IDENTIFICATION OF OPTICAL SPECTRAL SIGNATURES FOR DETECTING CHEAT AND RYEGRASS IN WINTER WHEAT, AND DETERMINATION OF OPTIMUM RATE AND GROWTH STAGE OF FOLIAR APPLIED PHOSPHORUS IN CORN

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CHAPTER I. IDENTIFICATION OF OPTICAL SPECTRAL SIGNATURES FOR DETECTING CHEAT AND RYEGRASS IN WINTER WHEAT

INTRODUCTION

Today, site specific application technology or precision farming is becoming an integral part of agriculture. One aspect of site specific application technology involves weed. Precision weed improves weed control efficiency, thereby reducing adverse effects on the environment while maintaining acceptable economic returns (Sawyer, 1994; Brown et al., 1994; Zwiggelaar, 1998; Thompson et al., 1991; Wibawa et al., 1993; Shaw, 2000).

To take full advantage of site specific weed management systems, accurate detection of the location of weeds within crop fields is necessary (Thompson et al., 1991). Cost-effective use of electronically controlled injection sprayers, chemical spot treatment (Stafford and Miller, 1993; Pérez et al., 1997) variable rate sprayers, and chemical mixture delivery systems all require accurate weed distribution records in a field in a form usable by the precision application equipment (Franz et al., 1991).

For weed detection in cultivated crops, two interrelated general approaches have typically been used (Thompson et al., 1990; Guyer et al., 1986; 1993; Woebbecke et al., 1995; Zhang and Chaisattapagon, 1995). The first is to detect certain morphological differences between the crop and weeds, such as

leaf shape or plant structure. Franz et al. (1995) used the morphological characteristics of plant species like hairiness, shininess and shape, which affect the absorption and reflection bands of plants to detect weeds.

Guyer et al. (1986) studied the feasibility of using leaf shape for plant identification on three crops and five weed species. According to their report, the differences between vegetation and soil reflectance in the near infrared (NIR) region proved to be successful for detecting plants from a soil background. This was true since plant reflectance in the NIR region which covers the spectra between 720-800 nm, is substantially greater than soil (a magnitude of 25% energy reflection than soil) (Guyer, 1993).

Likewise, Woebbecke et al. (1995) used the shape feature analysis for discriminating between monocots and dicots. In their work they tried to identify 10 common weed species in corn (*Zea mays* L.) and soybean (*Glycine max* L.) using roundness, aspect, perimeter/ thickness and elongatedness shape features. Aspect enabled them to correctly classify 60-90% of dicots as dicots from the monocots. Their work however, was restricted to individual plants and not canopy.

Zhang and Chaisattapagon (1995) studied three different approaches to identify weeds in wheat fields using machine vision: color, shape and texture analysis. They used black-white digital images with various color filters under laboratory conditions for color analysis. The red and green filters were effective in detecting reddish stems of some weed species. In their results they also showed that shape parameters such as eccentricity and compactness were effective in

distinguishing broadleaf weed species redroot pigweed (*Amaranthus retroflexus* L.), wild buckwheat (*Polygonum convolvulus* L.) and kochia (*Kochia scoparia* L.) from wheat. On the other hand, from texture analysis that used fineness index, species such as kochia (*Kochia scoparia* L.) were distinguished from other species with course texture. Humphries and Simonton (1993) identified Geranium (*Geranium maculatum* L.) plant parts using color feature with a success rate of 97, 95 and 93% for leaf, petiole and stem, respectively.

The second general approach is based on differences in spectral reflectance (Feyaerts et al., 1999; Lass and Thill, 2000). The visible and infrared portion of the electromagnetic spectrum captures the most discriminating information (Richards and Kelley, 1984). Combination of visible and NIR with Thermal infrared could permit effective use of existing indices, such as greenness (Price, 1987)

Feyaerts et al. (1999) developed a sensor based on reflectance in visible and NIR spectra, which can detect weeds in corn and sugar beets with a success rate of 80%. Lass and Thill (2000) tried to measure differences in reflectance for different weed species with a hand-held spectroradiometer, recording the full reflectance spectrum at 2 nm increments. However, species identification often was not easy with the remotely sensed aerial multispectral data. Despite the different problems encountered thus far in detecting weeds, some researchers argue that the spectral characteristics of plants are sufficient to differentiate plant species without introducing geometric complexities (Price, 1987; Gutman, 1991)

Hatfield and Pinter (1993) reviewed the potential of remote sensing techniques for crop protection in the field and suggested that one way to distinguish between weeds and crops was by examining the temporal patterns of vegetation indices throughout the growing season. This was also supported by Brown et al. (1994) who reported the potential for distinguishing weeds from agricultural crops based on their relative spectral reflectance characteristics over time. However, they have reservation in identifying individual species and suggested the necessity to group weeds based on some well defined criteria in real agricultural environments other than looking for individual weeds. According to Price (1994) unique discrimination of species would be possible using high spectral resolution.

Plant canopy architecture also has a significant effect on canopy reflectance. Moran et al. (1989) found that alfalfa has a more erectophile (vertical) leaf architecture when under water stress. The plants also tended to have a lower NIR reflectance when under stress that tended to support the result found in modeling winter wheat (Hatfield and Pinter, 1993). However, practically, canopy architecture might be more useful in detecting genetically distant species such as cereal crops and broadleaf weeds.

A close investigation into the leaf structure gives more insight about reflectance characteristics of vegetation. The upper and lower epidermis of leaves have a protective function with regard to the interaction with electromagnetic radiation, the mesophyll region being the most important part (Jordan, 1969; Lawrence and Ripple, 1998; Richardson and Wiegand, 1977).

Accordingly, the range between 400 nm and 700 nm (visible band) is characterized by very low reflectance due to intense absorption of the incident radiation by pigments in the plant, mainly chlorophyll. All pigments absorb at 430 - 450 nm (blue), and chlorophyll has an additional absorption band at about 650 nm (red). A small reflectance peak also exists at about 550 nm band (green). The range between 700 nm and 1300 nm is characterized by very little absorption and high reflectance. The high reflectance peak in this range is caused by the mesophyll structure, which causes multiple reflection of NIR radiation on the cell walls (Broge, 2003; Gates et.al., 1965; Gausman, 1985). The range between 1300 nm and 2600 nm is characterized by a pronounced minimum. Wavelengths between 580 and 680 nm (red) and between 725 and 1100 nm (NIR) are high reflectance bands for vegetation (Gausman, 1985).

Despite the importance of detecting multiple species in a mixture of crop and weeds, the task remains challenging to date. This task is complex when attempting to detect grass weeds in grass crops like wheat. To date, no study has fully achieved a sound method to detect cheat (*Bromus secalinus* L.) and ryegrass (*Lolium perenne* L.) in wheat (*Triticum aestivum* L.). In the current study we intended to bridge this gap by developing a procedure that could be integrated into sensors to detect cheat and ryegrass in wheat.

The objectives of this paper were to detect spectral signatures for cheat and ryegrass in wheat and to develop indices to detect each species in a mixture. Meeting the objective will provide new information necessary to identify cheat

and ryegrass in wheat and later to integrate the information into variable rate technologies developed to manage weeds.

MATERIALS AND METHODS

Experimental Design and Treatment Structure

Two experiments were conducted at the Agronomy Research Station, Stillwater, OK in December 2002 and one experiment in February 2003. A completely randomized experimental design with three replications was employed.

Three plant species, cheat, ryegrass and wheat were planted in separate pots (20.4 cm high and wide) filled with manure rich soil with nitrogen rate of 0 and 50 kg $ha^{-1}$and placed in a greenhouse. Emergence difference of species was accommodated by performing preliminary study on planting to emergence date of the two weed species with respect to wheat in identical growing conditions with the actual experimental conditions. It took both cheat and ryegrass three days more from planting to emergence compared with wheat. Thus the two species were planted three days before wheat. Species population densities after emergence were 250 plants m^2 for wheat while the density varied for cheat and ryegrass to obtain comparable stand when taking measurements. Nitrogen was applied to each pot as urea (46% N). A flat rate of 100 kg ha^{-1} triple super phosphate (46% P_2O_5) was applied to each pot. Wheat variety used for both experiments was Jaggar. The seed for the two weed species was obtained from Weed Science Research Program, Oklahoma State University. Germination test

was carried out for both species and was found to be above 90%. The greenhouse temperature was maintained at 25.5 ^{o}C with 12 hours day length. Any other species except the target was eliminated upon emergence though out the experimental period.

Spectral Readings

Spectral measurements were made at Feekes 3 and 5 wheat growth stages for each experiment from each pot using a SD2000 portable fiber optic spectrometer (Ocean Optics Inc, Dunedin, Florida) that operate in the visible and NIR region of the spectrum (350-1000 nm) with a resolution of 2 nm (for 50 μm slit) full width half maximum (FWHM). A 2 m long glass fiber (Ocean Optics Inc, Dunedin, Florida) with diameter of 200 nm was mounted at 80 cm above the top of the sample in a specially designed lighting system (Figure 1) for the experiment and back connected to the spectrometer. The lighting system was built as wooden box frame in a pyramid shape and had two compartments. The bottom compartment housed the electrical line and lamps while the top pyramid shape with height approximately 1 m used to place samples. The top compartment was totally painted with white color inside. The lamps were installed to light upwards to the wall of the pyramid box through circular openings (diameter slightly larger than that of the lump) at the top of the bottom compartment of the lighting system. Six TRU-AIM-R16 tungsten halogen lamps (Osram Sylvania, Danvers, Massachusetts) each 50 w and 12 v with beam angle of 40^{O} and diameter of 51 mm were installed. The tungsten halogen lamps were suitable for taking light

measurements from samples in the visible and infrared electromagnetic spectra while suppressing the ultraviolet light. The field of view at the sample pot was 10.2 cm in radius. The fiber optic spectrometer was attached to a SAD500 serial A/D (Ocean Optics Inc, Dunedin, Florida) which basically converts analog data to digital data. The SAD500 serial A/D was connected to a laptop computer that had Ocean Optics OIBase software that records the light intensity for separate wavelengths. Before readings of actual samples were made, reference and dark intensity readings were taken. Reference intensity count was determined by placing a barium sulfate coated metal plate (size 20 by 30 cm) in the light system while dark intensity count was made by blocking the fiber completely with black smooth rubber. Spectral reading of intensity for each sample was made in the same lighting, temperature, and integration time of 125 msec for each measuremente. Reflectence was then calculated as the ratio of reflected light intensity (from the sample plants) and to the incident count. Reflectance data were partitioned into 10 nm bandwidths. From the resulting averages, wavelength ratios were determined. The denominator wavelengths selected were 555 nm (the green peak), 675 (the red minimum) and 815 nm (highest point on the NIR plateau).

Data Analyses and Classification Methods

Spectral data were analyzed using three discriminant analysis procedures in SAS software (SAS Institute, 2001): Stepwise discriminant analysis (STEPDISC), discriminant analysis (DISCRIM) and canonical discriminant

analysis (CANDISC). The STEPDISC procedure was used to identify sets of suitable wavelengths and wavelength ratios. The procedure performs a stepwise discriminant analysis by stepwise selection of quantitative variables which are useful in discriminating species. It was assumed that the data (for the variables) represent a sample from a multivariate normal distribution and that the variance/covariance matrices of variables were homogeneous across species. The stepwise procedure was guided by the respective *F* to enter and remove reflection data at specific average wavelength or wavelength ratio. Further analysis of the data was based on the wavelengths and wavelength ratios selected by STEPDISC procedure.

Once the relevant variables were selected, discriminant functions were developed using DISCRIM procedure. This procedure computed generalized squared distances and various discriminant functions (classifications rules) for classifying observations into species. The generalized squared distance between species, otherwise known as Mahalanobis distance, was calculated using the following equation (Mahalanobis, 1936).

$$D^2_{ij} = \{Av(x_i) - Av(x_j)\}' \, cov^{-1} \{Av(x_i) - Av(x_j)\} \quad [1]$$

Where D^2_{ij} denotes the Mahalanobis distance between species i and j; cov^{-1} denotes the inverse covariance matrix; $Av(x_i)$ and $Av(x_j)$ denote the mean reflection for species i and j, respectively. The equation assumes the populations from which the groups are derived have common variance. It also takes into account the variances and covariances of the measuring distance.

Linear discriminant function (Fisher, 1936) for a species was given by the formula:

$$S_i = c_{0i} + C_{i1}*x_1 + C_{i2}*x_2 + ... + C_{im}*x_m \quad [2]$$

In this formula, the subscript *i* denotes the respective species; the subscripts 1, 2, ..., m denote the m wavelength or wavelength ratio; c_i is a constant for the *i*'th species, C_{ij} is the coefficient for the j^{th} wavelength or wavelength ratio in the computation of the classification score for the i^{th} species; x_j is the observed value for the j^{th} wavelength or wavelength ratio. S_i is the resultant classification score for a species.

The CANDISC procedure approximates the F statistic, and estimates the probabilities for Mahalanobis distance. It also computes the multivariate statistic (Hotelling-Lawley Trace) for the wavelength or wavelength ratio under consideration.

Using the resubstitution method, a method that uses the test observations to classify new observations, classification errors were determined by calculating the percentage of wrongly classified spectra for the categories of weeds and crop. In the discriminant function, every species was considered as a different class. The spectral measurements from the three experiments were combined by the two growth stages as preliminary analysis revealed that date of measurement and nitrogen levels were not significant.

RESULTS

Wavelength Selection

Using STEPDISC procedure for data at both Feekes 3 and 5 , individual and wavelength ratios were selected to be used in developing the discriminant functions (Table 1). The wavelengths and ratios obtained were different for measurements made at Feekes 3 and 5. Five categories (functions) of wavelengths were derived for data collected at Feekes 3. The categories include combinations of single average wavelength bands and wavelength ratios with denominators of 555, 675 and 815 nm and a combination of both were obtained by reselection. All categories except one were highly significant using multivariate statistic (Hotelling-Lawley trace statistic, Table 1). Associated r^2 values ranged from 0.36 to 0.76. The two functions that resulted in the two largest r^2 values contain ratios developed from denominator 675 and 815 nm. For data at Feekes 5, six significant groups of wavelength and wavelength ratios were identified. The r^2 values ranged from 0.38 to 0.54. For data at Feekes 3, more wavelengths and wavelength ratios were included in each function except one function compared with data at Feekes 5 (Table 1).

Data at Feekes 3

Reflection pattern of the three species in the spectra range 450-850 is presented in Figure 2. Discriminant function coefficients were determined and presented in Table 2. The larger the absolute value of the coefficient, the better the discriminating power. In general, most of the coefficients in the linear

discriminant functions in data at Feekes 3 had good discriminating power of a species, as absolute values of the coefficients were much greater than zero. However, the power of discrimination varied for each function resulting in a difference in the ability of discrimination of each coefficient for each species. For example, in Table 2 for function 1, the coefficients c_1 for cheat, ryegrass and wheat were 3756, 3239 and 4625, respectively. Since the c_1 coefficient was associated with the wavelength 725 nm in discriminant function "1-A", wheat had the largest coefficient and was more discriminable than the other two species at this wavelength band. Likewise, c_2 coefficients which correspond to 735 nm wavelength bands in this function indicated that wheat had the absolute value of the largest coefficient thus the highest discrimination. On the other hand, c_3 coefficients corresponding to 745 nm in the same function revealed that cheat and wheat were highly discriminable from ryegrass but were similar in magnitude to each other. The power of the function lies in the combined effect of all the wavelengths in the function.

The squared distance between species was significant between wheat and the two weed species for all functions (Table 3). The greatest discrimination among the three species was due to the function "1-E" with wavelength ratios 515/675, 555/675 and 805/815 nm/nm. In fact, this function also resulted in the highest r^2 (Table 1).

The misclassification of observations from one species into another is given in Table 4. Here, function "1-E" correctly classified all observations to the respective species except wheat (16.7% classified as ryegrass). Two functions

with 555 and 675 nm wavelength bands in the denominator correctly classified most observations. All functions correctly classified most observations of wheat into wheat. Few cheat or ryegrass plants were classified as wheat and visa versa in each function. On the other hand, functions “1-A” and “1-D” misclassified from 33 to 50% of the cheat and ryegrass samples.

Error rates or correct classification rates were determined for all functions assessed (Table 4). The error rate was zero for cheat and ryegrass while it was 6% for wheat for functions “1-C” and “1-E”. Function “1-B” (wavelength ratios with denominator 555 nm) attained a low error rate for all species although it achieved comparably better results for wheat.

Data at Feekes 5

Overall reflection pattern for data at this growth stage is presented in Figure 3 for the three species. At this stage, the results were somewhat different than the previous stage. The interpretation of the coefficients of linear discriminant functions was similar to data at Feekes 3. Overall, the linear function coefficient c_1 in each case was larger than either species for wheat in three of the linear functions. In each function, the wavelength or wavelength ratios associated with c_1 enabled the discrimination of wheat from the weed species. Similarly, c_2 was large for wheat in two of the linear functions (Table 5).

The squared distances between species were low and less consistent across wavelengths used (Table 6). Generalized squared distances between wheat and ryegrass were large and highly significant for most functions.

Likewise, the distance was significant for most functions between wheat and cheat. However, no distance was significant between cheat and ryegrass in any of the functions for data at Feekes 5. The magnitude of the squared distance difference was large between wheat and the weed species for two functions (function “2-E” with 755 nm, 855/675 nm/nm; and function “2-F” with 745,755 nm, 855/675, 685/815 nm/nm).

Misclassification of observations was very high for data at Feekes 5 (Table 7). Two functions (function “2-A” with 745, 755 nm; and “2-F”with 745, 755 nm, 855/675, 685/815 nm/nm) classified all observations from wheat as wheat while 66.7% of observations from cheat were classified as cheat by these functions. Most functions were not effective in classifying observations from ryegrass as ryegrass except function “2-B” developed using wavelength ratio 745/555 nm/nm (83.3%). In most functions, the highest misclassification of species was for cheat classified as rye and rye classified as cheat (Table 7).

