket-rate treatments in 3 of 4 site-yr. However, more research is needed to determine if fertilizer savings are consistent enough to offset the greater costs of variable-rate P fertilization.

In the Southern High Plains, N and water are the main constraints to cotton production (Morrow and Krieg, 1990). Phosphorus may be a third limitation in this region of alkaline and calcareous soils. Response of cotton to P fertilizer is often difficult to predict, even with soil tests (Walker and Onken, 1969; Funderburg et al., 1996; Bronson et al., 2001). Many studies indicate inconsistent cotton response to P fertilizer at medium or even low soil test P levels (Funderburg et al., 1996; Mitchell, 2000). Field variability or landscape position may contribute to uneven P responses (Bronson et al., 2001).

Few studies on cotton P fertilizer response have been conducted at a landscape scale. Kachanoski and Fairchild (1996) reported that fertilizer response trials conducted on small plots did not extrapolate well to typically large farmers' fields. Bronson et al. (2001) reported in a 5-yr landscape-scale cotton study that P fertilizer response varied by landscape position. Cotton response to P fertilizer occurred in 3 of 5 yr, in bottomslopes, but not in sideslopes. This was despite acidified NH_4OAc–extractable P levels of 8 mg kg^{-1} in the sideslopes and 11 mg P kg^{-1} in the bottomslope. In that study, soil properties such as sand content affected yields and P response as well. Landscape position has been widely reported to affect productivity and N response of crops like wheat (*Triticum aestivum* L.), due to redistribution of water to lowerlying landscape positions (Pennock et al., 1987; Fiez et al., 1994; Pennock et al., 1994; Fiez et al., 1995). In cotton, Li et al. (2001, 2002) reported that N accumulation and cotton lint yields were negatively correlated with elevation. However, N fertilizer response in those studies did not vary by landscape position or elevation.

Besides landscape position, soil series is an important factor that affects crop yields and fertilizer response. Carr et al. (1991) reported up to twofold differences in dryland wheat and barley (*Hordeum vulgare* L.) yields between soil series within fields. However, yield responses to fertilization by soil map unit or field were generally similar in that study. Soil series × N fertilizer rate interactions were reported in additional wheat and barley studies by Carr et al. (1992). Wibawa et al. (1993) reported differences between soil map units in both wheat and barley yields in North Dakota. Other studies showed no differences in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields between soil map units in Iowa (Colvin et al., 1997; Bakhsh et al., 1999). One possible reason for this is the large amount of variation within soil map units (Sadler et al., 1995).

Variable-rate P fertilization matches soil test P and P fertilizer rate on a site-specific basis. This approach should increase the probability of yield responses to P fertilizer. The amounts of fertilizer applied with grid soil sampling and variable-rate technology can be less than conventional blanket-rate approaches. Redulla et al. (1996) reported that in four site-years of corn study, 9 to 31 kg ha^{-1} less N was applied with variable-rate N compared with blanket-rate N. However, corn grain yield was not statistically different between the two fertilization strategies. Ferguson et al. (2002) reported no significant difference in the amount of N applied with blanket- or variable-rate treatments on 13 site-years of corn in Nebraska. Mallarino et al. (1999) reported that less P was applied in two of four fields with variable-rate P than with blanket-rate P in corn and soybean. Yang et al. (2001), however, reported greater P applications to grain sorghum with variable-rate treatments compared with blanket-rate treatments.

The hypothesis of our study was that P fertilizer response in cotton differs across landscape positions and soil series. We also hypothesized that variable-rate P

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Abbreviations: df, degrees of freedom; GPS, global positioning system; LEPA, low energy precision application.

fertilization can result in greater P use efficiency than blanket-rate P fertilization.

The objectives of the study were to (i) determine the effect of landscape position and soil series on P accumulation, P fertilizer response, and yield at two 11-ha irrigated cotton sites in the Southern High Plains, and (ii) compare variable-rate P, blanket-rate P, and zero P applications on P accumulation and yield.

MATERIALS AND METHODS

Experimental Design and Phosphorus Fertilization

The basic experimental design was implemented in 2000 and 2001 at two sites—Lamesa and Ropesville, TX—and consisted of a randomized complete block with three replicates. Each replicate was within a center-pivot irrigation span. There were three P treatments: variable-rate P, blanket-rate P, and zero P. The nine plots at each site were 16, 1-m rows wide and ranged from approximately 500 to >1000 m long. Rows were circular and therefore plot lengths were unequal. Phosphorus was applied as 148.5 g H_3PO_4–P kg^{-1} liquid fertilizer near the time of planting with a liquid fertilizer applicator, fitted with spoke applicators. Spoke application was used to minimize disturbance to terminated-wheat cover crop residue. Placement of P was 10 cm from the seed row and 10 cm deep, on one side of the row. The blanket rate of P was 14.7 and 22.0 kg P ha^{-1} in both years at Lamesa and Ropesville, respectively (Fig. 1) This was based on the average Mehlich-3 extractable P in the 0 to 15 cm soil of the blanket plots (21 and 13 mg P kg^{-1} for Lamesa and Ropesville, respectively) and recommendations from Zhang et al. (1998). Yield goals were not considered in these P fertilizer recommendations. Variable-rate P was applied with the same ground applicator, which was fitted with an AGRO/SOILTEQ (AGRO Corp., Minnetonka, MN) Fertilizer Applicator Local Controls Operating Network (FALCON). This consisted of variable-rate servo valves, field-duty computer, controlling software, ground-speed radar, hydraulic motor driven centrifugal pumps, flow meters, and shut-off valves (Yang et al., 2001). A submeter accurate SATLOC SLX (SATLOC, Scottsdale, AZ) differential global positioning system (GPS) receiver was used with the FALCON system. The FALCON software uses the inverse-distance method of interpolation in calculating its variable-rate application maps (Fig. 1). Mehlich-3 values from all points were used to create variable-rate application maps in 2000. In 2001, to avoid influence of adjacent zero P or blanket P plots, only Mehlich-3 values from the variable-rate plots were used in making variable-rate application maps. The following linear function derived from P fertilizer recommendations for cotton vs. Mehlich-3 P was entered into the FALCON software for the variable-rate P applications (Zhang et al., 1998):

