Phosphorus Fertilization of Late-Planted Winter Wheat into No-Till Fallow

L. K. Lutcher,* W. F. Schillinger, S. B. Wuest, N. W. Christensen, and D. J. Wysocki

ABSTRACT

Winter wheat (*Triticum aestivum* L.) is planted in low precipitation areas of north-central Oregon and east-central Washington after 14 mo of tilled fallow. No-till fallow (NTF) is an alternative to the tillage-based method. The disadvantage of NTF is the loss of seed-zone moisture and inability to plant early. Delayed plant growth and reduced grain yield (GY) associated with late planting in NTF may be offset by P fertilization. We conducted a field experiment at three locations for 3 yr to evaluate effects of 0, 5, and 15 kg ha^{-1} of P fertilizer on plant P concentration (PPC), dry matter accumulation (DMA), P uptake (PU), spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and GY. Soft white winter wheat was planted into NTF during the third week of October. Phosphorus fertilizer was placed below and beside the seed while planting. Application of 5 and 15 kg ha^{-1} P increased PPC and/or DMA and enhanced overall PU by 0.6 and 1.7 kg P ha^{-1}, respectively. Corresponding increases in SPU were equal to 35 and 55 spikes m^{-2}. Phosphorus application had no effect on KW or KPS. The 5 kg ha^{-1} P treatment increased overall GY by 4.4%. The 15 kg ha^{-1} P treatment increased overall GY by 7.6%. Significant GY responses to P application, across sites, ranged from 2.2 to 14.5%. Improvement in P nutrition and increases in SPU and GY were observed at sites where initial soil test P (STP) levels were <12 mg kg^{-1}.

The winter wheat–fallow rotation has been the dominant cropping system in low precipitation areas of the Inland Pacific Northwest since 1890. Tillage is conducted (1.5 million ha) in the spring of the fallow year to establish a low bulk density soil mulch that retains moisture in the seed-zone. Subsequent tillage operations are used to maintain the mulch and control weeds. Tilled fallow allows for early (late August to mid-September) planting and production of maximum yield, but wind erosion is a major soil loss and air quality concern (Papendick, 2004). Delayed and reduced tillage minimizes wind erosion (Schillinger, 2001; Janosky et al., 2002), but the problem could be essentially eliminated if farmers used NTF. Optimism about NTF, now practiced on 70,850 ha, is tempered by GY reductions that are a consequence of late planting (Donaldson et al., 2001). Planting of NTF in mid-October, or later, after the onset of fall rains, is necessary because seed-zone moisture for early planting is frequently less than that required for uniform germination and emergence (Oveson and Appleby, 1971; Lindstrom et al., 1974; Hammel et al., 1981; Schillinger and Bolton, 1993).

Yield reductions from late planting may be offset, to some extent, by P fertilization. Research conducted in tilled fallow suggests that response to applied P occurs more often when winter wheat is planted late in the fall (Pumphrey and Rasmussen, 1982). Similar results have been reported for annually-cropped wheat in higher rainfall areas (Blue et al., 1990; Sander and Eghball, 1999). The primary objective of this research was to determine if P fertilization would improve the GY of late-planted winter wheat in a low-rainfall, NTF system. Secondary objectives were to evaluate effects of fertilization on P nutrition and components of yield.

MATERIALS AND METHODS

A field experiment was conducted at three locations during the 2003–2004, 2004–2005, and 2005–2006 crop years. These locations will hereafter be referred to as the north, south, and southeast regions. North region field sites were on the Washington State University Dryland Research Station near Lind (47° N, 118°35′59.9′′ W) in Adams County, Washington. Sites in the south region were established on privately-owned farmland (45°30′ N, 119°42′ W) in Morrow County, Oregon. Southeast region sites were in Umatilla County, Oregon on privately-owned land (45°42′ N, 119°5′59.9′′ W) leased by the USDA-ARS. Soils are mapped as a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) or Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambid). These closely-related soils are representative of 1.57 million dryland hectares on the Columbia Plateau. They