Error rates for data at Feekes 5 were large as observations in most functions were misclassified at this later growth stage. Correct classification using the resubstitution method showed that all species were correctly classified by corresponding functions that resulted in low misclassification of observations presented above. Wheat was correctly classified by functions “2-E” and “2-F” (Table 7) without error. Cheat was also correctly classified by the same functions although the magnitude of correct classification rate was lower (66.7%). Ryegrass on the other hand was correctly classified with a rate of 83.3% by the wavelength ratio 745/555 nm/nm which exhibited poor performance for cheat and

wheat. Likewise, the order of correct classification for this data set was wheat > cheat > rye across all functions evaluated (Table 7).

DISCUSSION

The Stepwise discriminant function analysis showed that wavelength bands in the visible and NIR regions of the spectrum were required to discriminate the three species. Several researchers also reported similar results, while working on discrimination of different crop and weed species (Smith and Blackshaw, 2003; Feyaerts et al., 1998; Vrindts and De Baerdemaeker, 1996; Borregaard et al., 2000).

Using the discriminant functions and generalized square distances, the best functions to discriminate the three species were identified for the data at both stages. At Feekes 3 with high r^2, significant multivariate statistic, low misclassification of observations and low error rate, function “1-C” with wavelength ratios 515/675,545/675, 555/675 nm/nm and function “1-E” with 515/675, 555/675, 805/815 nm/nm were the best functions. However, since function “1-C” had slightly lower generalized square distance between species, lower r^2, and misclassified some wheat measurements, function “1-E” was the most preferred function. Using this function, all observations from cheat and ryegrass were correctly classified (Figure 4). Some researchers have successfully discriminated weed species in several crops which were morphologically very distinct from the crop (Smith and Blackshaw, 2003; Feyaerts et al., 1998). For this data, most functions resulted in excellent

discrimination of wheat and the two weed species with few exceptions. At the early stage of growth chlorophyll is not well developed and other pigments such as carotenoid are found in relatively high abundance. This subsequently caused higher reflectance in both red and NIR region of spectrum which was different for the three species evaluated. The composition of the best discriminant function for data at Feekes 3 strongly suggest that the green peak, red and NIR portion of the spectrum are good enough to discriminate cheat, ryegrass and wheat.

For data at Feekes 5, the performance of most of the functions was poor when discrimination of all species was attempted. However, functions “2-E” (with wavelengths and wavelength ratios 755 and 855/675) and “2-F” (with wavelength bands 745,755,855/675 and 685/815) resulted in good discrimination (100%) of wheat; although the weed species were not discriminated well between themselves. Of the two functions, the first is preferred since it had lesser number of variables (wavelengths) and adds simplicity. Inclusion of more wavelength bands in a discriminant function would enable more discrimination (Vrindts and De Baerdemaeker, 1997), however at the same level of precision, the simpler function would help in the use of selected wavelengths. The discrimination of the three species with the best selected function is presented in Figure 5 in two dimensional spaces.

Correct classification and percentage of observations classified from a species to another species was acceptable for data at Feekes 3 but not for data at Feekes 5. Error rates were larger between the two weed species than between

the weed species and wheat. According to past research (Vrindts et al., 1999; Vrindts et al., 2000), this is not a significant concern, since the primary objective of the research was to select wavelengths that differentiated the crop from weeds. Lower error rate however are desirable in laboratory tests because of better control of the factors. Total error of only 3% in crop-weed classification using a small number of simple ratios of 10-nm wavelength bands in a discriminant function has been reported (Vrindts et al., 1999).

The wavelength and wavelength ratios obtained for each data set were different. This suggests that as plants continue to grow from Feekes 3 to 5 and increase in height and canopy coverage, exposure of the sample and subsequently measured reflectance pattern is affected (Noble et al., 2002; Wang et al., 2001). Typically since chlorophyll concentration drastically increases with increase in growth the reflection pattern in the green region of spectrum decreases. Thus, measurements vary when compared with earlier measurements made on the same plants. At the early growth stage, wheat and cheat had distinctive appearances in this study and previous observations (Franz et al., 1991; Cooper, 1964; Jackson and Pinter 1986). This difference may contribute to the powerful discrimination of the two species by selected functions for data at Feekes 3. On the other hand, for data at Feekes 5, an increase in canopy closure coupled with a decrease in pubescence of leaves emerging at a later growth stage decreased discriminability. The significance of canopy cover in spectral weed detection was discussed in detail (Andreason et al., 1997). This has important consequences when using selected wavelengths to identify wheat

from the weeds. The lack of consistent results obtained across growth stages requires accurately defining the appropriate growth stage of the species where discrimination and treatment are optimal.

CONCLUSIONS

The results obtained here showed that measurements differed with growth stage of the plants. A thorough evaluation of change in reflectance pattern for the species under consideration is required. The best overall classification obtained for data at Feekes 3 (94%) and Feekes 5 (66.7%) was attributed to the discriminant functions with 515/675, 555/675, 805/815 nm/nm and 755 nm, 855/675 nm/nm, respectively. For data at Feekes 3, ryegrass was classified as cheat and visa-versa. Cheat was not classified as wheat in most instances except function “1-A” and “1-D”, whereas ryegrass was misclassified as wheat only in function “1-D”.

For data at Feekes 5, although the magnitude was small, some observations from cheat were classified as wheat. In several instances, ryegrass was classified as either cheat or wheat while cheat was classified as rye. Cheat was not classified as wheat in most instances. This suggests that it is possible to identify cheat in wheat using wavelength ratios developed from spectral readings in the 500 and 860 nm bands. At early growth stages, wheat and cheat have distinctive appearances. This difference might have contributed to the powerful discrimination of the two species by selected functions for data at Feekes 3. On

the other hand, for data at Feekes 5, an increase in canopy closure coupled with a decrease in pubescence of leaves that emerge at later growth stages decreased the power of discrimination. The discrimination results reported in here were based on pure stand of each species. The information can serve as basis for further evaluation of the three species in mixture.

REFERENCES

Andreason, C., M. Rudemo and S. Sevestre. 1997. Assessment of weed density at an early stage by use of image processing. Weed Res. 37:5-18.

Borregaard, T., H. Nielsen, L. Norgaard and H. Have. 2000. Crop weed discrimination by line imaging spectroscopy. J. Agric. Eng. Res. 75:389-400.

Broge, N.H. 2003. Prediction of green canopy area index and canopy chlorophyll density of homogeneous canopies from measurements of spectral reflectance in the visible and near-infrared domain. Ph.D. diss. DIAS report, Plant Production. 87:139.

Brown, R.W., J.P.G.A. Steckler and G.W. Anderson. 1994. Remote sensing for identification of weeds in no-till corn. Trans. ASAE. 37:297-302.

Cooper, J.P. 1964. Climatic variation in forage grasses. I. Leaf development in climatic races of Lolium and Dactylis. J. Appl. Ecol. 1:45-61.

Feyaerts, F., P. Pollet, L. Van Gool and P. Wambacq. 1998. Sensor for weed detection based on spectral measurements. pp. 1537-1548. *In* Robert et al. (eds). Precision Agriculture. Proc. 4th Int. Conf. Precision Agriculture. ASA/CSSA/SSSA, Madison, WI.

Fisher, R.A. 1936. The use of multiple measurements in taxonomic problems. Ann. Eugenics 7:179-188.

Franz, E., M.R. Gebhardt and K.B. Nuklesbay. 1991. The use of local spectral properties of leaves as an aid for identifying weed seedlings in digital images. Trans. ASAE. 34:682-687.

Franz, E., M.R. Gebhardt and K.B. Nunklesbay. 1995. Algorithms for extracting leaf boundary information from digital images of plant foliage. Trans. ASAE. 32:625-633.

Gates, D.M., H.J. Kegan, J.C. Scheter and V.R. Weidner. 1965. Spectral properties of plants. Appl. Opt. 4:11-20.

Gausman, H.W. 1985. Plant leaf optical properties in visible and near-infrared light. Texas Tech., Press, Lubock, Texas.

Gutman, G. 1991. Vegetation indices from AVHRR: An update and future prospects. Remote Sens. Environ. 35:121-136.

Guyer, D.E., G.E. Miles, M.M. Schreiber, O.R. Mitchell and V.C. Vanderbilt. 1986. Machine vision to shape analysis in leaf and plant identification. Trans. ASAE. 36:163-171.

Guyer, D.E., G.E. Miles, L.D. Gaultney and M.M. Schreiber. 1993. Application of machine vision and image processing for plant identification. Trans. ASAE. 29:1500-1507.

Hatfield, J.L. and P.J. Pinter. 1993. Remote sensing for crop protection. Crop Prot. 12:403-413.

Humphries, S. and W. Simonton. 1993. Identification of plant parts using color and geometric image data. Trans. ASAE. 36:1493-1500.

Jackson, R.D. and P.J. Jr. Pinter. 1986. Spectral response of architecturally different wheat canopies. Remote Sens. Environ. 20:43-56.

Jordan, C.F. 1969. Derivation of leaf area index from quality of light on the forest floor. Ecology 50:663-666.

Lass, L.W. and D.C. Thill. 2000. New remote sensing technology for more economical weed control. University of Idaho [Online]. Available at http://cipm.ncsu.edu/cipmprojects/Reports/98Reports2/lassl98F.html.

Lawrence, R.L. and W.J. Ripple. 1998. Comparison among vegetation indices and bandwise regression in a highly disturbed, heterogeneous landscape: Mount St. Helens, Washington. Remote Sens. Environ. 64:91-102.

Mahalanobis, P.C. 1936. On the generalized distance in statistics. Proc. Nat. Inst. Sci. India. 2:49-55.

Moran, M.S., P.J. Jr. Pinter, B.E. Clothier and S.G. Allen. 1989. Effect of water stress in the canopy architecture and spectral indices of irrigated alfalfa. Remote Sens. Environ. 29:251-261.

Noble, S.D., R.B. Brown and T.G. Crowe. 2002. The use of spectral properties for weed detection and identification-a review. *In* Canadian Society of Agricultural Engineers, Saskatoon, SK. 14-17 July 2002. CSAE Paper No. 02-208. Mansonville, QC, Canada: CSAE/SCGR.

Pérez, A.J., F. López, J.V. Benlloch and S. Christensen. 1997. Color and shape analysis techniques for weed detection in cereal fields. pp. 45-50 *In* Kure et al. (eds). First European Conference for Information Technology in Agriculture, Copenhagen, Denmark. 15-18 June 1997. Eur. Federation for Information Tech. Agric. (EFITA), Denmark.

Price, J.C. 1987. Calibration of satellite radiometers and the comparison of vegetation indices. Remote Sens. Environ. 21:15-27.

Price, J.C. 1994. How unique are spectral signatures? Remote Sens. Environ. 49:181-186.

Richards, J.A. and D.J. Kelly. 1984. On the concept of spectral class. Int. J. Remote Sens. 43:1541-1552.

Richardson, A.J. and C.L. Wiegand. 1977. Distinguishing vegetation from soil background information. Photogramm. Eng. Remote Sens. 43:1541-1552.

SAS Institute. 2001. The SAS system for windows version 8.02. SAS Institute Inc., Cary, NC.

Sawyer, J.E. 1994. Concepts of variable rate technology with considerations for fertilizer applications. J. Prod. Agric. 7:195-201.

Shaw, D.R. 2000. Remote sensing as a tool for site specific weed management. p. 245 *In* Proc. Southern Weed Sci. Soc. Weed Science Society of America, Champaign, IL.

Smith, A.M. and R.E. Blackshaw. 2003. Weed-crop discrimination using remote sensing: A detached leaf experiment. Weed Tech. 17:811-820.

Stafford, J.V. and P.C.H. Miller. 1993. Spatially selective application of herbicide to cereal crops. Comput. Electron. Agric. 9:217-229.

Thompson, J.F., J.V. Stafford and B. Ambler. 1990. Weed detection in cereal crops. ASAE Paper 90-1629. Am. Soc. Agric. Eng., St. Joseph, MI.

Thompson, J.F., J.V. Stafford and P.C.H. Miller. 1991. Potential for automatic weed detection and selective herbicide application. Crop Prot. 10:254-259.

Vrindts, E. and J. De Baerdemaeker. 1996. Feasibility of weed detection with optical reflection measurements. pp.443-444. *In* Conf. Proc. of the Brighton Crop Prot. Conf. – Pest and Diseases. November 18-21 1996. Brighton, UK.

Vrindts, E. and J. De Baerdemaeker. 1997. Optical discrimination of crop, weed and soil for on-line weed detection. pp. 537-544 *In* J.V. Stafford (ed). 1st Eur. Conf. Precision Agric., Warwick, UK. 8-10 Sept. 1997. Bios Scientific Publishers, Oxford, UK.

Vrindts, E., J. De Baerdemaeker and H. Ramon. 1999. Weed detection using canopy reflectance. *In* J.V. Stafford (ed). Precision Agric. '99. 2nd Eur. Conf. Precision Agric., Odense, Denmark. 11-15 July 1999. Bios Scientific Publishers, Oxford, UK.

Vrindts, E., J. De Baerdemaeker and H. Ramon. 2000. Using spectral information for weed detection in field circumstances. *In* Eur. Soc. Agric. Eng. Presented at Agricultural Engineering into the Third Millennium AgEng2000, EurAgEng Paper No. 00-PA-010,Warwick, UK.

Wibawa, W.D., D.L. Dludlu, L.K. Swenson, D.G. Hopkins and W.C. Dahnke. 1993. Variable fertilizer application based on yield goal, soil fertility and soil map unit. J. Prod. Agric. 6:255-261.

Wang, N., N. Zhang, F.E. Dowell, Y. Sun and D.E. Peterson. 2001. Design of an optical weed sensor using plant spectral characteristics. Trans. ASAE. 44:409-419.

Woebbecke, D.M., G.E. Meyer, K. Von Bargen and D. Mortensen. 1995. Shape features for identifying young weeds using image analysis. Trans. ASAE. 38:71-281.

Zhang, N. and C. Chaisattapagon. 1995. Effective criteria for weed identification in wheat fields using machine vision. Trans. ASAE. 38:965-974.

Zwiggelaar, R. 1998. A review of spectral properties of plants and their potential use for crop-weed discrimination in row crops. Crop Prot. 17:189-206.

Table 1. Wavelengths selected using STEPDISC procedure to develop discriminant functions.

Data at Feekes 3		Data at Feekes 5	
Wavelength (nm)/ wavelength ratio (nm/nm)	r^2	Wavelength (nm)/ wavelength ratio (nm/nm)	r^2
725, 735, 745 (***)	0.41	745, 755 (*)	0.49
565/555, 705/555 (***)	0.46	715/555 (*)	0.38
515/675, 545/675, 555/675 (***)	0.75	855/675 (**)	0.46
765/815, 785/815, 805/815 (NS†)	0.36	685/815 (***)	0.54
515/675, 555/675, 805/815 (***)	0.76	755, 855/675 (***)	0.48
		745, 755, 855/675, 685/815 (*)	0.49

*, **, and *** indicate significance at 0.05, 0.01, 0.001 probability levels, respectively. † NS, nonsignificant at 0.05 probability level using Hotelling-Lawley trace statistic.

Table 2. Parameter coefficients for linear discriminant functions for the different wavelengths as selected using STEPDISC procedure for data at Feekes 3 wheat growth stage.

Function	wavelength/ratio in the function	Cheat	Ryegrass	Wheat
		c_0[§] = -109.9	c_0 =-117.9	c_0 = -108.6
1-A	725	c_1 = 3756.0	c_1 = 3239.0	c_1 = 4625.0
	735	c_2 = -5266.0	c_2 =-4201.0	c_2 =-5822.0
	745	c_3 = 2651.0	c_3 = 2112.0	c3 = 2505.0
		c_0 = -13494.0	c_0 =-13534.0	c_0 = -14033.0
1-B	565/555	c_1 = 25315.0	c_1 = 25299.0	c_1 = 25777.0
	705/555	c_2 = 1978.0	c_2 = 2030.0	c_2 = 2053.0
		c_0 = -1466.0	c_0 =-1368.0	c_0 = -1221.0
1-C	515/675	c_1 = 3381.0	c_1 = 3220.0	c_1 = 3118
	545/675	c_2 = -4292.0	c_2 = -4203.0	c_2 = -4063
	555/675	c_3 = 3233.0	c_3 = 3212.0	c_3 = 3065.0
		c_0 = -9468.0	c_0 =-9463.0	c_0 = -9362.0
1-D	765/815	c_1 = -7884.0	c_1 = -7875.0	c_1 = -7922.0
	785/815	c_2 = 1898.0	c_2 = 1947.0	c_2 = 1909
	805/815	c_3 = 24781.0	c_3 = 24721.0	c_3 = 24694.0
		c_0 = -9418.0	c_0 =-9252.0	c_0 = -8997.0
1-E	515/675	c_1 = 4829.0	c_1 = 4678.0	c_1 = 4591.0
	555/675	c_2 = -1947.0	c_2 = -1883.0	c_2 = -1897.0
	805/815	c_3 = 16245.0	c_3 = 16164.0	c_3 = 16035.0

[§]c_0 denotes intercept; c_1, c_2 and c_3 denote the coefficients for a wavelength/wavelength ratio in the order each appeared in the function.

Table 3. Generalized squared distance between species for data at Feekes 3 wheat growth stage.

Function	Wavelengths (nm)/ wavelength ratios (nm/nm)	Distance between species		
		Cheat and Rye	Cheat and Wheat	Rye and Wheat
1-A	725, 735, 745	1.4 (NS[†])	7.9 (**)	11.1 (***)
1-B	565/555, 705/555	3.0 (*)	12.0 (***)	9.3 (***)
1-C	515/675, 545/675, 555/675	6.2	24.0 (***)	13.9 (***)
1-D	765/815, 785/815, 805/815	0.3 (NS)	1.6 (NS)	2.8 (NS)
1-E	515/675, 555/675, 805/815	6.3 (*)	24.8 (***)	14.2 (***)

*, **, and *** indicate significance at 0.05, 0.01, 0.001 probability levels, respectively. [†] NS, nonsignificant at 0.05 probability level using Hotelling-Lawley trace statistic.