$$\text{P to apply (kg ha}^{-1}) = -1.09 \times [\text{Mehlich-3 P (mg kg}^{-1})] + 35.2$$

This recommendation calls for no P fertilizer when Mehlich-3 P is >33 mg kg^{-1} and has a maximum P fertilizer recommendation of 35.2 kg P ha^{-1}.

Variable-rate P applied at Lamesa ranged from 2.4 to 26.9 (mean 18.2) kg P ha^{-1} in 2000 and 0.1 to 24.3 (mean 7.8) kg P ha^{-1} 2001. At Ropesville, variable-rate P applied ranged from 14.7 to 26.0 (mean 19.9) kg P ha^{-1} in 2000 and 0 to 25.4 (mean 9.3) kg P ha^{-1} in 2001.

A Trimble Survey Grade GPS, Model 4700 Dual Channel Real-Time Kinematic System (Trimble Navigation Ltd., Overland Park, KS) was used to measure elevation at a density of 60 measurements ha^{-1} at both sites.

Lamesa

The Lamesa site is 100 km south (32°46′ N;101°57′ W) of Lubbock, TX, and consisted of 11 ha under a 48-ha center

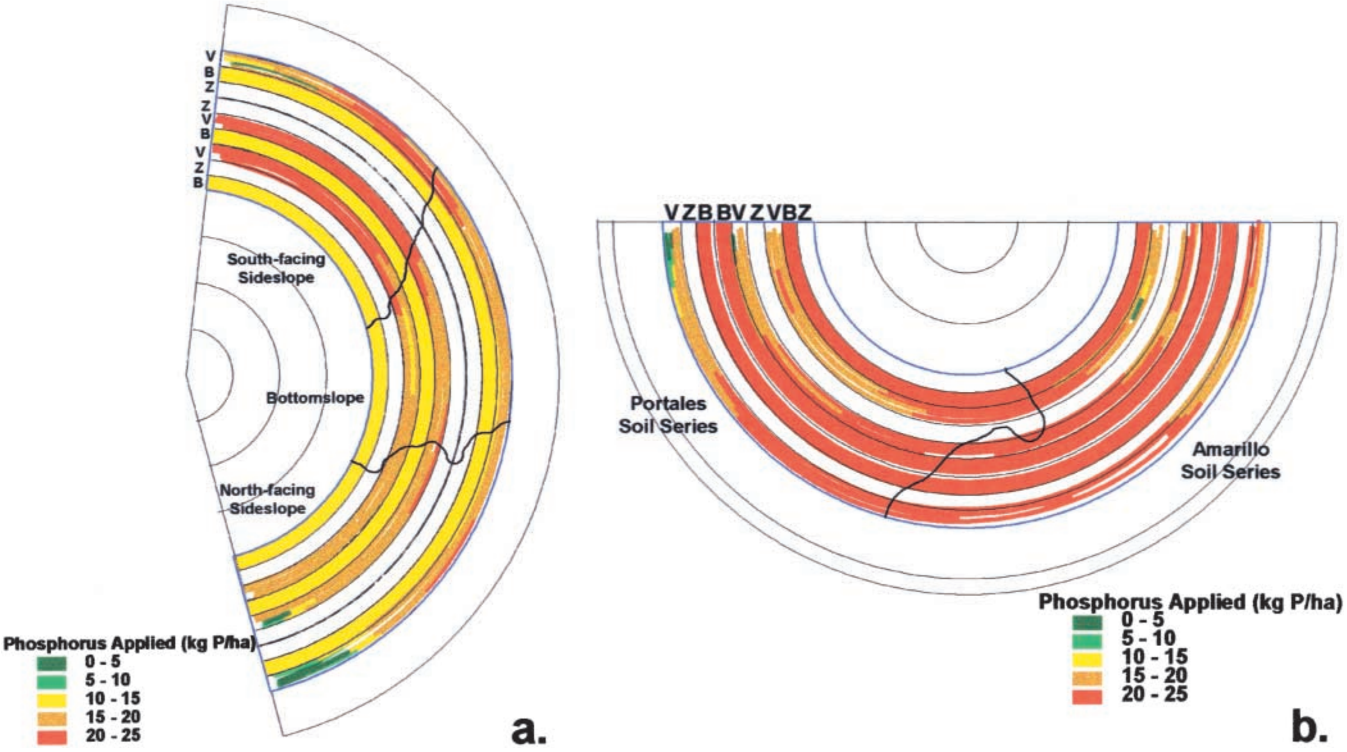

Fig. 1. (a) Lamesa, TX, and (b) Ropesville, TX. Phosphorus fertilizer application maps for cotton, spring 2000. Maps are interpolations of data points by inverse-distance to a square (V, B, and Z are variable-rate P, blanket-rate P, and zero P, respectively).

