# FOLIAR PHOSPHORUS FERTILIZATION AND THE EFFECT OF SURFACTANTS ON WINTER WHEAT

# (*Triticum aestivum* L.)

By

GUILHERME MARTIN TORRES

Bachelor of Science in Agronomy

Faculdades de Ciencias Agronomicas

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Thesis Approved:

Dr. William Raun

Thesis Adviser

Dr. Kefyalew Desta

Dr. Randy Taylor

Dr. Mark E. Payton

Dean of the Graduate College

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# CHAPTER I

## INTRODUCTION

Many scientists around the world have shown interest in foliar fertilization of phosphorus (P) due to the relevant benefits that this technique can have on cereal production. Foliar applied P can use reduced rates in relation to soil applied P, supplying the plant requirements at a specific time during the crop cycle when P is most needed. This avoids problems related to soil applications due to chemical reactions that can make the fertilizer unavailable for the plant, reducing cost, and potential environmental concerns due to runoff, such as eutrophication of water bodies.

The importance of foliar P fertilization becomes even more evident when its availability and demand are considered. Phosphorus is considered the second most limiting nutrient in many agricultural crops and it is a required element for all living organisms. Phosphate fertilizers are essential to support the growing human population and are associated with world food, bio-energy and fiber supply. Herring and Fantel (2005) modeled scenarios taking into consideration the depletion of phosphate reserves based on phosphate demand and the increasing population and found that world reserves will be depleted within the next 100 years. Tillman et al. (2001) expect that by 2020 an increase of 1.4 times the current amount ($34.3x10^6$Mt) of P fertilizer used, and 2.4x by 2050.

Broadcast application of P fertilizers followed by incorporation is a common agricultural production practice. Another method is banding P with the seed which has proven to be more efficient than broadcast application (Sander, 1990). Phosphorus fertilizer use is very inefficient in agriculture and its recovery is estimated to be between 10-15% of the P applied (Syers et al., 2007). The poor use efficiency of P fertilizers is related to the behavior of phosphorus in the soil. Literature suggests that water soluble P added in the soil can precipitate with other elements forming water insoluble minerals, variscite or strengite (aluminum and iron phosphate) in acid soils and in basic soils, P precipitates with calcium forming calcium phosphates which affects the availability of P for plant uptake (Sample, et al., 1980). Foliar nutrition for winter wheat comes into sight as a strategy to boost P use efficiency, avoiding the problems associated with soil application, using reduced rates to meet the plants requirement, and increasing yield and grain quality. According to Mosali et al. (2006), low rates were able to correct mid-season deficiencies in winter wheat and foliar applied P generally increased yield and P use efficiency. Girma et al. (2007) showed that foliar applied P on corn resulted in an increase in grain yield, and forage and P grain concentration. The fact that the P fertilizer applied does not come in contact with the soil, benefits both the crop and the environment. Over application of P in cropping systems and subsequent surface runoff which is the major transporter of P from fields to water bodies has led to extensive eutrophication of water supplies resulting in the decline of natural resources economic loss.

To investigate the benefits of foliar P found in the literature this study was proposed and triple super phosphate (TSP) was used as the P source to avoid confounding effects of other nutrients. The aim of this study was to identify whether foliar application of P with and/or without the addition of non-ionic and cropoil surfactants can enhance winter wheat yields, provide a better use efficiency and improve uptake of P fertilizer leading to a reduction in costs, and environmental risk.

# CHAPTER II

# REVIEW OF LITERATURE

## Role of P in the Plant

Phosphorus (P) is fundamentally important to plants and is an essential element for all living organisms. Phosphorus can persist as inorganic phosphate or it can be incorporated into the carbon chain through a hydroxyl group (phosphate ester) or an energy-rich pyrophosphate, which is formed by the bond of phosphate to another phosphate (Marschner, 1995). Phosphorus is a constituent of molecular structures such as nucleic acids that compose DNA and RNA molecules, and is fundamental to transport and translation of genetic information in the plant (Schönknecht, 2006). Furthermore, phosphate esters and energy-rich phosphates are responsible for the formation of adenosine triphosphate and adenosine diphosphate (ATP and ADP respectively), which are essential for starch synthesis. In addition, inorganic phosphates have a regulatory role controlling some enzymatic reactions (Marschner, 1995).

## Behavior of P in the Soil

Phosphorus, although found in large quantities, is considered immobile in the soil. The availability of P is a function of the amount removed by the crop, soil pH, concentration of P in the soil, and the P added that will go into the soil solution. Mosali et al. (2006) stated that the amount of available P will be a function of pH, contact between soil and P fertilizer, rate of dissolution and diffusion, temperature, soil type, and organic matter. Phosphorus availability can be influenced by soil pH (Chen and Barber, 1990).

When the soil is acidic, most of the P will complex with iron (Fe) and aluminum (Al) forming strengite and variscite respectively, and in basic soils, P will react with calcium (Ca) forming hydroxyapatite, dicalcium and octacalcium phosphates, all of which are very insoluble, and decrease the availability for plants (Lindsay et al., 1989). Currently the concept concerning P behavior in the soils suggests that soil P is found in equilibrium within different pools of soil phosphorus according to the accessibility and extractability (Kirby, 2008). Syers et al. (2008) suggested that P in the soil solution is the first pool and is immediately-extractable for root uptake. The second pool inorganic P ($P_i$) is readily available because, P is weakly bonded to the surface of soil particles, and is in equilibrium with the soil solution. In other words, P is transferred to the soil solution as the concentration of P in soil solution decreases. The third pool is less readily available; P is adsorbed to the soil matrices and becomes extractable over time. The fourth pool is precipitated forming insoluble P compounds. This P is very strongly bonded to the soil components and has a very low extractability and will only become available after a long period of time.

**Foliar Nutrition**

Foliar P nutrition arose as an alternative to minimize the impact related to soil fertilization, because it avoids contact between soil and fertilizer. Consequently this reduces other drawbacks related to P management such as euthrophication, reducing costs, and increasing P use efficiency, increasing crop productivity, and quality. Recommendations regarding foliar P fertilization are directed to dry top soils in semi-arid regions to slightly P deficient soils and as a supplemental source of P, and not as a substitute of soil applications. Fritz (1978) stated that foliar P fertilization should be used as a supplement to adequate soil applied P fertilizers because; by itself, foliar fertilization is not enough to fulfill the nutrient demand of the crop. Boynton (1954) compared soil applied versus foliar P fertilization and concluded that the absorption and metabolism of foliar applied P was superior to the soil applied P but over the plant cycle, foliar fertilization was not enough to meet the plant's requirements for P.

## Foliar Uptake Physiology

Nutrient uptake through the leaves by the plant involves two mechanisms, through leaf stomata (Eichert and Burkhardt, 1999) and through hydrophilic pores present on the leaf cuticle (Tyree et al., 1990). Mineral nutrients enter the epidermal cells through small pores called ectodesmata (Schonherr, 1976) and are affected by environmental factors and the physiological state of the leaves (Wöjcik, 2004). The plasma membrane is responsible for the transport of solutes against the concentration gradient and also for the selectivity of solutes (Marschner, 1995). The chemical properties of the foliar P formulations will affect the rate of uptake. Wöjcik (2004) suggested based on the literature that $NaH_2PO_4$, $NH_4H_2PO_4$ and $H_3PO_4$ are forms which P are absorbed at greater rate by the leaves.

## Factors Affecting Uptake

The uptake of mineral nutrients from foliar fertilization is highly affected by several factors. Some of the features that can affect foliar absorption include light, air temperature, humidity, the solution pH and concentration, the use of surfactants, plant species and varieties, leaf age, the plant's nutritional status, and development stage.

Wöjcik (2004) stated that light intensity facilitates nutrient uptake by the leaves. A positive correlation between light intensity and leaf absorption of urea, $Rb^{+}$, and $PO_4^{-3}$ on bean (*Phaseolus vulgaris*) was demonstrated by Jyung et al. (1965). When considering the influence of temperature on nutrient absorption the literature is controversial. Reed and Tukey (1982) found a negative relationship between air temperature and leaf wax surface coverage which may be favorable for nutrient absorption. However, Norris (1974) suggested that nutrient absorption will be a function of the chemical composition and arrangement of the waxes, and found no difference in uptake of minerals by the leaves due to wax deposition.

Moreover, the nutrient solution pH and concentration are likely to affect the uptake and can injure leaves leading to reduction in uptake. According to Knoche et al. (1994), the rate of uptake by epidermal cells is positively correlated with nutrient concentration. However, leaves that were injured have limited uptake due to damaged ectodesmata structures (Marschner, 1995). Kannan (1980) concluded that the optimum pH of spray solutions range between 3.0 and 5.5 for maximum mineral uptake. Anionic solutions with a low pH were found to facilitate a more rapid uptake by leaves when compared to a high pH solution (Fisher and Walker, 1955).