Table 4. Percentage of observations classified from species to species for data at Feekes 3 growth stage. Number of observations per species was 18.

function	Wavelengths/ratios in the function	ch-ch‡	ch-ry	ch-wh	ry-ch	ry-ry	ry-wh	wh-ch	wh-ry	wh-wh	Overall classification
1-A	725, 735, 745	50.0	33.3	16.7	50.0	50.0	0.0	16.7	0	83.3	61.1
1-B	565/555, 705/555	83.3	16.7	0.0	16.7	83.3	0.0	0.0	0.0	100.0	88.9
1-C	515/675, 545/675, 555/675	100	0.0	0.0	0.0	100	0.0	0	16.7	83.3	94.0
1-D	765/815, 785/815, 805/815	50.0	33.3	16. 7	50.0	33.3	16.7	16.7	0.0	83.3	56.0
1-E	755, 515/675, 555/675, 805/815	100	0.0	0.0	0.0	100	0.0	0.0	16.7	83.3	94.0

‡ The abbreviations ch, ry, and wh denote species cheat, ryegrass, and wheat, respectively. The abbreviations ch-ch, ch-ry etc. denote the percentage of observations classified from species cheat as cheat, species cheat as ryegrass etc., respectively.

Table 5. Parameter coefficients for linear discriminant functions for the different wavelengths as selected using STEPDISC procedure for data at Feekes 5 wheat growth stage.

Function	wavelength/ratio in the function	Cheat	Ryegrass	Wheat
2-A		c_0[§]= -62.8	c_0 =-56.0	c_0 = -44.8
	745	c_1 = 869.5	c_1 = 812.5	c_1 = 1050.0
	755	c_2 = -491.8	c_2 =-456.7	c_2 =-707.3
2-B		c_0 = -133.0	c_0 =-145.9	c_0 = -117.5
	715/555	c_1 = 170.0	c_1 = 178.0	c_1 = 159.7
2-C		c_0 = -14.7	c_0 =-16.2	c_0 = -7.1
	855/675	c_1 = 2.6	c_1 = 2.9	c_1 = 1.8
2-D		c_0 = -7.9	c_0 =-7.2	c_0 = -17.8
	685/815	c_1 = 145.7	c_1 = 138.7	c_1 = 218.4
2-E		c_0 =-63.9	c_0 =-59.3	c_0 = -39.1
	755	c_1 = 260.9	c_1 = 244.	c_1 = 210.3
	855/675	c_2 = 1.9	c_2 =2.0	c_2 = 1.2
2-F		c_0= -268.2	c_0 = -264.5	c_0 = -268.2
	745	c_1 = 2797.0	c_1 = 2779.0	c_1 = 2926.0
	755	c_2 =-2230.0	c_2 = -2231.0	c_2 = -2396.0
	855/675	c_3 = 21.3	c_3 = 21.5	c_3 = 21.8
	685/815	c_4 = 1483.0	c_4 = 1488.0	c_4 = 1573.0

[§]c_0 denotes intercept; c_1, c_2, c_3 and c_4 denote the coefficients for a wavelength/wavelength ratio in the order each appeared in the function.

Table 6. Generalized squared distance between the three species for data at Feekes 5 wheat growth stage.

Function	Wavelengths (nm)/wavelength ratios (nm/nm)	Distance between species		
		Cheat and Ryegrass	Cheat and Wheat	Ryegrass and Wheat
2-A	745, 755	0.4 (NS[†])	5.2 (**)	3.3 (*)
2-B	715/555	0.6 (NS)	1.0 (NS)	3.1 (*)
2-C	855/675	0.1 (NS)	2.7 (*)	3.7 (**)
2-D	685/815	0.0 (NS)	3.9 (***)	4.7 (***)
2-E	755, 855/675	0.5 (NS)	6.4 (***)	5.3 (***)
2-F	745, 755, 855/675, 685/815	0.5 (NS)	7.9 (***)	6.7 (***)

*, **, and *** indicate significance at 0.05, 0.01, 0.001 probability levels, respectively. [†] NS, nonsignificant at 0.05 probability level using Hotelling-Lawley trace statistic.

Table 7. Percentage of observations classified from species to species for data at Feekes 5 wheat growth stage. Number of observations per species was 18.

Function	Wavelengths/ratios in the function	ch-ch ‡	ch-ry	ch-wh	ry-ch	ry-ry	ry-wh	wh-ch	wh-ry	wh-wh	Overall classification
2-A	745, 755	66.7	33.3	0.0	50.0	16.7	33.3	0.0	16.7	83.3	56.0
2-B	745/555	33.3	50.0	16.7	0.0	83.3	16.7	33.3	0.0	66.7	61.1
2-C	855/675	33.3	50.0	16.7	33.3	50.0	16.7	16.7	0.0	83.3	55.6
2-D	685/815	33.3	50.0	16.7	50.0	50.0	0.0	33.3	0.0	66.7	50.0
2-E	755, 855/675	66.7	16.7	16.7	50.0	33.3	16.7	0.0	0.0	100	66.7
2-F	745,755, 855/675, 685/815	66.7	16.7	16.7	50.0	33.3	16.7	0.0	0.0	100	66.7

‡ The abbreviations ch, ry, and wh denote species cheat, ryegrass, and wheat, respectively. The abbreviations ch-ch, ch-ry etc. denote the percentage of observations classified from species cheat as cheat, species cheat as ryegrass etc., respectively.

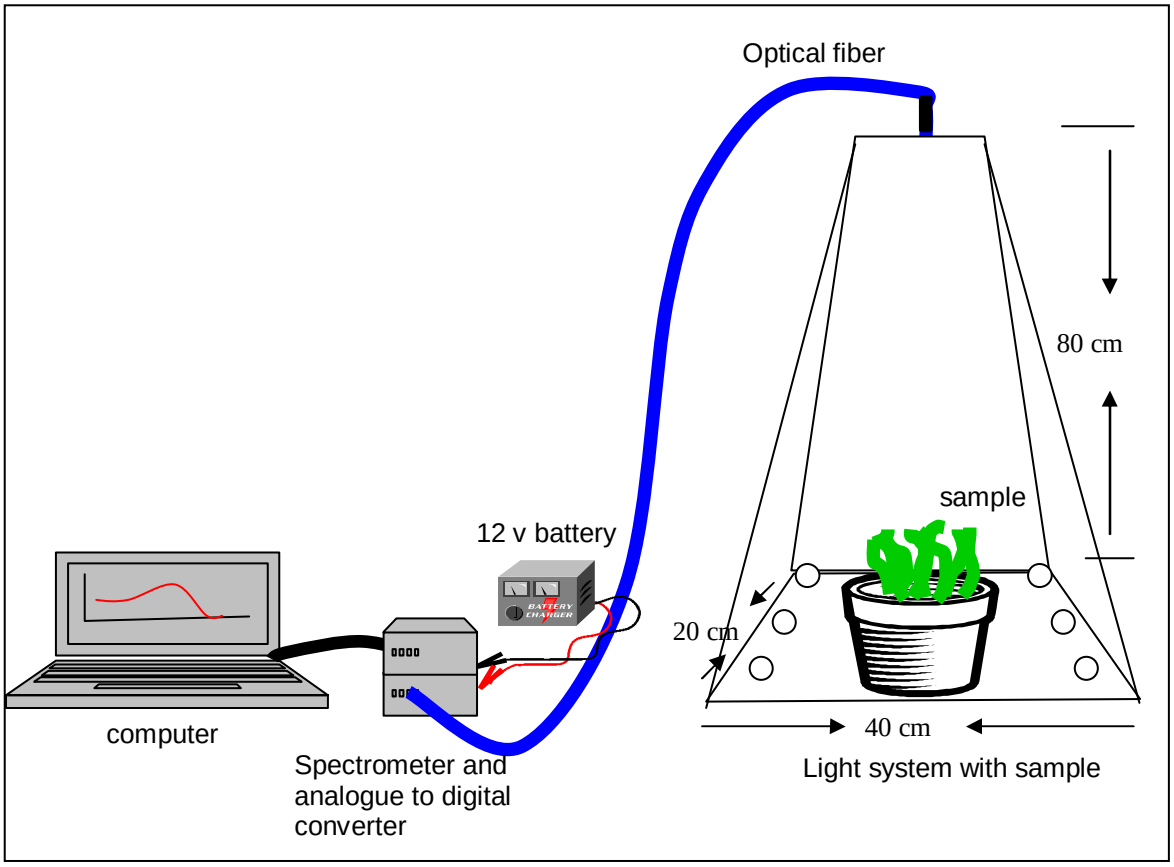


Figure 1. Spectrometer and lighting system used for collecting spectral data on cheat, perennial ryegrass and wheat (refer to materials and methods for details)

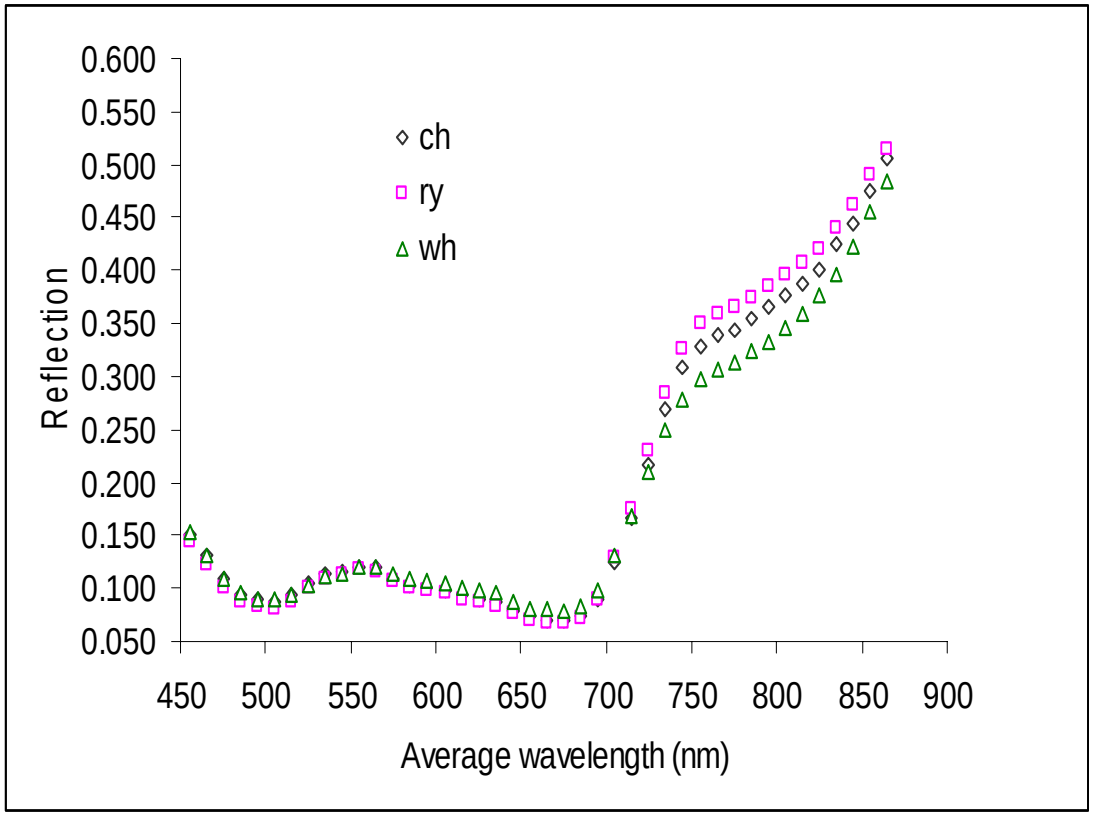


Figure 2. Reflection pattern of cheat (ch) ryegrass (ry) and wheat (wh) in the spectra between 450 and 865 nm for measurements made at Feekes 3 wheat growth stage.

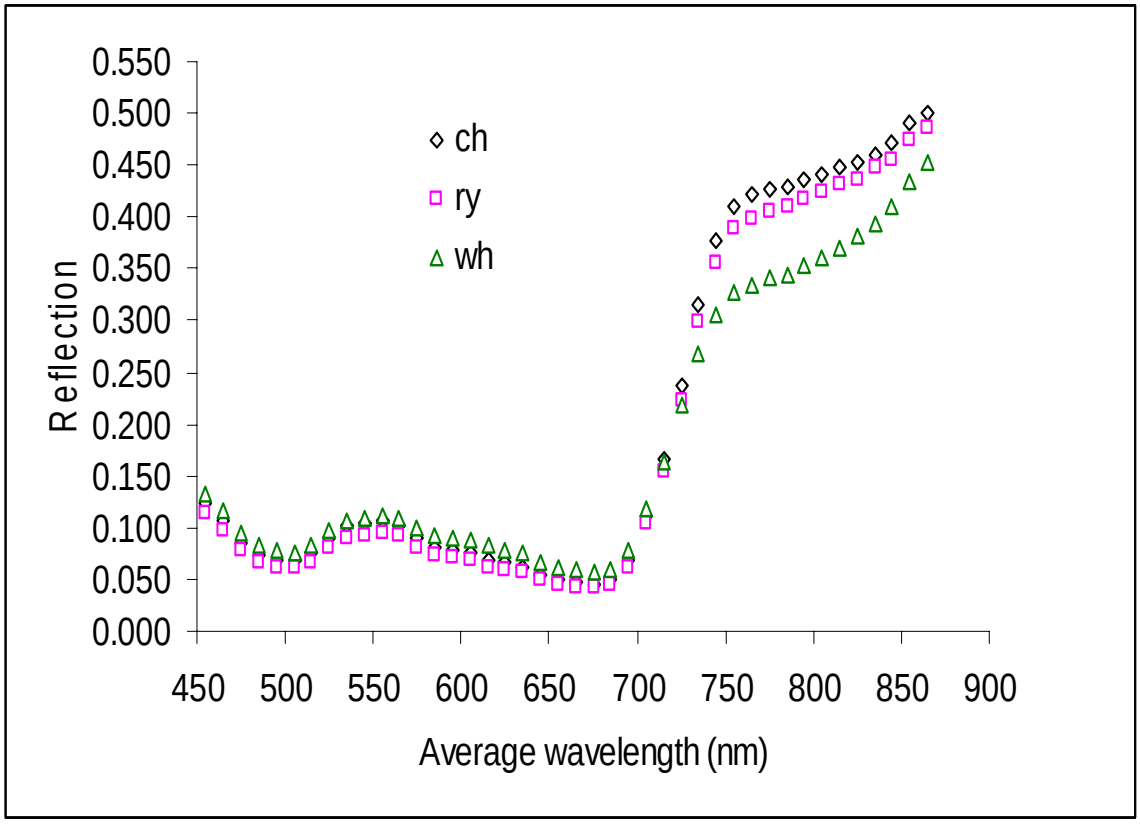


Figure 3. reflection pattern of cheat (ch) ryegrass (ry) and wheat (wh) in the spectra between 450 and 865 nm for measurements made at Feekes 5 wheat growth stage.

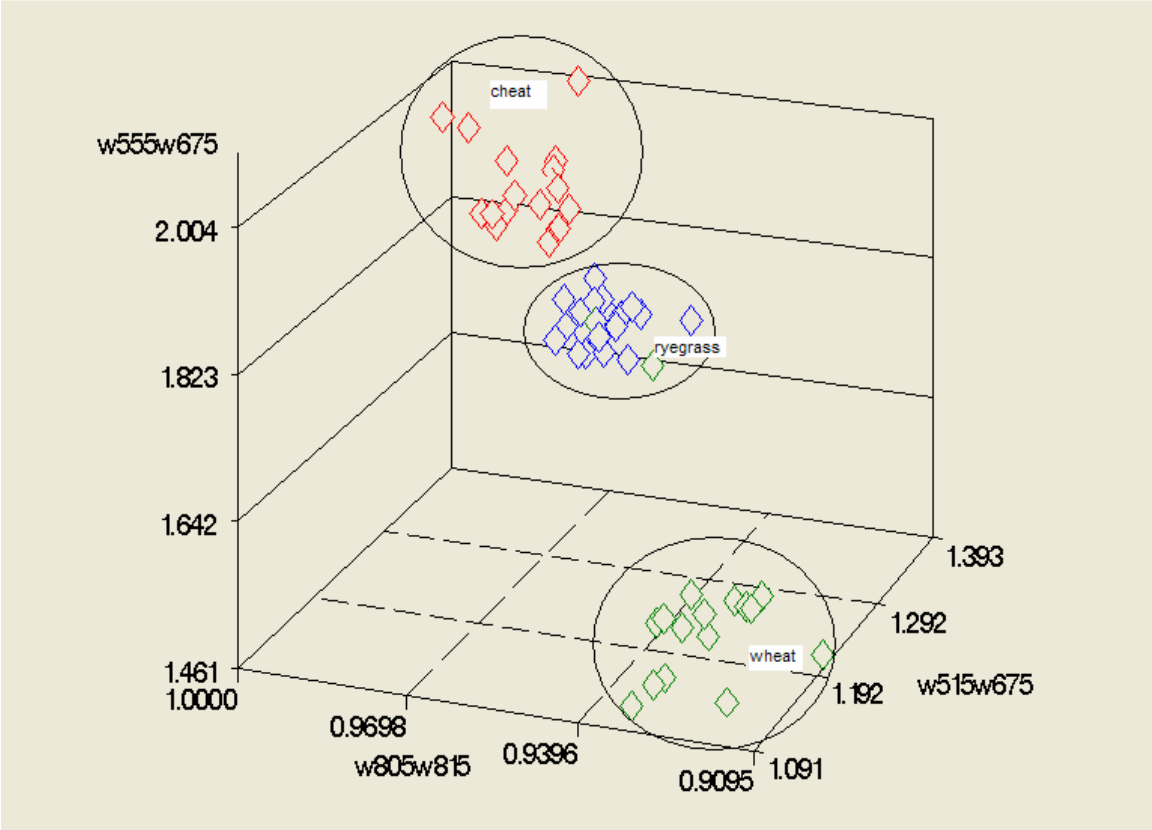


Figure 4. Discrimination of cheat (ch), ryegrass (ry) and wheat (wh) at Feekes 3 wheat growth stage with the discriminant function containing 515/675, 545/675 and 555/675 nm/nm wavelength ratios. Observations per species were 18. Note that 17% of observations from wheat were classified into ryegrass.