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Abbreviations: DMA, dry matter accumulation; GY, grain yield; KW, 1000 kernel weight; KPS, kernels per spike; NTF, no-till fallow; PPC, plant phosphorus concentration; PU, phosphorus uptake; SPU, spikes per unit area; STP, soil test phosphorus.

are characterized by low organic carbon (5.2–5.5 g kg^{-1}), pH values that vary from 6.5 to 7.2, and a cation exchange capacity of 10 to 13 $cmol_c$ kg^{-1}. Average, annual precipitation ranges from 240 mm in the north region to 290 mm in the southeast region. There are fewer growing degree-days in the north region where fall and winter temperatures are lower. Air temperatures in the southeast region usually exceed those in the north and south region during most or all months of the year.

Soft white winter wheat was planted during the third week of October after 15 mo of NTF. Cultivars were 'Eltan' in the north region, 'Tubbs' in the south region, and 'Stephens' in the southeast region. Selected cultivars have a proven performance record in their respective regions. Planting rate was approximately 216 seeds m^{-2}. Planting was accomplished using a customized Fabro plot drill equipped with narrow hoe-type openers (Fabro Enterprises, Ltd., Swift Current, SK) on 30-cm row spacing, or a Cross-Slot drill equipped with notched, coulter disc openers (Baker No-Tillage, Ltd., Fielding, NZ) on 20-cm spacing. The Cross-Slot drill was used at north region sites in 2003–2004 and 2004–2005. The Fabro drill was used at all other (seven) sites. Seed was treated (0.06 L 100 kg^{-1}) with a slurry of 32.8% difenoconazole (1-{2-[2-chloro-4-(4-chlorophenoxy)phenyl]-4-methyl-1,3-dioxolan-2-ylmethyl}-1H-1,2,4-triazole) before planting.

Treatments were three P application rates (0, 5, and 15 kg ha^{-1}) applied to plots 2.4 by 50 m in a randomized complete block design with four replications. Phosphorus fertilizer, banded 5 cm below and 2.5 cm beside the seed, was applied through the Fabro drill as triple superphosphate (0–45–0). Urea (46–0-0) was applied simultaneously with P and at a uniform rate across treatments. Ammonium polyphosphate (10–34–0) was used with the Cross-Slot drill. Urea-ammonium nitrate (solution 32) was applied with 10–34–0 to achieve desired N rates. Nitrogen rates varied from 15 to 40 kg N ha^{-1} and were based on recommendations in the Oregon State University fertilizer guide for winter wheat in summer fallow systems (Lutcher et al., 2007).

Effective weed control during the fallow cycle was achieved with a late-fall tank mix application of glyphosate [*N*-(phosphonomethyl)glycine] plus a water dispersible, granular formulation of sulfentrazone {*N*-[2,4-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]phenyl]methanesulfonamide}. Sulfentrazone is a soil residual herbicide used by farmers to control Russian thistle (*Salsola iberica* Sennen & Pau)—one of the most common and troublesome weed species in low-rainfall, fallow-based systems. A second glyphosate application in March or April was used to control broadleaf weeds and downy brome (*Bromus tectorum* L.) or volunteer wheat that emerged after the initial (late-fall) application. Glyphosate was applied in the fall and spring at a rate of 0.42 kg ae ha^{-1}. Sulfentrazone was applied at a rate of 0.21 kg ai ha^{-1}. In-crop weed control was accomplished by applying labeled rates of bromoxynil (3,5-dibromo-4-hydroxybenzo-nitrile) + MCPA [(4-chloro-2-methylphenoxy)acetic acid] when wheat was tillering and weed species were small and actively growing.

Initial STP levels (Table 1) were determined from samples collected in September of the crop year. Four soil samples were removed from the 0 to 30 cm depth at randomly-selected positions in each quadrant of the experimental area at each of the nine sites. Soil from each quadrant was combined into a single composite sample. Composited samples were air-dried and ground to pass a 2-mm sieve before extraction and analysis (Olsen et al., 1954). Initial STP levels encountered during this experiment fall within the range of values normally reported by local soil testing laboratories. Corresponding indices of plant-availability range from "low" to "high."

