IMPROVING THE YIELDS OF LATE-PLANTED WINTER WHEAT WITH SEEDING RATE AND PHOSPHORUS FERTILITY

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of Eric D. Harwood find it satisfactory and recommend that it be accepted.

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Abstract

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Dryland wheat producers in the low rainfall zone (<450 mm annual precipitation) of eastern Washington commonly utilize winter wheat-tillage fallow rotations. Annual cropping or chemical fallow reduces wind erosion in this susceptible area. However, late seeding is required in these situations due to a lack of seed zone moisture at normal planting times. The objective of this study was to determine if phosphorus (P) fertility and/or seeding rates can be altered to improve late seeded recrop or chemical fallow winter wheat yields. Winter wheat was grown at five locations in eastern Washington in 2004-05 and three locations in 2005-06. One site was in chemical fallow and the others recropped into standing winter wheat stubble. In the first year two sites were abandoned due to pest invasions while in the second year one site was abandoned due to volunteer wheat contamination. Seeding rates were 45 and 78 kg ha^{-1}. Phosphorus rates were 0, 22, 45, 67, and 90 kg ha^{-1} P_2O_5 in 2004-05, and 0, 11, 22, 45, and 67 kg ha^{-1} P_2O_5 in 2005-06. The chemical fallow site had both early and late seeding dates while the recrop sites had only late seeding dates. Measurements included stand density, dry matter accumulation and partitioning, grain yield, yield components, and total P uptake. Averaged across seeding rates, grain yield at recrop sites increased linearly with P rate (0.7 and 1.6 kg grain kg^{-1} P_2O_5 applied in

2004-05; 3.9 kg grain kg^{-1} P_2O_5 applied in 2005-06). The yield response to P at the chemical fallow site was quadratic in 2004-05, compared to a linear response with the 45 kg ha^{-1} seed rate and no response to P with the 78 kg ha^{-1} seed rate in 2005-06. At the chemical fallow site, yield for the early seeding date was 289 kg ha^{-1} (9.8%) higher than the late seeding date in 2004-05, and 865 kg ha^{-1} (30.6%) lower than late seeding in 2005-06 due to unfavorable seed zone moisture at early planting. Phosphorus increased yields of recrop and chemical fallow winter wheat; however, seeding date and rate showed variable responses depending on year.

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Dedication

This thesis is dedicated to my wife Judy and children Justin, Rolan, and Robin. Without their patience, understanding, support, and most of all love, the completion of this work would not have been possible.

CHAPTER ONE

INTRODUCTION

Winter wheat-summer fallow rotations are practiced on 1.56 million hectares in the low (150 to 300 mm) rainfall areas of eastern Washington and north-central Oregon (Schillinger and Young, 2004). Dryland wheat (*Triticum aestivum* L.) production in this low rainfall zone normally involves a 2-year winter wheat-tillage fallow rotation that is highly susceptible to wind erosion. The wheat-fallow system involves planting winter wheat in the fall after the ground has not been cropped for the previous year. During the fallow year, moisture is retained and weeds are controlled with tillage. The common practice of weed control in fallow fields uses different combinations of field machinery such as cultivators, rod-weeders, and sweep blades to cut weeds 5 to 15 cm under the soil surface. Problems such as wind erosion can arise from the frequency and depth of tillage that causes moisture loss at the surface, buries residue, and destroys soil structure (Schillinger, 2005). The fallow tillage practice is, however, necessary to break the capillary action and upward water movement to stop moisture loss due to evaporation (Schillinger, 2005).

The Great Plains wheat-growing region in the central United States has shown promising results that increasing cropping intensity and reducing tillage generally increased producer profitability (Schlegel et al., 2002). The climate in the Great Plains region has inherently low precipitation and high evaporation potential that limits dryland crop production. The implementation of conservation tillage practices that improve precipitation capture and decrease evaporation loss has permitted new and more intensive cropping systems. For example, Schlegel et al. (2002) determined that a wheat-sorghum-sorghum-fallow rotation had the highest net returns, followed by wheat-sorghum-fallow, wheat-wheat-sorghum-fallow, and finally continuous wheat. Similar approaches of new and more intensive cropping systems have been attempted in eastern Washington (Papendick, 2004).

Soil Loss from Wind Erosion

Fields maintained in summer fallow contribute to soil loss from wind erosion in low rainfall areas of eastern Washington and north-central Oregon. Feng et al. (2006) evaluated the quantity of soil and PM_{10} (particulate matter 10μm and smaller in diameter) eroded from fields in eastern Washington maintained in summer fallow during high wind events. Measurements taken in this area during a major windstorm in 2003 showed erosion losses of 2.3 Mg ha^{-1} from soil and 0.2 Mg ha^{-1} PM_{10} sized particulates from a 9 ha summer fallow field. Losses ranging from 0.3 to 30.4 Mg ha^{-1} per erosion event have been reported from monitoring studies in Alberta, Canada (Larney et al., 1995). The amount of soil loss from erosion is dependent on the local climate and soil morphology. Maintenance of sufficient crop residue or vegetative cover at the soil surface is the main component to controlling wind erosion in summer fallow fields.

Alternatives to Summer Fallow

The intention of alternatives to summer fallow is to provide year-round protecting cover for soils against wind erosion, and this may also conserve and store more soil moisture to allow annual cropping even in relatively dry years (Papendick, 2004). No-till farming is widely recognized throughout the world for excellent control of wind and water erosion, energy savings, and improved soil quality (Doran et al., 1996). Growers in the wind erosion-prone areas of eastern Washington are interested in conservation tillage and no-till farming. Reports in the Columbia Plateau PM_{10} Project, “Farming with the Wind II,” (Papendick, 2004) suggest the importance of seeking ways to control wind erosion on dryland farms by exploring alternatives to summer fallow such as no-till and controlling weeds mainly with herbicides (i.e., chemical fallow) instead of cultivation. Schillinger and Young (2004) suggested that chemical fallow should be investigated as a replacement for summer fallow. Schillinger (2005) also found that increasing cropping intensity (i.e., eliminate summer fallow), especially using no-till that provides stubble residue year round, is a best management practice to control wind erosion.

Lyon et al. (2004) studied alternatives to summer fallow in the Nebraska panhandle. Spring-planted crops were used as alternatives and they were convinced that a transition from the dominant wheat-fallow system to incorporate rotations of sunflower and sorghum were possible. Lyon et al. (2004) concluded that the eradication or significant decrease in the use of summer fallow in dryland cropping systems of the central Great Plains will help guard the delicate soil resource from further degradation, improve water use efficiencies, and enhance the long-term viability of dryland farming.

Annual Cropping Compared to Conventional Summer Fallow Rotations

It is well known that moisture and nutrients are the main factors determining crop yield and quality in arid regions. Continuous annual no-till wheat would greatly reduce predicted dust emissions by providing sufficient cover throughout both cropping cycles. A computer model designed by Lee et al. (1998) estimated that annual cropping would reduce predicted dust emissions by 94% during severe wind events compared to a conventional winter wheat–summer fallow rotation.

Papendick (2004) reported on a study initiated in 1998 at the Washington State University Dryland Research Station at Lind. Following an average rainfall year (240 mm precipitation) in 1998, winter wheat yielded 2,690 kg ha^{-1} after two crops of spring wheat compared with 1,614 kg ha^{-1} for continuous spring wheat. This intensive cropping system compared well with a station average of 3,228 kg ha^{-1} for winter wheat after summer fallow. Due to a drought and spring frost in 2001, a reduction in crop yields produced a winter wheat yield of 874 kg ha^{-1} after three years of annual no-till spring wheat compared with 605 and 1,010 kg ha^{-1} from spring wheat after winter wheat and continuous spring wheat, respectively (Schillinger, 2001). The 2002 winter wheat crop after 3 years of spring wheat yielded 1,010 kg ha^{-1}, which was significantly higher than continuous spring wheat yielding 605 kg ha^{-1}. During 2003, winter wheat yield after 3 years of spring wheat produced 1,096 kg ha^{-1}. This was significantly higher than continuous no-till spring wheat at 572 kg ha^{-1} (Papendick, 2004).

Schillinger and Young (2004) completed a cropping systems research project in the Horse Heaven Hills area of south-central Washington. The cropping systems compared were continuous annual direct seeded dark northern spring wheat (DNS) to the traditional winter wheat-summer fallow practice. The winter wheat-summer fallow rotation averaged 1,190 kg ha^{-1} while the annual no-till DNS rotation averaged 531 kg ha^{-1}. This research found that continuous no-till hard red spring wheat (HRSW) was not economically competitive with the winter-wheat summer-fallow system in either the relatively wet years or the drought years of the study. The production costs are double for HRSW compared to winter wheat-summer fallow. Annual no-till HRSW failed to cover total costs in all 6 years, whereas winter wheat-summer fallow covered total costs in 3 of 6 years (Schillinger and Young, 2004).

Continuous winter wheat cropping is a common practice on irrigated lands in central Washington (Papendick, 2004). This system produces 6,000 to 9,000 kg ha^{-1} with residue yields of 11,000 kg ha^{-1}. Problems with continuous winter wheat cropping on irrigated lands are the need to burn excess stubble residue, which is environmentally an issue due to smoke emission, and that fall plowing increases the wind erosion hazard prior to crop cover establishment (Papendick, 2004). Annual cropping systems have experienced problems with grassy weeds such as downy brome (*Bromus tectorum* L.) (Young et al., 1999), and have difficulty with diseases such as Take-all (*Gaeumannomyces graminis)* and Rhizoctonia (*Rhizoctonia solani)* that have been shown to reduce yields by as much as 670 kg ha^{-1} in continuous winter wheat (Cook et al., 2002).

Chemical Fallow

Chemical fallow, which substitutes the use of chemicals for cultivation to control weeds, continues to be under consideration as a best management practice (BMP) during the fallow period to reduce wind erosion (Papendick, 2004). Stubble residue from the previous crop is left standing and the soil is undisturbed. New chemicals are now available for use on chemical fallow that have shown superb control of problem weeds such as Russian thistle (*Salsola iberica*) and downy brome (Young and Thorne, 2004). Chemical fallow involves 2 to 3 applications of glyphosate (N-(phosphonomethyl)glycine) mixed with 2, 4-D (2,4-dichlorophenoxyacetic acid) or other herbicides applied for weed control usually in May, July, and September. Seeding after chemical fallow involves seedbed preparation by tillage or by the use of a no-till drill to seed directly into the standing stubble.

Economic and agronomic reasons are two disadvantages to chemical fallow in the low rainfall zone. They include the expense of chemical herbicide program and lower soil moisture retention in the seed zone, which causes overall lower yields. Soil moisture is often insufficient for early planting in chemical fallow due to early losses of moisture from the seed-zone compared with tilled soil (Hammel et al., 1981). Postponing planting until rain falls in October for germination reduces wheat yields by up to 25% (Donaldson et al., 2001). However, growers in this region are still interested in pursuing research on chemical fallow.

To ensure germination of winter wheat in annual cropped or chemical fallow in eastern Washington, moisture has to be in the seed zone. Late seeding (normally October) is often necessary with these alternatives since they do not provide adequate seed zone moisture for germination at the normal planting time of mid- to late-August. Limitations or restrictions of moisture availability or growing degree days to annual cropping and/or chemical fallow may be redirected with improved management of seeding rate, date and P fertility.

Seeding Date Effects on Wheat Yield

Many studies have reported on the effects of seeding date on wheat grain yield. Blue et al. (1990) reported that the influence of planting date on grain yield was influenced by P rate. Early planting dates along with the highest seeding and P rates generally produce the highest grain yields. For the first two years of their study, Blue et al. (1990) found no interactions among planting date and P rate for grain yield, but in the third year the research showed that P application reduced the negative influences of delayed planting and low seeding rates on grain yield. Kernel weight (KW) contributions to grain yield increased with delayed planting, which suggests that under conditions resulting in late planting, low seeding rate, and low P rate, seed size was extremely important in yield determination (Blue et al., 1990).

Thill et al. (1978) reported that early-planted wheat has a higher yield potential than late-planted wheat because of increased tillers, spikes, and KW. The early-planted wheat maintained a larger percentage of the tillers due to sufficient soil moisture and a more productive rooting system.

Donaldson et al. (2001) compared three seeding dates, approximately 20 August, 16 September, and 21 October, and three seeding rates 22, 44, and 66 kg ha^{-1}. They determined that, if seed-zone water is plentiful, seeding could generally be delayed until mid-September without yield penalty. The high seeding rate for either September or October seeding dates had no apparent advantage compared to the early August seeding date for stover or grain yield. They established that the August seeding date more than doubled the straw produced from the October seeding and also produced higher grain yield than October seeding dates. Low grain yield from late seeding was associated with fewer spikes per unit area (SPU) (Donaldson et al., 2001).

Phosphorus Rate Effects on Wheat Yield

Knapp and Knapp (1978) determined that, as planting date was delayed, applications of P fertilizer with the seed, increased in importance for increasing grain yields in soft white wheat. Applications of P during planting resulted in improved winter survival and highest grain yields (Knapp and Knapp, 1978). They also reported that increased winter survival rate could be attributed to rapid and vigorous seedling growth in the fall. This greatly improved tillering and resulted in significantly greater numbers of SPU. Knapp and Knapp (1978) stated that the beneficial effects of P were observed on medium P fertility soils, and that the value of P fertilization would be even greater on soils containing less P. They also suggest a favorable response is possible on soils with higher P levels because of the ready availability of the band-applied P for small seedlings.