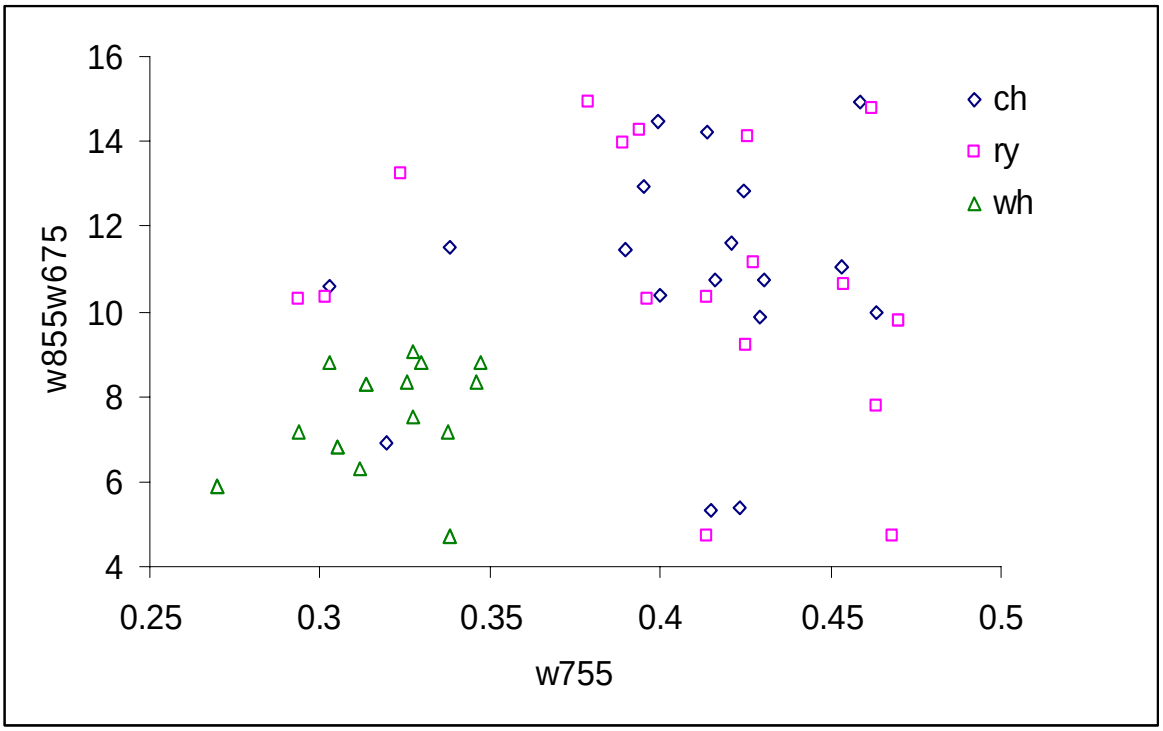


Figure 5. Discrimination of cheat (ch), ryegrass (ry) and wheat (wh) at Feekes 5 wheat growth stage with the discriminant function containing wavelength 755 nm and wavelength ratio 855/675 nm/nm.

CHAPTER II. DETERMINATION OF OPTIMUM RATE AND GROWTH STAGE FOR FOLIAR APPLIED PHOSPHORUS IN CORN

INTRODUCTION

Phosphorus (P) is a structural component of nucleic acids and responsible for energy transfer, which is accomplished by phosphate ester (C-P) and energy rich phosphate (P-P) (Glass et al., 1980). If the level of available P in soil is not adequate for optimum crop growth, phosphate fertilizers must be used to insure that there are adequate amounts of this nutrient in the solution phase, which is usually variable and unpredictable (Chen and Barber, 1990). The formation of insoluble compounds due to soil chemical reactions limits the plant available P making phosphate fertilization use efficiency very low by crops (Barber, 1984). Therefore, appropriate management of phosphate fertilizers is a major concern. Also, stimulated by economic as well as environmental concerns, the efficient use of P is becoming more and more important (Kaeppler et al., 1998).

Early on, P fertilizers were surface applied or incorporated after broadcast. Later research noted that banding was a more efficient method of P placement (Sander et al., 1990). The banded P usually increased early crop growth more than the broadcast placement (Mallarino and Rueber, 2001) because of increased plant uptake (Rehm et al., 1998; Eghball et al., 1990; Barber, 1984). In corn (*Zea mays* L.), Zhang and Barber (1992) studied the effect of P placement on P uptake and reported similar results. It is important to improve phosphorus use of the plant by investigating alternative methods including foliar application.

Research towards foliar fertilization was possibly started in late 1940s and early 1950s (Dion et al., 1949a; b). Unlike many technologies, its pace followed an unpredictable sequence of events. In the early 1980s, studies on foliar application of fertilizers was investigated for selected crops including cereals. The research was however, limited to micronutrients (Eddy, 1999) in high value horticultural crops (Kuepper, 2000). In recent years Lewis and Kettlewell (1993) and Kaya et al. (2001) studied foliar P fertilization in potato (*Solanum tuberosum* L.) and tomato (*Lycopersicon esculentum* L.), respectively.

Some researchers concluded that in corn and other cereals, foliar P was not important (Jones, 1995; Kuepper, 1992; Kuepper, 2000). Others advocated foliar fertilization (Faust, 1996; Anonymous, 1985; Eddy, 2000) as a viable economical way of supplementing the plant's nutrients for more efficient fertilization. Foliar treatment of P can be applied only when the crop needs it and thus decrease cost of production (Faulkner, 1999). The major reason for continued P applications to the soil is to maintain reserves in the soil since foliar P might not directly contribute to the soil P level which is very important at the very early stage of growth. However in cropping systems involving corn stock chopping and incorporation, some proportion of P will be returned to the soil in organic form contributing to the soil P. Foliar P is very effective in high fixing soils since having P applied to the soil would not help the plant in the long run due to formation of insoluble aluminum and iron phosphate compounds. In P rich soils it may be preferable probably to apply on the leaves if a deficiency is expected and demands are high (Silberbush, 2002). This will not only increase efficiency and

decrease cost of production but also reduce runoff of soil applied P, which is responsible for eutrophication of many of lakes and streams (Sharpley et al., 1994).

Indeed, several factors including plant, management and environmental factors influence the benefit of foliar P applied. Foliar application should be made when the plant is not in water stress, either too wet or too dry (Denelan, 1988). Nutrients are best applied when the plant is cool and filled with water (Turgid). Applications that are misapplied or too late in the season may not be effective. The most critical times to apply are when the crop is under P stress. Stress periods occur during periods of great growth activity (Anonymous, 1995). This is likely when the plant is changing from a vegetative to a reproductive stage (Cantisano, 2000).

The mechanism of uptake and transport of foliar applied nutrients involves a complex plant tissue system including dermal, vascular, and ground systems (Rathore, 2000; Römheldl et al., 1999). Previous research showed that a foliar applied nutrient passes through the cuticular wax, the cuticle, the cell wall, and the membrane in that order (Middleton and Sanderson, 1965; Franke, 1967). Sometimes the nutrient will pass through these various layers, while at other times it may pass through the spaces between these layers, which are typical for inorganic ions (Dybing and Currier, 1961). However it was discovered later that stomata are the major means of foliar applied nutrients absorption into the plant

(Eichert et al., 1998; Eichert and Burkhardt, 2001). When the stomata are open, foliar absorption is often easier (Burkhardt et al., 1999).

Advances in agriculture include treating small scale variability to maximize input use and maintain environmental health. Current concerns call for nutrient application methods compatible with location specific technologies. Foliar P in corn is such a method. Therefore the objectives of this study were to assess the suitability of foliar P for corn production and to determine appropriate application timing, rates and efficiency of the method.

MATERIALS AND METHODS

Experimental Locations

Seven field and two greenhouse experiments were conducted at five locations in Oklahoma in 2002 and 2003. In 2002, three experiments were conducted at Perkins using two corn hybrids (Bt corn 108 and Bt corn 109) and Guymon (hybrid Asgrow730RR) while in 2003 four experiments were conducted at Efaw, Goodwell, Lake Carl Blackwell (LCB) and Perkins using Hybrid 111, H9226BtRR, Hybrid 107 and 104, respectively at each location. The source of hybrids used at Efaw, LCB and Perkins (both years) was Pioneer Hibred Int. Inc. (Johnston, IA) while the hybrids at Goodwell and Guymon were obtained from Golden Harvest Seeds Inc. (Bloomington, IL) and Monsanto (St. Louis, Mo) Companies, respectively. The two greenhouse experiments were carried out at Stillwater Agronomy station in 2003 using Hybrid 111. The soil at Perkins is a Teller sandy loam; fine-loamy, mixed, thermic Udic Argiustoll; at both Goodwell and Guymon Richfield clay loam; fine-loamy, mixed, superactive, mesic Aridic

Haplustepts; at Efaw, Norge loam; fine-silty, mixed thermic Udic Paleustoll; and at LCB, Port silt loam; fine-silty, mixed, thermic Cumulic Haplustolls. Table 1 presents surface (0-15 cm) soil characteristics of experimental sites.

Treatment Structure and Experimental Design

The field experiments used a randomized complete block design with three replications. In 2002, treatments comprised ten factorial combinations of three foliar P application timings and four rates of foliar P (Table 2). In 2003, two additional basal P treatments were included. Foliar P application times were collar of fourth leaf visible (V4), collar of eighth leaf visible (V8) and last branch of the tassel completely visible but silks not yet emerged (VT) (Hanway, 1971). The foliar P rates were 0, 2, 4 and 8 kg P ha^{-1}. The two basal P rates were 25 and 50 kg ha^{-1} applied as broadcast at all locations. For foliar treatments, potassium phosphate monobasic (KH_2PO_4) was used as the P source while triple super phosphate (46% P_2O_5) was used for soil applied treatments. Solutions for foliar treatments were prepared by dissolving 100 ml of KH_2PO_4 in 1000 ml of water. A backpack Solo sprayer (Epinions Inc. Brisbane, CA) with a flat fan nozzle spraying systems was used for spraying the solution.

In the greenhouse experiments, 10 treatments consisting basal and foliar rates and one check were arranged in completely randomized design. The basal rates were 0, 25, 50 and 150 kg P ha^{-1}. The foliar rates were the same as the rates used for the field experiments indicated. For the first greenhouse experiment (Greenhouse I) soil with very low Mehlich III extractable phosphorus

levels (4 mg kg^{-1}) from Efaw was used while for the second greenhouse experiment (Greenhouse II) soil with moderate Mehlich III extractable phosphorus levels (9 mg kg^{-1}) from Perkins was placed in pots. Nitrogen and zinc were applied to the 10 treatments at a rate of 112 and 4 kg ha^{-1}, respectively as urea (46% N) and zinc sulfate. Six pioneer hybrid 111 corn seeds were planted by hand in each pot. All foliar rates were applied to the corn at V4 growth stage using a hand held pressurized micro-sprayer (designed and fabricated by Department of Biosystems and Agricultural Engineering, Oklahoma State University). Shoots were then removed 10 days after foliar spraying and were dried and ground for determination of P concentration.

Corn was planted at each location during April-May, with a John Deere 'MaxEmerge' planter at 54,000 and 66,000 plants per hectare at Perkins and Guymon, respectively in 2002 and at 54,000 plants per hectare in 2003 for all locations. Plots were four rows wide (76.2 cm row width) and 9.14 m long in 2002 while the length was reduced to 6.1 m in 2003. Nitrogen was applied at planting at the rate of 112 kg N ha^{-1} using urea (46% N). The center two rows were used for harvest. All crop management practices were carried out as per the Oklahoma State University, Plant and Soil Sciences Department recommendation for respective locations.

Measurements and Laboratory Analysis

Four soil samples, each averaged from 12 soil cores, were collected prior to planting from 0-15 cm depth with a bucket auger for determining available soil P. Samples for forage P concentration determination were taken 10 days after

each foliar application at Guymon in 2002 and at R1 growth stage for the rest of the experiments in 2002 and 2003. Corn plants were removed from 1.39 m^2 area. In 2002, forage samples taken after tassel appearance were separated into leaf, stalk and reproductive (young ear with husk and silk, and tassel) components for all the three experiments. All forage samples were dried in a forced air oven at 30 ^oC for 10 days and weighed before grinding. For 2003, weighed forage samples were used to calculate forage yield.

At maturity, corn from the center two rows was harvested and grain yield was measured and adjusted to a 13% moisture level. Grain and forage samples were ground to pass a 140 mesh sieve (100 um) and analyzed for available total P using a nitric acid digestion (Jones and Case, 1990) followed by ICP analyses (Fassel and Kneseley, 1974). Available soil P was extracted using the Mehlich III method (Mehlich, 1984).

Phosphorus use efficiency (PUE) in grain of corn was calculated based on the following relationship:

$$PUE = \frac{Grain\ P\ uptake\ in\ P\ treated\ \ plot - Grain\ P\ uptake\ of\ \ control}{P\ rate}. \qquad [1]$$

In 2003 at LCB some plots were damaged by wild hogs. Grain yield was accordingly adjusted using plant population count and percent damage per plot.

Data Analysis

All data were subject to statistical analyses using General Linear Model (GLM) and Mixed procedures in SAS (SAS Institute, 2001) and Microsoft Excel (Microsoft Corporation, 2000). Data for PUE was transformed using square-root

variance stabilization method as square-root (PUE+0.5). Means were then detransformed back to original scale for data presentation. Treatment comparisons were made using Fisher's LSD and single degree of freedom contrast analysis. Correlation analysis was also conducted to assess association among yield and P concentration.

RESULTS

Combined analysis of treatments across year and locations revealed that data across years and locations were significant at $p<0.05$ for grain and forage yields, grain and forage P concentration and P use efficiency. Thus each experiment was analyzed separately for assessing treatment effects on the measured variables mentioned.

Cropping Year 2002

Grain Yields

At Perkins, mean gain yields were 1118 and 2213 kg ha^{-1} for hybrid Bt corn 108 and Bt corn 109, respectively. At Guymon, mean grain yield was 10453 kg ha^{-1}(Table 3). Test of the Interaction effect of stage by foliar P rate at Guymon revealed that the grain yield obtained was different among the three growth stages with the application of 2 kg P ha^{-1} (Table 9). Grain yield reached its peak when foliar P was applied at V8 growth stage, with increases of 3000 kg ha^{-1} when applied at this stage.

Grain P Concentration

Grain P concentration was significant across treatments for all experiments in 2002 (Means are presented in Table 4). Foliar P rates were significant at Guymon and Perkins for Bt corn 109. At both locations the largest foliar P rate (8 kg ha^{-1}) resulted in superior grain P concentration (Figure 1). Interaction of stage by foliar P rate was also significant at Guymon and at Perkins for Bt corn 109. Foliar P rates were significantly different for rates applied at V4 and VT growth stages of corn. At both stages at Guymon and at VT stage at Perkins for Bt corn 109, 8 kg ha^{-1} P resulted in higher grain P concentration than any of the other rates. A comparison made between check and foliar rates showed that grain P concentration was increased by foliar treatment (5% more at Guymon and 14% more at Perkins for hybrid Bt corn 109 than the check).

Forage P Concentration

In 2002 at Perkins for both Bt corn 108 and 109, overall treatment effect on corn leaf and stalk P concentration was not significant but was significant on corn reproductive (young ear with husk and silk and tassel, Table 5) P concentration. Across treatments the average P concentration of all the three parts was different from each other for both varieties. Consequently, forage P concentration was high for rates applied at VT growth stage (Table 9). Further, P concentration in the leaf and reproductive components was significant among the three stages of foliar P application times while non-significant in the stalk for Bt corn 109. With the application of 8 kg P ha^{-1} foliar rate, more clear difference was observed among the three application timings for leaf for both varieties. Accordingly, at VT growth stage P concentration of leaf was larger than that of

the other growth stages specially with that applied at V4 with a magnitude difference of 500 and 450 ppm, respectively for Bt corn 108 and 109. Similar results were obtained for reproductive samples with application of 4 kg P ha^{-1} for Bt corn 109.

Foliar P rates were not significant for any of the three plant parts for P concentration for Bt corn 109 but significant for Bt corn 108 where 8 kg P ha^{-1} increased forage P concentration by 17%. Stage by foliar P rate interaction for Bt corn 109 revealed that at VT growth stage, for reproductive samples, the three foliar rates differed although the means were not consistent with the rate increase. The correlation analysis of grain yield with the P-concentration of the three components revealed no significant association of any sort.

On the other hand, at Guymon where forage P concentration was evaluated one week after foliar application at each growth stage, foliar P rate did not result in appreciable difference in forage P concentration. The P concentration in different plant components was significant at this location. More forage P concentration was attained when foliar P was applied at VT growth stage than the other two growth stages (109% more on average).

Phosphorus Use Efficiency

Phosphorus use efficiency was significant across treatments (excluding the untreated check) at Guymon. Detransformed treatment means are presented in Table 6. At this location, stage foliar P rates and their interactions were significant. For this experiment single degree of freedom polynomial contrast also revealed that quadratic relationship occurred among the foliar rates. At Perkins

for Bt corn 108, PUE was not significant across treatments, stage, foliar P rates and their interaction. No trend was also observed for this hybrid. On the other hand for Bt corn 109 linear relationship was observed for foliar P rates considered.

Stage main effect at Guymon was highest (148% more) for P applied at V8 growth stage than that applied either at V4 or VT growth stages. The lowest P rate (2 kg ha^{-1}) was superior in PUE than the other two higher rates and showed a decreasing linear trend (Figure 2). Application of 2 kg ha^{-1} at V8 growth stage exhibited exceptionally high (510%) PUE at this location. Detection of significant interaction effects guided by test of effect slices at 5% level of significance showed that at V8 growth stage the lowest P rate resulted in highest PUE (More than 10 fold). Conversely, the application of 2 kg ha^{-1} at V8 resulted in superior PUE (data not shown).