Furthermore, leaf uptake is influenced by air humidity. According to Bukovac and Wittwer (1959) , P uptake of bean leaves was enhanced when the leaf surface was kept moist compared with a dry leaf surface. Tukey and Marczynki (1984) stated that high air humidity helps by reducing the droplets drying rate resulting in an increase in nutrient uptake by the leaves. To enhance the effect of the foliar fertilization, applications with surfactants are recommended. Normally used in agrochemical formulations to enhance the solution physical and chemical features of a solution, surfactants increase the efficiency of foliar applied solutions (Holloway and Stock, 1990). The surfactants decrease the surface tension between the leaf and solution leading to an increase in leaf surface wetness (Wöjcik, 2004). In addition, surfactants increase leaf and liquid contact (Figure 1 and 2) and consequently enhance penetration of solutes through cuticular membranes, stomata, cell walls and with limited drying effect (Grieve and Pitman, 1978). Biological characteristics can also affect nutrient uptake for biological species, leaf surface area, and leaf age. Absorption of mineral nutrients will depend on plant species due to the different amounts of ectodesmata on the leaf (Marschner, 1995) and the specific characteristics of the cuticular membrane (Wöjcik, 2004).

**Nutritional Status and Plant Development Stage**

Even though P uptake occurs through the leaves, P is rapidly absorbed, metabolized, and thereby, moved to the newer growing regions of the plant. The expected response to foliar fertilization will be relative to the nutrient insufficiency at the time of application and the quantity absorbed through the leaves. Experiments conducted with corn and beans showed that foliar application of ortho-phosphoric acid containing radioactive P confirmed the absorption and movement of P in the plants (Boyton, 1954). In tropical soils, the utilization of phosphoric acid by the roots can be as low as 10%, while the phosphate utilization via leaves can be as high as 50% (Fritz, 1978). Foliar applied inorganic phosphate is absorbed and incorporated into sugar, lipid, and protein, therefore, converted into organic phosphate in the leaf (Wittwer and Teubner, 1959).

## Phosphorus Requirement and Time of Application in Wheat

Phosphorus stress in early growth stages can negatively impact the plant due to the importance P has on the plant metabolism especially considering that P is required for energy processes (Grant, 2001). The literature suggests that wheat produces maximum grain yields if P is supplied prior to heading (Batten et al., 1986). Johnston et al. (1999) stated that wheat plants remove between 75 and 80% of the P from the soil to the grain. They suggest that 45% is accumulated during flowering and the remaining 55% of P is accumulated during grain fill, of which 50% of the total P in the grain is translocated from leaves, stem and head. Johnston et al. (1999) found evidence that P uptake takes place as late as physiological maturity. At the period of maximum growth nearly all P needed was taken up (ISMA, 1982). The P content for cereals can vary from 0.10% to 0.15% in dry matter and 0.4% to 0.5% in storage tissues and grain (IMPHOS, 2002a). Ali and Mian (1968), showed that percent P in wheat grain varies between 0.23 and 0.25%. Elliott et al., (1997) found that wheat P grain concentration ranged between 0.19 and 0.25%.

## Foliar Phosphorus Effect on Yield, PUE and Grain P Concentration

Studies regarding the foliar application effect of P on wheat yields are being conducted in several parts of the world. For instance in China, potassium phosphate was foliar applied in wheat at 1 to 4 kg ha$^{-1}$ and all rates resulted in an increase of yield especially under low temperature environments, but there was no effect under high temperature regimes (Sherchand and Paulsen, 1985). Mosali et al. (2006) applied 1, 2, 4, 8, 12, 16 and 20 kg P ha$^{-1}$ with and without preplant rates of P (30 kg P ha$^{-1}$ ) and found that foliar P applications usually increased yield and P uptake at Feekes 7 when compared to no foliar applied P, however the higher P use efficiency was obtained at Feekes 10.5. Girma et al., (2007) reported a small yield increase and a large improvement on forage and grain concentration in corn with foliar rates of 8 kg of P $ha^{-1}$. Another experiment conducted in Morocco, revealed up to 1 Mg $ha^{-1}$ increase in wheat grain yields with foliar application of $KH_2PO_4$ at rates of 1.1 to 2.2 kg P $ha^{-1}$ after anthesis. The increase in yield was attributed to the delayed senescence promoted by the fertilizer under water and heat stress (Benbella and Paulsen, 1998).

# CHAPTER III

## HYPOTHESIS AND OBJECTIVES

The hypothesis for this experiment was that foliar P fertilization could improve yield, PUE, and grain P concentration when compared to the preplant P fertilization. Furthermore, a second hypothesis was that treatments that received non-ionic or cropoil surfactants would improve P uptake, resulting in higher grain P concentration, phosphorus use efficiency and grain yield when compared to preplant P fertilization.

The objective of this study was to evaluate and compare the effect of applying triple super phosphate as a foliar P source with non-ionic and cropoil surfactant and without surfactant at the rates 5 kg $ha^{-1}$ and 10 kg $ha^{-1}$ with soil applied P and with combinations of preplant and foliar P (10:5 and 20:5 kg $ha^{-1}$) on winter wheat grain yield, phosphorus use efficiency and grain P content.

# CHAPTER IV

## MATERIALS AND METHODS

Four field trials at two experimental sites were established in 2008/2009 and 2009/2010 to evaluate effectiveness of foliar application of P with and without the addition of surfactants in winter wheat. Two trials were located at Lake Carl Blackwell (Port silt loam-fine-silty, mixed, thermic Cumulic Haplustolls) and the other two trials were located at Efaw (Norge loam, fine-silty, mixed thermic Udic Paleustoll). The wheat variety planted in 2008 for both sites was ‘Overley’. The fields were planted on October 3, 2008 at Lake Carl Blackwell (LCB) and on October 10, 2008 at Efaw. In 2009, wheat was planted on November 7 and 8 at LCB and Efaw, respectively and the variety used was ‘Endurance’. In both years and sites winter wheat was planted with a row spacing of 19.05 cm with a seeding rate of 100.8 kg ha$^{-1}$. Plots were 6.09 m long and 3.50 m wide. A Randomized Complete Block design with three replications was used to evaluate treatments ranging from 9 to 15 depending on trial. Treatments were applied at Feekes 7 and TSP (20% P) was used as the foliar P source. In 2008/2009, the preparation method of the foliar solution consisted of finely grinding TSP to pass through a sieve with openings of 250 µm. This finely ground TSP was mixed with water at the time of application and applied with a backpack sprayer over the wheat canopy (Figure 3). In 2009/2010, instead of finely grinding the TSP, a solution was prepared dissolving TSP in water at a ratio of 1:3 (TSP:water) resulting in a concentration of approximately 6.6% P (66 g P L$^{-1}$) and a pH of 2.3. All treatments received 112 kg N ha$^{-1}$ preplant, in both trials (Figures 4 and 5). Preplant rates of 0, 10, 20 and 40 kg P ha$^{-1}$ and foliar top-dress rates of 0, 5, 10 kg P ha$^{-1}$ with and without surfactants were also evaluated. For one experiment, the surfactant type used was a nonionic ‘AG-98’ (Alkylphenol ethoxylate-based non-ionic surfactant manufactured by Dow AgroSciences, Indianapolis, IN) and this same product plus crop oil were used in the other experiment. Comprehensive soil samples, 0-15 cm were taken prior to the start of each trial (Table 1). At maturity, the center of each plot was harvested using a Massey Ferguson 8XP experimental plot combine, equipped with a Harvest Master automated weighing system (HarvestMaster Inc, Logan, Utah) to collect individual plot weights. A subsample of wheat grain from each treatment was collected for P quantification using nitric perchloric acid digestion (Jones Jr and Case, 1990). Grain yield, grain P concentration (GPC) and P use efficiency (PUE) were determined for each treatment. Phosphorus use efficiency was computed by utilizing the following formula; PUE = [(total grain P uptake treated – total grain P uptake check)/P rate applied]. Grain yields for all treatments were adjusted to standard moisture of 12.5%. Statistical analysis was performed using SAS procedures such as contrasts (orthogonal/non-orthogonal single degree of freedom, trend, and ANOVA (SAS, 2003) using alpha=0.05 and 0.10 to be considered significant.

# CHAPTER IV

# FINDINGS

Grain yield response to P applied using various methods, including broadcast, foliar, and combinations of the two, with and without surfactant differed by location and year, thus, results are reported separately. Data was not presented for Lake Carl Blackwell in 2008-2009 for both with and without surfactant experiments due to freeze damage that occurred in the first two weeks of April.