The interaction of P fertilization with planting date has been researched in Australia by Batten et al. (1999), where they found crops seeded early required less P to achieve 90% of the maximum yield for the site. They reported that the late seeding date had lower yields at 0 kg ha^{-1} P and required more P to achieve the maximum yield. Lee (1940) also found that the presence of a small quantity of available P in soils increased the efficiency of P fertilizers applied later. When one-fourth of the P was added before sowing, the yield was nearly doubled, revealing the harmful effect of P deficiency in the early stages of growth. They noted a severe shortage of P caused an abnormal decrease of P concentration in the plant cells. The work also established that a P deficiency delayed plant maturity. Blue et al. (1990) found that increasing the P rate from 0 to 34 kg ha^{-1} P resulted in 671, 531, and 791 kg ha^{-1} yield increase in three consecutive years.

Seed Rate Effects on Wheat Yield

Darwinkel et al. (1977) found that seeding rate positively influenced yield for late-planted wheat and had an insignificant influence on yield for early-planted wheat. Darwinkel (1978) concluded that compensation among yield components resulted in high yields produced over a wide range of seeding rates. For example, maximum grain yield was achieved at 100 plants m^{-2}, which corresponded to 430 heads m^{-2} and 19,000 seeds m^{-2}. At higher densities, more heads and more seeds were produced, but grain yield remained constant due to a decrease in KW. The productivity of individual heads decreased with increasing plant density and with later emergence of shoots.

Shah et al. (1994) established that the higher seeding rate (168 compared to 84 kg ha^{-1}) had little effect on grain yield of early-planted wheat at one location but raised yield of late-planted wheat to a level comparable with early-planted wheat at another location. They concluded that late planting and higher seeding rate produced a greater number of SPU, but reduced the number of KPS and KW. Shah et al. (1994) also concluded that yield losses due to late planting could be reduced by a higher seeding rate. Blue et al. (1990) evaluated yields by increasing the seeding rate from 34 to 101 kg ha^{-1} resulting in yield increases of 390, 481, and 210 kg ha^{-1} in three consecutive years.

Seeding rate effects on grain yield of wheat was investigated by Donaldson et al. (2001) using 22, 44, and 66 kg ha^{-1} rates on four cultivars of winter wheat. Results showed that altering the seeding rate caused significant changes in all variables measured: straw weight, SPU, KPS, KW, grain yield and harvest index (HI). They advised growers to seed winter wheat early, in mid-to-late August, using a medium (44 kg ha^{-1}) seeding rate. Early seeding of winter wheat resulted in the greatest straw production and the highest grain yield in two out of three years. There was no difference among seeding rates in straw or grain yield at the September or October seeding dates. The low and medium seeding rates produced maximum grain yield in the first year of the study, while in the next two years, the medium and high seeding rates produced the best yields. This study clearly demonstrates that seeding winter wheat in mid-to-late August using a medium seeding rate is effective for maximizing straw and grain production.

Goal

The purpose of this study is to determine the optimum combination of seeding rate, seeding date, and P rate to promote the yield of annual cropped winter wheat and winter wheat on chemical fallow. Reducing or eliminating tillage fallow by enhancing the adoption of these alternatives will greatly reduce the wind erosion potential of the dry wheat-growing region in eastern Washington.

Objectives

1. Determine the effect of seeding rate and P fertility on grain yield of direct-seeded annual cropped winter wheat and direct seeded winter wheat into chemical fallow in the low rainfall zone of eastern Washington.
2. Evaluate the effects of seeding rate and P fertility on winter wheat grain yield components and straw production.
3. Evaluate P uptake and partitioning in the stover and grain portions of winter wheat.

Materials and Methods

Three field sites were established in eastern Washington in the fall of 2004 and fall of 2005 (Lind, Ralston, and Ritzville). The soil types are noted in Table 1. Annual precipitation in this area ranges from 150 mm to 300 mm. Baseline soil properties at each study are listed by year in Table 2. The preliminary soil P test levels at the Lind and Ritzville 2004 locations are approaching the minimal threshold (Koenig, 2005) (Table 2). Soil sampled from the 0-305mm soil depth measured 13.0-18.3 mg kg^{-1} P by the bicarbonate (Olsen et al., 1954) method and Na acetate method (Morgan, 1941); therefore, the P response in the plants might not be expected. The field sites had winter wheat stubble except for the Ritzville site, which was on chemical fallow stubble.

The individual plot dimensions were 2.3 m wide by 15.2 m long, except for Lind and Ralston, which had 2.3 m by 30.5 m plots. A randomized complete block design was used for the recrop sites of Lind and Ralston while a split plot design was used at the chemical fallow Ritzville site, while all sites included a factorial combination of two seeding rates and five P rates. Eltan, a soft white winter wheat variety, was sown at all locations. The seeding rates were

45 and 78 kg ha^{-1}. Plots were also established at two other sites, Walla Walla and Harrington; however, they were abandoned due to poor stand establishment and insect infestation.

Table 1. The location, cooperator, and soil taxonomic classification for each crop year in the study.

Location	**Crop Year**	**Cooperator**	**Taxonomic Classification**
Lind	2004-05 2005-06	Lind WSU Station	Ritzville silt loam---Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls
Ralston	2004-05 2005-06	Jerry Snyder	Ritzville silt loam---Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls
Ritzville	2004-05 2005-06	Rob Dewald	Ritzville silt loam---Coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls

Table 2. Baseline soil properties at each study location.

				Soil test phosphorus method†	
Location	**Year**	**pH**	**OM**	**Na Bicarbonate**	**Na Acetate**
			--%--	-------------------mg kg^{-1} soil------------------	
Lind	2004	6.1	0.96	18.3	7.6
Lind	2005	6.3	0.81	15.3	4.9
Ralston	2004	6.3	1.70	13.0	5.6
Ritzville	2004	5.8	1.70	18.2	4.2
Ritzville	2005	6.0	1.19	13.5	3.7

†Soil test P methods used Na Bicarbonate (Olsen 1954) and Na Acetate (Morgan 1941).

The seeding at all sites was accomplished using a Fabro no-till plot drill (Fabro Inc., Swift Current SK, Canada) with double-disk openers. The plots were seeded on 19 cm row spacing with 10 rows per plot. The seed was placed approximately 5 cm below the soil surface.

Liquid fertilizer was deep banded (5 cm) below the seed at planting time. The liquid fertilizer contained 67.3 kg ha^{-1} N at all sites. The source was urea ammonium nitrate solution (32% N). The P was from liquid ammonium polyphosphate (11-37-0). The P rates were 0, 22, 45, 67, and 90 kg P_2O_5 ha^{-1} in 2004-05 and 0, 11, 22, 45, and 67 kg P_2O_5 ha^{-1} in 2005-06. At the Ritzville site, two seeding dates were used: Sept. 17 and Oct. 25 for 2004-05; Sept. 12 and Oct. 5 for 2005-06. The other sites used the late seeding date only. The plots were sprayed for broadleaf and grassy weeds using 0.03 kg a.i.(active ingredient) Sulfosulfuron ha^{-1} and 0.13 kg a.i. Metribuzin ha^{-1} {4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one} on April 21 2005. The following year 0.021 kg a.i. ha^{-1} Harmony Extra (50% Thifensulfuron-methyl {Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5- triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate} + 25% Tribenuron-methyl {Methyl 2-[[[[N-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino] sulfonyl]benzoate}and 0.42 kg Bromoxynil a.i. + 0.42 kg MCPA a.i. ha^{-1} applied as Bronate Advanced, were applied on April 18, 2006.

Plant stand counts were taken on March 24, 2005 and February 3, 2006. A random section of two adjoining rows in each plot were selected and the number of plants per two linear meters was counted. Head density and above-ground dry biomass production were measured at anthesis by hand-cutting the above-ground portion of plants from one meter of two adjoining rows from each plot, and expressed on an area basis from the dry weight of plants. Samples were dried at 60° C for plant biomass determinations.

Harvest was completed at physiological maturity. This was accomplished by two successive methods on each plot. First, a whole plant hand harvested sample of one meter of two adjoining rows was taken and bagged. The heads were removed from the stems and processed in a head threshing machine to obtain the grain, and the chaff was recombined with the stover. The above-ground biomass was expressed on an area basis from the dry weight of head grain and stover. Dry matter, SPU, KPS, and KW were determined from the hand harvested plant samples.

A Hege 125C plot combine (Hege Co., Salt Lake City, UT) was used to cut a 1.5 m wide area to full length of the plot minus trim areas on each end. Grain yield was determined by measuring the area harvested by the combine and the weight of the grain for each plot. The machine-combined grain was then ground into flour using a Udy mill (Udy Corporation, Fort Collins, CO) in preparation for P analysis.

The stover and chaff were ground with a Wiley mill in preparation for P analysis. The plant tissue analysis was conducted by using a nitric acid digestion of 1 gram of plant tissue (Jones and Case, 1990). The digest was analyzed using inductively coupled argon plasma spectrometry (Spectrometer 61, Thermo Jarrell Ash, Franklin, MA).

Statistical Procedures

Analysis of variance was conducted for early season dry matter, grain yield, grain yield components, HI, and total P uptake. The treatments of means were compared using Tukey's honest significant difference (HSD) and polynomial contrasts. All statistical tests were done at the five percent level of significance. All data was analyzed using Statistix 8 v.1.0, by Analytical Software 2003, Tallahassee FL.

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CHAPTER TWO

RESULTS AND DISCUSSION

Stand Density

Stand density was significantly higher with late seeding at the 78 kg ha^{-1} seed rate (Figure 1), due to better germination, which was a result of higher seed zone moisture at the time of planting. The high seeding rate increased stand density at all sites in all years except Ritzville in 2006 in the early seeding treatment, which was due to low seed zone moisture content at the time of seeding.

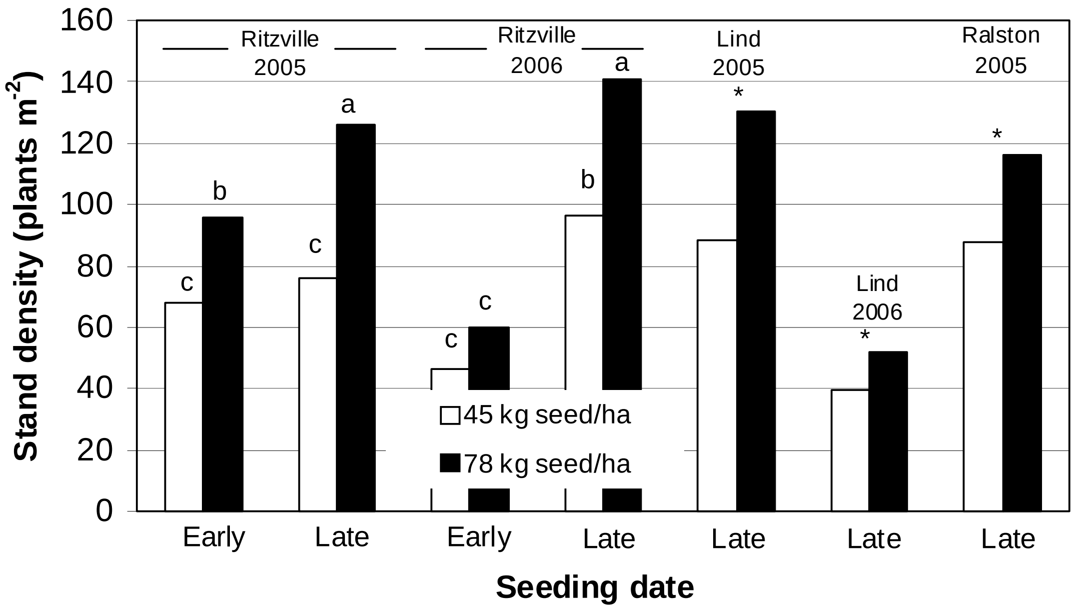
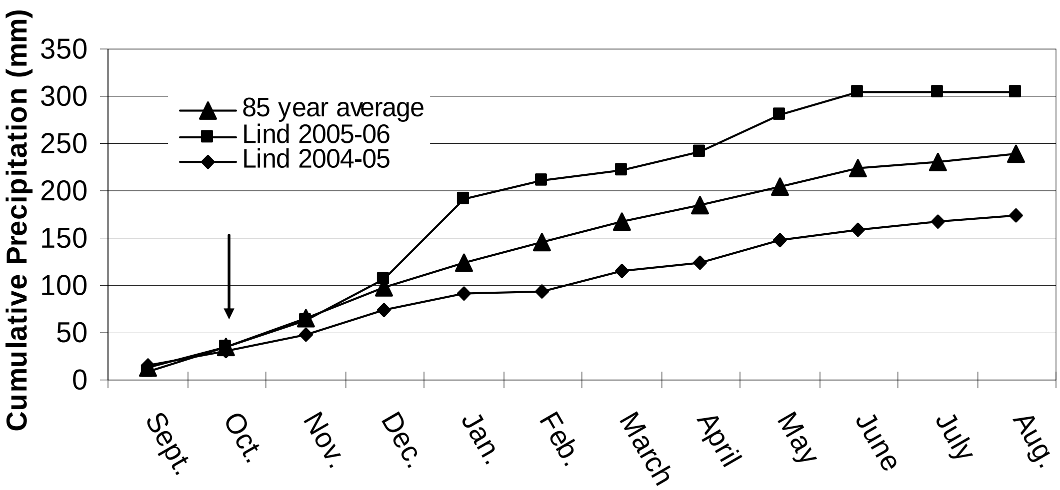


Figure 1. The interaction between seeding rate and date at Ritzville, and the main effect of seeding rate at Lind and Ralston, on stand density. Within a location and year, bars capped with the same letter are not significantly different; * indicates a significant difference between seeding rates at ($p < 0.05$).