Table 1. Initial soil test phosphorus (STP) levels and resin P values for sites in the north, south, and southeast regions, by year.

Year	STP†			Resin P‡		
	North region	South region	Southeast region	North region	South region	Southeast region
	mg P kg^{-1}			µg PO_4–P cm^{-2}		
2003–2004	14.3	9.4	6.8	1.40	1.18	1.26
2004–2005	12.5	8.7	16.1	1.23	1.70	2.04
2005–2006	11.1	11.7	13.5	0.74	1.01	2.27

† $NaHCO_3$–extractable P values for samples (0–30 cm depth) collected in the fall before seeding.

‡ Measured during the growing season in control (0 kg ha^{-1} P fertilizer) plots only.

Resin P (Table 1), measured in late March to early April of the growing season (Feekes growth stage 5), was determined by quantifying the concentration of phosphate adsorbed to synthetic, anion-exchange resins (Skogley and Dobermann, 1996). Synthetic, anion-exchange resins, placed in the soil for 48 h, were rectangular (2.5 by 7.5 cm) sheets saturated with $NaHCO_3$. A single sheet of resin was oriented vertically into a 10-cm-deep hole made with a 9-cm diam. sampling auger. One side of the sheet was pressed against the undisturbed face of soil that extended from the 2.5 to 10 cm depth. The other side of the sheet was covered with backfill soil initially removed with the sampling auger. This process was repeated until three sheets of resin were placed in-row at each of three randomly-selected locations within control (0 kg ha^{-1} P fertilizer) plots. Once removed from the soil, sheets were cleaned with a toothbrush and distilled water. Cleaned sheets of resin were shipped to the Central Analytical Laboratory at Oregon State University where they were placed in quart-sized, ziplock freezer bags (three sheets per bag) containing 150 mL of 0.5 mol L^{-1} HCl. The bags were sealed and placed on an oscillating, slow-speed mechanical shaker for 2 h. The concentration of extracted phosphate was measured using an inductively coupled plasma–atomic emission spectrophotometer (ICP-AES). Resin P values, reported as µg PO_4–P cm^{-2} of anion exchange resin, were calculated from extract concentrations and membrane surface area. Measurements of resin P were used to estimate the flux of P diffusion in soil. We used these estimates, in conjunction with STP data, to improve our understanding of treatment effects.

Meter-row sampling for PPC and DMA occurred in mid-to-late April when the first node on the main stem of wheat plants was detectable just above the soil surface. Plants were cut at ground level, placed in paper bags, and dried at 65°C for 5 d. Dry matter accumulation was estimated by weighing dried plant samples on a digital scale with 0.01-g accuracy. Plant P concentration was determined using a dry ash by ICP–AES procedure (Gavlak et al., 1994). Spikes per unit area was measured by counting the number of spikes along 1 m of row. Spikes were clipped and threshed, and KW was determined using an electronic seed counter. Kernels per spike was calculated from KW and SPU. Sampling for PPC, DMA, and yield component determinations occurred at three randomly-selected locations in each plot. Collected plants, or spikes,

Table 2. Analysis of variance for overall plant phosphorus concentration (PPC), dry matter accumulation (DMA), phosphorus uptake (PU), spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and grain yield (GY).

Source	df	Mean square						
		PPC	DMA	PU	SPU	KW	KPS	GY
Year (YR)	2	0.873	1,805,917	17.644	22,413	56.446	97.871	3,042,121
Region (REG)	2	1.536	9,803,822	96.899	95,640	699.937	722.363	35,334,856
YR × REG	4	0.608	2,141,282	24.483	51,159	18.405	76.976	3,935,984
YR × REG × Rep (Error)	27	0.120	258,510	2.358	1,300	5.507	15.503	77,957
P Rate (PR)	2	0.670	1,871,675	23.667	27,729	0.938	15.414	438,988
YR × PR	4	0.017	104,891	0.427	1,409	0.850	2.624	8,758
REG × PR	4	0.044	69,675	0.350	1,080	2.796	11.435	31,065
YR × REG × PR	8	0.083	59,859	1.301	573	2.479	2.562	32,563
YR × REG × PR × Rep (Error)	54	0.046	53,141	0.395	939	3.96	6.557	16,189