At Perkins the interaction of foliar rate and growth stage showed that with application of 2 kg P ha^{-1}, both at V8 and VT stages improved PUE by at least 60% versus that applied at V4 growth stage. The PUE at V4 was not better than the check. For Bt corn 108 at Perkins two treatment combinations, 4 kg P ha^{-1} at V4 (62%) and VT (65%) stages resulted in highest PUE.

Cropping Year 2003

Grain Yields

Treatment means are presented in Table 3 for all locations in 2003. At Goodwell foliar P rate of 2 kg ha^{-1} applied at V8 growth stage resulted in more grain yield than the earlier or later applied P (Table 9). At LCB overall treatment effects were significant. Further investigation showed that foliar P rates were

significant for grain yield where 8 kg ha $^{-1}$ resulted in significantly higher (34% more) yield than the lower rates and check combined which were not significantly different among themselves.

Forage Yields

Treatment means are given in Table 7 for Efaw, Goodwell, LCB and Perkins locations for forage yield response to treatments in 2003. At Efaw, forage yield was not significant across treatments, growth stage and P rates. However, single degree of freedom contrasts showed that forage yield was increased by 601 kg ha $^{-1}$ when either soil or foliar P were applied.

At Goodwell forage yield was significant across treatments, stage, P rates and interaction of stage and P rates. Foliar P applied at VT growth stage out yielded the rates applied at V4 growth stage by 15%. Specifically, foliar P applied at VT growth stage with the rates of 4 and 8 kg ha^{-1} resulted in highest forage yield (Figure 3).

At LCB, three single degree of freedom contrasts were found significant. Accordingly, soil applied P resulted in greater dry matter accumulation than foliar applied P (900 kg ha^{-1} more). Application of basal and foliar P improved forage production when compared with no P (425 kg ha^{-1}). Comparison made between foliar and no P also showed that foliar application of P resulted in additional forage yield of 600 kg ha^{-1}.

Grain P Concentration

Summary of treatment means for grain P concentration in 2003 is given in Table 4. At LCB across growth stages, grain P concentration was significantly

higher when foliar P was applied at VT stage than V4 stage (9% more P when applied at VT stage, Table 9). There was significant interaction effect for grain P concentration at this location. Close investigation into this effect revealed that grain P concentration was significantly higher at VT than either V4 or V8 growth stages with the application of 8 kg P ha^{-1}. Foliar P rates applied at VT growth stage were also different unlike foliar P applied at the other stages.

At Goodwell, foliar P applied at VT growth stage resulted in superior grain P concentration than that applied at V4 (Table 9). At this location regardless of growth stage, lower foliar rates (2 and 4 kg ha^{-1}) resulted in higher grain P concentration than the highest foliar rate.

At Perkins on the other hand both stage and foliar P rates were not significant but there interaction was significant. Accordingly a similar result like LCB was obtained where foliar rates at VT stage with foliar rate of 8 kg ha^{-1} showed significant effect.

Single degree of freedom comparisons for grain P concentration showed significant effects at LCB and Perkins. At LCB basal applied P resulted in 870 ppm more grain P content than foliar applied P. At this location application of either basal or foliar P resulted in superior grain P concentration than the untreated check (850 and 698 ppm for basal and foliar, respectively). Likewise, at Perkins basal and foliar applied P increased grain P concentration by 201 and 198 ppm, respectively compared with untreated check. Linear (at Efaw and Perkins) and quadratic (Goodwell) trends for foliar p rates were also discovered (Figure 4).

Forage P Concentration

Overall treatment effects were significant at Efaw and Goodwell (treatment means are presented in Table 8). Foliar P application stages differed significantly at Efaw and Goodwell only. At both locations foliar P applied at VT growth stage resulted in superior P concentration (Table 9). With regard to foliar P rates, significant difference was obtained at Goodwell while marginally significant effect was obtained at Perkins. In both cases foliar P rate of 8 kg ha^{-1} resulted in higher forage P concentration than the lower rates considered in the study (Figure 5). Some interaction of stage and foliar P rates were also obtained at Efaw and LCB (with 8 kg P ha^{-1}) and Goodwell (with 2 kg P ha^{-1}). At both foliar P rates, forage P concentration was high when the rates were applied at VT growth stage of corn.

At Goodwell, contrasts made between no fertilizer versus fertilizer P (foliar or basal) and no P and foliar P showed significant difference where forage P concentration was increased by 19.3 and 17.3%, respectively. Additionally at this location linear foliar P response was observed (data not shown).

The results of the Greenhouse I experiment showed that P concentration in corn dry matter was substantially increased by high basal rate (150 kg P ha^{-1}) in the presence of adequate N supply. However, low basal rates and all foliar rates did not improve the P concentration in corn dry matter. An interesting outcome of this experiment was that as the amount of basal P increased from the 0 and 25 kg ha^{-1} to 50 kg P ha^{-1}, a remarkable response in foliar P rates was observed (Figure 6). However, this only occurred before the P rate was elevated beyond 50 kg P ha^{-1}. In the Greenhouse II experiment similar result was

observed where the highest P rate resulted in superior P concentration in forage. No foliar rate response was obtained, however.

Phosphorus Use Efficiency

Treatment means for PUE are given in table 6. In 2003 there was not a significant overall treatment effect, stage or P rate for Efaw and Perkins. However foliar P rate at Goodwell and basal versus foliar applied P contrast at LCB were significant. At Goodwell, the highest foliar rate resulted in the highest PUE (Figure 2). On the other hand at LCB foliar rate of 2 kg P ha^{-1} resulted in 35% more PUE than the basal P.

DISCUSSION

Grain and Forage Yields

Across years and locations the stages in which the rates were applied or the foliar rates did not impact yield very much except at Guymon in 2002 and LCB in 2003. There are several possible explanations for this. First, it is suspected that the foliar rates might not be sufficient to deliver additional statistically detectable yield difference among treatments. In winter wheat, Mosali (2004) found a lack of response in grain yield to foliar rates of 2 and 4 kg ha^{-1} which were attributed to the low rates considered. Second, the soil phosphorus level explains the lack of response to foliar rates considered in this study. Most of the locations considered in the study have reasonable initial soil test P level. The fact that corn plant root system can extend and explore the soil by increasing the surface contact of roots to phosphorus coupled with good growing conditions might explain the improved sufficiency once plant roots are well developed.

Third, the lack of good growing conditions might interfere with the plants capacity to make use of supplied phosphorus at some locations. For example, Perkins is located in relatively high evapo-transpiration area of Oklahoma and high yield is not expected. At this location, we suspected that high heat and low moisture status for optimum corn growth might have affected treatment effects. On the other hand, at this location the soil test P index was 40 which is sufficiency level of 95%, slightly less than the amount required by corn crop (Bundy, 1998; Heckman et al., 2001). Consequently absence of significant foliar applied P was not surprising. At Guymon in 2002 mean grain yield was higher since the corn at this location was supplied with irrigation. The preplant soil test P index was nearly 140 which was in excess of corn P requirement. Despite the large amount of available P reported in the soil for this location, analysis of interaction effects revealed that the grain yield obtained was higher at V8 with the application of 2 kg ha^{-1} foliar P. This was largely due to stimulating effect of the supplemental foliar P of the irrigated corn root system allowing more exploration of phosphorus and other nutrients that are required for improved yield. The results obtained are also supported by the work of Ling and Silberbush (2002) who concluded that foliar fertilization may partially compensate for insufficient uptake of essential nutrients by the roots of corn which are required for grain filling.

The results from LCB showed that when soil P level was low response to basal or foliar rates were considerable. The significant stage effect also warrant that the application of foliar P at later growth stage would likely help obtain higher

yield that could have been lost due to P deficiency when the nutrient was needed most.

Several research findings were reported on both presence and lack of yield response to foliar P rates. Harder et al. (1982) found that foliar fertilizer applied after silking did not translate into increased grain yield. On the other hand Barel and Black (1979b) reported an increased grain yield due to foliar P compared with control (untreated check).

Grain and Forage P Concentration

Grain and forage P concentration differed due to stage and foliar P rates in several of the experiments. The foliar P rates applied at V8 and VT growth stages generally resulted in higher concentration indicating the effectiveness of foliar fertilization. With regard to foliar P rates, the results showed that the 8 kg ha^{-1} preferably increased P concentration. When higher foliar rates were applied at later growth stages at least in the current context VT stage, high level of grain or foliar P concentration is possible to achieve. One consistent result of the study was that all foliar applied P treatments achieved higher concentration than the check. In their study Harder et al. (1982) found that percent P in grain was increased by 230 ppm (4.7% increases) by foliar fertilization compared with the control. However their analysis did not detect significant differences within foliar P rates. High P concentration in forage might be remobilized if needed during grain filling while high concentration in grain might improve yield or kept in the seed as P in the seed is very important for germination and initial development until roots extend to contact soil (Pellerin et al., 2000).

In 2002, estimation of P concentration by plant parts revealed that the concentration in reproductive parts was larger for forage collected at VT growth stage followed by leaf with application of foliar P rate of 8 kg ha^{-1}. Barel and Black (1979b) detected P concentration difference in leaves of foliar and check and also in the check P concentration was lower than foliar treated plots. Overall, the P concentration in all the three components of corn plant would be able to support normal growth of corn which was also reflected in lack of grain yield increase. In corn, the concentration of P in plant ranges between 0.3-0.5% (3000-5000 ppm) of plant dry matter during vegetative growth (Barry and Miller, 1989). Basically its concentration is high in young leaves (Pellerin and Plénet, 2000). Unlike the concentration reported in here Pellerin and Plénet (2000) indicated that P concentration was low in grain. This could be partly true since as compared to total plant P concentration the final concentration in grain would be far below the total value as the P level in grain reaches maximum possible that can be stored.

Phosphorus Use Efficiency

Phosphorus use efficiency was generally higher for foliar applied than basal applied P. The results obtained here also revealed that foliar P rate applied at V8 growth stage resulted in higher PUE than the earlier or later applied foliar P rates. The lowest foliar P rate was found more efficient than the higher rates of foliar applied P rates. Interaction effect at Goodwell and Perkins experiments in 2002 revealed that applying 2 kg P ha^{-1} at V8 growth stage highly improved PUE. The decrease in efficiency with higher rates of foliar P could be due to several

reasons that influence the actual amount of applied P that comes in contact with plant, retained on the corn leaf or stalk, absorbed by leaves and translocated.

The formulation used as foliar fertilizer coupled with hot summer condition at the experimental locations might interfere with the retention and uptake of the fertilizer. In their study Barel and Black (1979a) found that ammonium salts of orthophosphate dried rapidly and leave dry crystals on the surface of the leaf which depending on moisture availability and conditions such as temperature, humidity and moisture availability might be taken up later or washed away. In moist conditions potassium phosphate is rapidly absorbed by leaf. Since most of the foliar ionic nutrients are absorbed through stomata, their opening and closure greatly affect the uptake of foliar P although according to Linskens et al. (1965) leaf hairs have thinner cell walls near their base which enhances entrance of ionic foliar nutrients at any time.

CONCLUSIONS

The responses in grain and forage yields, grain and forage P concentration obtained from foliar P indicates that this work should be pursued further. Foliar P applied at VT growth stage improved grain and forage P concentration while P use efficiency was high only when low foliar P rates were applied.

Foliar P rate at 8 kg ha^{-1} improved to some extent yields and largely forage and grain P concentration of corn compared to the lower rates although again this was not translated to high use efficiency. The benefit of foliar P might

be indirect through initiation of chain of processes in the cell that in turn enhances photosynthesis which in turn increase water uptake which obviously leads to nutrient absorption through the root. The result is healthy growth and increased grain yield. In conclusion the benefit of foliar phosphorus entirely depends on the type of soil and weather conditions prevailing in corn growing environment plus the effective formulation. Further investigation is required before consistent conclusions are drawn for foliar fertilization of P on corn in Oklahoma. It is also important to note that foliar fertilization is not meant to substitute soil application totally at least at early growth stage leaf area is small to intercept foliar P rates required as starter fertilizer and the economically achievable number of foliar application are limited. Therefore foliar P fertilization must be considered as essential part of fertilization plan in corn and not as a separate phosphorus management tool by itself.

REFERENCES

Anonymous. 1985. Principles of foliar feeding. Trans National Agronomy, Grand Rapids, MI.

Anonymous. 1995. Foliar nutrition. pp. 64-65. Acres U.S.A., Metairie, LA.

Barber, S.A. 1984. Soil nutrient bioavailability: A mechanistic approach. John Wiley & Sons, New York.

Barel, D. and C.A. Black. 1979a. Foliar Application of P. I. Screening various inorganic and organic P compounds. Agron. J. 71:15-21.

Barel, D., and C.A. Black. 1979b. Foliar application of P. II. Yield response of corn and soybeans sprayed with various condensed phosphates and P-N compounds in greenhouse and field experiments. Agron. J. 71:21-24.

Barry, D. A. J. and M. H. Miller. 1989. P nutritional requirement of maize seedlings for maximum yield. Agron. J. 81:95-99.

Bundy, L.G. 1998. Corn fertilization. University of Wisconsin Extension, no. A3340, Madison, WI.

Burkhardt, J., S. Dreitz, H.E. Goldbach and T. Eichert. 1999. Stomatal uptake as an important factor for foliar fertilization. *In* Proceedings of the Second International Workshop on Foliar Fertilization. April 4-10, 1999, Bangkok, Thailand.

Cantisano, A. 2000. What to use for foliar feeding. pp. 4-6. *In* L. Byczynski (ed.). Growing for Market. Fairplain Publications, Lawrence, KS.

Chen, J. and S.A. Barber. 1990. Soil pH and phosphorus and potassium uptake by maize evaluated with an uptake model. Soil Sci. Soc. Am. J. 54:1032-1036.

Denelan, P. 1988. Foliar feeding. pp. 58, 60-61. Mother Earth News. Issue no.111, May-June. Ogden Publications, Inc. Topeka, Kansas.

Dion, H. G., J.W.T. Spinks and J. Mitchell. 1949a. Experiments with radio phosphorus on the uptake of phosphorus by wheat. Sci. Agr. 29:167-172.

Dion, H. G., J.E. Dehm and J.W.T. Spinks. 1949b. Study of fertilizer uptake using radioactive phosphorus. IV. The availability of phosphate carriers in calcareous soils. Sci. Agr. 29:512-526.

Dybing C.D. and H.B. Currier. 1961. Foliar penetration by chemicals. Plant Physiol. 36:169-174.

Eddy, D. 1999. Application and micronutrients. Am. Fruit Grower. 119:30-35, Willoughby, Oh.

Eddy, D. 2000. A future for foliars. pp. 46-47. Am. Vegetable Grower. Meister publishing Co., Willoughby, Oh.

Eghball, B., D.H. Sander and J. Skop. 1990. Diffusion, adsorption and predicted longevity of banded phosphorus fertilizer in three soils. Soil Sci. Soc. Am. J. 54:1161-1165.

Eichert, T. and J. Burkhardt. 2001. Quantification of stomatal uptake of ionic solutes using a new model system. J. Exp. Bot. 52:771-781.

Eichert, T, H.E. Goldbach and J. Burkhardt.1998. Evidence for the uptake of large anions through stomatal pores. Botanica Acta 111:461–466.

Fassel, V.A. and R.N. Kneseley. 1974. Inductively coupled plasma optical emission spectroscopy. Anal. Chem. 46:111-112.

Faulkner, S.P. 1999. Foliar feeding when your plants need it fast. pp. 42-47. The Growing Edge, Corvallis, OR.

Faust, R.H. 1996. Why foliar fertilization works. http://www.humic.com/fol-fert.html. (visited May 2004).

Franke, W.1967. Mechanism of foliar penetration of solutions. Annu. Rev. Plant Physiol. 18:281–300.

Glass, A.D.M., J.D. Beaton and A. Bomke. 1980. Role of phosphorus in plant nutrition. Pp. 357-368. *In* Proceedings of the Western Canada Phosphate Symposium. The Western Canada Soils Coordinating Committee and the Western Canada Fertilizer Association, Calgary, Canada.

Hanway, J.J. 1971. How a corn plant develops. Cooperative Extension Service. Iowa State Ext. Service, Ames, IA.

Harder, H.J., R.E. Carlson and R.H. Shaw. 1982. Corn grain yield and nutrient response to foliar fertilizer applied during grain fill. Agron. J. 74:106-110.

Heckman, J.R., J.T. Sims, D.B. Beegle, F.J. Coale, S.J. Herbert and T.W. Bruulsema. 2001. Phosphorus and potassium removal in corn. Better Crops 85:4-6.

Jones, T. 1995. Are foliar fertilizers appropriate? NewHarvest, Cooperative Extension Service of Kentucky college of Agriculture, KY.

Jones, J.B. Jr. and V.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples. pp. 389-447. *In* R.L. Westerman (ed.). Soil testing and plant analysis, third ed. Soil Sci. Soc. Am. Inc., Madison, WI.

Kaeppler, S., J. Parke, B.Tracy, C.W. Stuber and L. Senior. 1998. Genetics of microbe-mediated P nutrition in maize. 40th Maize Genetics Conference March 19-22, 1998. Grand Geneva Resort, Lake Geneva, WI.

Kaya, C., H. Kirnak and D. Higgs. 2001. Enhancement of growth and normal growth parameters by foliar application of potassium and P in tomato cultivars grown at high NaCl salinity. J. Plant Nut. 24:357-367.

Kuepper, G. 1992. Experiences with electronic scanning and foliar feeding in commercial small fruits. GAIA, Goshen, AR.

Kuepper. G. 2000. Foliar fertilization. National Sustainable Agriculture Information Service (ATTRA), Fayetteville, AR.

Lewis, D.J. and P.S. Kettlewell. 1993. A comparison of the uptake of P from foliar applied phosphate by the leaves of eleven varieties of potato. Aspec. Appl. Biol. 34:243-248.