There were distinct differences between the two study years at Ritzville. In 2004-05, a significant rainfall event occurred immediately after the early planting at Ritzville, while there was no precipitation and seed zone moisture was low at the early seeding date in 2005-06. As a result, stand establishment was generally good with the early seeding date at Ritzville in 2004-05, but not in 2005-06 (Figure 1). See annual precipitation figures for Lind and Ritzville for the study years and the 85 year average (Figure 2).



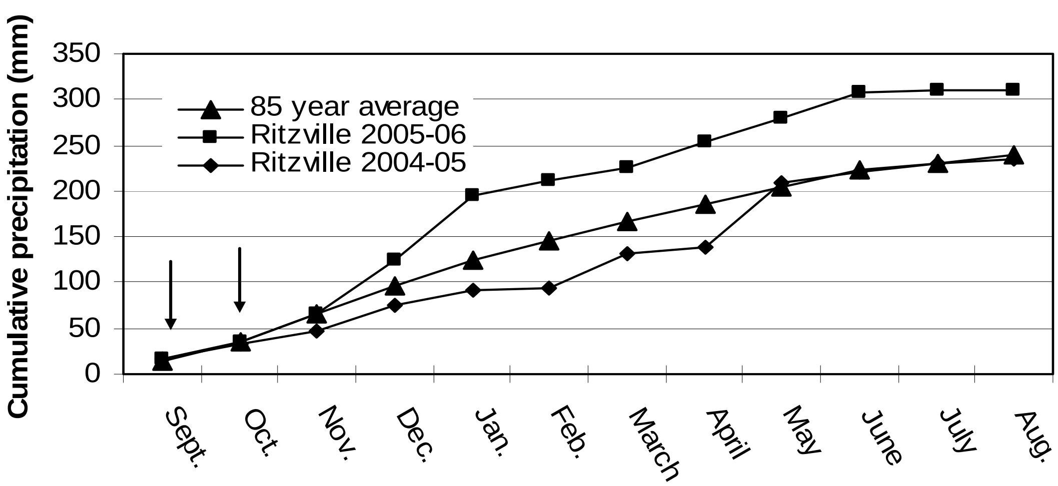


Figure 2. Annual precipitation figures for Lind and Ritzville for the study years and the 85 year average. Arrows indicate planting dates.

P Rate

At Ritzville in 2005, the P rate effect had a significant linear response to early seeding compared to a non-significant response on late seeding on stand density (Figure 3). Similarly, at Ritzville in 2005 there was a significant linear response to P rate at the 78 kg ha^{-1} seed rate compared to a non-significant response to the 45 kg ha^{-1} seed rate for stand density (Figure 4). At Ralston in 2005, the P rate effect had a significant linear response to 78 kg ha^{-1} seed rate compared to a non-significant response on the 45 kg ha^{-1} seed rate on stand density (Figure 5). This data may explain why the higher P rates could induce a burning effect that could injure the seedlings during this stage of growth.

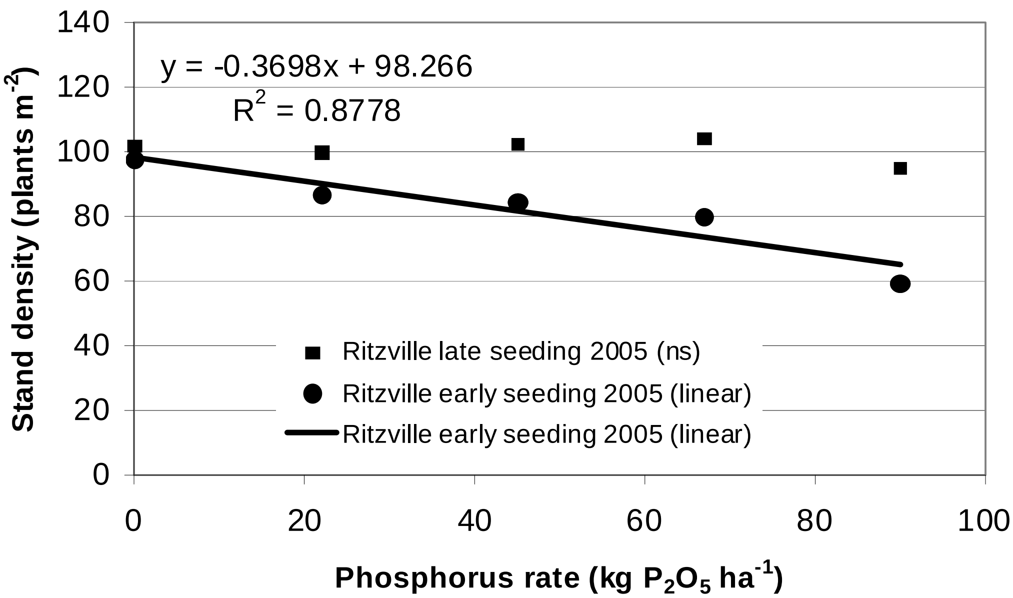


Figure 3. The effect of seeding date and P rate on stand density at Ritzville in 2005. Trend indicated in the legend is significant at ($p < 0.05$).

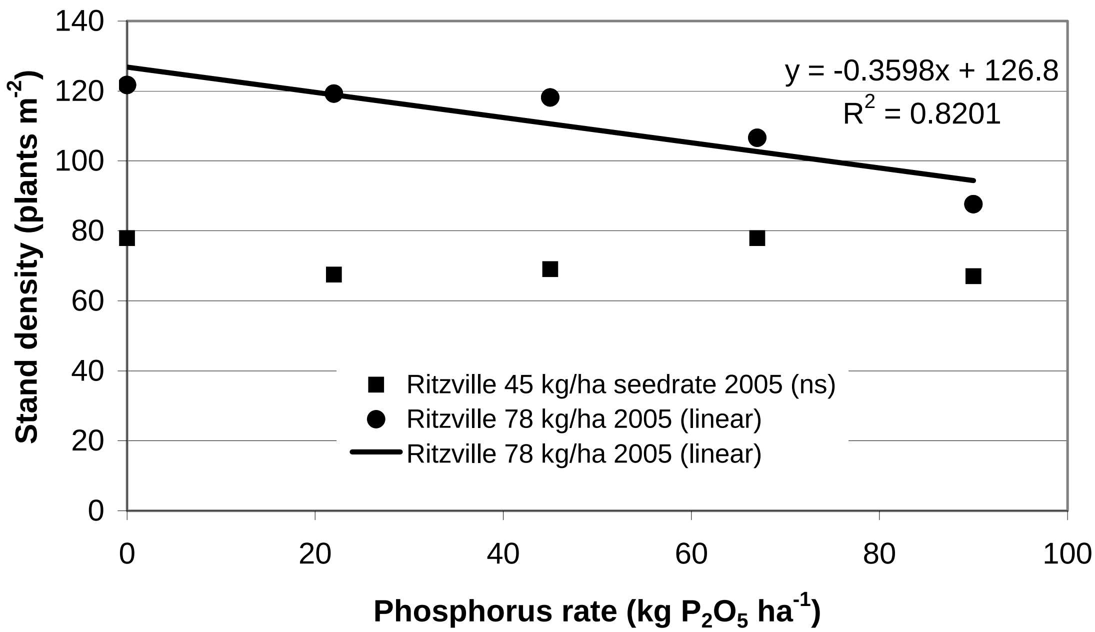


Figure 4. The effect of seed rate and P rate on stand density at Ritzville in 2005.

Trend indicated in the legend is significant at ($p < 0.05$).

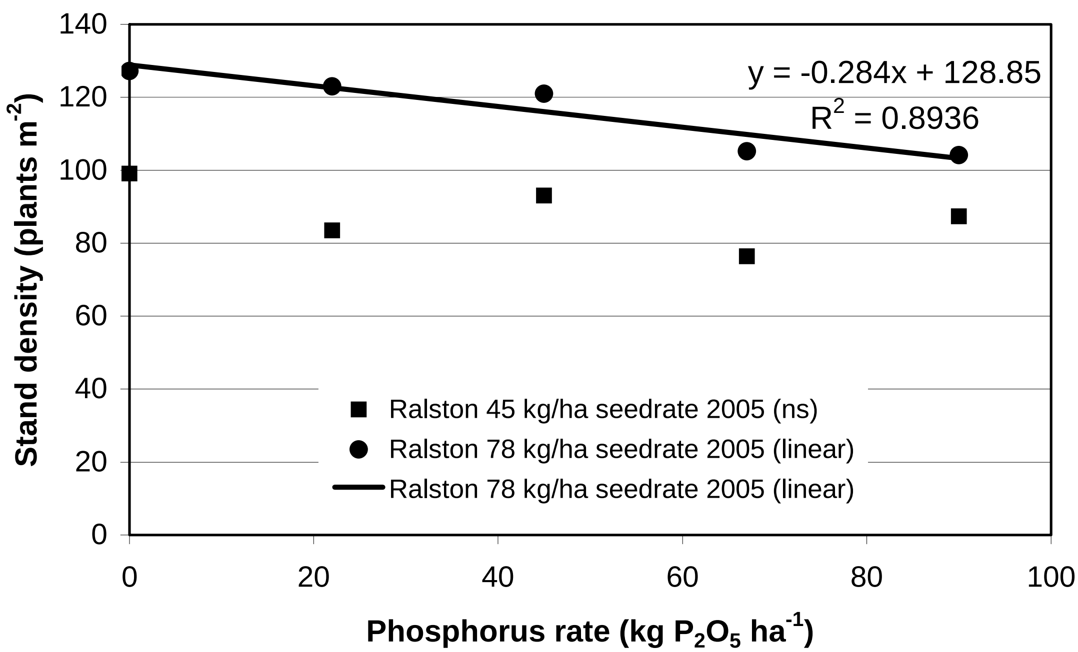


Figure 5. The effect of seeding rate and P rate on stand density at Ralston in 2005.

Trend indicated in the legend is significant at ($p < 0.05$).

At Ritzville in 2006, P rate had no effect on stand density at either the early or late seeding date (Figure 6). The anticipated results at Ritzville in 2006 would be a larger negative response to P rate if fertilizer inhibited germination or emergence. However, there were no significant interactions for P rate on stand density at either high or low seeding rate in at Ritzville 2006.

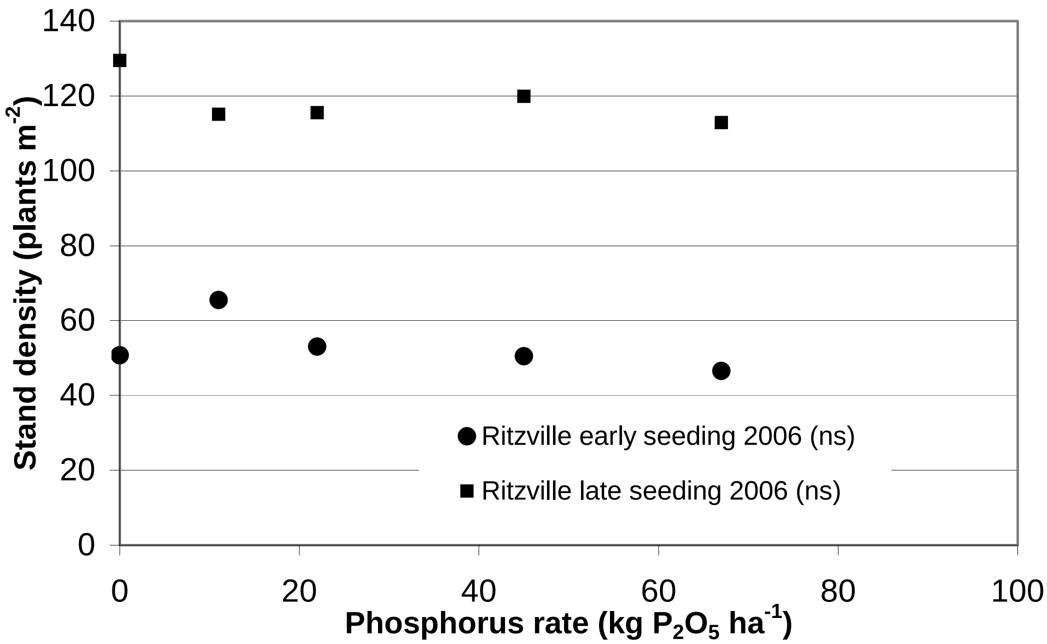


Figure 6. The effect of seeding date and P rate on stand density at Ritzville in 2006.

Biomass

<u>Seed Date</u>

Early-season biomass showed a linear increase with P rate in 2005 and 2006 for late seeding at Ritzville (Figures 7 and 8). The quadratic response to P rate at the early seeding date in 2005 may indicate reduction in growth to seedlings at the higher P rates due to interplant competition for soil moisture (Figure 7). The early seeding resulted in greater early-season biomass response to P rate at Ritzville in 2005.