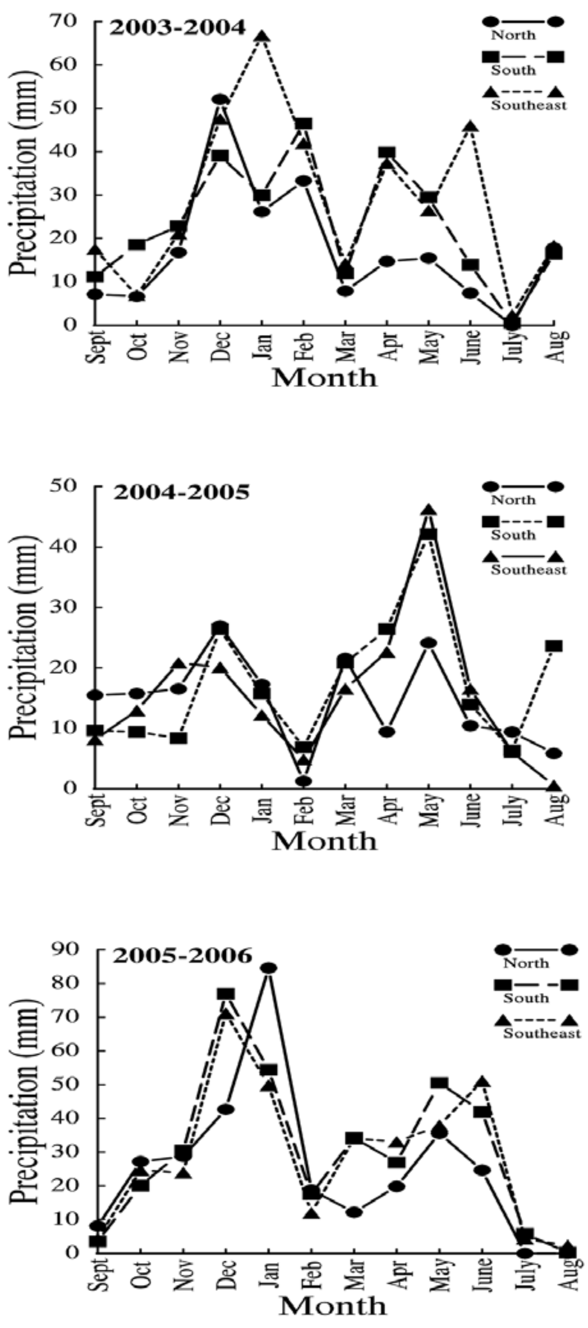

Fig. 1. Monthly precipitation in the north, south, and southeast regions, by year.

were composited into a single sample before being dried, weighed, processed, or analyzed. Border rows were not used for sampling. Wheat was harvested from the center of plots using a research combine equipped with a 1.5-m cutting platform. Grain yield was calculated from the weight of harvested grain after adjustment to 10% moisture. The 10% adjustment was used because it is a better approximation of grain moisture contents normally encountered by local farmers and elevator operators.

Data were analyzed with the Statistix 8 program (Analytical Software, 2006; Analytical Software, Tallahassee, FL). The ANOVA/ANCOVA option was used to partition error terms and degrees of freedom among sources of variation from all nine sites (Table 2). Data from individual sites were analyzed using the model for a randomized complete block design. Overall and site-specific treatment effects were evaluated according to the orthogonal contrast procedure (Saville and Rowarth, 2008).