Ling, F. and M. Silberbush. 2002. Response of maize to foliar versus soil application of nitrogen-phosphorus-potassium fertilizers. J. Plant Nut. 25:2333-2342.

Linskens, H.F., W. Heinen and A.L. Stoffers. 1965. Cuticula of leaves and the residue problem. Residue Rev. 8:136-178.

Mallarino, A. and D. Rueber. 2001. Phosphorus and potassium fertilization for corn and soybeans managed with no-till and chisel-plow tillage. Iowa State University, Northern Research and Demonstration Farm; ISRF00-22, IA.

Middleton, L.J. and J. Sanderson. 1965. The uptake of inorganic ions by plant leaves. J. Exp. Bot. 16:197–215.

Mehlich, A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commu. Soil. Sci. Plant Anal. 15:1409-1416.

Microsoft Corporation. 2000. Microsoft office excel 97. Microsoft Corporation Inc., Redmond, WA.

Mosali, J. 2004. Effect of foliar application of phosphorus on winter wheat grain yield. PhD. Dissertation. Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Ok.

Pellerin, S., A. Mollier and D. Plénet. 2000. P deficiency affects the rate of emergence and number of maize adventitious nodal roots. Agron. J. 92:690-697.

Rathore, S.V.S. 2000. Effect of foliar application of iron and zinc on growth, flowering and corn production. Ann. Plant Soil Res. 2:222-224.

Rehm, G., J. Lamb, M. Schmitt G. Randall and L. Busman. 1998. Agronomic and environmental management of phosphorus. University of Minnesota Extension Service, FO-06797-GO, Twin Cities Campus, MN.

Römheldl, V. and M. M. El-Fouly. 1999. Foliar nutrients application: Challenge and limits in agriculture. *In* Proceedings of the Second International Workshop on Foliar Fertilization. April 4-10, 1999, Bangkok, Thailand.

Sander, D.H., E.J. Penas and Bahaman Eghball.1990. Residual effects of various phosphorus application methods on winter wheat and grain sorghum. Soil Sci. Soc. Am. J. 54:1473-1478.

SAS Institute. 2001. The SAS system for windows, Version 8.02, SAS Institute, Cary, NC.

Sharpley, A. N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel and K. R. Reddy. 1994. Managing agricultural P for protection of surface waters: Issues and options. J. Environ. Qual. 23:437-451.

Silberbush, M. 2002. Simulation of ion uptake from the soil. pp. 651-661. *In* Y. Waisel, A. Eshel, U. Kafkafi (eds.). Plant roots: The hidden half (3rd Ed.), Marcel Dekker, New York.

Zhang, J. and S.A. Barber. 1992. Maize root distribution between phosphorus fertilized and unfertilized soil. Soil Sci. Soc. Am. J. 56:819-822.

Table 1. Initial surface (0-15 cm) soil test characteristics at Efaw, Goodwell, Lake Carl Blackwell, and Perkins, OK.

Location	pH	NH_4-N[€]	NO_3^--N	P	K
		---------- mg kg^{-1} ----------			
Efaw	5.6	14.1	3.05	15.2	100
Guymon	7.2	-	26.5	31.0	610
Goodwell	7.5	-	22.5	13.0	596
LCB	5.4	11.0	1.3	9.7	102
Perkins	4.9	12.2	2.0	13.2	105
Greenhouse I[†]	4.8	5.0	4.5	4.4	130
Greenhouse II[†]	4.9	17.0	2.8	9.4	129

[€] NH_4-N and NO_3-N were extracted with 2 M KCl solution while P and K were extracted with Mehlich III solution. pH was determined by 1:1 Soil-Water ratio.

[†] Soil for greenhouse I was obtained by scratching away top soil from upland Efaw while for greenhouse II soil was top soil from Perkins.

Table 2. Treatment structure for foliar P study experimental locations at Efaw, Goodwell, Guymon, Lake Carl Blackwell, and Perkins, OK in 2002 and 2003.

Treatment no.	Application timing (corn growth stage)	P rate (kg ha^{-1})	Application method	Source
1	-	0	Foliar	KH_2PO_4
2	V4	2	Foliar	KH_2PO_4
3	V4	4	Foliar	KH_2PO_4
4	V4	8	Foliar	KH_2PO_4
5	V8	2	Foliar	KH_2PO_4
6	V8	4	Foliar	KH_2PO_4
7	V8	8	Foliar	KH_2PO_4
8	VT	2	Foliar	KH_2PO_4
9	VT	4	Foliar	KH_2PO_4
10	VT	8	Foliar	KH_2PO_4
11	Preplant	25	Soil, broadcast	TSP‡
12	Preplant	50	Soil, broadcast	TSP‡

‡ Triple super phosphate (46% P_2O_5)

Table 3. Mean grain yield of seven field experiments conducted in 2002 and 2003 at five locations.

Treatment	Growth stage	P Rate (kg ha^{-1})	2002			2003			
			Perkins Bt 108	Perkins Bt 109	Guymon	Efaw	Goodwell	LCB*	Perkins
		----------	----------	----------	kg ha^{-1}	----------	----------	----------	----------
1	-	0	1203	2422	11078	6564	10710	3158	5063
2	V4	2	1346	2095	9177	6687	9776	3674	4940
3	V4	4	2375	1920	10216	7084	9087	3470	5069
4	V4	8	440	2294	10480	5862	8829	4072	4760
5	V8	2	660	2478	12180	7714	11253	2931	4854
6	V8	4	1266	2387	10070	5773	10075	3809	4871
7	V8	8	634	2143	10967	6677	10380	5401	5286
8	VT	2	345	2477	10167	6287	10424	3484	4745
9	VT	4	1501	1989	10527	6984	11691	3469	5283
10	VT	8	1412	1922	9670	5580	12192	4398	5364
11	Preplant	25	-	-	-	6594	10562	4765	5080
12	Preplant	50	-	-	-	5871	10509	4688	5392
Mean			1118	2213	10453	6486	10457	3850	5061
SED‡			622	263	932	763	1273	608	345

‡ Standard error of difference of two treatment means * Lake Carl Blackwell

Table 4. Mean grain P concentration of seven field experiments conducted in 2002 and 2003 at five locations.

Treatment	Growth stage	P Rate	2002			2003			
			Guymon	Perkins Bt 108	Perkins Bt 109	Efaw	Goodwell	LCB*	Perkins
		kg ha^{-1}	ppm						
1	-	0	4463	2599	2107	3108	2894	2723	2584
2	V4	2	4570	2729	2323	3155	2461	2602	2725
3	V4	4	4330	3404	2208	3509	2624	3218	2765
4	V4	8	5134	2890	2630	2827	2981	3189	2605
5	V8	2	4891	3030	2690	3367	3076	3007	2882
6	V8	4	4912	2703	2383	3189	3235	3102	2640
7	V8	8	4574	2960	2218	3185	2979	3072	2700
8	VT	2	4827	2958	2475	3366	3150	3017	2468
9	VT	4	4624	2773	2503	3292	3255	3104	2852
10	VT	8	5031	3182	2755	3016	3272	3612	3176
11	Preplant	25	-	-	-	3272	2972	3183	2977
12	Preplant	50	-	-	-	3586	2881	3086	2845
Mean			4735	2923	2429	3239	2982	3076	2768
SED‡			298	214	226	332	292	257	189

‡ Standard error of difference of two treatment means * Lake Carl Blackwell

Table 5. Mean forage P concentration by plant parts for the two experiments at Perkins in 2002.

Treatment	Growth stage	P Rate	Bt corn 108				Bt Corn 109			
			Leaf	stalk	Reproductive	Total	Leaf	stalk	Reproductive	Total
		kg ha^{-1}	---------- ppm ----------							
1	-	0	1800	1003	2406	5209	1236	694	1900	3830
2	V4	2	1847	881	2516	5244	1385	730	2067	4182
3	V4	4	1583	869	2212	4665	1247	716	2092	4054
4	V4	8	1508	810	2780	5098	1142	671	1824	3636
5	V8	2	1807	997	2467	5271	1356	820	1929	4105
6	V8	4	1594	878	2453	4925	1225	713	1921	3860
7	V8	8	1822	1077	2772	5671	1214	738	1954	3906
8	VT	2	1790	856	2980	5625	1350	720	1959	4028
9	VT	4	1571	828	2479	4878	1470	910	2346	4727
10	VT	8	1976	772	2772	5520	1485	693	2101	4279
Mean			1741	915	2554	5211	1310	740	2009	4061
SED‡			209	142	262	407	179	135	154	415

‡ Standard error of difference of two treatment means * Lake Carl Blackwell

Table 6. Square-root detransformed phosphorus use efficiency of seven field experiments conducted in 2002 and 2003 at five locations.

Treatment	Growth stage	P Rate (kg ha^{-1})	2002			2003			
			Guymon	Perkins Bt 108	Perkins Bt 109	Efaw	Goodwell	LCB*	Perkins
2	V4	2	0.000	0.461	0.000	0.022	0.213	0.539	0.000
3	V4	4	0.520	0.617	0.277	0.721	0.067	0.363	0.389
4	V4	8	0.570	0.000	0.043	0.000	0.000	0.124	0.000
5	V8	2	5.169	0.462	0.628	1.909	1.922	0.367	0.655
6	V8	4	0.220	0.167	0.146	0.000	1.037	0.471	0.217
7	V8	8	0.350	0.000	0.014	0.073	0.000	0.675	0.147
8	VT	2	0.313	0.000	0.628	0.273	1.448	0.291	1.111
9	VT	4	0.496	0.654	0.051	0.741	0.780	0.338	0.428
10	VT	8	0.205	0.350	0.094	0.000	0.056	0.649	0.464
11	Preplant	25	-	-	-	0.023	0.049	0.089	0.035
12	Preplant	50	-	-	-	0.001	0.007	0.042	0.020
Mean (detransformed)			0.871	0.301	0.209	0.342	0.507	0.359	0.224
Square-root transformed SED‡			0.194	0.184	0.137	0.252	0.258	0.137	0.158

‡ Standard error of difference of two treatment means * Lake Carl Blackwell

Table 7. Mean forage yield[#] of four field experiments conducted in 2003 at four locations.

Treatment	Growth stage	P Rate ()	Efaw	Goodwell	LCB[*]	Perkins
		---------- kg ha^{-1} ----------				
1	-	0	7343	11226	3333	4984
2	V4	2	7940	10652	4360	6128
3	V4	4	7658	11075	4187	5272
4	V4	8	9079	10380	4046	5608
5	V8	2	8341	11476	3937	5380
6	V8	4	8189	9730	3959	5597
7	V8	8	7083	8829	4154	5380
8	VT	2	7517	10532	3775	5640
9	VT	4	6779	11693	3720	5814
10	VT	8	8005	12192	4350	6063
11	Preplant	25	8743	10803	4632	5684
12	Preplant	50	8048	10261	5185	5521
Mean			7815	10807	4058	5498
SED[‡]			808	822	643	857

[‡] Standard error of difference of two treatment means [*] Lake Carl Blackwell
[#] determined from harvest made at corn growth stage between VT and R1.

Table 8. Mean forage P concentration of four field experiments conducted in 2003 at four locations.

Treatment	Growth stage	P Rate	Efaw	Goodwell	LCB*	Perkins
		kg ha^{-1}	---------- ppm ----------			
1	-	0	2215	1432	1919	2312
2	V4	2	2149	1343	1583	2311
3	V4	4	2301	1413	1948	1762
4	V4	8	2339	1567	1559	2421
5	V8	2	2443	1785	1709	2340
6	V8	4	2229	1739	1911	2100
7	V8	8	2065	2016	1962	2644
8	VT	2	2653	1853	1932	2113
9	VT	4	2700	1631	1968	2524
10	VT	8	2681	1779	2138	2762
11	Preplant	25	2240	1695	1720	2192
12	Preplant	50	2390	1976	2098	2157
Mean			2367	1650	1866	2291
SED‡			204	151	203	306

‡ Standard error of difference of two treatment means * Lake Carl Blackwell

Table 9. Effect of foliar P applied at three growth stages of corn and check at different locations in 2002 and 2003.

	Check	V4	V8	VT
Grain yield	---------- Kg ha^{-1} ----------			
Guymon	11078 ab	9177 b	12180 a	10167 ab
Goodwell	10894 ab	9476 b	11716 a	10295 ab
Grain P concentration	---------- ppm ----------			
Goodwell	2894 ab	2689 b	3096 ab	3226 a
Lake Carl Blackwell	2723 b	3003 b	3060 ab	3244 a
Forage P concentration	---------- ppm ----------			
Perk bt 108	1734 a	1667 b	1763 a	1780 a
Perk bt 109	1277 b	1319 b	1320 b	1448 a
Efaw	2215 b	2229 b	2246 b	2678 a
Goodwell	1432 b	1441 b	1756 a	1846 a

Values followed by the same letter across row for each location are not significantly different at $p<0.05$ based on least significant difference (LSD) procedure.

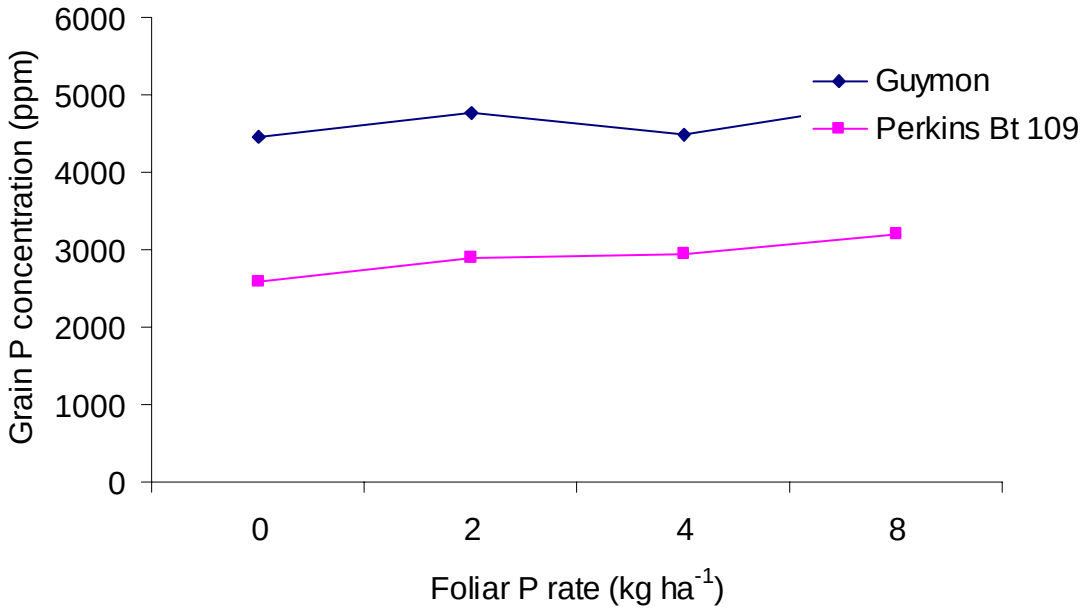


Figure 1. Grain P concentration as affected by foliar P rates at Guymon and Perkins (Bt corn 109) in 2002.

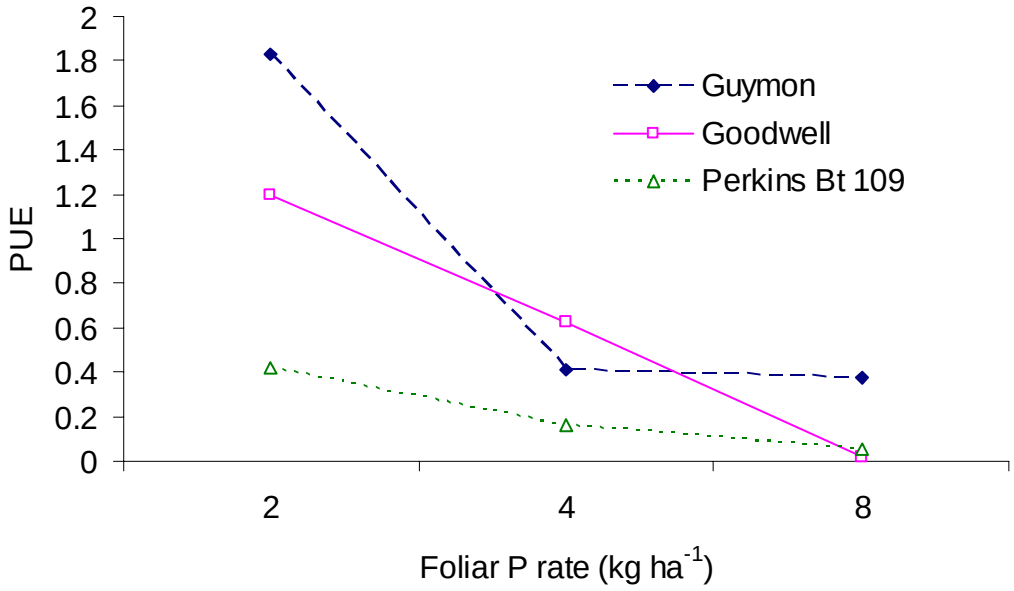


Figure 2. Phosphorus use efficiency of corn as affected by foliar P rates at Guymon and Perkins (Bt corn 109) in 2002 and Goodwell 2003.