## Foliar P with Non-ionic Surfactant

### EFAW, 2008-2009

Analysis of variance (Table 2) showed that there was a significant difference between treatments for grain yield and P use efficiency, however, no significant differences were found for grain P concentration. Grain yields ranged from 1945 to 2431 kg $ha^{-1}$ (mean of 2183 ± 167). In general, foliar applied P as well as the application of preplant and foliar P combined resulted in higher yields than the check and 20 and 40 kg $ha^{-1}$ applied preplant. For this location and year the highest yield was achieved with foliar P at 5 kg $ha^{-1}$ using a surfactant. Grain P concentration values ranged from 2283 to 2957 mg $kg^{-1}$ (mean 2730 ± 230). Overall, PUE was improved when P was supplied through the leaves compared to preplant applied P (20 and 40 kg $ha^{-1}$). The values for PUE varied from 0 to 15% (mean 6.3 ± 4.2). For this trial foliar fertilization of 10 kg P $ha^{-1}$ without surfactant was the most efficient method of fertilization of P for winter wheat.

The non-orthogonal single degree of freedom analysis results revealed a significant yield difference when compared the use of a surfactant to no surfactant, in addition estimates showed that the application of P with no surfactant resulted in 274 kg $ha^{-1}$ yield increase compared to the application of P with surfactant (Table 3). Likewise, significant differences were found between foliar applied P and preplant fertilization (22 kg $ha^{-1}$). Nevertheless, there was a significant grain yield difference of 159 kg $ha^{-1}$ when foliar P with surfactant was compared to broadcast preplant P fertilization. When foliar P with and without surfactant was compared to broadcast preplant applied P (20 and 40 kg P $ha^{-1}$) there was a significant difference in yield of 22 kg $ha^{-1}$. For grain P concentration (GPC) and PUE no significant differences were found when comparing the same foliar P rates, with and without surfactant (Table 3).

Polynomial orthogonal single degree of freedom contrasts showed that there was a significant linear increase in grain yield for foliar P (0, 5 and 10 kg $ha^{-1}$) without surfactant (Table 4). However, there was no trend either linear or quadratic for yield when the same rates were applied with non-ionic surfactant. There was no effect of P rate without the non-ionic surfactant for grain P concentration, but there was a significant quadratic trend for grain P concentration when the surfactant was added. Grain P concentration decreased as foliar P rate increased to 5 kg $ha^{-1}$ and then increased as P rate continued to increase to 10 kg $ha^{-1}$. The detrimental effect of foliar P at 10 kg $ha^{-1}$ is likely due to a elevated P concentration that potentially cause some kind of injury in the plant and therefore resulting on lower GPC in comparison to 5 kg P $ha^{-1}$.

**EFAW, 2009-2010**

Analysis of variance showed that treatments did not significantly affect grain yield, grain P concentration and P use efficiency (Table 5). Grain yield ranged from 2110 to 2573 kg ha$^{-1}$ (mean of 2335 ± 153, Table 5). Overall, foliar applied P as well as the application of soil and foliar P combined resulted in higher yields than the check and 20 and 40 kg ha$^{-1}$ applied preplant, with the exception of foliar applied P with the addition of surfactant, but this was again, not significant. For this location and year, maximum yields were achieved with foliar P at 10 kg ha$^{-1}$ without surfactant. Grain P concentration values ranged from 3057 to 3390 mg kg$^{-1}$ (mean 3223 ± 122). Highest grain P concentration resulted from P broadcast preplant at a rate of 20 kg P ha$^{-1}$ (3390 mg kg$^{-1}$) followed by the combined application of 10 kg ha$^{-1}$ preplant and 5 kg ha$^{-1}$ foliar (3353 mg kg$^{-1}$). Phosphorus fertilization through the leaves tended to improve PUE compared to preplant applied P (20 and 40 kg ha$^{-1}$). The values for PUE varied from 1 to 15% (mean 6 ± 5). For this trial foliar fertilization of 5 and 10 kg of P ha$^{-1}$ without surfactant was the most efficient method of fertilization of P for winter wheat (Table 5).

Orthogonal single degree of freedom contrasts showed that there was a significant linear increase in grain yield for foliar P (0, 5 and 10 kg ha$^{-1}$) without surfactant at Efaw, in 2009. However, there was no trend either linear or quadratic for yield when the same rates were applied with non-ionic surfactant. There was no effect of P rate with and without the non-ionic surfactant for grain P concentration. The lack of a linear or quadratic trend was due to a slight reduction in yield and grain P concentration when 10 kg P ha$^{-1}$ was applied through the leaves. There was significant different for GPC between foliar application without and with surfactant, and it was estimated that with surfactant improved GPC by 324 mg $kg^{-1}$ over the application without surfactant

**Lake Carl Blackwell, 2009-2010**

Results for this site revealed that PUE was improved with foliar P fertilization compared to preplant applications, however, differences between treatments were small (Table 8). The highest PUE was achieved with 5 kg P $ha^{-1}$ with and without surfactant (32% and 23% respectively) while preplant application of 20 and 40 kg P $ha^{-1}$ resulted in PUE of 7% and 5% respectively. Phosphorus use efficiency ranged from 5 to 35 % (mean 14 ± 10). There was no significant difference between the treatments for yield and grain P concentration. Values for yield ranged from 1839 to 2301 kg $ha^{-1}$ (mean 2088 ± 175) and maximum yield was achieved with the combination of 20 kg $ha^{-1}$ preplant and 5 kg $ha^{-1}$ foliar. Furthermore, all foliar treatments produced higher yield than the 0-P check, but not more than P broadcast, with the exception of 5 kg $ha^{-1}$ foliar without surfactant. The addition of surfactant with foliar applications significantly improved grain P concentration when compared to foliar application without surfactant and with the preplant applied P. Grain P concentration ranged between 3636 to 4217 mg $kg^{-1}$ (mean 3905 ± 197) (Table 8).

Non-orthogonal contrasts showed no significant differences regarding yield, grain P concentration and PUE between foliar and broadcast preplant. There was a significant difference between the presence and absence of surfactant which the use of surfactant was estimated to be 324 mg $kg^{-1}$ greater than the lack of of surfactant. There was a trend for a linear increase in yield and grain P concentration for the P rates applied with surfactant although statistically not significant. No significant trends were found for yield and grain P comparing the foliar rates without surfactant. Again, although not significant, the application of 10 kg P $ha^{-1}$ without surfactant resulted in a yield and grain P concentration decrease.

**<u>Foliar P with Non-ionic or Cropoil Surfactant</u>**

**EFAW, 2008-2009**

For this trial, grain yield was generally increased when P was supplied foliar or combined with broadcast preplant applications compared to the check, and to the broadcast preplant applications at 20 and 40 kg P $ha^{-1}$. Nevertheless, no significant yield or GPC differences were found between these treatments. Grain yield values ranged from 1623 to 2183 (mean 1958 ± 149), GPC ranged from 3060 to 3890 mg $kg^{-1}$ (mean 3424 ± 205), and PUE ranged from 1 to 51% (mean of 12 ± 16) (Table 7). Maximum yield was achieved with the application of 10 kg P $ha^{-1}$ with surfactants (non-ionic and cropoil). For grain P concentration the highest values were achieved with 5 kg P $ha^{-1}$ foliar with the addition of the cropoil surfactant. Treatments significantly affected PUE. For PUE, 5 kg P $ha^{-1}$ applied foliar often resulted in improved use efficiency compared to other rates or methods of application and the most efficient treatment was a result of the foliar application of 5 kg $ha^{-1}$ with crop-oil (Table 7).

Non-orthogonal single degree of freedom contrasts showed that there were significant differences between methods of P application (preplant and foliar), and also between the presence and absence of surfactant for yield. Foliar fertilization (with and without surfactant) was significantly different from preplant P. Foliar P fertilization performed 206 kg $ha^{-1}$ higher yield than the preplant. Foliar P application with surfactant (non-ionic and cropoil) showed to improve yield by 226 kg $ha^{-1}$ in comparison to foliar application of P without surfactant. These differences were found to be significant (Table 8). There was however, no significant influence of the surfactant and methods of P application on grain P concentration. In all cases, foliar P resulted in improved PUE compared to preplant applications (Table 8). Estimates showed that with foliar application PUE was improved by 23%. When compared foliar P without and with surfactant, foliar P with surfactant resulted on improvement on PUE of 6%.

For the combination of preplant and foliar P fertilization (0:5, 10:5, and 20:5 kg P $ha^{-1}$), there was no significant linear or quadratic trend for yield or grain P with cropoil and without surfactant. When non-ionic surfactant was added a significant quadratic trend could be observed for yield and no significant linear or quadratic trend for grain P concentration.