Table 1. Mehlich-3 P in soil (0–15 cm) by landscape position and P fertilization, Lamesa, TX, spring, 2000 and 2001.

P treatment	North-facing sideslope	Bottom slope	South-facing sideslope	SE of the difference	Mean	North-facing sideslope vs. bottom slope	South-facing sideslope vs. bottom slope
	mg kg^{-1}						
					2000		
Variable-rate P	14.5	15.6	8.9	2.5	13.0 b†		
Blanket-rate P	20.6	22.2	19.3	2.4	20.7 a		
Zero P	12.8	13.5	10.3	2.4	12.2 b		
SE of difference	2.2	2.5	2.4		1.4		
Mean	16.0	17.1	12.8	1.4		NS‡	*
P fertilized vs. Zero P	*	*	NS				
					2001		
Variable-rate P	24.6	23.4	18.8	4.6	22.3 a†		
Blanket-rate P	19.5	23.8	18.9	4.5	20.7 a		
Zero P	14.3	16.3	8.1	4.4	12.9 b		
SE of difference	4.2	4.5	4.4		2.6		
Mean	19.4	21.2	15.2	2.6		NS	NS
P fertilized vs. Zero P	NS	NS	*				

* Significant at $P < 0.05$.

† Means in this column of main P treatments followed by the same letter are not significantly different at $P = 0.05$. Means followed by different letters are significantly different at $P < 0.05$.

‡ NS is not significant.

pivot irrigation system. The soil series at this site is Amarillo sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) (Sanders, 1960). In March 2000, before fertilization, soil samples were taken at 63 GPS-referenced points within the 11-ha experimental area. There were 6, 7, and 8 GPS sampling points per plot in the first, second, and third replicates, respectively. On average, the density of GPS-referenced soil sampling was 0.2 ha. Ten subsamples were taken by hand soil probe, of the 0- to 15-cm depth. Two subsamples were taken of the 15- to 30-, 30- to 60-, and 60- to 90-cm depths. The surface soil samples were analyzed for Mehlich-3 P (Table 1) and other routine elements, and particle-size distribution (Table 2). Soils from all depths were analyzed for KCl-extractable NO_3–N. A blanket N fertilizer rate was calculated using an N requirement of 134 kg N ha^{-1} for a 1100 kg lint ha^{-1} yield goal (Zhang et al., 1998). The average amount of NO_3–N measured in the 0- to 60-cm profile of all GPS-referenced sampling points (19 kg N ha^{-1}) was subtracted from 134 kg N ha^{-1} to give an N fertilizer recommendation of 115 kg N ha^{-1} in 2000 (Zhang et al., 1998).

On 10 May 2000, 'Paymaster Round-up Ready 2326' ('PM 2326 RR', Delta and Pine Land Co., Scott, MS) cotton was planted into glyphosate-terminated (Monsanto Co., St. Louis, MO) wheat in 1-m rows at a seeding rate of 18 kg ha^{-1}. Nitrogen fertilizer was applied in three 38 kg N ha^{-1} applications through the irrigation system as urea ammonium nitrate (320 g N kg^{-1}) at planting, early squaring, and early bloom. On 3 July, at early squaring, biomass samples of 0.6 m from each of two rows near the GPS-referenced points were cut at ground level. Leaves and stems were dried at 65°C, weighed, ground, and analyzed for P by digestion with HNO_3 and $HClO_4$ (Jones and Case, 1990) followed by colorimetric analysis on a Lachat autoanalyzer (Lachat Instruments, Milwaukee, WI). Phosphorus accumulation was calculated from the leaf and stem dry weights, and P concentrations. Lint was hand harvested from 2-m lengths from each of four rows at each GPS-referenced point on 4 Oct. 2000. Seed cotton was ginned and lint weighed for each sample. Low energy precision application (LEPA) of irrigation was used in both years at 75% replacement of estimated evapotranspiration (Lyle and Bordovsky, 1981). In LEPA irrigation water is delivered through plastic socks that drag on the ground of every other furrow. Between 1 May and mid-September 2000, 155 mm of rain was recorded and 310 mm of irrigation water was applied.

In spring 2001, the soil sampling practices and soil analyses were conducted as in 2000 to evaluate residual effects of 2000

Table 2. Selected soil properties by landscape position (Lamesa) and by soil series (Ropesville), spring, 2000.