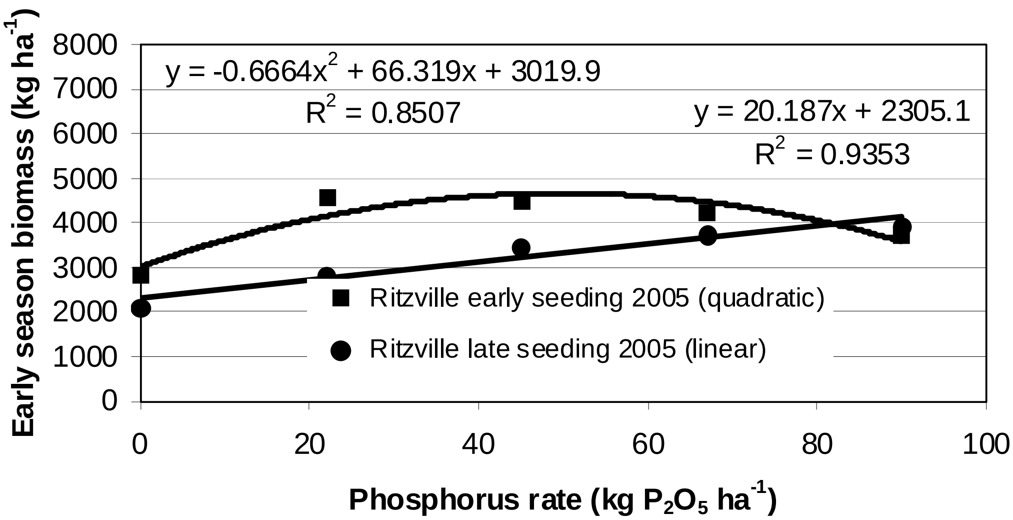


Figure 7. The effect of seeding date and P rate on early-season biomass for Ritzville in 2005. Trends indicated in the legend are significant at ($p < 0.05$).

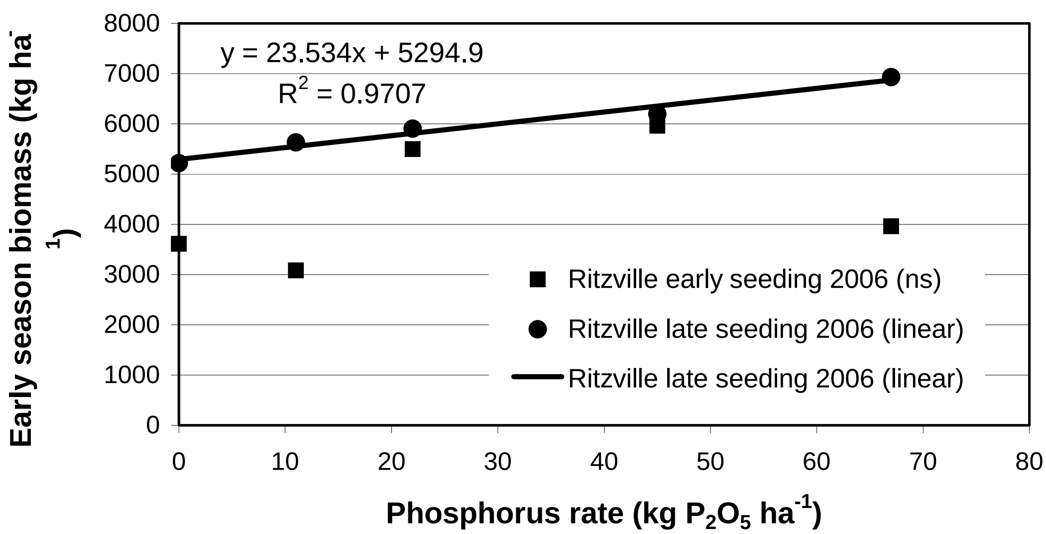


Figure 8. The effect of seeding date and P rate on early-season biomass for at Ritzville in 2006. Trend indicated in the legend is significant at ($p < 0.05$).

Biomass for the early seeding date at Ritzville was variable (non-significant) in 2006 (Photo 1) due perhaps to the lack of seed zone moisture at planting time. The moisture deficit may have contributed to the reduced seed germination as shown by spotty/non-uniform stand counts seen in photo below (Photo 1), and low stand counts for early seeding (Figure 1).

Photo 1. Ritzville 2005. Comparison of early-seeded 45 kg ha^{-1} seed, 67 kg ha^{-1} P plot on left with 78 kg ha^{-1} seed, 0 kg ha^{-1} P plot on right of space. Spotty stands and visual differences were observed between +/- P treatments.

The late seeded plots contained higher stand densities due to better seed zone moisture conditions during germination which may have attributed to the plants ability for active root uptake of P. (Photo 2).

Seed Rate

There was no effect of seeding rate on early-season biomass in 2005 at any of the locations. This is due to the low precipitation accumulated in this first growing season.

However, in 2006 there was a contrasting high accumulation of precipitation (Figure 2) that produced greater early-season biomass at the 78 kg ha^{-1} seed rate at Ritzville and Lind (Figure 9). When moisture is adequate at seeding time, the higher seed rate has the potential to produce more seedlings and early-season biomass as shown here and in the stand density by location results (Figure 1).

Photo 2. Ritzville 2005. Comparison of late-seeded 78 kg ha^{-1} seed, 0 kg ha^{-1} P plot on left with 78 kg ha^{-1} seed, 45 kg ha^{-1} P plot on right of space. Clear visual differences were observed between +/- P treatments.

P rate

The Ralston recropped site (Figure 10) showed a linear increase in biomass with P rate. This was similar to biomass production for the late seeding date at Ritzville in 2005 (Figure 7), which was seeded the same day as the late seeding in Ritzville.

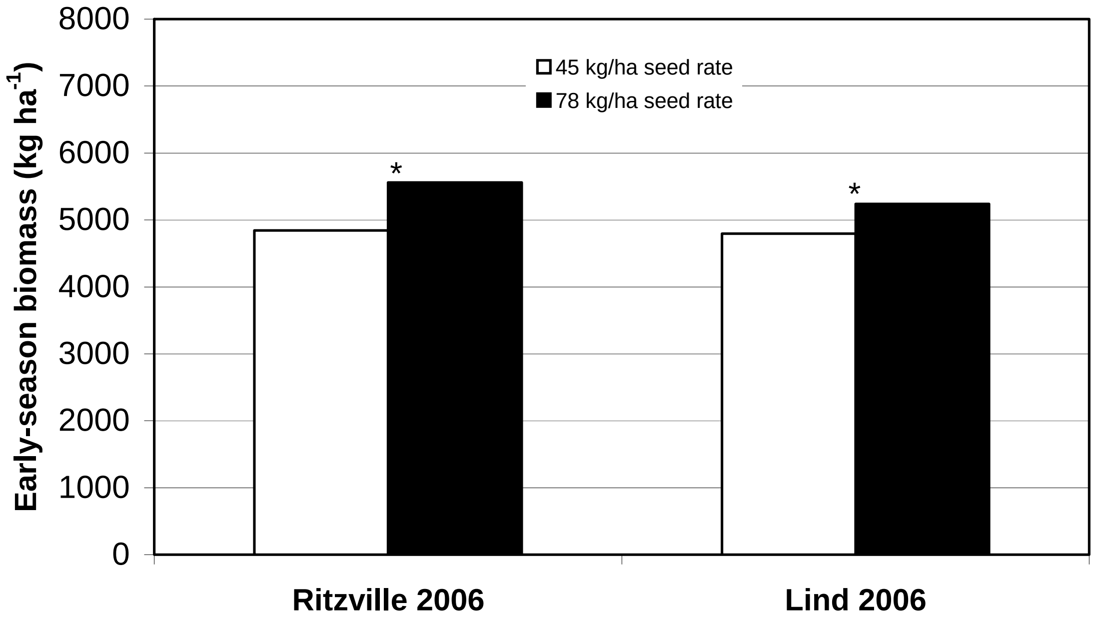


Figure 9. The effect of seed rate on early-season biomass at Ritzville and Lind in 2006.

* indicates a significant difference between seeding rates ($p < 0.05$).

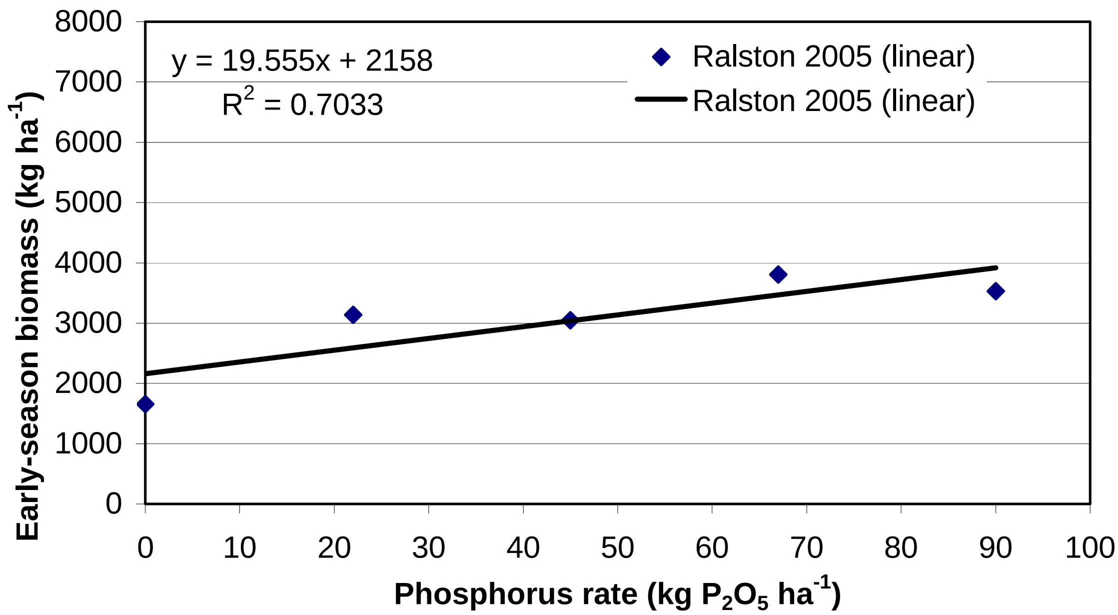


Figure 10. The effect of P rate on early-season biomass at Ralston in 2005. Trend indicated in the legend is significant at ($p < 0.05$).

Early-season biomass was increased linearly by P rate at the late seeding date at Ritzville in 2005 (Figure 7). Observing this linear response both years at the Ritzville site suggests that increasing P during the late planting season was especially important for increasing dry matter yield. The quadratic response at Ritzville in 2005 indicates possible injury to seedlings due to moisture depletion or limitation at the higher P rates, which is indicated by the early season biomass production (Figure 7).

Grain Yield

Seed Date

At Ritzville, an 8.9 % decrease in grain yield is shown from early to late seeding in 2005 (Figure 11). Whereas, in 2006 there was a 23.4 % increase in grain yield for the late planting date compared to early seeding. These 2005 yield differences at Ritzville can be explained by receiving a significant rainfall immediately after the early planting. This rainfall increased seed zone moisture availability for improved germination, which in turn increased early-season biomass, heads m^{-2} and grain yield. This trend is verified by stand densities at Ritzville in 2006 but not in 2005 (Figure 1). Similarly, there was a quadratic response to P rate for the early seeding date on early season biomass at Ritzville in 2005. The linear response is also supported by early-season biomass demonstrating a linear influence of P rate for late seeding at Ritzville in 2006 (Figure 8).

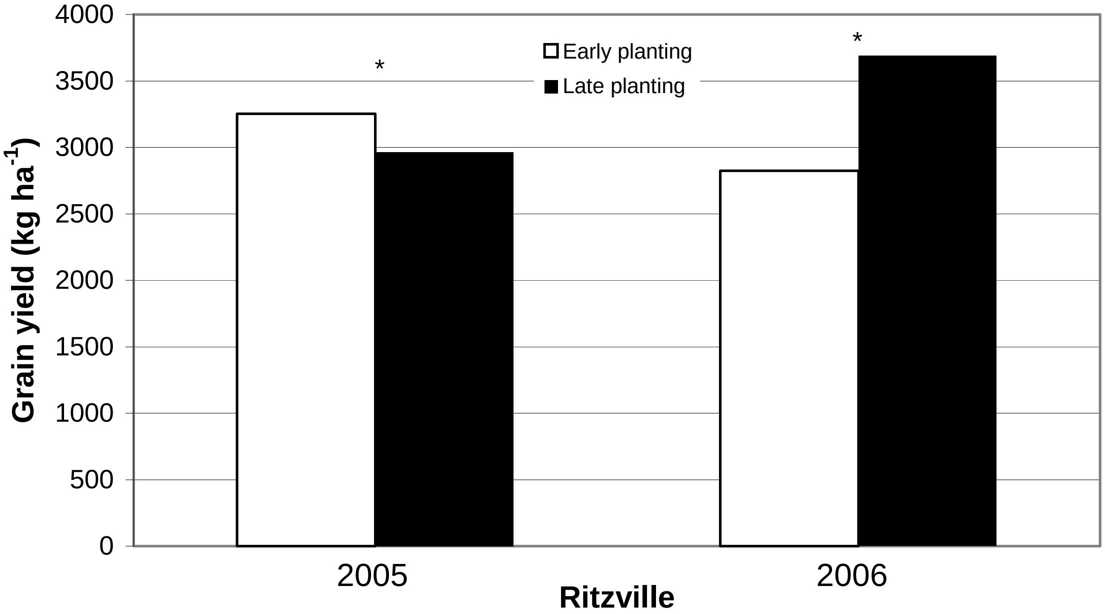


Figure 11. The effect of planting date on grain yield at Ritzville in 2005 and 2006.

* indicates a significant difference between seeding dates ($p < 0.05$).