**EFAW, 2009-2010**

Analysis of variance for this site/year (Table 9) revealed no differences between the treatments for yield, grain P concentration and PUE. Maximum yield was reached with a broadcast application of 40 kg P $ha^{-1}$. The combination of preplant and foliar fertilization (10 and 5 kg $ha^{-1}$) and by the foliar application of 5 kg $ha^{-1}$ without surfactant produced near maximum yields. Yield values ranged from 2697 to 3130 kg $ha^{-1}$ (mean 2928 kg $ha^{-1}$ ± 127). All foliar and/or combined fertilization resulted in higher yield than the preplant application of 20 kg $ha^{-1}$. Grain P concentration varied from 2913 to 3557 mg $kg^{-1}$ (mean 3184 mg $kg^{-1}$ ± 176), where 20 and 40 kg $ha^{-1}$ applied preplant resulted in higher P concentration in the grain. Furthermore, the combined fertilization method often resulted in improved grain P concentration when compared to foliar fertilization and the 0-P check. In general, P use efficiency was low for this site/year. Values ranged from 0 to 11% (mean 5 ± 3). In 5 out of 12 treatments foliar or combined application resulted in better use efficiency of P. Foliar P without surfactant was 9% better than foliar P with non-ionic surfactant, this difference showed to be significant (Table 10).

Comparisons between methods of fertilization showed that foliar and combined (preplant + foliar) application was not significantly different from the broadcast application for grain yield. However, there were significant differences among foliar P applications and the preplant method for grain P concentration. Estimates showed that for GPC preplant fertilization was 382 mg kg$^{-1}$ better than the foliar fertilization. Grain P concentration showed a linear trend for the combined fertilization without surfactant, however there was no significant response when surfactants were used.

**Lake Carl Blackwell, 2009-2010**

The results for this site are summarized in Table 11. Yield values ranged from 2415 to 3066 kg ha$^{-1}$ (mean 2803 ± 188), where 5 kg P ha$^{-1}$ without surfactant produced maximum yield (3066 kg ha$^{-1}$) while the broadcast application of 20 and 40 kg ha$^{-1}$ produced 2943 and 2452 kg ha$^{-1}$, respectively. The application of 20 kg P ha$^{-1}$ preplant plus foliar application with cropoil at 5 kg P ha$^{-1}$ resulted in higher grain P concentration. Foliar applied P at 5 kg P ha$^{-1}$ also achieved levels near maximum for grain P concentration. Often, treatments that received foliar application of P with non-ionic surfactant resulted in grain P concentration lower than the check. The preplant applied P at rates of 20 kg P ha$^{-1}$ resulted in P concentration in the grain higher than the check but at 40 kg P ha$^{-1}$ a reduction could be observed, thus values were lower than the check.

Phosphorus concentration values ranged from 4233 to 4950 mg $kg^{-1}$ (mean 4581 ± 232). Generally treatments that received foliar P resulted in increased PUE compared to preplant treatments. Maximum PUE was 79% when 5 kg P $ha^{-1}$ without surfactant was applied, varying from 3% to 79%. Lowest PUE was observed with the preplant application of 40 kg P $ha^{-1}$ (PUE of 3%).

Single degree of freedom non-orthogonal contrasts (Table 12) showed that foliar fertilization was not significantly different from preplant application for grain P concentration and yield. In addition, no significant differences were found between the combined application (preplant + foliar) and preplant. There were no significant differences between foliar, combined and preplant P fertilization for yield. When treatments that received foliar fertilization without surfactant were compared to treatments with surfactant, no differences were noted. For PUE significant differences were found when comparing foliar P without surfactant and foliar P with non-ionic and cropoil surfactants. Estimates showed that the use of non-ionic surfactants decreased PUE by 21% compared to the application of P without surfactant. Also, significant differences were found between foliar P with cropoil and without surfactant and the preplant, in which without surfactant was estimated to perform 19% more efficient than with cropoil. In addition, there was a significant difference when the overall foliar P method was compared to the preplant. Phosphorus use efficiency was improved by 28% using foliar P fertilization in relation to preplant P.

A negative, significant linear response was found for yield when foliar fertilization was made with the surfactant (Table 13). No significant trend was found for foliar applied P without surfactant. Foliar fertilization at 10 kg P $ha^{-1}$ caused a yield reduction and therefore no linear or quadratic trend was observed. Regarding the effect of increasing rates on the concentration of P in the grain no trends were found (Table 13). Furthermore, it was found that there was no significant trend for combined P fertilization concerning yield and GPC.

# CHAPTER V

# DISCUSSION

For most trials and years, foliar fertilization as well as the combination of preplant + foliar applied P resulted in yield increases compared to the check and the preplant application (20 and 40 kg $ha^{-1}$). These two methods of fertilization (foliar and preplant + foliar) often produced maximum yield. Benbella and Paulsen (1998) found a significant yield increase with foliar P fertilization at 2.2 and 4.4 kg P $ha^{-1}$. In addition, Mosali et al. (2006) reported yield increases with foliar application of P. Initial soil P test values were relatively high (ranging from 85 to 100% sufficiency). This condition was adequate for foliar nutrition that is recommended to be a supplemental source of P, although P responses and thus significant differences are more difficult to be detected on sites where soil P levels are close to sufficiency. Nevertheless, significant differences were not found between foliar, combined and preplant P fertilization, less fertilizer was used to produce similar yield levels which direct influenced the PUE estimates, therefore using the fertilizer more efficiently. One of the reasons that likely contributed for the lack of significant difference between treatmennts can be attributed to the use of a P fertilizer source that was not designed for foliar application and that had low solubility.

In general, P use efficiency was improved with foliar nutrition compared to preplant fertilization. Other authors also suggest that foliar fertilization can improve P use efficiency (Girma et al., 2007; Silberstein and Wittwer, 1951). Girma et al. (2007) reported higher PUE at lower rates (2 kg P $ha^{-1}$ at V8). Initial soil P test was elevated and also affected PUE. The reason behind that is the method used to calculate PUE. Phosphorus use efficiency was calculated using the difference method which takes into consideration P uptake difference between the check plot and the fertilized plot and divide by the fertilize rate applied at the fertilized plot. So, if the P uptake in the check plot is high (Mehlich 3 P, 32.1 mg $kg^{-1}$) the apparent recovery of other treatments will be relatively low. The resulted of high levels of P at the start of the experiment resulted on large variability in PUE estimates.

The effect of foliar nutrition on GPC was inconsistent. In general it was observed a trend for higher GPC when P was applied at preplant. However, sometimes foliar P fertilization resulted in improved GCP. Harder et al. (1982) stated that foliar P fertilization increased grain P concentration in corn. Sherchand and Paulsen, (1985) suggested that phosphorus applied at anthesis could improve foliage and GCP in wheat grain.

The influence of surfactant was also not consistent. In some cases the use of non-ionic surfactant helped to improve PUE, grain yield and GCP compared to the lack of surfactant. In other cases the surfactant had a negative influence on the dependent variables measured. The reason for this inconsistence may be due to use of inappropriate surfactant, or rate of surfactant, or even to the interaction of surfactant and P source. Additionally, it was noted in these trials that at the high foliar P application rate, (10 kg P $ha^{-1}$) yield and GCP decreased. This became more evident with the frequent lack of linear and/or quadratic response to P using single degree of freedom polynomial orthogonal contrasts. The foliar rate of 10 kg P $ha^{-1}$ may have exceeded that required and as such adversely affected yield and grain P content in most of the sites/year, with exception to EFAW 2008-2009. The effects of salt loading in the leaves due to foliar fertilization were reported by Harder et al., (1982) and; Silberstein and Wittwer, (1951) and this too could have been a factor that could lead to detrimental effect of 10 kg P $ha^{-1}$ applied foliar.

# CHAPTER VI

# CONCLUSIONS

Even though significant differences were not detected for grain yield, this study showed that foliar P can be used as a method of P fertilization in season to correct slight P deficient soils in-season. Yield levels were in general improved but not significant different when the rates 5 and 10 Kg P $ha^{-1}$ applied foliar were compared to 20 to 40 kg P $ha^{-1}$ applied preplant and the 0-P check. Because foliar fertilization uses lower rates in comparison to preplant application, and yield levels are not significantly different the fertilizer use efficiency is improved with foliar application.

Foliar P at 5 kg $ha^{-1}$ increased yield and PUE compared to preplant treatments and the 0-P check. At 10 kg P $ha^{-1}$ a trend for lower yields was observed. The use of surfactants had an inconsistent influence on yield, PUE and GPC. Grain P concentration was generally higher when P was applied preplant. Yield and GPC response to foliar fertilization were affected by the initial soil P levels, fertilizer P source and surfactant type used consequently influencing PUE.