RESULTS AND DISCUSSION

Dependent variables were affected by a two-way (year × region) interaction. Interactions appear to be unrelated to weather conditions. The quantity and timing of precipitation (Fig. 1) and accumulation of growing degree-days (data not shown) varied over the duration of the experiment, but year-to-year trends were consistent among regions. Weeds were effectively controlled in all plots. Symptoms of damage from insect or foliar pathogens were not apparent in any region during the 3 yr this research was conducted. A chocolate-brown discoloration of stems just above the crown of plants, apparent in the north region during the second year of the experiment, was evidence of a minor crown rot infection caused by *Fusarium pseudograminearum* and *F. culmorum* (Smiley et al., 2005). Interactions may be explained by site-to-site differences in disease pressure, and/or carryover effects of sulfentrazone—a soil residual herbicide. Crop injury from sulfentrazone, evident in the north and southeast regions during 2005–2006, was expressed as leaf "banding" and a subsequent reduction in DMA and PU. Values for DMA and PU, at these sites, were lower than those observed during the previous 2 yr. This trend is contradictory to values measured in the south region. Dissimilar trends were also noted for PPC, SPU, KW, KPS, and GY. Phosphorus uptake was also influenced by a three-way (year × region × treatment) interaction. All other variables responded to treatments in a noninteractive fashion and were evaluated as main effects.

Phosphorus Nutrition

The 5 kg ha^{-1} P rate had no effect on overall PPC (Tables 3a and 3b). Overall response to the 15 kg ha^{-1} P rate was statistically significant. The magnitude of this response, compared to the control (0 kg ha^{-1} P fertilizer) and 5 kg ha^{-1} P treatment, was equal to 0.3 and 0.2 g P kg^{-1}, respectively. Treatment-induced differences were evident in the southeast region during 2003–2004 and the south region during 2004–2005 (Tables 4a and 4b). The initial STP level at these two sites was 6.8 and 8.7 mg kg^{-1}, respectively.

Overall DMA was greatest in plots treated with 15 kg ha^{-1} of P fertilizer (Table 3a). The difference in DMA, among plots treated with either the 5 or 15 kg ha^{-1} P rate, was highly significant (Table 3b) and equal to 273 kg ha^{-1}. The positive effect of P on DMA is probably related to improvements in leaf area (Mollier and Pellerin, 1999), the number of tillers per plant (Boatwright and Viets, 1966), and/or the rate at which plants grow and develop (Knapp and Knapp, 1978).

The 5 and 15 kg ha^{-1} P rates had a relatively pronounced, although similar, effect on DMA in the 2003–2004 southeast

Table 3. a. Phosphorus rate and corresponding values for overall plant phosphorus concentration (PPC), dry matter accumulation (DMA), and phosphorus uptake (PU).

P rate	PPC	DMA	PU†
kg P ha^{-1}	g P kg^{-1}	kg ha^{-1}	kg P ha^{-1}
0	2.5	1707	4.3
5	2.6	1886	4.9
15	2.8	2159	6.0

Table 3. b. Phosphorus rate contrasts for overall plant phosphorus concentration (PPC), dry matter accumulation (DMA), and phosphorus uptake (PU).

Contrast	PPC	DMA	PU†
		P > F	
P(0) vs. P(5)	ns‡	*	**
P(0) vs. P(15)	§	§	§
P(5) vs. P(15)	**	§	§

* Significant at the 0.05 level.

** Significant at the 0.01 level.

† Phosphorus uptake affected by a three-way (year × region × treatment) interaction.

‡ Nonsignificant.

§Significant at the 0.0001 level.

Table 4. a. Treatment means for plant phosphorus concentration (PPC), dry matter accumulation (DMA), and phosphorus uptake (PU) in the north, south, and southeast regions, by year.

P rate	North region			South region			Southeast region		
	PPC	DMA	PU	PPC	DMA	PU	PPC	DMA	PU
kg P ha^{-1}	g P kg^{-1}	kg ha^{-1}	kg P ha^{-1}	g P kg^{-1}	kg ha^{-1}	kg P ha^{-1}	g P kg^{-1}	kg ha^{-1}	kg P ha^{-1}
2003–2004									
0	2.9	1370	4.0	2.8	2254	6.3	2.3	2120	4.9
5	3.1	1535	4.8	2.9	2340	6.8	2.3	2707	6.2
15	3.1	1578	4.9	2.9	2642	7.7	2.9	2765	8.0
2004–2005									
0	2.6	1231	3.2	2.5	1952	4.9	2.6	2183	5.7
5	2.8	1215	3.4	2.6	1904	5.0	2.7	2271	6.1
15	2.8	1680	4.7	2.8	2256	6.3	2.8	2485	7.0
2005–2006									
0	2.4	705	1.7	2.7	2423	6.5	2.0	1121	2.2
5	2.7	1149	3.1	2.7	2481	6.7	2.0	1376	2.8
15	3.0	1576	4.7	2.8	2893	8.1	2.2	1559	3.4

Table 4. b. Phosphorus rate contrasts for plant phosphorus concentration (PPC), dry matter accumulation (DMA), and phosphorus uptake (PU) in the north, south, and southeast regions, by year.