Soil properties	North-facing sideslope	Bottom slope	South-facing sideslope	SE of the difference	North-facing sideslope vs. bottom slope	South-facing sideslope vs. bottom slope
				Lamesa		
Sand, g kg^{-1}†	802	810	805	8.0	NS‡	NS
Silt, g kg^{-1}†	76.5	79.3	77.8	3.8	NS	NS
Clay, g kg^{-1}†	121	111	117	4.4	NS	NS
CEC, cmol$_c$ kg^{-1}†	9.2	8.6	9.1	3.0	NS	NS
Ca^{2+}, mg kg^{-1}†	728	654	709	43.5	NS	NS
NO_3^-–N, kg ha^{-1}§	19.5	16.3	20.6	1.8	NS	NS
Relative elev., 0–1	0.58	0.19	0.54	0.06	**	**
				Ropesville		
	Amarillo series	Portales series		SE of the difference	Amarillo vs. Portales	
Sand, g kg^{-1}†	693	566		17.1	*	
Silt, g kg^{-1}†	125	169		11.3	NS	
Clay, g kg^{-1}†	183	265		13.9	*	
CEC, cmol$_c$ kg^{-1}†	13.6	27.3		0.9	**	
Ca^{2+}, mg kg^{-1}†	1780	4510		144	**	
NO_3^-–N, kg ha^{-1}‡	18.8	22.4		2.5	NS	
Relative elev., 0–1	0.31	0.29		0.06	NS	

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

† 0- to 15-cm layer, unless noted, extract is 1 M NH_4OAc.

‡ NS is not significant.

§ 0- to 60-cm layer, extract is 2 M KCl.

P treatments and to base 2001 blanket- and variable-rate P treatments. PM 2326 RR cotton was planted on 10 May, at which time P fertilizer was applied, similar to 2000, without changing plot-treatment designations. On 28 May, the same cotton variety was replanted, after the 10 May planting was damaged by hail. As calculated above (Zhang et al., 1998), 45 kg N ha^{-1} was knifed-in preplant as urea ammonium nitrate–N (320 g N kg^{-1}) with a ground applicator on 7 May and another 45 kg urea ammonium nitrate–N N ha^{-1} was knifed-in at early squaring on 17 July 2001. Biomass was sampled from 0.6-m lengths from each of two rows near the GPS points at early squaring and analyzed for P. Lint harvest (2 m each from four rows per GPS point) was on 9 Oct. 2001, and ginning was done a few days later. Rainfall from 1 May to mid-September 2001 was 128 mm and supplemented with 368 mm applied through irrigation.

Ropesville

The Ropesville site is 50 km southwest (33°26′ N; 102°5′ W) of Lubbock, TX, and the study area was 11 ha under a 48-ha center-pivot irrigation system. There are two soil series at this site, Amarillo sandy loam and sandy clay loam and Portales sandy clay loam (fine-loamy, mixed, superactive, thermic Aridic Calciustolls) (USDA-NRCS, 1999). Before fertilization in March 2000, soil samples were taken at 60 GPS-referenced points in the 11-ha study area in the same manner as described for the Lamesa site. Particle-size distribution, routine elements, NO_3–N (Table 2), and Mehlich-3 P (data in text) were analyzed as described above. There were 5, 7, and 8 GPS points per plot in the first, second and third replicates, respectively. On average, the density of GPS-referenced soil sampling was 0.2 ha. On 6 May 2000, PM 2326 RR cotton was planted into glyphosate-terminated wheat in 1-m rows at a seeding rate of 18 kg ha^{-1}. Urea was broadcast applied once with a ground rig at 116 kg N ha^{-1} (calculated as described above, Zhang et al., 1998), before an irrigation 3 wk after planting.

At early squaring (7 July), 0.6-m lengths of biomass from each of two rows were sampled near the GPS points. Leaves and stems were dried at 65°C, weighed, ground, and analyzed for P. Lint was hand harvested on 29 September from 2-m lengths from each of four rows at the GPS points. All seed cotton samples were ginned and the lint weighed. Rainfall from 1 May to mid-September in 2000 was 305 mm and irrigation (LEPA irrigation at 75% replacement of estimated ET) totaled 175 mm.

On 2 May 2001, PM 2326 RR cotton was planted into glyphosate-terminated wheat in 1-m rows at a seeding rates of 18 kg ha^{-1}. On 4 May, 25 kg urea ammonium nitrate–N (320 g N kg^{-1}) was applied through the irrigation system. A hailstorm with 150 mm rain on 25 May destroyed the 2 May planted cotton at the four-leaf stage. The wet soil conditions precluded any possibility of replanting cotton before the 5 June cutoff date for cotton crop insurance. On 25 June 2001, 'Asgrow 94B81 Roundup Ready' soybean was planted at a seeding rate of 45 kg seed ha^{-1}. Granular *Bradyrhizobia* inoculant was applied at 5 kg ha^{-1} at planting.

Biomass was sampled at early bloom (R1–R2) on 9 August from 0.6-m lengths from each of two rows. Leaves and stems were dried at 65°C, weighed, ground, and analyzed for P. Chlorosis of soybean leaves in the Portales soil prompted the producer to make a foliar application of 2.2 kg $FeSO_4$–Fe ha^{-1} to the entire field on 20 August at beginning pod (R3). Soybean pods were hand harvested on 2 October from 2-m lengths from each of four rows for each GPS point. Pods were threshed in a small plot thresher; and weights and moisture content of seed recorded. Irrigation for soybean was by the LEPA system at 50% replacement of estimated evapotranspiration. Rainfall from late June to mid-September in 2001 was 78 mm and supplemented with 120 mm through irrigation events.