<u>Seed Rate</u>

At Ritzville in 2005, there was a seed rate effect on grain yield where yield was 7.2 % higher for the 78 kg ha^{-1} seed rate compared to the low seed rate of 45 kg ha^{-1} (Figure 12). At Lind in 2006, there was a main effect of seed rate on yield where yield was 4.5 % lower for the 78 kg ha^{-1} seed rate compared to the lower seed rate of 45 kg ha^{-1}. Seed-zone moisture in the 2005 plot at Ritzville may have attributed to the increased grain yield for the 78 kg ha^{-1} seed rate. This is likely due to the higher seed rate producing more tillers resulting in more heads m^{-2}. The increased stand density at Ritzville in 2005 (Figure 1) also suggests that seed zone moisture is the contributing factor to increased grain yield. However, at the Lind site in 2006 the opposite occurred and none of the measurements made explain this result. This yield decrease may have been due to the higher plant population from the higher seed rate using more moisture and, since this was a recrop site, it might have caused more environmental moisture stress, resulting in lower yields.

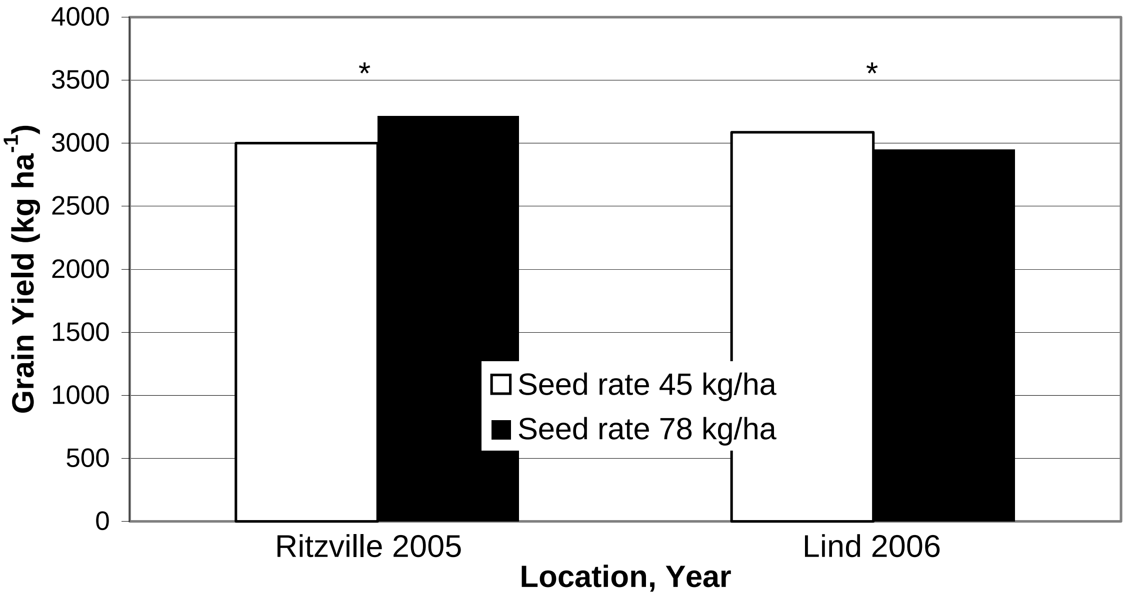


Figure 12. The effect of seeding rate on grain yield at Ritzville in 2005 and 2006, and Lind in 2006. * Indicates a significant difference between seeding rates ($p < 0.05$).

Tompkins et al. (1991) suggested that grain yield is optimized at a higher seed rate (58-148 kg ha^{-1}) depending on the site annual precipitation. Their lower optimal seed rate is comparable to our rate and is from a dry area in Canada, similar to the Ritzville, Lind, and Ralston sites. The optimum seed rate on the Canadian prairies is directly related to crop yield potential, i.e. high seed rate is required before high yield potential is realized. The recropped site at Lind produced lower yields at the higher seeding rate (Figure 12), which might be attributed to the previous crop removing necessary moisture for yield production. Other research has shown that the grain yield was increased due to more heads m^{-2} (Donaldson et al., 2001), this is illustrated in (Figures 16 and 17) at Ritzville in 2005 and 2006. Heads m^{-2} and kernels $head^{-1}$ generally are the most important determinants of grain yield (Knapp and Knapp, 1978; Shah et al., 1994). The higher seeding rate at Lind in 2006 produced less grain yield as compared to Ritzville in 2005 (Figure 12) possibly due to excessive vegetative growth from the higher seeding rate that could have depleted the stored soil moisture that is necessary for achieving higher grain yield at the recropped Lind site.

P rate

There was an interaction between seed rate and P rate on grain yield at Ritzville in 2006 (Figure 13). The low seed rate (45 kg ha^{-1}) had a linear response to P rate whereas the high seed rate (78 kg ha^{-1}) showed no effect of P rate on grain yield. The results suggest lack of seed-zone moisture at seeding time at Ritzville in 2006 induced poor seed germination as shown by spotty/non-uniform stand counts (Photo 1). The lower seed rate produced lower stand densities (Figure 1), which in turn resulted in lower heads m^{-2} (Figure 16 and 17). The linear response shown in Figure 13 indicates that P may have stimulated more tillering and heads $area^{-1}$ at the low seeding rate, thus resulting in the positive grain yield response to P at the low seeding rate but not the high seeding rate. Yield limitations may be overcome by increasing P rates as shown by the linear increase in yield by P rate (Figures 13, 14, and 15). Blue et al. (1990) found that when P was applied, the grain yield response to increasing the seeding rate was unpredictable. Hence, during low moisture planting conditions, P fertilization is beneficial for lower seeding rates. Blue et al. (1990) confirmed that applying P was more important to optimize grain yield than was increasing the seeding rate. This is shown by the lower seeding rate at Ritzville in 2006.

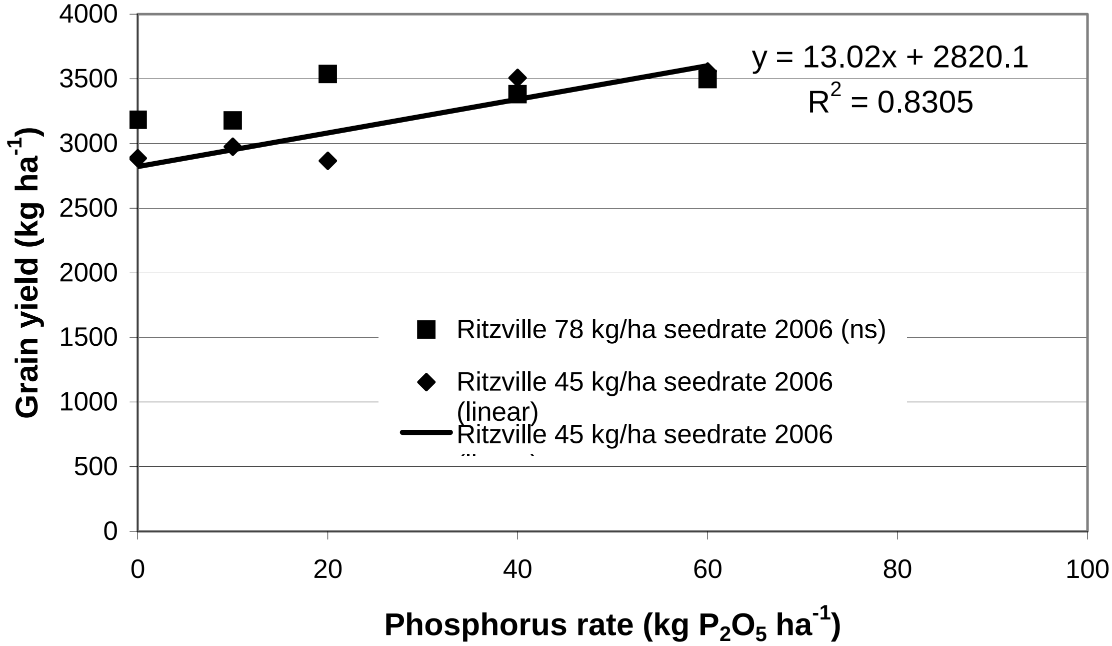


Figure 13. The effect of seeding rate and P rate on grain yield at Ritzville in 2006. The trend indicated in the legend is significant at ($p < 0.05$).

The Ritzville site in 2004 had preliminary soil test results (Table 2) approaching the minimal threshold (Koenig, 2005) in which the P response in the plants might not be expected. However, the Ritzville site revealed a linear influence of P rate on grain yield in 2005 (Figure 14). This response was not expected in this P enriched soil. One other site, Lind 2004 with high preliminary soil test results, showed no significant difference for P fertilizer application, which is more consistent with the expectations of a high soil test P. While the plots at Ralston in 2005 (Figure 14) and Lind in 2006 (Figure 15) also revealed a linear trend for P rate on grain yield, the yields from the dry year at Ralston were one-half of the Ritzville location. This likely was due to the difference of seeding into chemical fallow at Ritzville, which has more stored soil moisture than the recrop winter wheat stubble at the Ralston site where the annual cropping system has depleted the soil moisture.

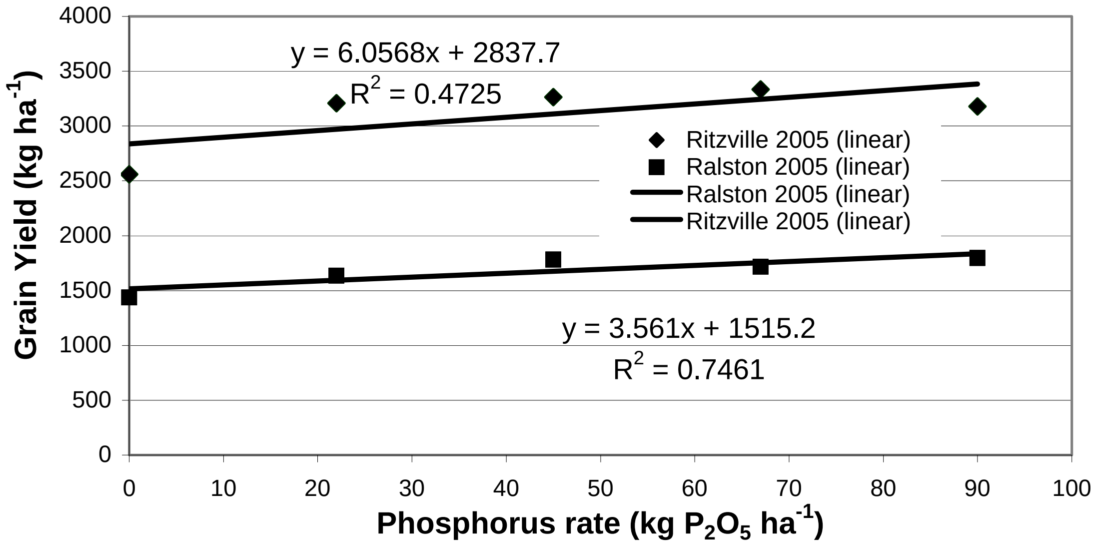


Figure 14. The effect of P rate on grain yield for Ritzville and Ralston in 2005. Trends indicated in the legend are significant at ($p < 0.05$).

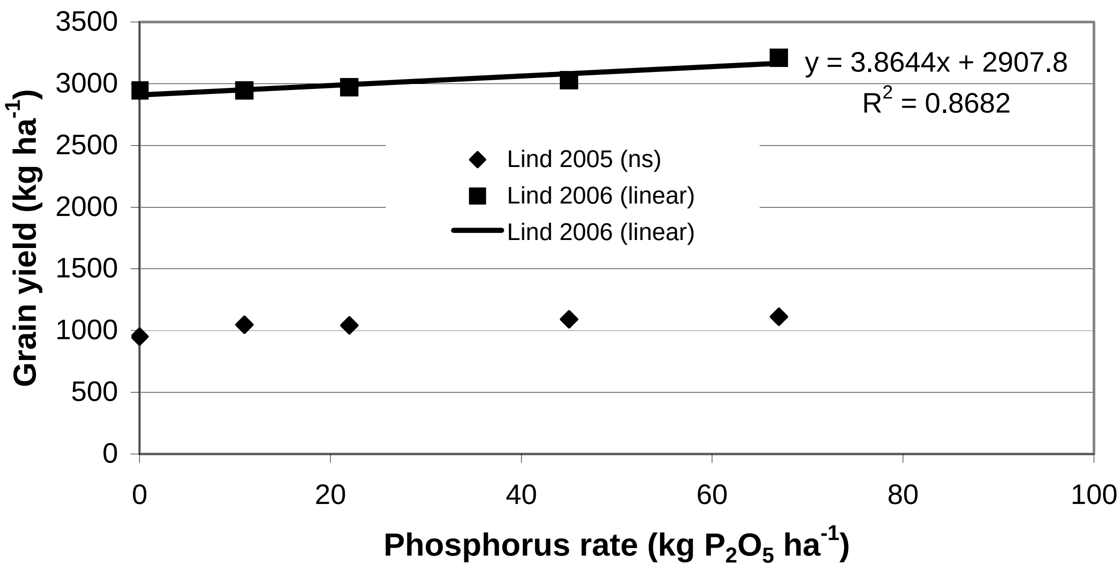


Figure 15. The effect of P rate on grain yield for Lind in 2005 and 2006. Trend indicated in the legend is significant at ($p < 0.05$).