Contrast	North region			South region			Southeast region		
	PPC	DMA	PU	PPC	DMA	PU	PPC	DMA	PU
					P > F				
2003–2004									
P(0) vs. P(5)	ns†	ns	ns	ns	ns	ns	ns	*	ns
P(0) vs. P(15)	ns	ns	ns	ns	*	*	*	*	**
P(5) vs. P(15)	ns	ns	ns	ns	ns	ns	*	ns	ns
2004–2005									
P(0) vs. P(5)	ns	ns	ns	ns	ns	ns	ns	ns	ns
P(0) vs. P(15)	ns	*	ns	**	ns	*	ns	ns	ns
P(5) vs. P(15)	ns	*	ns	ns	*	*	ns	ns	ns
2005–2006									
P(0) vs. P(5)	ns	**	*	ns	ns	ns	ns	ns	ns
P(0) vs. P(15)	ns	‡	***	ns	ns	ns	ns	ns	ns§
P(5) vs. P(15)	ns	**	**	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Nonsignificant.

‡ Significant at the 0.0001 level.

§ *P* = 0.17.

Table 5. a. Phosphorus rate and corresponding values for overall spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and grain yield (GY).

P rate	SPU	KW	KPS	GY
	spikes m^{-2}	g		kg ha^{-1}
0	267	37.5	31.2	2886
5	302	37.6	30.8	3012
15	322	37.8	29.7	3106

Table 5. b. Phosphorus rate contrasts for overall spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and grain yield (GY).

Contrast	SPU	KW	KPS	GY
			P > F	
P(0) vs. P(5)	***	ns†	ns	***
P(0) vs. P(15)	‡	ns	ns	‡
P(5) vs. P(15)	*	ns	ns§	**

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Nonsignificant.

‡ Significant at the 0.0001 level.

§ *P* = 0.11

region (Tables 4a and 4b). The 15 kg ha^{-1} P rate enhanced DMA in the north and south region during 2004–2005 when precipitation was below normal (Fig. 1). Phosphorus application at these two sites may have alleviated stunted root growth and nutrient uptake problems often associated with dry soil (Saneoka et al., 1990; Al-Karaki et al., 1995; Rodriquez et al., 1996; Singh and Sale, 2000; Jones et al., 2005). The increase in DMA, relative to the control, was equal to 36.5% (449 kg ha^{-1}) in the lower-yielding north region (STP = 12.5 mg kg^{-1}). The corresponding increase in the south region (STP = 8.7 mg kg^{-1}) was only 15.6% or 304 kg ha^{-1}. The greater response in the north region may be due to a reduced early-season P supply (Grant et al., 2001) as indicated by measurements of resin P. Greater resin P values in the south region may be the result of an accelerated rate of diffusion in the soil, but this explanation seems unlikely after review of soil water content and temperature values (data not shown). Improved early-season P supply in the south region appears to be a concentration effect and may be the result of previous farming practices. The field where this site was located has a history of NTF and intermittent, shallow band applications of P fertilizer. Nutrient stratification under these conditions is known to occur and may be the reason for the discrepancy between the initial STP level and resin P.