Statistical Analysis

A spatial joining of the elevation data and the northing and easting coordinates of the 60 or 63 records of GPS-referenced soil and plant sampling data was done with ArcView GIS 3.2 (ESRI, 1992). The elevation data was first interpolated with the Interpolate Grid routine by inverse distance to a square with 12 neighbors. The Create Buffers routine was used to create 12-m diameter zones centered on each of the GPS points. Next, the Summarize Zones routine averaged the interpolated elevation values in each buffer zone at each GPS point and added this column of data to the existing table of 60 or 63 records of soil and plant data (ESRI, 1992). The number of interpolated elevation data values in each 12-m diameter zone from which averages were calculated ranged from 4 to 6.

Analysis of variance (ANOVA) was performed for each site-year on the dependent variables biomass, leaf P, P accumulation, and lint or grain yield. PROC MIXED (SAS Inst., 1999) was used for analysis of variance of each site-year with replicate and interaction of replicate by other sources of variation assigned as random. Phosphorus treatment (all 4 site-years), landscape position (Lamesa) and soil series (Ropesville), P treatment × Landscape position (Lamesa) and P treatment × Soil series (Ropesville) were considered fixed. Landscape position was included in the ANOVA for Lamesa because previous research at Lamesa indicated that crop yields and P response differs between sideslope and bottomslope positions (Bronson et al., 2001; Li et al., 2001). In addition to replicates (3), and P treatments (3), the ANOVA included landscape position (north-facing sideslope, bottomslope, and south-facing sideslope, delineated with the elevation data). One disadvantage of this approach is that landscape position is not replicated nor randomized. However, the three landscape positions did span all three replicates (Fig. 1a) and therefore the statistical test for P treatment × Landscape position is a strong point of this design (Nelson and Buol, 1990). The error term used to statistically test P treatment at both sites was Replicate × P treatment. The Replicate × Landscape position term was used to test landscape position. Phosphorus treatment × Landscape position was tested with the Replicate × P treatment × Landscape position term.

Soil series was included in the ANOVAs for Ropesville because of the two large and distinct soil series mapped by USDA-NRCS in the most recent soil survey (USDA-NRCS, 1999). The producer at Ropesville has reported that in most years, crop growth is poorest on the calcareous Portales soil, compared with the Amarillo soil. Fleming et al. (1999) reported that farmer knowledge is valuable in delineating productivity zones in farmers' fields. Elevation (Table 2) and landscape position are similar between the two soil series at Ropesville. Soil series is not replicated, but the two soil series spanned all three replicates (Fig. 1b). The error term used to statistically test soil series was Replicate × Soil series. Phosphorus treatment × Soil series was tested with the Replicate × P treatment × Soil series term.

Standard errors of difference for simple and interaction means were calculated. If the main P fertilizer effect *F* test was significant in the ANOVA at either site, then least significant differences were calculated to separate P fertilizer treatment means. Single degree of freedom (df) contrasts were calculated to separate interaction means. The contrasts "North-facing

Table 3. Effect of landscape position on leaf P, biomass and P accumulation at early squaring, and lint yield, Lamesa, TX, 2000 and 2001.

	2000				2001			
Landscape position	**Leaf P**	**Biomass**	**P accumulation**	**Lint**	**Leaf P**	**Biomass**	**P accumulation**	**Lint**
	g kg^{-1}	kg ha^{-1}			g kg^{-1}	kg ha^{-1}		
North-facing sideslope	3.6	623	1.91	707	3.5	751	2.30	1026
Bottomslope	3.8	629	2.07	792	3.7	735	2.47	1150
South-facing sideslope	3.4	499	1.46	620	3.4	652	1.97	941
SE of difference	0.10	35.5	0.12	30.7	0.06	45.7	0.16	32.2
North-facing sideslope vs. bottom slope	NS †	NS	NS	*	*	NS	NS	*
South-facing sideslope vs. bottom slope	*	*	*	**	*	NS	*	**

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
† NS is not significant.

sideslope vs. bottomslope" and "South-facing sideslope vs. bottomslope" were calculated at Lamesa. The contrast "Amarillo soil vs. Portales soil" was calculated for Ropesville, which is identical to the F test for soil in the mixed ANOVA. Additionally, the single df contrast "Average of variable-rate P and blanket-rate P vs. zero P" was calculated for each landscape position at Lamesa, and for each soil series at Ropesville.

Simple correlation analysis (PROC CORR; SAS Inst., 1999) was done with all 60 or 63 data points within site-years. Slope of the row was calculated from the elevation data. The correlations were performed by site-years and included the variables biomass, leaf P, P accumulation, and lint or grain yield, all measured soil parameters, relative elevation, and slope of the row.

RESULTS AND DISCUSSION

Lamesa

At Lamesa, relative elevation was negatively correlated in 2000 and 2001 (-0.35 to -0.42) with biomass, P accumulation at early squaring, and with lint yield. Soil properties, in general, did not affect measured plant parameters at Lamesa in either year (data not presented). Greater lint yields on the lower lying bottomslope at this site were also reported by Li et al. (2001, 2002) and Bronson et al. (2001). Li et al. (2001, 2002) measured greater soil water content in the bottomslopes, presumably due to runoff of rain and irrigation. Slope of the row, however, had stronger negative relationships with leaf P, biomass, P accumulation at early squaring, and lint yield (-0.34 to -0.55) than did elevation in both years. We therefore, redelineated our landscape positions using slope of the row data instead of relative elevation (Fig. 1a). The bottomslopes were defined as having slope with the row <0.4%. Soil properties did not differ among landscape positions (Table 2).