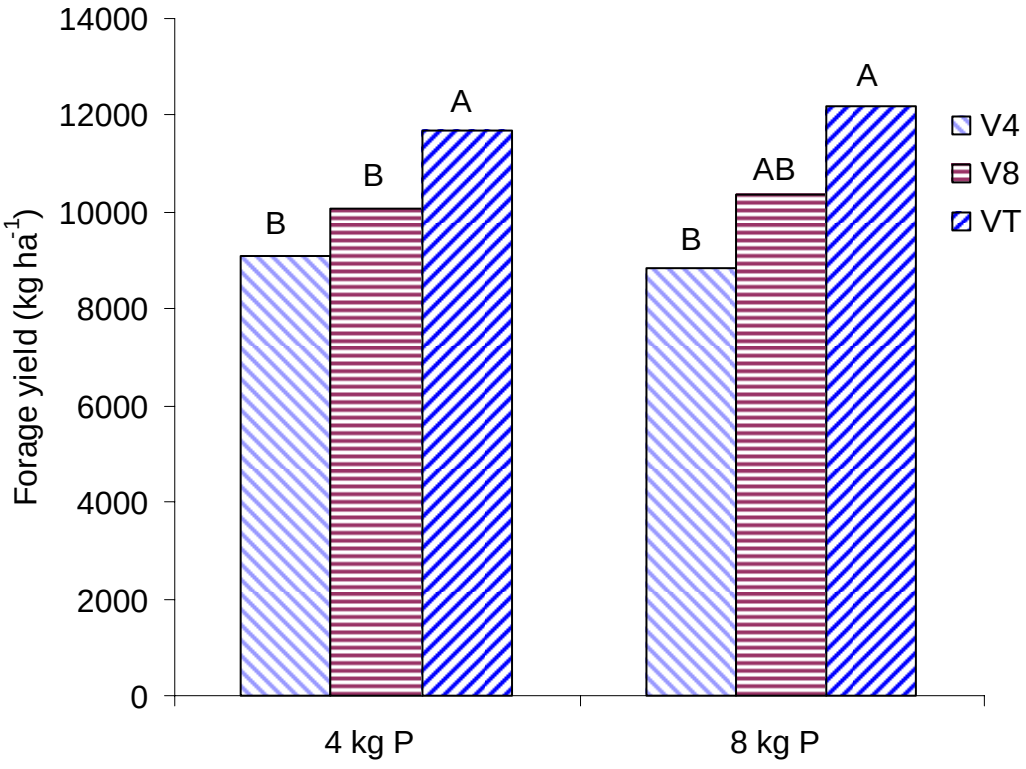

14000
12000
10000
8000
6000
4000
2000
0
Forage yield (kg ha-1)
B
B
A
B
AB
A
V4
V8
VT
4 kg P
8 kg P

Figure 3. Response of forage yield to foliar rates of 4 and 8 kg P ha^{-1} at three growth stages of corn at Goodwell in 2003. Within P rates, bars followed by common letters are not significantly different at $p<0.05$ based on least significant difference (LSD) procedure.

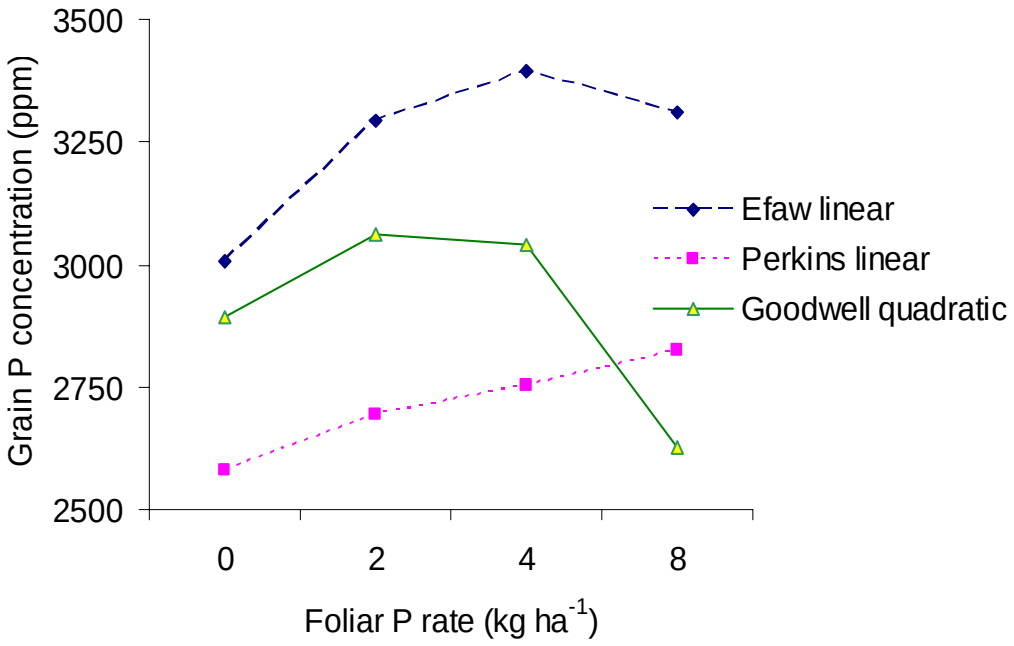


Figure 4. Response of Corn grain P concentration to foliar P rates at three locations in 2003.

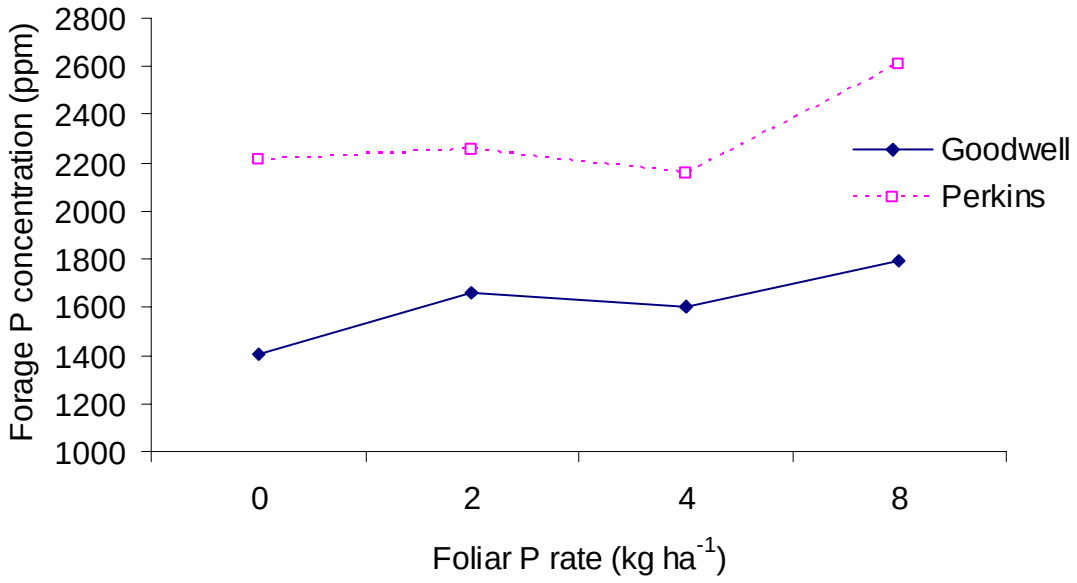


Figure 5. Response of forage P concentration to foliar P rates at Goodwell and Perkins in 2003.

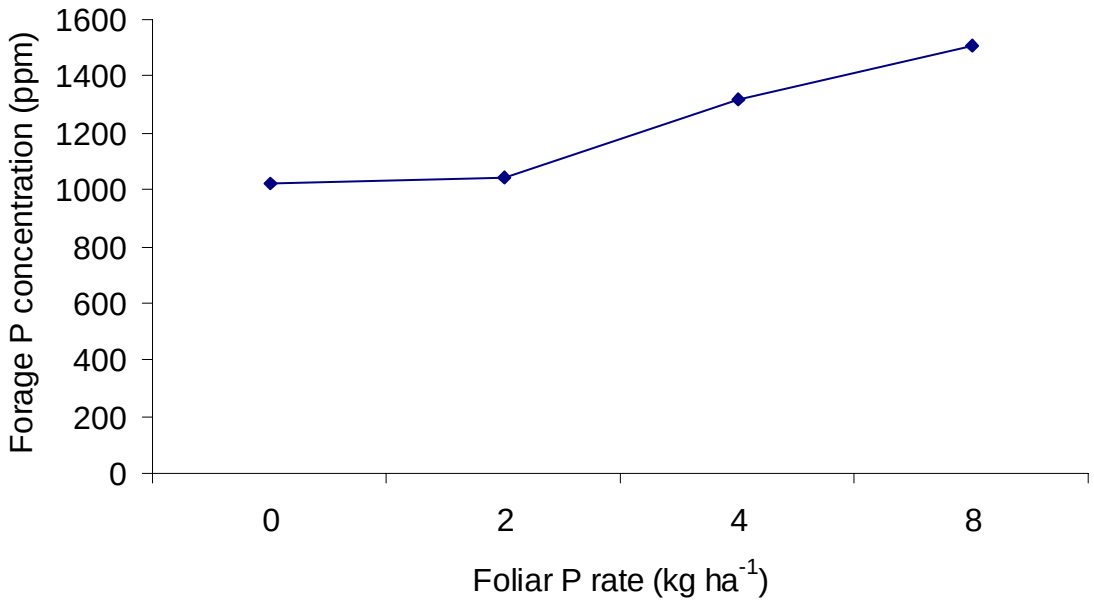


Figure 6. Phosphorus concentration in corn forage at V4 growth stage with application of rates of foliar P at 50 kg ha^{-1} basal P in greenhouse experiment I.

APPENDICES

Appendix 1.Field plot activities for the foliar P experiment in corn in 2002.

Activity	Perkins		Guymon
	Bt corn 108	Bt corn 109	
Planting date	04/29/2002	04/29/2002	05/15/2002
Hybrid	Hybrid 108	Hybrid 109	Asgrow730RR
Population (plants per hectare)	54,000	54,000	66,000
Spacing (cm)	76.2	76.2	76.2
Plot size (m^2)	27.9	27.9	27.9
Net plot (m^2)	13.94	13.94	13.94
V4 P application date	05/30/2002	05/30/2002	06/17/2002
V8 P application date	06/27/2002	06/27/2002	07/10/2008
VT P application date	07/11/2002	07/11/2002	07/22/2002
Harvesting date	09/05/2002	09/05/2002	10/23/2002

Appendix 2. Field plot activities for the foliar P experiment in corn in 2003.

Activity	Efaw	Goodwell	LCB	Perkins
Planting date	31/3/03	03/18/03	08/04/03	02/04/03
Hybrid	Hybrid 111	H9226Bt-RR	Hybrid 107	Hybrid 104
Population (plants per hectare)	54,000	54,000	54, 000	54,000
Spacing (cm)	76.2	76.2	76.2	76.2
Plot size (m^2)	18.6	18.6	18.6	18.6
Net plot (m^2)	9.3	9.3	9.3	9.3
V4 P application date	05/12/03	05/15/03	05/13/03	05/12/03
V8 P application date	05/28/03	06/10/03	05/27/03	05/28/03
VT P application date	06/16/03	06/27/03	06/16/03	06/16/03
Harvesting date	16/08/2003	28/09/2003	08/08/2003	19/08/2003

Appendix 3. Summary of test of significance of overall treatment, growth stages and basal and foliar P rates for grain yield at Efaw, Goodwell, Guymon, Lake Carl Blackwell (LCB) and Perkins in 2002 and 2003.

Source	2002			2003			
	Guymon	Perkins Bt 108	Perkins Bt 109	Efaw	Goodwell	LCB	Perkins
Treatment	NS[†]	NS	NS	NS	*	**	NS
Stage	NS	NS	NS	NS	NS	NS	NS
P rate	NS	NS	NS	NS	P<0.1	*	NS
Stage by P rate	*	NS	NS	NS	NS	NS	NS
Foliar P linear	NS	NS	NS	NS	**	NS	NS
Foliar P quadratic	NS	NS	NS	NS	NS	NS	NS
Foliar vs basal contrast	-	-	-	NS	NS	**	NS
No P vs some P contrast	-	-	-	NS	NS	**	NS
No P vs Foliar P contrast	NS	NS	NS	NS	*	*	NS

*, ** ,*** indicate significance at 0.05, 0.01 and 0.001 probability levels, respectively; [†] NS nonsignificant at p≤ 0.1.

Appendix 4.Test of significance of overall treatments, corn growth stages and basal and foliar P rates for grain P concentration at Efaw, Goodwell, Guymon, Lake Carl Blackwell (LCB) and Perkins in 2002 and 2003.

source	2002			2003			
	Guymon	Perkins Bt 108	Perkins Bt 109	Efaw	Goodwell	LCB	Perkins
Treatment	*	NS†	**	NS	NS	p<0.1	*
Stage	NS	NS	NS	NS	p<0.1	p<0.1	NS
P rate	*	NS	**	NS	**	NS	NS
Stage by P rate	NS	NS	*	NS	NS	*	P<0.1
Foliar P linear	*	NS	**	**	NS	NS	*
Foliar P quadratic	NS	NS	NS	NS	**	NS	NS
Foliar vs basal contrast	-	-	-	NS	NS	NS	NS
No P vs some P contrast	-	-	-	*	NS	NS	*
No P vs Foliar P contrast	p<0.1	NS	***	*	NS	NS	P<0.1

*, ** ,*** indicate significance at 0.05, 0.01 and 0.001 probability levels, respectively; † NS nonsignificant at p≤ 0.1.

Appendix 5. Test of significance of overall treatment, growth stage and P rates for forage P concentration in 2002 at Perkins on two Bt corn varieties.

	Bt corn 108			Bt corn 109		
	Leaf	Stalk	Reproductive	Leaf	Stalk	Reproductive
Treatment	NS[†]	NS	*	NS	NS	p<0.1
Stage	NS	NS	NS	p<0.1	NS	*
Foliar P rate (FP)	NS	NS	*	NS	NS	p<0.1
Stage X FP	P<0.1	NS	NS	p<0.1	NS	p<0.1

* indicates significance at 0.05 probability level; [†] NS nonsignificant at p≤ 0.1.

Appendix 6. Test of significance of overall treatments, stage, P rates and interactions for PUE at Efaw, Goodwell, Guymon, Lake Carl Blackwell (LCB) and Perkins in 2002 and 2003.

source	2002			2003			
	Guymon	Perkins Bt 108	Perkins Bt 109	Efaw	Goodwell	LCB	Perkins
Treatment	***	NS[†]	NS	NS	NS	NS	NS
Stage	***	NS	NS	NS	NS	NS	NS
P rate	***	NS	NS	NS	*	NS	NS
Stage by P rate	***	NS	NS	NS	NS	NS	NS
Foliar P linear	***	NS	*	NS	*	NS	NS
Foliar P quadratic	**	NS	NS	NS	NS	NS	NS
Foliar vs basal contrast	-	-	-	NS	NS	*	NS

*, ** ,*** indicate significance at 0.05, 0.01 and 0.001 probability levels, respectively; [†] NS nonsignificant at $p \leq 0.1$.

Appendix 7. Test of significance of overall treatments, growth stages, foliar P rates and interactions for forage yield at different locations in 2003.

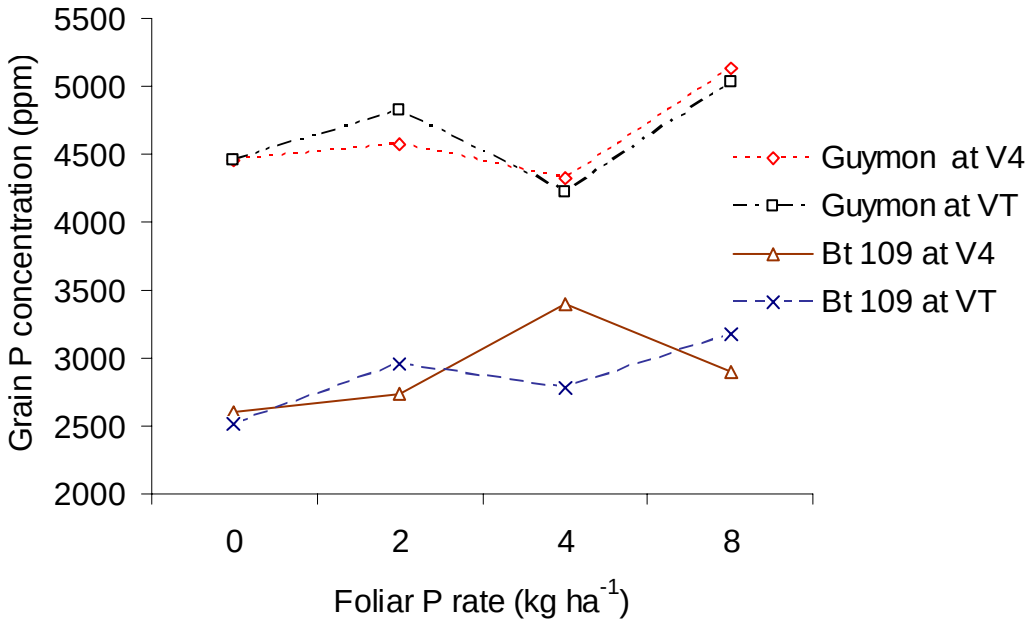
Source	Efaw	Goodwell	Lake Carl Blackwell	Perkins
Treatment	NS[†]	***	NS	NS
Stage	NS	***	NS	NS
P rate	NS	NS	NS	NS
Stage by P rate	NS	***	NS	NS
P rate linear	NS	**	NS	NS
P rate quadratic	NS	NS	NS	NS
Foliar vs basal contrast	NS	NS	***	NS
No P vs some P contrast	**	NS	**	NS
No P vs Foliar P	NS	NS	**	NS

*, ** ,*** indicate significance at 0.05, 0.01 and 0.001 probability levels, respectively; [†] NS nonsignificant at $p \leq 0.1$.