Phosphorus uptake was influenced by a three-way (year × region × treatment) interaction. Increased PU was apparent at four sites (Tables 3a and 3b) where initial STP levels ranged from 6.8 to 11.1 mg kg^{-1}. Responses, compared to the control, varied from 1.4 kg P ha^{-1} for the 5 kg ha^{-1} P treatment to 3.1 kg P ha^{-1} for the 15 kg ha^{-1} P treatment. Maximum PU response to the 15 kg ha^{-1} P rate, evident in the southeast region during 2003–2004 and the north region during 2005–2006 (Tables 4a and 4b), is consistent with observed increases in DMA. Differences between the 5 and 15 kg ha^{-1} P treatments were significant in the south region during 2004–2005 and the north region during 2005–2006. A trend of increased PU in the southeast region (2005–2006) was unexpected because STP and resin P values were relatively high. A possible explanation for this anomaly can be found in a subsequent paragraph that describes GY response at sites where STP levels were >12 mg kg^{-1}.

Yield Components and Grain Production

The overall effect of the 5 kg ha^{-1} P rate was a 13.1% (35 spikes m^{-2}) increase in SPU (Table 5a). The 15 kg ha^{-1} rate increased SPU by 20.6% or 55 spikes m^{-2}. Measured values were statistically different for all three P rate contrasts (Table 5b). A positive SPU response was evident at six of the nine sites (Tables 6a and 6b). Treatment effects were most pronounced in the north region (2005–2006) when growing season precipitation was greater than average, the initial STP level was 11.1 mg kg^{-1}, and resin P was relatively low (0.74 µg PO_4–P cm^{-2}).

Phosphorus had no effect on KW or KPS, although there was an overall tendency for reduced KPS in plots fertilized with the maximum application rate. This trend (Table 5b) may have been a compensating adjustment to increased tillering and SPU (Thill et al., 1978; Sander et al., 1991; Sander and Eghball, 1999; Donaldson et al., 2001).

Compared to the control, the 5 and 15 kg ha^{-1} P treatments increased overall GY by 4.4% (126 kg ha^{-1}) and 7.6% (220 kg ha^{-1}), respectively. Phosphorus application improved GY at six sites (Tables 6a and 6b) where there was a significant SPU response. The initial STP level at four of these sites was <12 mg kg^{-1}. Corresponding responses to the 5 kg ha^{-1} P rate were significant at two sites and ranged from 1.3% (37 kg ha^{-1}) to 6.1% (139 kg ha^{-1}), compared to the control. A 9.5% (275 kg ha^{-1}) response to the 15 kg ha^{-1} P rate was evident in the south region during 2004–2005. A 14% (319 kg ha^{-1}) increase to the maximum P rate was apparent in the north region during 2005–2006 when above-normal rainfall in April, May, and June improved yield potential.

There was no GY response to treatments in the south region during 2005–2006 even though initial STP and resin P values indicated a response was probable. Analysis of postharvest soil samples collected at this site revealed a moderately alkaline reaction (soil pH ranged from 7.6–8.3), a $CaCO_3$ content that varied from 10.1 to 43.0 g kg^{-1}, and an enhanced buffering capacity (0 to 30 cm depth) in 5 of the 12 plots. Phosphorus fertilizer may have been made less available in these plots by reactions with $CaCO_3$ or organic carbon-metal complexes that exist on the surface of $CaCO_3$. This hypothesis cannot be substantiated by work conducted in this experiment, but seems reasonable after review of work by others (Sharpley et al., 1989; Westermann, 1992; Robbins et al., 1999; Leytem and Westermann, 2003).

Grain yield response on soils with initial STP levels >12 mg kg^{-1} was limited to sites where suspected root injury may have been caused by soil-borne pathogens or carryover effects of sulfentrazone. Application of 15 kg ha^{-1} P increased GY, compared to the control, by 14.5% (230 kg ha^{-1}) in the north region during 2004–2005 (Tables 6a and 6b). Fusarium crown rot is a frequent problem at this location and other dryland areas of the Pacific Northwest. It is possible that P application alleviated root injury normally associated with this disease. A 10.2% (312 kg ha^{-1}) response to the 5 kg ha^{-1} P rate was observed in the southeast region during 2005–2006. Grain yield response to the maximum P rate was equal to 13% (398 kg ha^{-1}).

Table 6. a. Treatment means for spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and grain yield (GY) in the north, south, and southeast regions, by year.