Yield Components

Seed Date

Seeding date and rate had a significant effect on heads m^{-2} at Ritzville in 2006 (Figure 16), with the late seeding having more heads m^{-2} than the early seeding and higher seeding rate producing more heads per area than the lower seeding rate. This response was due to higher stand densities (Figure 1) noted in 2006 resulting from more soil moisture available at the late planting time compared the dry planting conditions during the early planting. Planting conditions at Ritzville in 2005 were just the opposite of 2006, where just before the early planting, a rain event happened which in turn increased stand densities and grain yields.

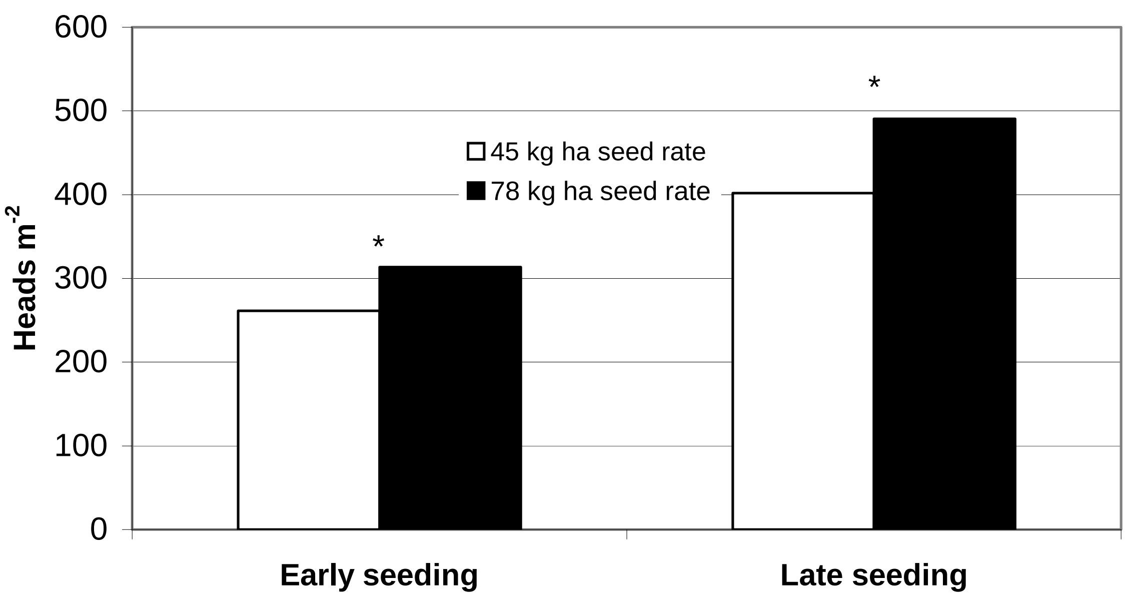


Figure 16. The effect of seeding rate and date on heads m^{-2} at Ritzville in 2006. * indicates a significant difference between seeding rates ($p < 0.05$).

Seed Rate

At Ritzville in 2005 (Figure 17) there was a seed rate effect on heads m^{-2} where the 45 kg ha^{-1} seed rate had an average of 300 heads m^{-2} and the 78 kg ha^{-1} seed rate had an average of 365 heads m^{-2}. In addition, at Ritzville in 2006, there was a seed rate effect on heads m^{-2} where the 45 kg ha^{-1} seed rate produced an average mean of 332 heads m^{-2} and the 78 kg ha^{-1} seed rate produced average of 402 heads m^{-2}. These differences were also supported by Tompkins et al. (1991) and Donaldson et al. (2001) noting that heads m^{-2} rose incrementally with increased seeding rate at later seeding dates. Higher soil moisture availability at the later seeding date was associated with stand densities which in turn are linked to more heads m^{-2}. This can be seen in Figure 1 where both years of the study, the stand densities were higher for the late seeding date.

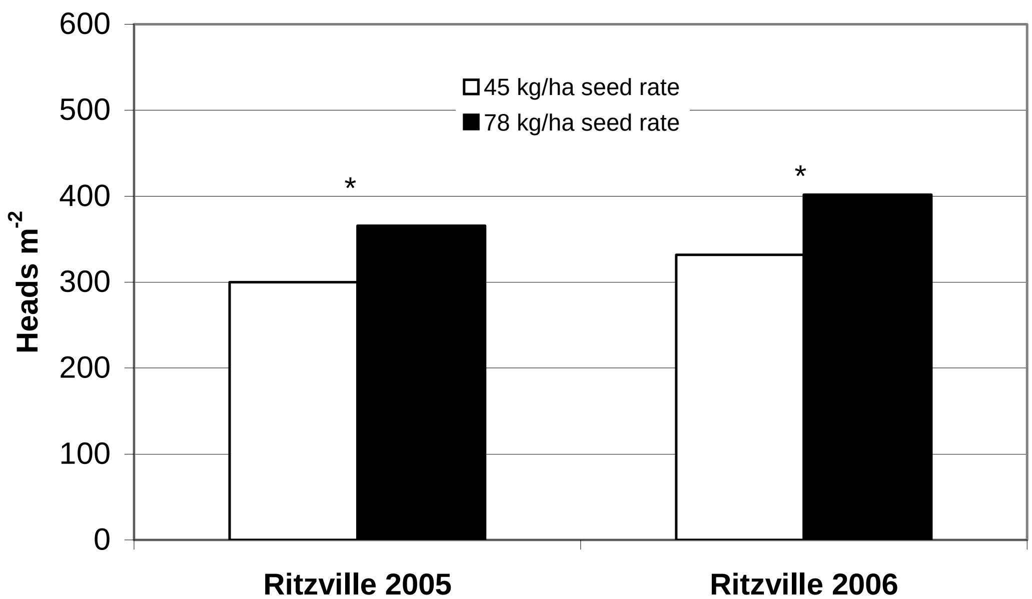


Figure 17. The effect of seeding rate on heads m^{-2} at Ritzville in 2005 and 2006. * indicates a significant difference between seeding rates ($p < 0.05$).

P rate

At Ralston in 2005, there was a quadratic P rate effect at the 78 kg ha^{-1} seeding rate on heads m^{-2}, while the 45 kg ha^{-1} seed rate was non significant (Figure 18). Knapp and Knapp (1978) and Blue et al. (1990) observed that P increased the number of heads m^{-2} and consequently resulted in higher grain yields. At the Ralston site in 2005, there was a linear increase in early-season biomass with P rate (Figure 10). Elevated grain yields may be established by higher plant populations given optimal P fertility (Blue et al., 1990; Tompkins et al., 1991) in an environment that is not stressed by the lack of soil moisture. Also, in order to increase grain yields it is important to have the best seedling growth environment consisting of

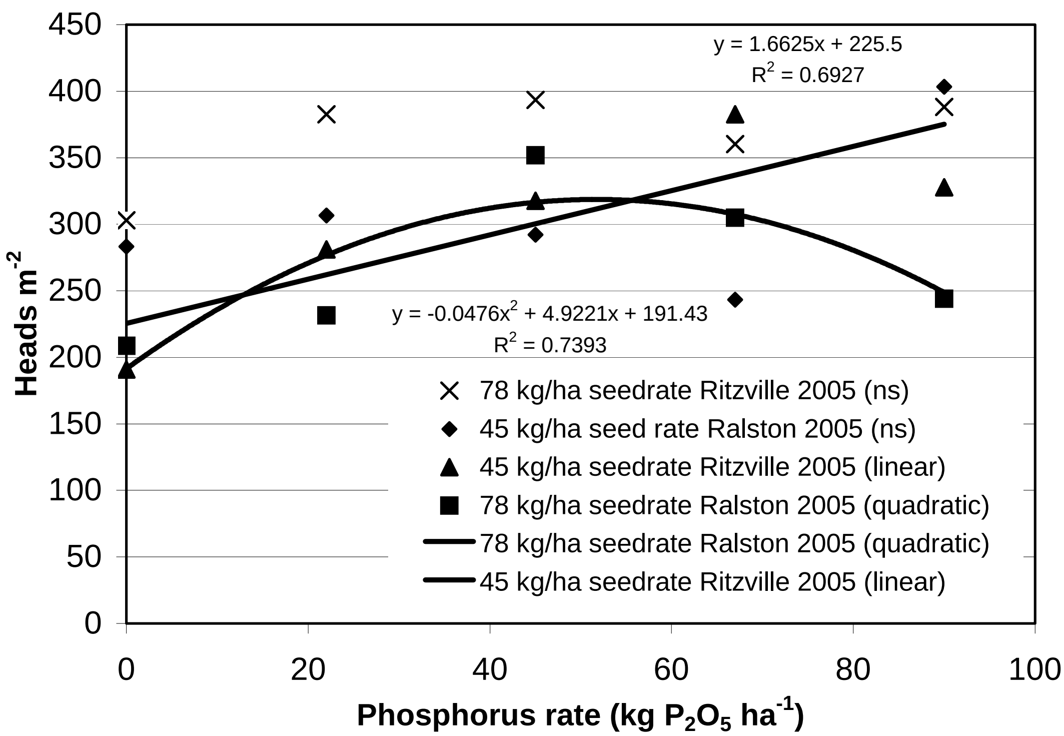


Figure 18. The effect of seed rate and P rate on heads m^{-2} at Ralston and Ritzville in 2005. Trend indicated in the legend is significant at ($p < 0.05$).

soil moisture and P fertility which will in turn produce the components most responsible for yield, heads m^{-2} and kernels $head^{-1}$ (Blue et al., 1990).

The lower seed rate consistently produced higher kernels $head^{-1}$ at Ritzville in 2005 and 2006 and Lind in 2006 (Figure 19). Normally, when an increase in heads m^{-2} is achieved, a negative correlation is seen for kernels $head^{-1}$ and KW. Blue et al. (1990) indicated at high seeding rates the number of heads m^{-2} contributed to more grain yield than KW. Under conditions of drought, kernels $head^{-1}$often has the greatest effect on grain yield (Schillinger and Young, 2004).

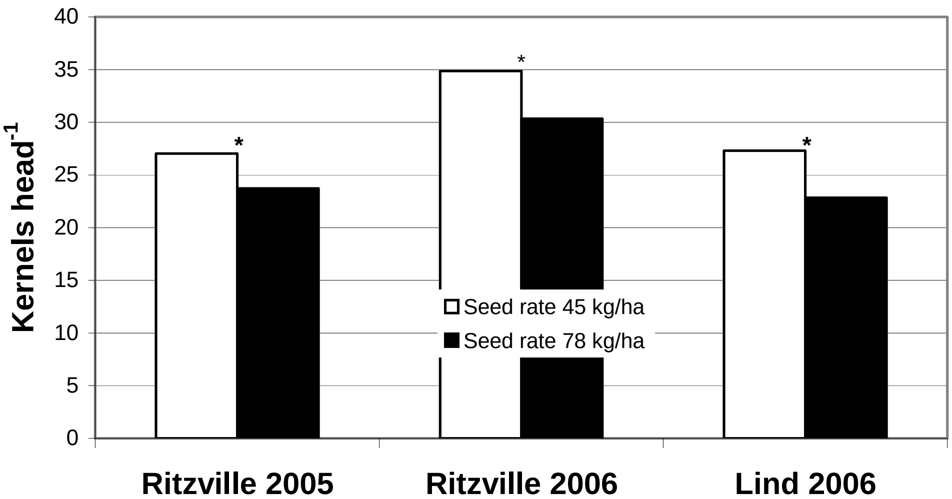


Figure 19. The effect of seed rate on kernels $head^{-1}$ at Ritzville 2005-2006 and Lind 2006.

* indicates a significant difference between seed rates ($p < 0.05$).

Early seeding at Ritzville in 2006 (Figure 20) resulted in more kernels $head^{-1}$ compared to the late seeding, The yield components of wheat have a way of responding to differences in environmental stress, which is the indicator of the Ritzville 2006 early and late planting. More kernels $head^{-1}$ indicated that there was a strong ability for compensation among the individual components for yield. The data indicates that the heads m^{-2} at the early seeding was less than the late seeding as shown in (Figure 16). It is apparent that KW was increased by the plant as competition for grain filling nutrients was less due to the reduction in the number of heads m^{-2} from the early seeding. The response is also reflected in Figure 1, indicating low seed zone moisture during the early seeding date at Ritzville in 2006. Conversely, Thill et al. (1978) found that early sowing of winter wheat was associated with low kernels $head^{-1}$ due to primarily to the greater number of tillers and heads m^{-2} along with heavier KW.

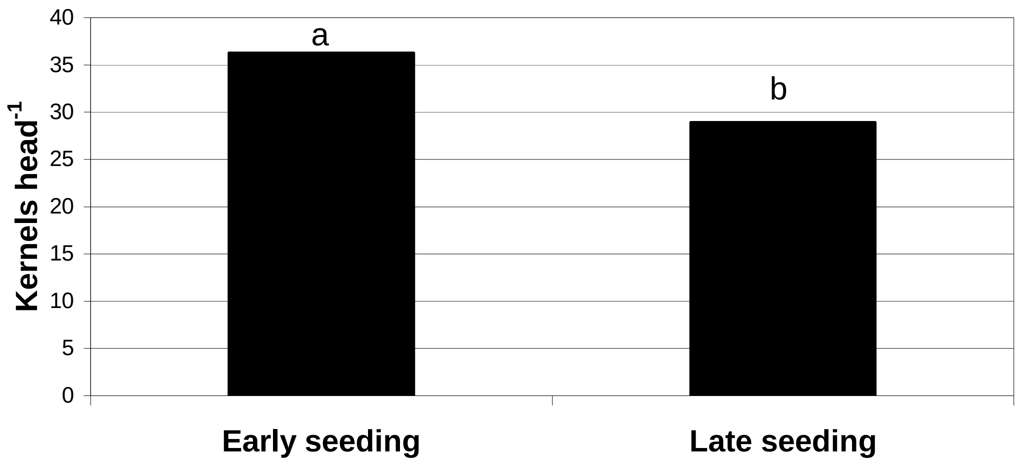


Figure 20. The effect of seeding date on kernels $head^{-1}$ at Ritzville in 2006. Bars capped with same letter are not significantly different.