Leaf P at early squaring in 2000 and 2001 was greater in the bottomslope than in the south-facing sideslope (Table 3). At early squaring in 2001, both sideslopes had less leaf P than in the bottomslope. Cotton biomass at early squaring followed a similar trend with landscape in 2000, but in 2001 there was no landscape effect (Table 3). Phosphorus accumulation at early squaring was greater in the bottomslope than in the south-facing sideslope in both years (Table 3). Less biomass at early squaring in 2000 compared with 2001 was due to cooler than average temperatures in May and June 2000.

Early squaring leaf P was not affected by P fertilizer in 2000 (data not shown). Leaf P in 2001 was enhanced with variable-rate and blanket-rate P compared with zero P in the bottomslope (data not shown), and in the south-facing sideslope at early squaring (Table 4). Leaf P concentration in both years at Lamesa was above the critical level of 3 g P kg^{-1} suggested by Plank (1979) and Jones et al. (1991), which separates sufficiency from deficiency. Cotton biomass and P accumulation at early squaring were not affected by P fertilizer in either year (data not shown).

Lint yields were greatest in the bottomslope during both years of the study (Table 3). As mentioned above, water was apparently redistributed to the bottomslope in this location, resulting in greater plant growth. The greater overall lint yields in 2001 compared with 2000 may have been related to the greater early season growth in 2001. Additionally, strong insect pressure was observed in the second half of the season in 2000, but not in 2001. Fruit damage from beet army worms (*Spodoptera exigua* Hubner) and boll weevils (*Anthonomus grandis grandis* Boheman) was common in 2000, as was leaf damage from cabbage loopers (*Trichoplusia ni* Hubner).

Lint yield response to P fertilizer was less consistent than landscape position. Phosphorus fertilizer did not affect lint yields in 2000 in any landscape position (data not shown). In 2001, Lamesa lint yields responded to variable-rate and blanket-rate P in the south-facing sideslope only (Table 4). This reflects the low soil test P level of 8.1 mg P kg^{-1} in the zero P plots of that landscape position in spring 2001 (Table 1). Averaged across landscape positions, lint yields were similar among variable-rate, blanket-rate P, and zero P treatments in both years (data not shown). Lack of response to P in 2000 and in 2001 in the other landscape positions suggests that there may be some P reserves in the soil based on P soil fertility recommendations at these soil test levels (Anderson and Bullock, 1998). Another possible factor is

Table 4. Effect of P fertilization on leaf P at early squaring and lint yield at the south-facing sideslope, Lamesa, TX, 2001.

P treatment	**Leaf P**	**Lint yield**
	g kg^{-1}	kg ha^{-1}
Variable-rate P	3.5	970
Blanket-rate P	3.7	991
Zero P	3.1	861
SE of difference	0.14	55.5
P fertilized vs. zero P	**	*

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

enhanced P availability to cotton by vesicular–arbuscular mycorrhizae (Pugh et al., 1980). Zak et al. (1998) reported that the terminated-wheat cotton system has greater levels of vesicular–arbuscular mycorrhizae colonization than conventional cotton in the Southern High Plains.

In 2000, greater P was applied to the variable-rate plots (18.2 kg P ha^{-1} on average) than to the blanket plots (14.7 kg P ha^{-1}) (Fig. 1a), in part because plots randomly assigned to blanket-rate P treatments had greater Mehlich-3 P than the variable-rate P or the zero P plots (Table 1). Mehlich-3 P in spring 2001 increased from spring 2000 levels in the variable-rate plots, but not in the blanket-rate plots, possibly reflecting the difference in P rates. Constant Mehlich-3 P in the blanket-rate and zero P plots was not surprising. Other studies have reported slow increases in levels of extractable P levels in soil (1–1.7 kg P ha^{-1} yr^{-1}) with P fertilizer applications <20 kg P ha^{-1} in long-term cropping systems on alkaline and acidic soils (Selles et al., 1995; Otto and Kilian, 2001). Extractable P remained stable in zero P plots in these same studies (Selles et al., 1995; Otto and Kilian, 2001). On average in 2001, 47% less P was applied to the variable-rate plots than to the blanket-rate plots, despite similar Mehlich-3 P levels (Table 1).

Ropesville

At Ropesville, soil Ca^{2+} was negatively correlated with leaf P, P accumulation, and biomass at early squaring (−0.74, −0.51, and −0.40, respectively). High soil Ca^{2+} levels were associated with the calcareous Portales soil, on the west half of the Ropesville study site. This soil is grayish-brown in color and has many small $CaCO_3$ nodules on the surface. The Amarillo soil on the east half of the study area is reddish-brown in color, with essentially no $CaCO_3$ nodules. Unlike the Lamesa site, there were no correlations between elevation or slope with the row and plant measurements. As mentioned earlier, we decided to incorporate the two obvious soil series in our data sets, and incorporate soil series and Soil series × P management into the ANOVA (Fig. 1b). We made slight adjustments to the soil survey map unit lines that were mapped without benefit of GPS, based on our GPS-referenced, 0.2-ha grid soil sampling and analysis. Soil Ca^{2+} was the most obvious soil measure to base the partition between the two soil series as Portales is a calcareous soil and Amarillo is not (Table 2).