Combining preplant and foliar fertilization can also be an efficient method to supply P for winter wheat. With this method P would be available for the crop at the initial stages when there is demand for the nutrient for establishment, then later in the season P would be supplied via foliar application when the requirement is greater and to correct small deficiencies. Foliar P fertilization can be an important management strategy especially for dry environments and on soils where soil P test levels are close to sufficiency and used as a supplemental source of P. This would allow for the application of lower P rates in relation to soil applied while still being able to correct deficiencies in-season, and achieve yield levels compatible to the preplant fertilization.

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TABLES

Table 1- Initial surface (0-15 cm) soil test characteristics, EFAW and Lake Carl Blackwell (LCB), OK, 2008.

| Site | Trial | pH[(1)] | $NO_3$-N[(2)] ($mg\ kg^{-1}$) | K[(3)] ($mg\ kg^{-1}$) | P[(4)] ($mg\ kg^{-1}$) |
|---|---|---|---|---|---|
| EFAW | Foliar P | 4.94 | 1.70 | 200 | 32.1 |
| EFAW | Foliar P + Surfactant | 5.06 | 1.69 | 196 | 29.0 |
| LCB | Foliar P | 5.07 | 2.12 | 99.5 | 16.1 |
| LCB | Foliar P + Surfactant | 4.82 | 3.22 | 100 | 18.3 |

(1) pH, 10g of soil and 10ml of DI water. Equipment: Accumet Excel XL 20 pH/ conductivity Meter.

(2) NO3- test, 2.5g of soil and 12.5ml of 2M KCl solution. Equipment: Lachat 8000 flow injection analyzer.

(3) K test, 2.0 g of soil and 20 ml of Mehlich III. Equipment: ICP.

(4) P test, 2.0g of soil and 20 ml of Mehlich III. Equipment: Milton Ray Spectronic 401.

Table 2- Foliar phosphorus trial - Analysis of variance for grain yield, grain P concentration, and P use efficiency (PUE) in wheat, EFAW, OK, 2008-2009.

| Source of Variation | | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | * | * | ns |
| Treatment | | 8 | * | ns | p<0.1 |
| Preplant (kg $ha^{-1}$) | Foliar (kg $ha^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 1945 | 2937 | . |
| 20 | 0 | | 2024 | 2813 | 4 |
| 0 | 5 | | 2037 | 2520 | 6 |
| 40 | 0 | | 2099 | 2957 | 2 |
| 0 | 10 | | 2210 | 2837 | 15 |
| 20 | 5 | | 2352 | 2887 | 5 |
| 10 | 5 | | 2223 | 2540 | 6 |
| 0 | 10++ | | 2325 | 2793 | 10 |
| 0 | 5++ | | 2431 | 2283 | 3 |
| SED | | | 147 | 241 | 3 |
| C.V. (%) | | | 8 | 11 | 61 |

*, and ** significant at the 0.05 and 0.01 probability levels, respectively; ns = not significant; ++ Foliar treatments applied with the addition of a non-ionic surfactant; df = degrees of freedom; C.V. = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means.

Table 3- Foliar phosphorus trial - Single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and P use efficiency (PUE), EFAW, OK, 2008-2009.

| Contrast description | | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| | | | Estimates and Significance Level (Pr > F) | | |
| Without surfactant | With surfactant | 1 | 255 * | -2 ns | 9 ns |
| Preplant | Foliar | 1 | -189 * | 218 p<0.1 | -7 p<0.1 |
| Preplant | Without surfactant | 1 | -62 ns | 219 ns | -11 * |
| Preplant | With surfactant | 1 | 317 ** | 217 p<0.1 | -2 ns |

*, and ** significant at the 0.05 and 0.01 probability levels, respectively; ns = not significant; df = degrees of freedom; † Estimates values were calculated as the difference between the groups in the contrast using the SAS statement ‘estimate’ to indicate which group performed better, the direction is indicated by signs (- or none).

Table 4- Foliar phosphorus trial- Means and single degree of freedom polynomial orthogonal contrasts for grain yield and grain P concentration for the foliar applied treatments with and without the addition of surfactant, EFAW, OK, 2008-2009.

| | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) |
|---|---|---|---|---|---|
| Foliar Rates (kg ha$^{-1}$) | | Treatment Means | | | |
| 0 | | 1945 | 2937 | 1945 | 2937 |
| 5 | | 2037 | 2520 | 2431 | 2283 |
| 10 | | 2210 | 2837 | 2325 | 2793 |
| | | Significance Level (Pr > F) | | | |
| Linear | 1 | P<0.1 | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | * |

* significant at the 0.05 probability level; ns = not significant; df = degrees of freedom.

Table 5- Foliar phosphorus trial- Analysis of variance for grain yield, grain phosphorus concentration, and phosphorus use efficiency in wheat, EFAW, OK, 2009-2010.

| Source of Variation | | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | ns | ns | ns |
| Treatment | | 8 | ns | ns | ns |
| Mean Square Error | | 16 | 73945 | 140368 | 132 |
| Preplant (kg ha$^{-1}$) | Foliar (kg ha$^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 2110 | 3103 | . |
| 20 | 0 | | 2354 | 3390 | 3 |
| 0 | 5 | | 2391 | 3200 | 15 |
| 40 | 0 | | 2292 | 3330 | 1 |
| 0 | 10 | | 2573 | 3083 | 11 |
| 20 | 5 | | 2540 | 3257 | 4 |
| 10 | 5 | | 2336 | 3353 | 5 |
| 0 | 10++ | | 2199 | 3057 | 4 |
| 0 | 5++ | | 2217 | 3230 | 4 |
| SED | | | 222 | 306 | 9 |
| C.V. (%) | | | 12 | 12 | 191 |

++ Foliar treatments applied with the addition of a non-ionic surfactant; ns = not significant; df = degree of freedom; CV = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means; PUE = phosphorus use efficiency.

Table 6- Foliar phosphorus trial- Analysis of variance for grain yield, grain P concentration, and P use efficiency (PUE) in wheat at Lake Carl Blackwell (LCB), OK, 2009-2010.

| Source of Variation | | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | * | ns | ns |
| Treatment | | 8 | ns | ns | p<0.1 |
| Preplant (kg ha$^{-1}$) | Foliar (kg ha$^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 1839 | 3630 | . |
| 20 | 0 | | 2289 | 3673 | 7 |
| 0 | 5 | | 2232 | 3903 | 23 |
| 40 | 0 | | 2153 | 4063 | 5 |
| 0 | 10 | | 1863 | 3773 | 7 |
| 20 | 5 | | 2301 | 3850 | 5 |
| 10 | 5 | | 2038 | 3923 | 12 |
| 0 | 10++ | | 2126 | 4217 | 23 |
| 0 | 5++ | | 1954 | 4107 | 32 |
| SED | | | 336 | 254 | 22 |
| C.V. (%) | | | 20 | 8 | 162 |

* significant at the 0.05 probability level; ns = not significant; ++ Foliar treatments applied with the addition of a non-ionic surfactant; df = degree of freedom; C.V. = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means.

Table 7- Foliar phosphorus with surfactant trial- Analysis of variance for grain yield, grain P concentration, and P use efficiency (PUE) in wheat, EFAW, OK, 2008-2009.

| Source of Variation | | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | ns | * | * |
| Treatment | | 14 | ns | ns | * |
| Mean Square Error | | 27 | 63792 | 117995 | 91 |
| Preplant (kg ha$^{-1}$) | Foliar (kg ha$^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 1861 | 3313 | . |
| 20 | 0 | | 1914 | 3330 | 2 |
| 40 | 0 | | 1755 | 3447 | 1 |
| 0 | 5 | | 1929 | 3547 | 39 |
| 0 | 5‡ | | 2041 | 3890 | 51 |
| 0 | 5++ | | 2057 | 3417 | 30 |
| 0 | 10 | | 1850 | 3057 | 1 |
| 0 | 10‡ | | 2182 | 3290 | 10 |
| 0 | 10++ | | 2183 | 3440 | 13 |
| 10 | 5 | | 1990 | 3497 | 9 |
| 10 | 5‡ | | 2041 | 3297 | 4 |
| 10 | 5++ | | 1623 | 3523 | 0 |
| 20 | 5 | | 1917 | 3557 | 5 |
| 20 | 5‡ | | 2014 | 3630 | 7 |
| 20 | 5++ | | 2012 | 3123 | 2 |
| SED | | | 206 | 280 | 8 |
| C.V. (%) | | | 13 | 10 | 64 |

* significant at the 0.05 probability level; ns = not significant; ++ foliar treatments applied with the addition of a non-ionic surfactant; ‡ foliar treatments applied with the addition of a cropoil surfactant; df = degrees of freedom; C.V. = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means.