Kernel weight predominantly depends on how much carbohydrate the plant assimilates during the stage of grain filling, and this is closely related to the area of long-lived green leaves (Darwinkel, 1978). Seeding date had a significant effect on KW at Ritzville in 2005 and 2006 (Figure 21). Kernel weight was decreased by 10.4% with the late seeding in 2005 and by 6.4% in 2006 at Ritzville respectively. With increasing plant densities at the late seeding, the kernel corresponds by increasing its need for carbohydrates that are required for grain filling. This increased demand for carbohydrates will be limited due to high stand density and therefore KW will decrease. A comparison of KW (Figure 21) to plant densities (Figure 1) shows the KW decreased with increasing plant densities.

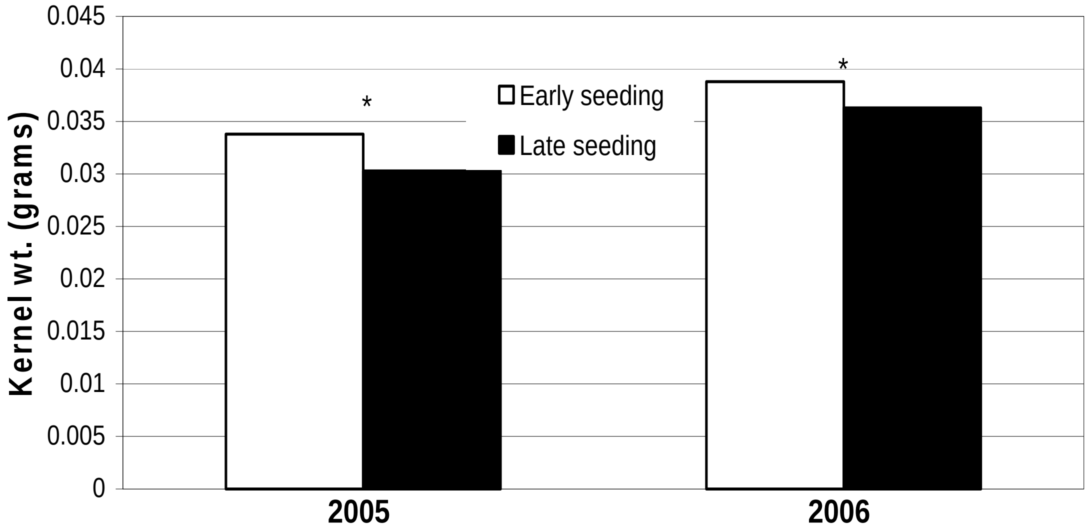


Figure 21. The effect of seeding date on KW at Ritzville in 2005 and 2006.

* indicates a significant difference between seed rates ($p < 0.05$).

The effect of P rate on KW at Ritzville in 2005 shows KW decreased slightly with a linear trend (Figure 22). In contrast, the grain yields and heads m^{-2} improved with increasing P rates (Figures 13, 14, 15, and 18).

On the contrary, reduced interplant competition has been shown to be related with low seeding rates and generally results in proportional increases in kernels $head^{-1}$ and KW (Donaldson et al., 2001). The data in this study shown in Table 3 does not support the trends indicated by Darwinkel (1978) and Donaldson et al. (2001) as a result of the grain yield being positively related to all three yield components: heads m^{-2}, kernels $head^{-1}$ and KW (Table 3).

This is contrary to results of other studies showing negative correlations between kernels head^{-1} and KW (Donaldson et al., 2001; Tompkins et al., 1991; Blue et al., 1990).

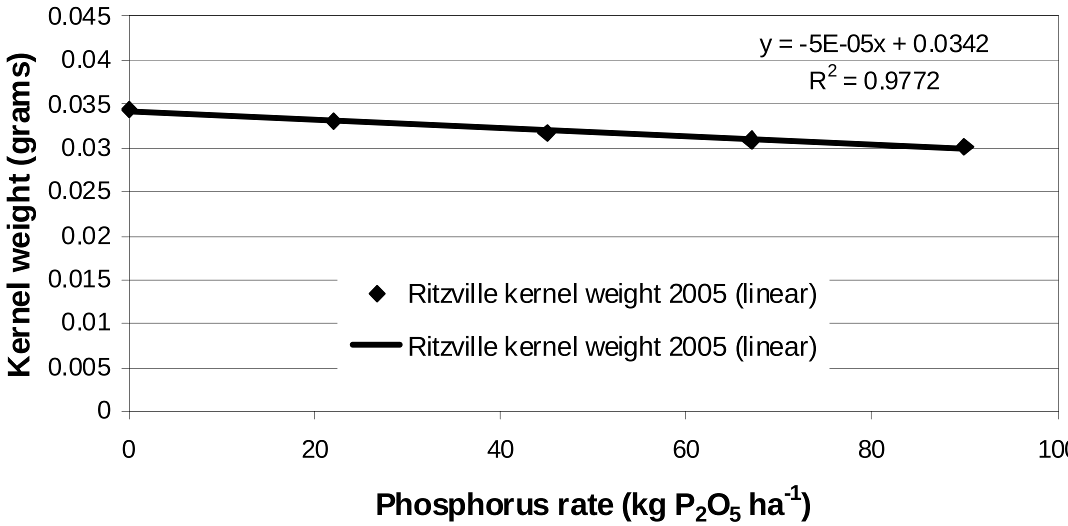


Figure 22. The effect of P rate on KW at Ritzville in 2005. Trend indicated in the legend is significant at ($p < 0.05$).

Table 3. Correlation Matrix for grain yield and yield components. (n=275)

	Grain yield	Heads area^{-1}	Kernels head^{-1}	Kernel weight
Grain yield				
Heads area^{-1}	0.53*			
Kernels head^{-1}	0.34*	0.03		
Kernel weight	0.19*	0.04	0.47*	

*R values are significant at ($p < 0.05$)

Harvest Index

Harvest index is defined as percentage grain in the total plant biomass. Both the Ritzville site in 2005 and the Lind site in 2006 indicate an interaction between seed rate and P rate on HI (Figure 23 and 24), which revealed a linear trend of P rate with the high seed rate.

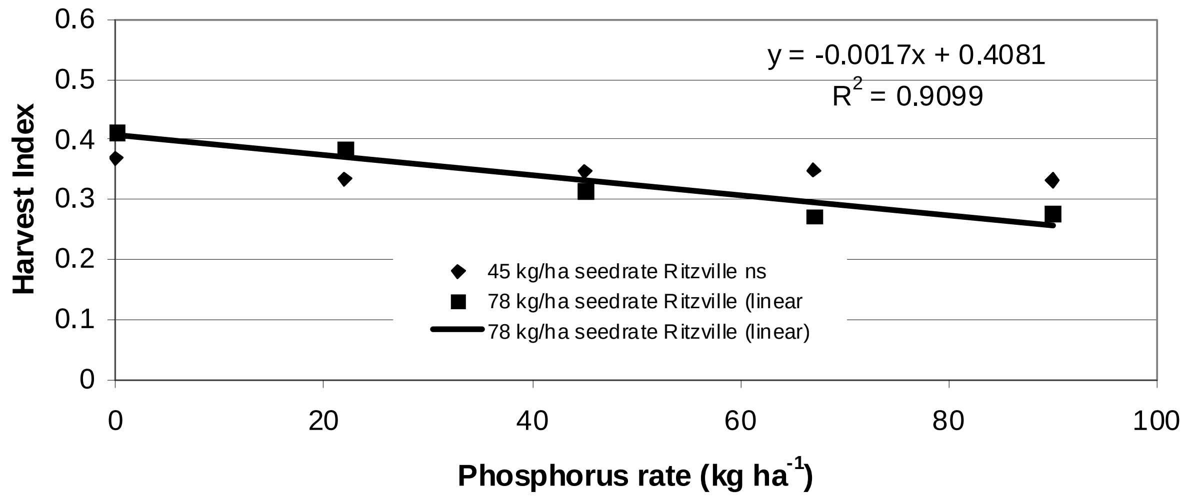


Figure 23. The effect of seed rate and P rate on HI at Ritzville in 2005. Trend indicated in the legend is significant at ($p < 0.05$).

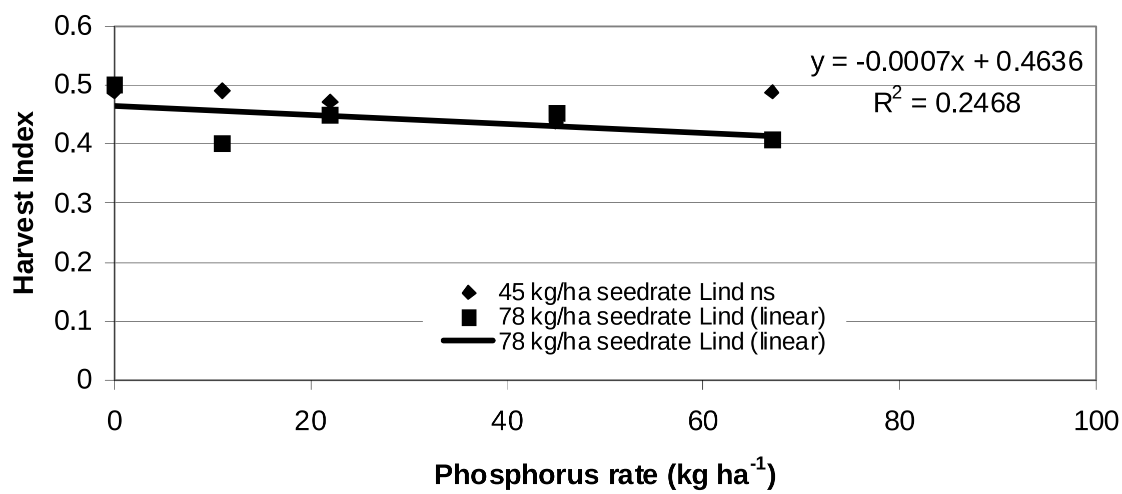


Figure 24. The effect of seed rate and P rate on HI at Lind in 2006. Trend indicated in the legend is significant at ($p < 0.05$).

At Ritzville in 2005 and 2006 (Figure 25), there was an effect of seeding date on HI. While the Ritzville site in 2005 had an early seeding HI mean of 0.38 and late seeding HI mean of 0.29. In 2006, Ritzville had early seeding HI mean of 0.50 and late seeding HI mean of 0.46. Conversely, Donaldson et al. (2001) consistently found that early seeding always resulted in the lowest HI. This inconsistency may result from their seeding depth of 10 cm compared to 5 cm in this study or possibly due to no banding of P and N fertilizer 5 cm directly below the seed that may have contributed to greater HI at the early seeding in this study. The Donaldson et al. (2001) results are similar in KW to the Ritzville 2005. However, the higher stover yields at Ritzville in 2006 for late seeding may have been achieved by P fertility producing more stover therefore representing a lower HI, compared to Ritzville 2005 stover yields.

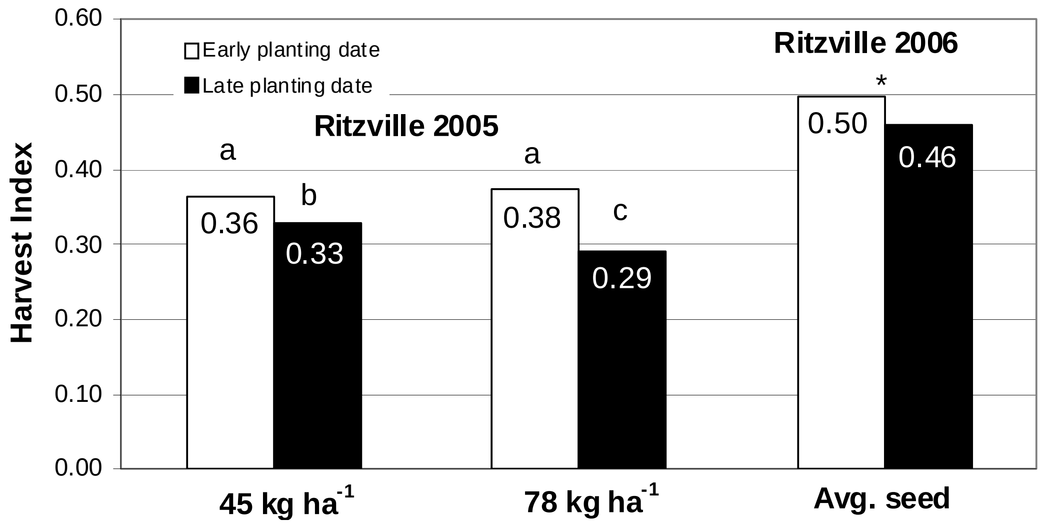


Figure 25. The effect of seeding date and rate, and seeding date averaged over rate, on HI at Ritzville in 2005 and 2006. Bars capped with the same letter are not significantly different; *indicates a significant difference between seeding date ($p < 0.05$).