At early squaring of cotton in 2000, leaf P concentration was not affected by added P (data not shown). However, leaf P and P accumulation was lower in the Portales soil compared with the Amarillo soil (Table 5). Average leaf P concentration in the Portales soil was at the critical level of 3 g P kg^{-1} suggested by Plank (1979) and Jones et al. (1991). Biomass and P accumulation responded to blanket-rate and variable-rate P compared with zero P, but only in the Amarillo soil (Table 6). Apparently soil and added P was less available on the calcareous Portales soil. In alkaline soils, relatively insoluble Ca–P compounds such as dicalcium phosphate and octocalcium phosphate are dominant (Lindsay et al., 1989). Phosphorus is also adsorbed on $CaCO_3$–calcite surfaces, and only released on dissolution of the $CaCO_3$ (White, 1980; Freeman and Rowell, 1981). Similar to early squaring biomass and P accumulation, a lint yield response to P was observed in the Amarillo soil only (Table 6). However, averaged across P management, lint yields were similar between soil series (Table 5). The reason for this result is not clear; however, it is possible that plant-available P was released from Ca–P compounds in the Portales soil between squaring and harvest. Averaged across soil series, there was no difference in lint yield among the variable-rate, blanket-rate P, or zero P treatments (data not shown).

Table 5. Effect of soil series on cotton leaf P, biomass and P accumulation at early squaring, and on lint yield, Ropesville, TX, 2000.

Soil series	Leaf P	Biomass	P accumulation	Lint yield
	g kg^{-1}		kg ha^{-1}	
Amarillo	3.5	771	2.22	690
Portales	3.0	618	1.54	683
SE	0.08	38.9	0.11	25.3
Amarillo vs. Portales	*	NS †	*	NS

* Significant at $P < 0.05$.
† NS is not significant.

Table 6. Effect of P fertilization on cotton biomass and P accumulation of early squaring and on lint yield for Amarillo soil series, Ropesville, TX, 2000.

P treatment	Biomass	P accumulation	Lint yield
		kg ha^{-1}	
Variable-rate P	875	2.56	743
Blanket-rate P	833	2.42	724
Zero P	605	1.67	602
SE	76.3	0.22	42.9
P fertilized vs. zero P	*	*	*

* Significant at $P < 0.05$.

Similar to the 2000 cotton results, negative correlations between soil Ca^{2+} and soybean leaf P (−0.29), P accumulation (−0.67), and biomass (−0.58) at early bloom were observed in 2001. As with cotton in 2000, elevation did not affect soybean grain yields. However, there was a negative correlation between grain yield and slope of the row (−0.34), similar to the report of Kravchenko and Bullock (2000) for soybean in Illinois and Indiana. We also observed a negative correlation between clay content and grain yield (−0.50). The Portales soil has greater clay content than Amarillo (Table 2). However, we did not observe a correlation between grain yield and soil Ca^{2+}. We do not believe this suggests a redelineation of the two soil series. The presence of $CaCO_3$ clearly best distinguishes the Portales and the Amarillo soils. Clay content is less important, as sandy clay loams of both soil series exist in this field.

At early bloom of soybean (R1–R2), leaf P concentrations were greater with variable-rate and blanket-rate P than with zero P, but only in the Amarillo soil (data not shown). Averaged across P treatments, soil series

Table 7. Effect of soil series on soybean leaf P, biomass and P accumulation at early bloom (R1 to R2) at Ropesville, TX, 2001.

Soil series	Leaf P	Biomass	P accumulation
	g kg^{-1}	kg ha^{-1}	
Amarillo	3.0	465	1.35
Portales	2.8	289	0.79
SE	0.07	34.5	0.08
Amarillo vs. Portales	NS †	*	**

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
† NS is not significant.

did not affect leaf P at early bloom (Table 7). Biomass and P accumulation at early bloom were not affected by P fertilizer, but were lower in the Portales soil compared with the Amarillo soil (Table 7). A weak negative correlation between soil Ca^{2+} and leaf P (−0.29) was not as strong as the correlation between soil Ca^{2+} and leaf Fe (−0.55). Iron deficiency may have occurred in the Portales soil for the first half of the season.

Grain yields of soybean averaged 1.2 Mg ha^{-1} and were not affected by soil series or P management (data not shown). This similar result to the cotton probably reflects recovery and compensation from early season P and Fe deficiencies. The soybean grain yields were low, however, due to the late planting date and the limited irrigation in a drought year.

Ten percent less P was applied at Ropesville with variable-rate P than with blanket-rate P to cotton in 2000, while this value was 58% less P for the soybean crop in 2001. Averaged across soil series, Mehlich-3 P in 2001 did not increase with P fertilization. Mehlich-3 P in both 2000 (mean 13.6 mg kg^{-1}), and 2001 (mean 17.2 mg kg^{-1}) did not differ by soil series. Mehlich-3 P, however, was greater in the P-fertilized plots in the Portales soil in 2001 (20.1 mg kg^{-1}) than in 2000 (14.3 mg kg^{-1}). This may have been due to release of fertilizer P applied in 2000 that was adsorbed on $CaCO_3$ particles in the Portales soil.