Table 8- Foliar phosphorus with surfactant trial- Single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and P use efficiency (PUE), EFAW, OK, 2008-2009.

| Contrast description | | df | Grain Yield | Grain P Concentration | PUE |
|---|---|---|---|---|---|
| | | | Estimates and Significance Level (Pr > F) | | |
| Preplant | (Foliar) Without surfactant | 1 | -55 ns | 87 ns | -19 ** |
| Preplant | (Foliar) Cropoil | 1 | -277 p<0.1 | -202 ns | -29 *** |
| Preplant | (Foliar) Non-ionic | 1 | -286 p<0.1 | -40 ns | -20 *** |
| (Foliar) Cropoil | Non-ionic | 1 | -9 ns | 162 ns | 9 p<0.1 |
| (Foliar) Without surfactant | Cropoil | 1 | -222 ns | -288 ns | -11 * |
| (Foliar) Without surfactant | Non-ionic | 1 | -231 ns | -127 ns | -2 ns |
| (Foliar) Without surfactant | With surfactant | 1 | -226 p<0.1 | -207 ns | -6 ns |
| Preplant | (All Foliar) No surf. + Cropoil + Non-ionic | 1 | -206 p<0.1 | -52 ns | -23 *** |
| (Foliar and Preplant + Foliar) Cropoil | Non-ionic | 1 | 210 ns | 141 ns | 5 p<0.1 |
| (Preplant+Foliar) No surf. | With surf. | 1 | 136 ns | 204 ns | 6 ns |
| (Preplant+Foliar) Cropoil | Non-ionic | 1 | 210 ns | 141 ns | 5 ns |
| Preplant | (Preplant+Foliar) | 1 | -98 ns | -49 ns | -3 ns |
| (Foliar and Preplant + Foliar) No surfactant | With surf. | 1 | -98 ns | -37 ns | -1 ns |

*, **, and *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively; ns = not significant; df = degrees of freedom; surf. = surfactant. † Estimates values were calculated as the difference between the groups in the contrast using the SAS statement ‘estimate’ to indicate which group performed better, the direction is indicated by signs (- or none).

Table 9- Foliar phosphorus with surfactant trial- Analysis of variance for grain yield, grain P concentration, and P use efficiency (PUE) in wheat, EFAW, OK, 2009-2010.

| Source of Variation | | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | p<0.1 | ns | ns |
| Treatment | | 14 | ns | ns | ns |
| Mean Square Error | | 28 | 51316 | 60067 | 29 |
| Preplant (kg ha$^{-1}$) | Foliar (kg ha$^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 2925 | 3137 | . |
| 20 | 0 | | 2697 | 3357 | 3 |
| 40 | 0 | | 3130 | 3557 | 5 |
| 0 | 5 | | 3058 | 2973 | 11 |
| 0 | 5‡ | | 2744 | 3133 | 10 |
| 0 | 5++ | | 2849 | 3003 | 0 |
| 0 | 10 | | 2984 | 3217 | 8 |
| 0 | 10‡ | | 2984 | 3213 | 5 |
| 0 | 10++ | | 2825 | 2913 | 1 |
| 10 | 5 | | 3128 | 3293 | 8 |
| 10 | 5‡ | | 2855 | 3297 | 5 |
| 10 | 5++ | | 2985 | 3263 | 6 |
| 20 | 5 | | 2974 | 3327 | 3 |
| 20 | 5‡ | | 2937 | 2960 | 2 |
| 20 | 5++ | | 2848 | 3117 | 1 |
| SED | | | 185 | 200 | 4 |
| C.V. (%) | | | 8 | 8 | 153 |

ns = not significant; ++ foliar treatments applied with the addition of a non-ionic surfactant; ‡ foliar treatments applied with the addition of a cropoil surfactant; df = degrees of freedom; CV = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means.

Table 10- Foliar phosphorus with surfactant trial- Single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and P use efficiency (PUE), EFAW, OK, 2009-2010.

| Contrast description | | df | Grain Yield | Grain P concentration | PUE |
|---|---|---|---|---|---|
| | | | Estimates and Significance | Level (Pr > F) | |
| Preplant | (Foliar) Without surfactant | 1 | -108 ns | 362** | -6 ns |
| Preplant | (Foliar) Cropoil | 1 | 50 ns | 284 * | -4 ns |
| Preplant | (Foliar) Non-ionic | 1 | 70 ns | 499 *** | 4 ns |
| (Foliar) Cropoil | Non-ionic | 1 | 27 ns | 215 ns | 7 ns |
| (Foliar) Without surfactant | Cropoil | 1 | 157 ns | -78 ns | 2 ns |
| (Foliar) Without surfactant | Non-ionic | 1 | 184 ns | -137 ns | 9 p<0.1 |
| (Foliar) Without surfactant | With surfactant | 1 | 171 ns | 30 ns | 6 ns |
| Preplant | (All Foliar) No surf. + Cropoil + Non-ionic | 1 | 6 ns | 382 *** | -2 ns |
| (Foliar and Preplant + Foliar) Cropoil | Non-ionic | 1 | -21 ns | -62 ns | 0 ns |
| (Preplant+Foliar) No surf. | With surf. | 1 | 135 ns | 120 ns | 2 ns |
| (Preplant+Foliar) Cropoil | Non-ionic | 1 | -21 ns | -62 ns | 0 ns |
| Preplant | (Preplant+Foliar) | 1 | -41 ns | 248 * | 0 ns |
| (Foliar and Preplant + Foliar) No surfactant | With surf. | 1 | -158 * | 90 ns | 4 ns |

*, **, and *** significant at the 0.05, 0.01 and 0.001 probability levels, respectively; ns = not significant; df = degrees of freedom; surf. = surfactant. † Estimates values were calculated as the difference between the groups in the contrast using the SAS statement 'estimate' to indicate which group performed better, the direction is indicated by signs (- or none).

Table 11- Foliar phosphorus with surfactant trial- analysis of variance for grain yield, grain P concentration, and phosphorus use efficiency (PUE) in wheat at Lake Carl Blackwell (LCB), OK, 2009-2010.

| Source of Variation | | df | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | PUE (%) |
|---|---|---|---|---|---|
| Replication | | 2 | ns | ns | p<0.1 |
| Treatment | | 14 | ns | ns | * |
| Preplant (kg ha$^{-1}$) | Foliar (kg ha$^{-1}$) | | Treatment Means | | |
| 0 | 0 | | 2932 | 4520 | . |
| 20 | 0 | | 2943 | 4797 | 4 |
| 40 | 0 | | 2752 | 4463 | 3 |
| 0 | 5 | | 3066 | 4793 | 79 |
| 0 | 5‡ | | 2781 | 4850 | 41 |
| 0 | 5++ | | 2719 | 4233 | 22 |
| 0 | 10 | | 2667 | 4327 | 7 |
| 0 | 10‡ | | 2415 | 4517 | 8 |
| 0 | 10++ | | 2528 | 4423 | . |
| 10 | 5 | | 2803 | 4813 | 10 |
| 10 | 5‡ | | 2982 | 4693 | 5 |
| 10 | 5++ | | 2627 | 4267 | . |
| 20 | 5 | | 2986 | 4370 | 4 |
| 20 | 5‡ | | 2858 | 4950 | 8 |
| 20 | 5++ | | 2988 | 4697 | 8 |
| SED | | | 275 | 342 | 15 |
| C.V. (%) | | | 12 | 9 | 22 |

* significant at the 0.05 probability level; ns = not significant; ++ foliar treatments applied with the addition of a non-ionic surfactant; ‡ foliar treatments applied with the addition of a cropoil surfactant; df = degrees of freedom; CV = coefficient of variation; SED = standard error of the difference between two equally replicated treatment means.