Phosphorus uptake into Whole Plant

In 2006, the late seeding showed a 14.9 % increase in P uptake into the total plant tissue compared to the early seeding in Ritzville (Figure 26). Total P uptake is calculated as a function of yield multiplied by P concentration in the plant tissue. This difference resulted from the increased seed zone soil moisture availability expanding the plants ability to uptake more P into the plant tissue during late seeding at Ritzville in 2006. Phosphorus application results in higher P quantities available to the plant, only if there is sufficient moisture to influence the grain yield increase.

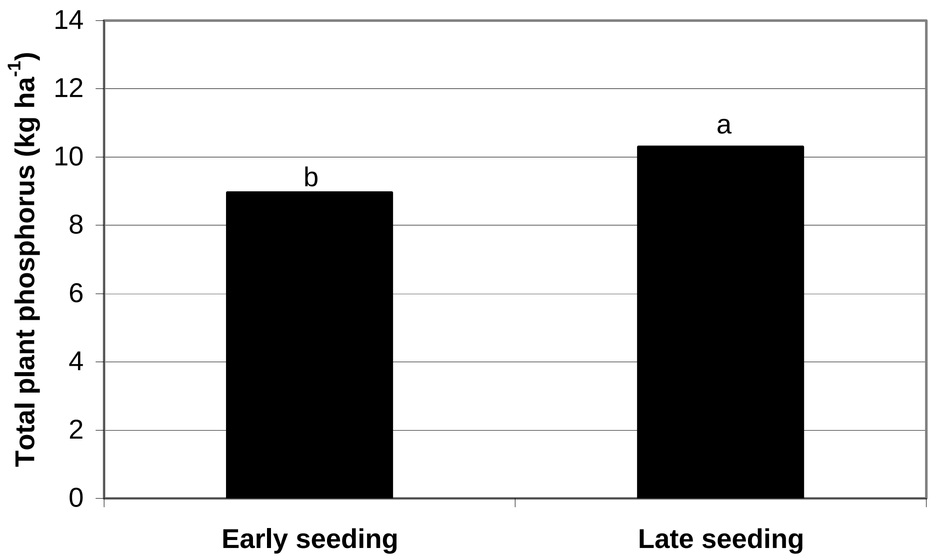


Figure 26. The effect of total P uptake on early and late seeding at Ritzville in 2006. Bars capped with the same letter are not significantly different.

These results show a similar pattern noted in Figure 11 for grain yield at Ritzville in 2006. Batten et al. (1999) presented data that demonstrated the late seeded winter wheat requires higher rates of applied P than early seeded wheat to achieve 90% of the maximum calculated yield. The total P uptake in the whole plant tissue increased with the late seeding at Ritzville in

2006 (Figure 26). The applied P treatments attributed to improved P uptake in the tissue at Ralston and Ritzville in 2005 and Lind in 2006 (Figure 29).

At Ritzville in 2005, there was a significant effect of seed rate on P uptake with a 12.4% increase in whole plant P uptake with the higher seed rate. This may be attributed to increased yield and P concentration in the tissue at the 78 kg ha^{-1} seed rate. At Ralston there was 9.8 % higher whole plant P uptake for the lower seed rate (Figure 27). In 2005, the Ritzville site also indicated a similar increase in grain yield for the higher 78 kg ha^{-1} seed rate.

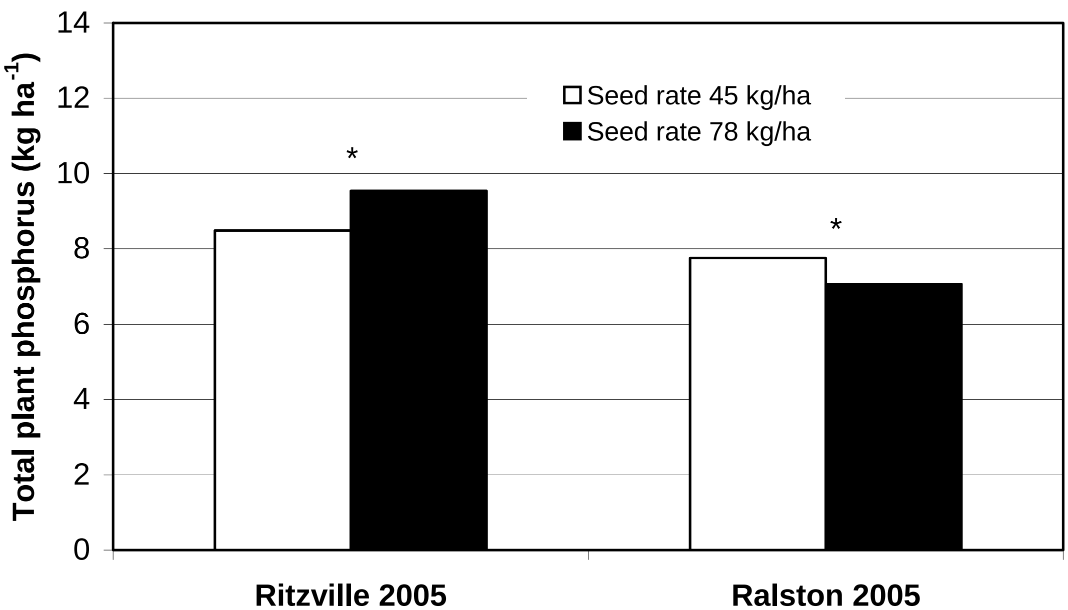


Figure 27. The effect of seeding rate on total plant P at Ritzville and Ralston in 2005. *indicates a significant difference between seeding rate ($p < 0.05$).

A linear response of P rate for P uptake is shown in Figure 28 that resulted in improved grain yields for Ralston and Ritzville in 2005 and Lind in 2006 (Figure14 and 15). At Ritzville, there was a linear effect of P rate on P uptake in the whole plant tissue in 2005, but not in 2006. Ralston showed a linear effect P rate on P uptake into whole plant tissue for 2005. These results are from a combination of grain yields increasing linearly with increasing P rates. As a result, the total plant P showed a linear increase of P uptake at all sites (Figure 28) and a linear effect for the 78 kg ha^{-1} seed rate at Lind in 2006 (Figure 29).

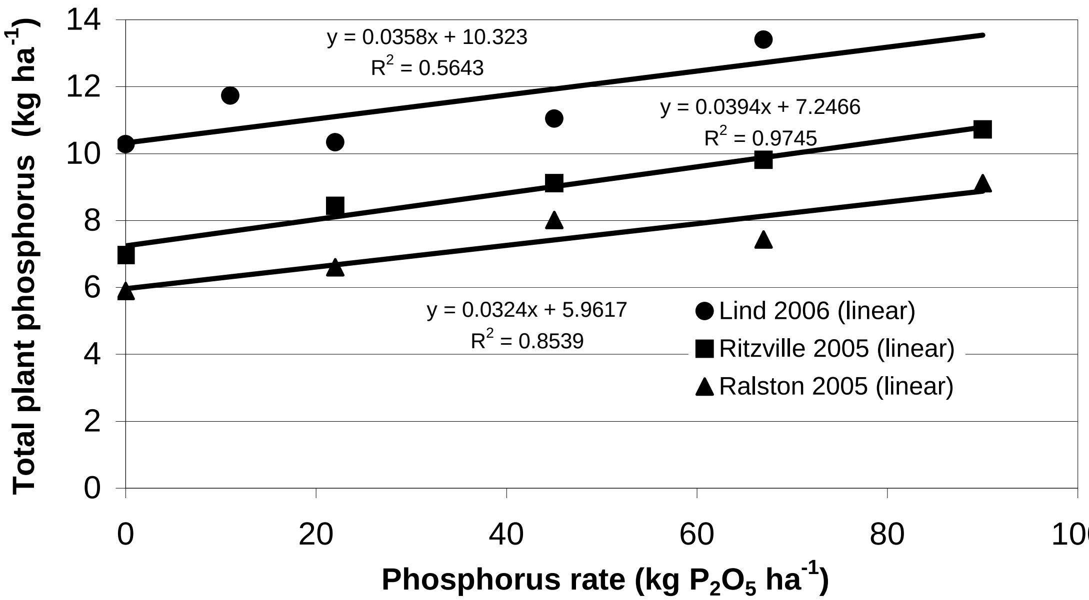


Figure 28. The effect of P rate on total P uptake at Ritzville and Ralston in 2005 and Lind in 2006. The trends indicated in the legend are significant at ($p < 0.05$).

At Lind in 2006, there was a seed rate by P rate interaction with a linear response of P rate at the high seed rate on P uptake into whole plant (Figure 29). The higher P uptake into the whole plant is due to grain yields increasing linearly with increasing P rates at the Lind site in 2006 (Figure 15).

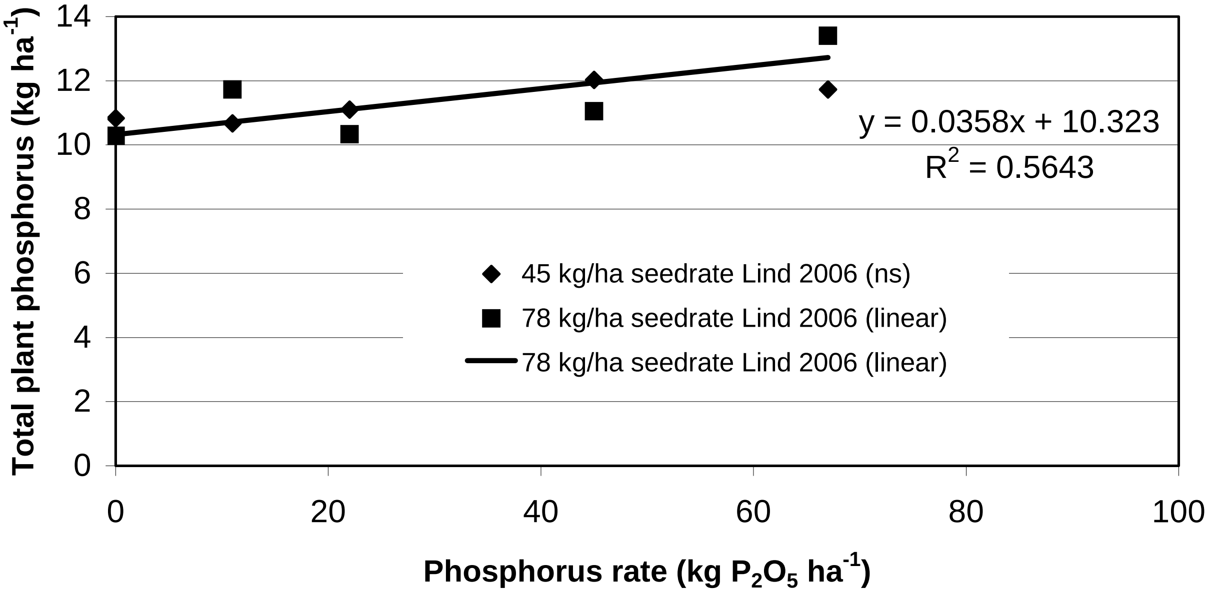


Figure 29. The effect of P rate and seed rate on total plant P at Lind in 2006. Trend indicated in the legend is significant at ($p < 0.05$).

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CHAPTER THREE

Summary

The findings from this study showed that stand density proved to be higher with late seeding due to better seed germination and emergence. The high seeding rate increased stand density at all sites in all years. Increasing P rate resulted in a linear decrease in stand density at higher seeding rates.

High seeding rate increased early-season biomass at the Ritzville and the Lind recropped site in 2006. In addition, there was a quadratic response to the P rate for early season biomass at Ritzville in 2005. Increasing the P rate application caused a linear increase in the biomass for late seeding at Ritzville in 2005 and 2006.

The grain yield improved with early seeding due to a rainfall event during seeding time at Ritzville in 2005. Furthermore, the grain yield was higher with late seeding due to the lack of seed zone moisture during the early seeding at Ritzville in 2006. The higher seeding rate increased the grain yield by 196 kg ha^{-1} (2.9 bu ac^{-1}) in 2005 and 216 kg ha^{-1} (3.2 bu ac^{-1}) in 2006, on the chemical fallow sites at Ritzville. The responses to P at recrop sites (Ralston in 2005 and Lind in 2006) showed yield increases of 81 to 344 kg ha^{-1} (1.2 to 5.1 bu ac^{-1}). The responses to P rate at Ritzville (the chemical fallow site) in 2005 suggest a yield increase of approximately 650 kg ha^{-1} (9.7 bu ac^{-1}). The responses to P rate at Ritzville, the chemical fallow site, in 2006 suggest a yield increase of approximately 620 kg ha^{-1} (9.2 bu ac^{-1}).

Conclusions

In conclusion, the research from this study showed that when the seed zone soil moisture is good, seed early. In addition, when the seed zone moisture is low, delay seeding. Increasing the seeding rate may increase the yields in chemical fallow, but not in recrop situations. Increasing P rate produces a substantial increase in grain yield for chemical fallow regardless of early or late seeding. Additionally, it is possible to over fertilize with P in a dry year. Higher rates of P evidently encouraged additional plant growth that may have depleted stored soil moisture. However, my research showed there was a small increase in yield when P was applied to the recrop sites. Finally, growers in dry areas can improve yields of late planted wheat by increasing seed rate (in chemical fallow) or P rate (in chemical fallow and recrop). Growers should complete a cost effective analysis of the price of seed to the price of P fertilizer before making a final decision on a method to improve their wheat yields. Further study is needed to explore the production costs and net returns. Continued research utilizing larger plots and full sized equipment would be advantageous.