Discussion of Both Sites

Yield responses between the P-fertilized treatments and zero P control were observed in just one of six landscape position–year combinations at Lamesa, and in only one of four soil series–year combinations at Ropesville. The lowest Mehlich-3 P level in soil we measured in these studies was 8 mg P kg^{-1} in the south-facing sideslope that had a lint yield response to P in Lamesa in 2001. Due to limited numerator degrees of freedom (df), we could not statistically compare measured dependent variables between variable-rate P and blanket-rate P within the three landscape positions at Lamesa or within the two soil series at Ropesville. This was because there were only 2 df associated with Soil series × P treatment and only 4 df for Landscape position × P treatment. We decided that the most important single df contrasts were the average of variable-rate and blanket-rate P vs. zero P within each soil series at Ropesville and within each landscape position at Lamesa. However, our findings that 38% less P fertilizer was used in 3 of the 4 site-years with variable-rate P compared with blanket-rate P is notable. More research is needed to further assess possible savings in fertilizer rates with variable-rate fertilization.

It is clear that the impact of P fertilizer on early squaring and early bloom leaf P, biomass, P accumulation, and yields was inconsistent, and not always related to Mehlich-3 P (Bronson et al., 2001). Funderburg et al. (1996) observed no cotton response to P additions on soils that tested between 18 and 38 mg Mehlich-3 P kg^{-1}. Ortega et al. (1997) reported inconsistent response of wheat to P fertilizer on a landscape-scale study. They stated that at one site, 72% of their sample points were <14 mg $NaHCO_3$–P kg^{-1} (critical level in Colorado) yet only 38% of these points responded to added P. As mentioned earlier, mycorrhizal colonization may have enhanced P availability above that reflected in the Mehlich-3 soil tests. Finally, Kachanoski and Fairchild (1996) reported that soil test calibrations derived from small plots with low variability will underpredict fertilizer recommendations for highly variable sites. Their conclusions were based on stochastic equations describing N fertilizer response in corn in Ontario.

The 2-yr cotton data at Lamesa demonstrated that landscape position–slope of row had greater impact on early season growth and P accumulation than P fertilizer management. This result was shown with both landscape position in the ANOVAs, and with slope and elevation in the correlations. The trend of larger bottomslope yields may suggest a greater importance of soil water relations compared with P fertility, as Li et al. (2001, 2002) measured greater soil water in the bottomslope at this same site. Unlike the report of Bronson et al. (2001), we did not find that P response differed by landscape position, as the lint yield response in the south-facing sideslope was probably associated with the low (8 mg P kg^{-1}) Mehlich-3 P level. At Lamesa in 2001, the greater lint yields in the bottomslope compared with both sideslopes (Table 3) were apparently not related to soil test P levels, which were similar among landscape positions (Table 1). However, greater early season leaf P, biomass, and P accumulation in 2000 in the bottomslope compared with the south-facing sideslope, but similar to the north-facing sideslope (Table 3) reflected Mehlich-3 P levels in the soil in spring 2000 (Table 1).

Results at Ropesville indicated that even for two different crops in 2 yr, soil series consistently affected early season growth and P uptake. The ANOVAs with soil series and the correlations with soil Ca^{2+} indicted the importance of soil series and soil Ca^{2+} at Ropesville. Phosphorus fertilizer management affected early season growth and P accumulation less than did soil series. The calcareous nature of the Portales soil was apparently the dominant soil property that led to depressed growth and plant P relative to the Amarillo soil. Other soil or site properties of the two soil series were apparently less important. Slope of the row was similar between soil series (0.6% for Amarillo and 0.7% for Portales). The greater clay content in the Portales soil profile compared with Amarillo soil can be related to slightly greater available water holding capacity in Portales soils (Blackstock et al., 1979). The lower biomass and leaf P accumulation in the Portales soil compared with the Amarillo soil may suggest that soil Ca^{2+} was more influential than clay or water relations. Soil series affected yield response to P fertilizer in the cotton crop, but not in soybean. This may have been because the yield potential was low in the late-planted, limited-irrigated soybean.

CONCLUSION

Landscape position and slope had significant impact on cotton yields in both years, but not on P fertilizer response. Calcareous vs. noncalcareous soil series affected early season growth and P accumulation in both years, and yield response to added P in 1 yr.

Few responses to variable-rate and blanket-rate P were observed among the 4 site-years. Two cases of lint yield response to P were on soils testing 8 and 13.6 mg Mehlich-3 P kg^{-1}, suggesting that 33 mg Mehlich-3 P kg^{-1} may be too high of a critical soil test P level for cotton. Variable-rate P fertilization did not produce greater lint yields than blanket-rate P. This study demonstrated that there is potential for P fertilizer savings with variable-rate fertilization. However, more research is needed to determine if fertilizer savings are consistent and widespread enough to offset the additional costs of intensive soil sampling, analysis and specialized equipment that variable-rate fertilization requires.

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