Table 12- Foliar phosphorus with surfactant trial- single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and phosphorus use efficiency (PUE), at Lake Carl Blackwell (LCB), OK, 2009-2010.

| Contrast description | | df | Grain Yield | Grain P Concentration | PUE |
|---|---|---|---|---|---|
| | | | Estimates and Significance Level (Pr > F) | | |
| (Foliar) Without surfactant | Broadcast | 1 | -19 ns | 70 ns | -40 *** |
| (Foliar) Cropoil | Broadcast | 1 | 250 ns | -54 ns | -21 p<0.1 |
| (Foliar) Non-ionic | Broadcast | 1 | 224 ns | 302 ns | -19 ns |
| (Foliar) Cropoil | Non-ionic | 1 | -26 ns | 356 ns | 3 ns |
| (Foliar) Without surfactant | Cropoil | 1 | 269 ns | -124 ns | 19 * |
| (Foliar) Without surfactant | Non-ionic | 1 | 243 ns | 232 ns | 21 * |
| (Foliar) Without surfactant | With surfactant | 1 | 256 ns | 54 ns | 19 * |
| (All Foliar) No surf. + Cropoil + Non-ionic | Broadcast | 1 | 152 ns | 106 ns | -28 * |
| (Foliar and Preplant + Foliar) Cropoil | Non-ionic | 1 | 113 ns | 340 * | -2 ns |
| (Preplant+Foliar) No surf. | With surf. | 1 | 87 ns | 110ns | -1 ns |
| (Preplant+Foliar) Cropoil | Non-ionic | 1 | 113 ns | 340 ns | -2 ns |
| (Preplant+Foliar) | Broadcast | 1 | -27 ns | -2 ns | -4 ns |
| (Foliar and Preplant + Foliar) No surfactant | With surf. | 1 | 143 ns | -3 ns | 10 p<0.1 |

*, and ***, significant at the 0.05, and 0.001 probability levels, respectively; ns = not significant; df = degrees of freedom; surf. = surfactant. † Estimates values were calculated as the difference between the groups in the contrast using the SAS statement ‘estimate’ to indicate which group performed better, the direction is indicated by signs (- or none).

Table 13- Foliar phosphorus with surfactant trial- single degree of freedom polynomial orthogonal contrasts for grain yield, and grain P concentration for the treatments applied via foliar with and without the addition of surfactant at Lake Carl Blackwell (LCB), OK, 2009-2010.

| Source of Variation | df | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| | | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) | Grain Yield (kg ha$^{-1}$) | Grain P Concentration (mg kg$^{-1}$) |
| Foliar Rates (kg ha$^{-1}$) | | Treatment Means | | | | | |
| 0 | | 2932 | 4520 | 2932 | 4520 | 2932 | 4520 |
| 5 | | 3066 | 4793 | 2781 | 4850 | 2719 | 4233 |
| 10 | | 2667 | 4327 | 2415 | 4517 | 2528 | 4423 |
| | | Significance Level (Pr > F) | | | | | |
| Linear | 1 | ns | ns | * | ns | p<0.1 | ns |
| Quadratic | 1 | ns | ns | ns | ns | ns | ns |

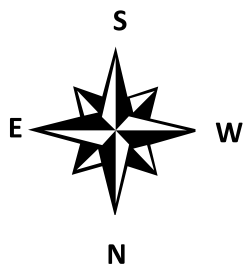
*, significant at the 0.05 probability level; ns = not significant; df = degrees of freedom.

Figure 1- Triple super phosphate solution in contact with winter wheat leaves with (left) and without (right) surfactant.

Figure 2- Application of foliar P treatments at Lake Carl Blackwell (LCB) and EFAW, OK, 2008-2009 and 2009-2010.

# WHEAT FOLIAR P

Location: **EFAW**




| Treatment | Preplant N lb/ac | Preplant P kg P / ha | Topdress P kg P / ha |
|---|---|---|---|
| 1 | 100 | 0 | 0 |
| 2 | 100 | 20 | 0 |
| 3 | 100 | 0 | 5 |
| 4 | 100 | 40 | 0 |
| 5 | 100 | 0 | 10 |
| 6 | 100 | 20 | 5 |
| 7 | 100 | 10 | 5 |
| 8 | 100 | 0 | 10* |
| 9 | 100 | 0 | 5* |

* - applied with a surfactant

Plot Size: 10’ x 20’
Alleys: 6’

NOTE: 40 kg P / ha is equivalent to 40 lbs $P_2O_5$ / ac

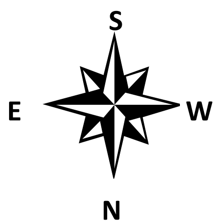
OBJECTIVE: To determine the effectiveness of foliar applications of phosphorus compared to conventional methods of phosphorus application.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rep 3 | 3 | 5 | 4 | 2 | 7 | 9 | 6 | 1 | 8 |
| Rep 2 | 8 | 1 | 4 | 5 | 6 | 3 | 7 | 9 | 2 |
| Rep 1 | 9 | 7 | 8 | 3 | 5 | 2 | 4 | 1 | 6 |

Figure 3- Plot plan with treatment structure for the Foliar P trials established at Lake Carl Blackwell (LCB) and EFAW, OK, 2008-2009 and 2009-2010.

# WHEAT FOLIAR P WITH SURFACTANTS

Location: **EFAW**




| Treatment | Preplant N lb/ac | Preplant P kg P / ha | Topdress P kg P / ha | Surfactant Type |
|---|---|---|---|---|
| 1 | 100 | 0 | 0 | |
| 2 | 100 | 20 | 0 | |
| 3 | 100 | 40 | 0 | |
| 4 | 100 | 0 | 5 | |
| 5 | 100 | 0 | 5 | Spreader |
| 6 | 100 | 0 | 5 | Non-ionic (AG-98) |
| 7 | 100 | 0 | 10 | |
| 8 | 100 | 0 | 10 | Spreader |
| 9 | 100 | 0 | 10 | Non-ionic (AG-98) |
| 10 | 100 | 10 | 5 | |
| 11 | 100 | 10 | 5 | Spreader |
| 12 | 100 | 10 | 5 | Non-ionic (AG-98) |
| 13 | 100 | 20 | 5 | |
| 14 | 100 | 20 | 5 | Spreader |
| 15 | 100 | 20 | 5 | Non-ionic (AG-98) |

NOTE: 40 kg P / ha is equivalent to 40 lbs $P_2O_5$ / ac

Plot Size: 10' x 20'
Alleys: 10'

OBJECTIVE: To determine the effectiveness of foliar applications of phosphorus with surfactants compared to conventional methods of phosphorus application.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rep 3 | 11 | 2 | 7 | 9 | 10 | 12 | 3 | 13 | 1 | 14 | 6 | 15 | 5 | 8 | 4 |
| Rep 2 | 13 | 3 | 2 | 11 | 15 | 9 | 7 | 8 | 12 | 10 | 4 | 6 | 14 | 5 | 1 |
| Rep 1 | 5 | 7 | 3 | 12 | 15 | 2 | 10 | 6 | 13 | 1 | 11 | 4 | 9 | 14 | 8 |

Figure 4- Plot plan with treatment structure for the Foliar P trials established at Lake Carl Blackwell (LCB) and EFAW, OK, 2008-2009 and 2009-2010.

APPENDIX

Table 14- Foliar phosphorus trial- Single degree of freedom, orthogonal contrasts for grain yield and grain P concentration for foliar applied treatments with and without the addition of surfactant, EFAW, OK, 2009-2010.

| | | Without Surfactant | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|
| Source of Variation | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Foliar Rates (kg $ha^{-1}$) | | Treatment Means | | | |
| 0 | | 2110 | 3103 | 2110 | 3103 |
| 5 | | 2391 | 3200 | 2217 | 3230 |
| 10 | | 2573 | 3083 | 2199 | 3057 |
| | | Significance Level (Pr > F) | | | |
| Linear | 1 | * | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns |

* significant at the 0.05 probability level; ns = not significant; df = degrees of freedom;

Table 15- Foliar phosphorus trial- Single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and phosphorus use efficiency (PUE), EFAW, OK, 2009-2010.

| Source of Variation | | df | Grain Yield | Grain P Concentration | PUE |
|---|---|---|---|---|---|
| Foliar Applied vs. Preplant | | | Estimates and Significance Level (Pr > F) | | |
| Without surfactant | With surfactant | 1 | 274 * | ns | ns |
| Preplant | Foliar | 1 | -22 ns | ns | ns |
| Preplant | Without surfactant | 1 | -159 ns | ns | ns |
| Preplant | With surfactant | 1 | 115 ns | ns | ns |

PUE = phosphorus use efficiency; ns = not significant; df = degrees of freedom;

Table 16- Foliar phosphorus trial- Single degree of freedom, non-orthogonal contrasts for grain yield, grain P concentration and phosphorus use efficiency (PUE), Lake Carl Blackwell (LCB), OK, 2009-2010.

| Contrast description | | df | Grain Yield | Grain P Concentration | PUE |
|---|---|---|---|---|---|
| | | | Significance Level (Pr > F) | | |
| Without surfactant | With surfactant | 1 | 8 ns | -324 p<0.1 | -13 ns |
| Preplant | Foliar | 1 | 177 ns | -132 ns | -15 ns |
| Preplant | Without surfactant | 1 | 174 ns | -30 ns | -9 ns |
| Preplant | With surfactant | 1 | 181 ns | -294 ns | -22 ns |

ns = not significant; df = degrees of freedom.