P rate	North region				South region				Southeast region			
	SPU	KW	KPS	GY	SPU	KW	KPS	GY	SPU	KW	KPS	GY
kg P ha^{-1}	spikes m^{-2}	g		kg ha^{-1}	spikes m^{-2}	g		kg ha^{-1}	spikes m^{-2}	g		kg ha^{-1}
2003–2004												
0	211	32.2	38.7	1438	272	42.6	34.2	3667	403	41.9	26.9	4448
5	233	33.3	36.7	1603	289	40.7	35.4	3746	467	41.5	26.3	4638
15	224	34.6	35.3	1562	320	40.0	33.6	3739	467	42.2	25.2	4861
2004–2005												
0	245	31.7	31.8	1589	270	35.8	32.2	2901	222	40.1	26.4	3381
5	275	33.1	31.3	1720	286	35.9	32.3	2938	266	40.5	25.2	3433
15	270	32.4	28.6	1819	319	36.2	32.2	3176	284	41.1	25.6	3517
2005–2006												
0	241	33.0	30.8	2278	220	38.2	34.9	3212	318	41.8	25.3	3059
5	285	32.6	27.8	2417	258	37.9	36.9	3244	357	42.7	25.7	3371
15	324	32.9	28.5	2597	278	38.2	34.9	3223	412	42.5	23.3	3457

Table 6. b. Phosphorus rate contrasts for spikes per unit area (SPU), 1000 kernel weight (KW), kernels per spike (KPS), and grain yield (GY) in the north, south, and southeast regions, by year.

Contrast	North region				South region				Southeast region			
	SPU	KW	KPS	GY	SPU	KW	KPS	GY	SPU	KW	KPS	GY
	$P > F$											
2003–2004												
P(0) vs. P(5)	ns†	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns
P(0) vs. P(15)	ns	ns	ns	ns	*	ns	ns	‡	*	ns	ns	**
P(5) vs. P(15)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
2004–2005												
P(0) vs. P(5)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
P(0) vs. P(15)	*	ns	ns	*	***	ns	ns	**	ns	ns	ns	ns
P(5) vs. P(15)	ns	ns	ns	ns	**	ns	ns	**	ns	ns	ns	ns
2005–2006												
P(0) vs. P(5)	*	ns	ns	**	ns	ns	ns	ns	*	ns	ns	*
P(0) vs. P(15)	***	ns	ns	***	ns	ns	ns	ns	*	ns	ns	**
P(5) vs. P(15)	*	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Nonsignificant.

‡ Significant at the 0.0001 level.

Applied P, in this case, may have lessened the deleterious effect of sulfentrazone on root growth (Dayan et al., 1996, 1997; Li et al., 1999) in a manner similar to that reported for plants stressed by root pathogens (Cook et al., 2000).

CONCLUSIONS

Results from this research will be used to refine P fertilizer recommendations for low-rainfall, NTF systems. Current recommendations, which do not differentiate between fallow methods and early or late planting dates, advise against P application if initial STP levels are >15 mg kg^{-1}. Analysis of data collected from this experiment revealed a consistent PU, SPU, and GY response to P application at sites where the initial STP level was <12 mg kg^{-1}. Response at sites where the initial STP level was >12 mg kg^{-1} (and <15 mg kg^{-1}) was limited to situations where root injury may have been caused by Fusarium crown rot pathogens or carryover effects of sulfentrazone. Future efforts to evaluate effects of P fertilization might include methods to quantify the source and extent (if any) of root damage. This kind of work would be particularly useful to dryland farmers in the Pacific Northwest because they rely on soil-residual herbicides and frequently experience yield loss from soil-borne diseases that have a detrimental effect on root growth.

In this experiment, maximum benefit from fertilization was usually achieved with the 15 kg ha^{-1} P rate, but there were cases when observed responses to this treatment were no different than those resulting from the application of only 5 kg P ha^{-1}. The significant overall effect of the 15 kg ha^{-1} P rate on PU, SPU, and GY is evidence that decisions to apply more than 5 kg ha^{-1} of P fertilizer would not be unreasonable, and this appears to be particularly true during years of greater-than-average yield potential.

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