Table 17- Foliar phosphorus trial- Single degree of freedom, orthogonal contrasts for grain yield and grain P concentration for foliar applied treatments with and without the addition of surfactant at Lake Carl Blackwell (LCB), OK, 2009-2010.

| | | Without Surfactant | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|
| Source of Variation | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Foliar Rates (kg $ha^{-1}$) | | Treatment Means | | | |
| 0 | | 1839 | 3630 | 1839 | 3630 |
| 5 | | 2232 | 3903 | 1954 | 4107 |
| 10 | | 1863 | 3883 | 2126 | 4217 |
| | | Significance Level (Pr > F) | | | |
| Linear | 1 | ns | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns |

ns = not significant; df = degrees of freedom.

Table 18- Foliar phosphorus with surfactant trial- Single degree of freedom polynomial orthogonal contrasts for grain yield, and grain P concentration for the treatments applied via foliar with and without the addition of surfactant, EFAW, OK, 2008-2009.

| Source of Variation | df | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| | | Grain Yield (kg $ha^{-1}$) | Grain P concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Foliar Rates (kg $ha^{-1}$) | | Treatment Means | | | | | |
| 0 | | 1861 | 3313 | 1861 | 3313 | 1861 | 3260 |
| 5 | | 1929 | 3547 | 2041 | 3890 | 2057 | 3416 |
| 10 | | 1850 | 3057 | 2182 | 3290 | 2183 | 3440 |
| | | Significance Level (Pr > F) | | | | | |
| Quadratic | 1 | ns | ns | ns | ns | ns | ns |

ns = not significant; df = degrees of freedom.

Table 19- Foliar phosphorus with surfactant trial- Single degree of freedom, polynomial orthogonal contrasts for grain yield, and grain P concentration for foliar applied treatments with and without the addition of surfactant, EFAW, OK, 2008-2009.

| Source of Variation | df | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| | | Grain Yield (kg $ha^{-1}$) | Grain P concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Preplant and Foliar Rates (kg $ha^{-1}$) | | Treatment Means | | | | | |
| 0 - 5 | | 1929 | 3547 | 2041 | 3890 | 2057 | 3417 |
| 10 - 5 | | 1990 | 3497 | 2041 | 3297 | 1608 | 3523 |
| 20 - 5 | | 1916 | 3556 | 2014 | 3630 | 2012 | 3123 |
| | | Significance Level (Pr > F) | | | | | |
| Linear | 1 | ns | ns | ns | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns | p<0.1 | ns |

ns = not significant; df = degrees of freedom.

Table 20- Foliar phosphorus with surfactant trial- single degree of freedom orthogonal contrasts for grain yield, and grain P concentration for the treatments applied via foliar with and without the addition of surfactant, EFAW, OK, 2009-2010.

| Source of Variation | df | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| | | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Foliar Rates (kg $ha^{-1}$) | | Treatment Means | | | | | |
| 0 | | 2925 | 3137 | 2925 | 3137 | 2925 | 3137 |
| 5 | | 3058 | 2973 | 2744 | 3133 | 2849 | 3003 |
| 10 | | 2984 | 3217 | 2984 | 3231 | 2825 | 2913 |
| | | Significance Level (Pr > F) | | | | | |
| Linear | 1 | ns | ns | ns | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns | ns | ns |

ns = not significant; df = degrees of freedom.

Table 21- Foliar phosphorus with surfactant trial- Single degree of freedom, orthogonal contrasts for grain yield, and grain P concentration for the treatments applied via foliar with and without the addition of surfactant, EFAW, OK, 2009-2010.

| | | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| Source of Variation | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg/kg) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Preplant and Foliar Rates (kg $ha^{-1}$) | | Treatment means | | | | | |
| 0 - 5 | | 3058 | 2973 | 2744 | 3133 | 2849 | 3003 |
| 10 - 5 | | 3128 | 3293 | 2855 | 3897 | 2985 | 3263 |
| 20 - 5 | | 2974 | 3327 | 2937 | 2960 | 2548 | 2117 |
| | | Significance Level (Pr > F) | | | | | |
| Linear | 1 | ns | p<0.1 | ns | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns | ns | ns |

ns = not significant; df = degrees of freedom.

Table 22- Foliar phosphorus with surfactant trial- single degree of freedom orthogonal contrasts for grain yield and grain P concentration for the treatments applied via foliar with and without the addition of surfactant, Lake Carl Blackwell (LCB), OK, 2009.

| | | Without Surfactant | | With Surfactant (Cropoil) | | With Surfactant (Non-Ionic) | |
|---|---|---|---|---|---|---|---|
| Source of Variation | df | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg/kg) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) | Grain Yield (kg $ha^{-1}$) | Grain P Concentration (mg $kg^{-1}$) |
| Preplant And Foliar Rates (kg $ha^{-1}$) | | | | Treatment Means | | | |
| 0 - 5 | | 3066 | 4793 | 2781 | 4850 | 2419 | 4233 |
| 10 - 5 | | 2803 | 4813 | 2982 | 4693 | 2627 | 4267 |
| 20 - 5 | | 2986 | 4370 | 2858 | 4950 | 2988 | 4697 |
| | | | | Significance Level (Pr > F) | | | |
| Linear | 1 | ns | ns | ns | ns | ns | ns |
| Quadratic | 1 | ns | ns | ns | ns | ns | ns |

ns = not significant; df = degrees of freedom.

VITA

Guilherme Martin Torres

Candidate for the Degree of

Master of Science

Thesis: FOLIAR PHOSPHORUS FERTILIZATION AND THE EFFECT OF SURFACTANTS ON WINTER WHEAT (*Triticum aestivum* L.)

Major Field: Soil Fertility

Biographical:

Education: Graduated from Curso Osvaldo Cruz, Catanduva, São Paulo, Brasil in December 2001. Received a Bachelor of Sciences in Agronomic Engineer from Universidade Estadual Paulista "Julio de Mesquita Filho"- UNESP/ Faculdade de Ciências Agronômicas, Botucatu, São Paulo, Brazil in June 2008. Completed the requirements for the Master of Science in soil fertility at Oklahoma State University, Stillwater, Oklahoma in, May, 2011.

Experience: Employed by Oklahoma State University, Department of Plant and Soil Sciences as a graduate research assistant from august 2008 to present. Worked as graduate teaching assistant from January 2009 to May 2009 at Oklahoma State University, Department of Plant and Soil Sciences. Employed by Group COSAN S.A., Costa Pinto Unity, Piracicaba, São Paulo, Brazil worked with geo-processing and remote sensing for crop monitoring from June 2007 to June 2008.

Professional Memberships: American Society of Agronomy, Crop Science Society of America and Soil Science Society of America.

Name: Guilherme Martin Torres Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: FOLIAR PHOSPHORUS FERTILIZATION AND THE EFFECT OF SURFACTANTS ON WINTER WHEAT (Triticum aestivum L.)

Pages in Study: 64 Candidate for the Degree of Master of Science

Major Field: Soil Fertility

Scope and Method of Study: Reactions of phosphorus fertilizer in soils make its use efficiency very low. The common application practices are to broadcast and incorporate or to band P with the seed. Foliar application of P can be used as a supplemental P source allowing for the application of lower rates and when it is most needed, reducing costs and potential environment concerns due to surface run-off. The objective of this study was to evaluate the effect of applying triple super phosphate as a foliar P source with and without surfactant on winter wheat grain yield, phosphorus use efficiency, and grain P content. Four field trials at two experimental sites were established in 2008/2009 and 2009/2010 in Oklahoma using a randomized complete block design with three replications. Treatments were applied at Feekes 7 using triple super phosphate dissolved in water as a foliar fertilizer. The solution had a concentration of 66 g P $L^{-1}$. All treatments received 112 kg N $ha^{-1}$ preplant in both trials. The effect of broadcast preplant at rates of 0, 10, 20, and 40 kg P $ha^{-1}$ and foliar top-dress at rates of 0, 5, and 10 kg P $ha^{-1}$ were evaluated, with and without surfactants.

Findings and Conclusions: Foliar P fertilization and the combination of preplant and foliar P often resulted in a yield increase compared to the check and/or the broadcast application of 20 and 40 kg P $ha^{-1}$. These methods of fertilization frequently produced maximum yield. Phosphorus use efficiency was improved with foliar nutrition compared to broadcast. The effect of foliar P on grain P concentration was not consistent. The influence of surfactant was also not consistent over trials. Non-ionic surfactant and crop oil improved phosphorus use efficiency, grain yield and grain P concentration compared to the lack of a surfactant in some cases but had a negative impact in other occasions. Foliar fertilization using TSP at 10 kg P $ha^{-1}$ had a negative impact on yield and grain P concentration. Foliar P allows for supplemental applications of phosphorus and when it is most needed. Foliar P allows for the application of lower rates in relation to soil applied P while still being able to correct in-season deficiencies, and improve yield and phosphorus use efficiency.

ADVISER'S APPROVAL: ______________________________