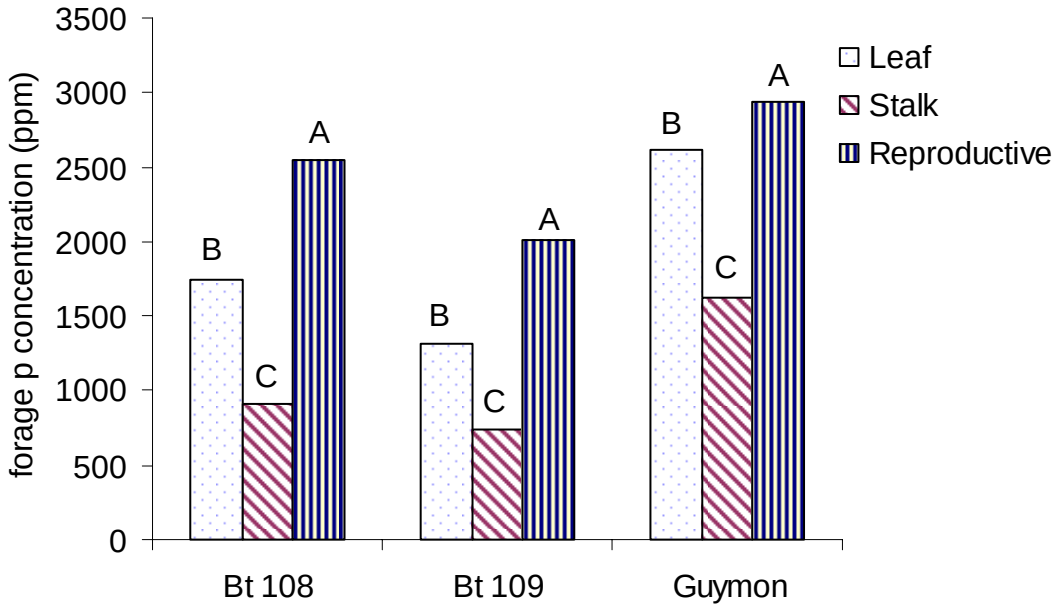
Appendix 8. Test of significance of overall treatment, growth stage, P rates and interactions for forage P concentration in 2003.

Source	Efaw	Goodwell	LCB	Perkins
Treatment	*	**	NS†	NS
Stage	*	***	NS	NS
P rate	NS	*	NS	P<0.1
Stage by P rate	P<0.1	P<0.1	P<0.1	NS
Foliar P linear	NS	*	NS	*
Foliar P quadratic	NS	NS	NS	NS
Foliar vs basal contrast	NS	NS	NS	NS
No P vs some P contrast	NS	**	NS	NS
No P vs Foliar P contrast	NS	***	NS	NS

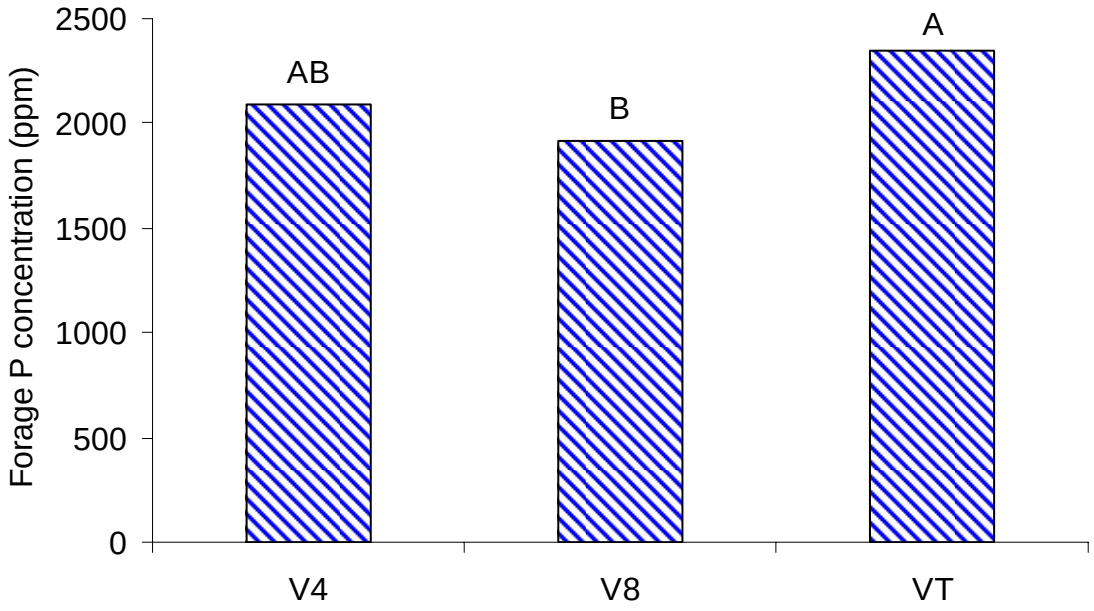
*, ** ,*** indicate significance at 0.05, 0.01 and 0.001 probability levels, respectively; † NS nonsignificant at p≤ 0.1.



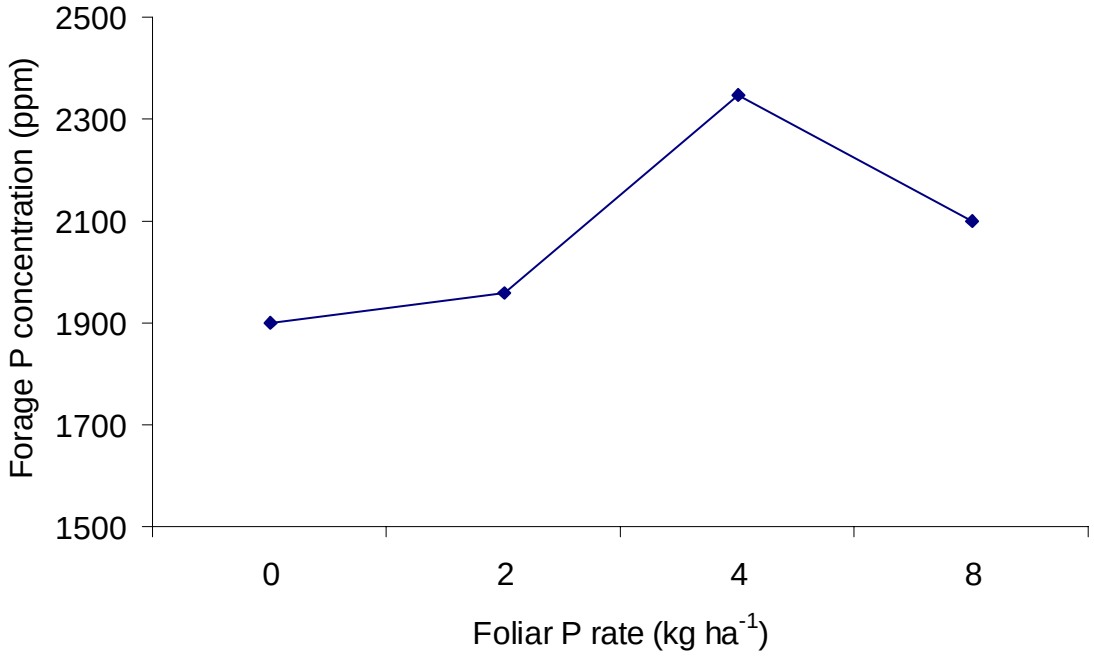
Appendix 9. Grain P concentration as affected by foliar P rates at two growth stages of corn in 2002.



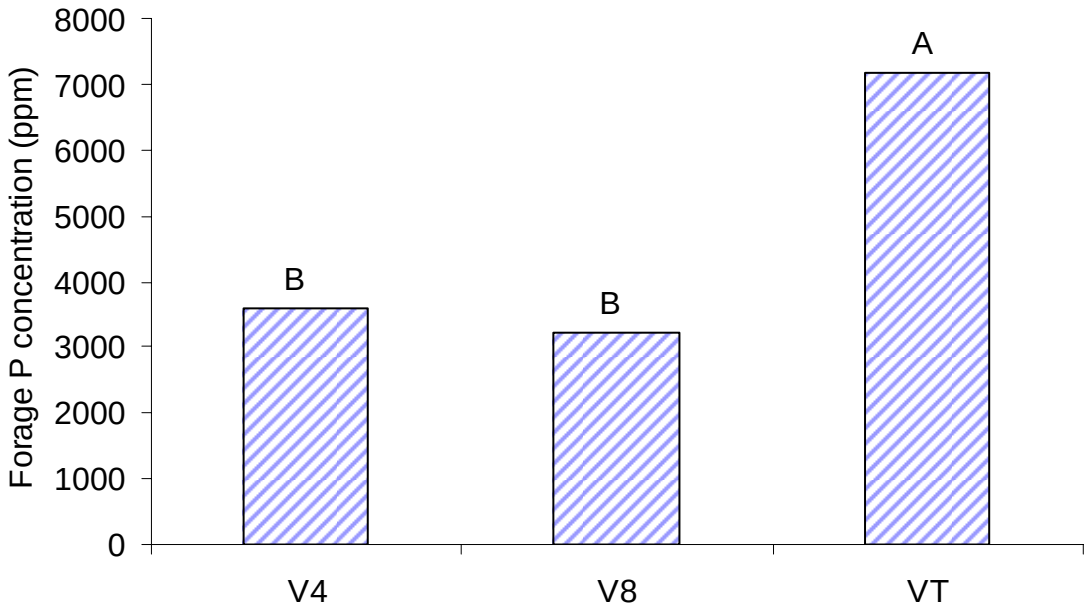
Appendix 10. Forage P concentration in different parts of hybrid Bt corn 108 and 109 at Perkins in 2002 and Asgrow730RR hybrid at Guymon. Means for all the three parts are significantly different at $P<0.05$ based on least significant difference (LSD) procedure.



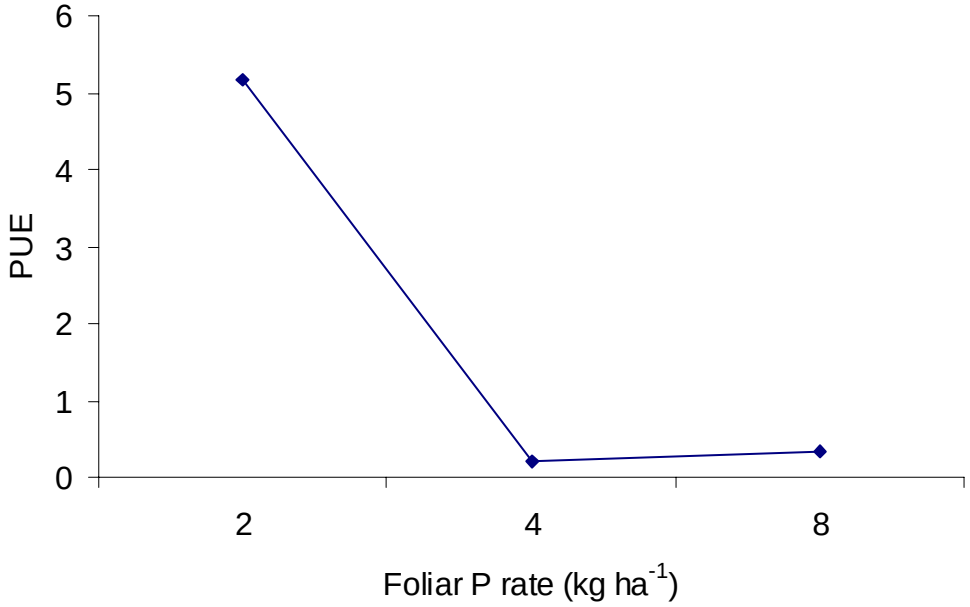
Appendix 11. Forage P concentration at V4, V8 and VT corn growth stages with the application of 4 kg ha^{-1} foliar P at Perkins for varieties Bt corn 109 in 2002. Bars followed by common letter are not significantly different at $P<0.05$ based on least significant difference (LSD) procedure.



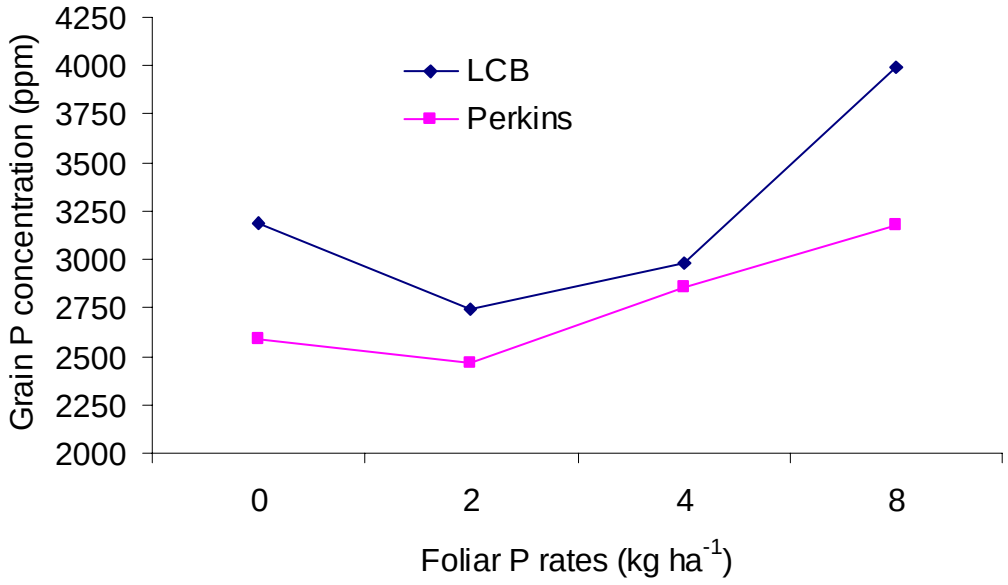
Appendix 12. Effect of foliar P rates on forage P concentration of reproductive parts at VT corn growth stage.



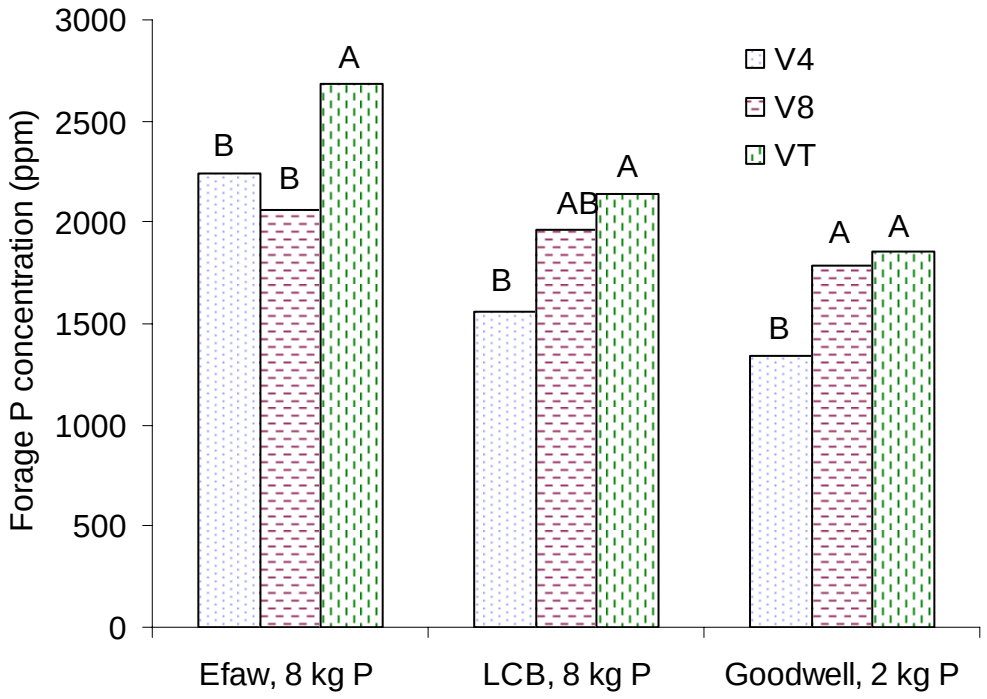
Appendix 13. Forage P concentration at Guymon in 2002 at the three corn growth stages. Forage P concentration was determined from vegetative parts for growth stages V4 and V8 while it was obtained by summation of the P concentration in leaf , stalk and reproductive parts in the case of VT growth stage. Bars followed by common letter are not significantly different at $p<0.05$ based on least significant difference (LSD) procedure.



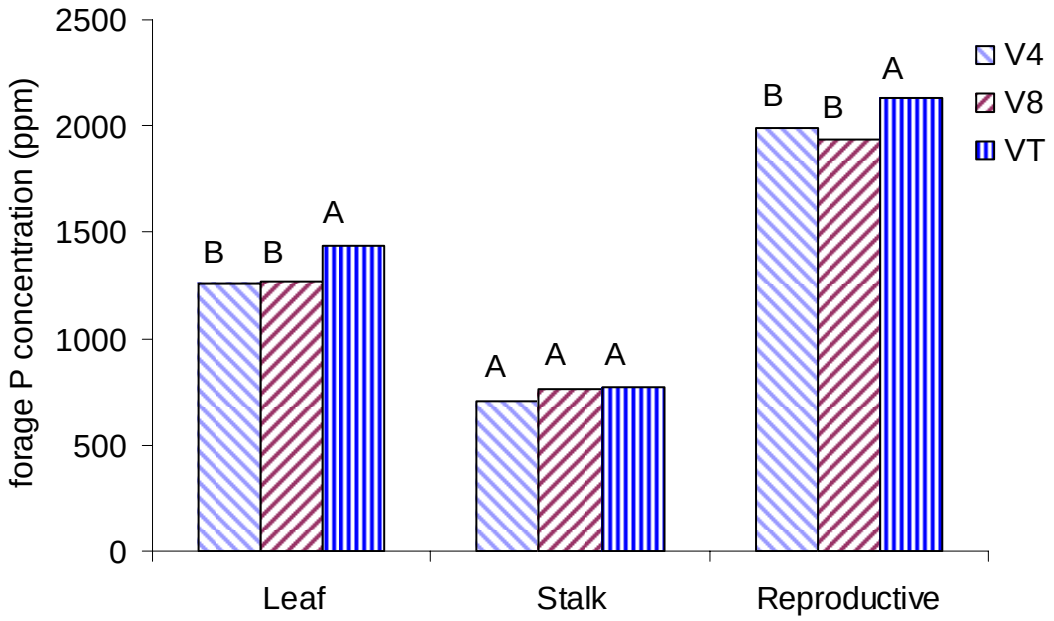
Appendix 14. Phosphorus use efficiency (PUE) at V8 growth stage of foliar P rates at Guymon in 2002.



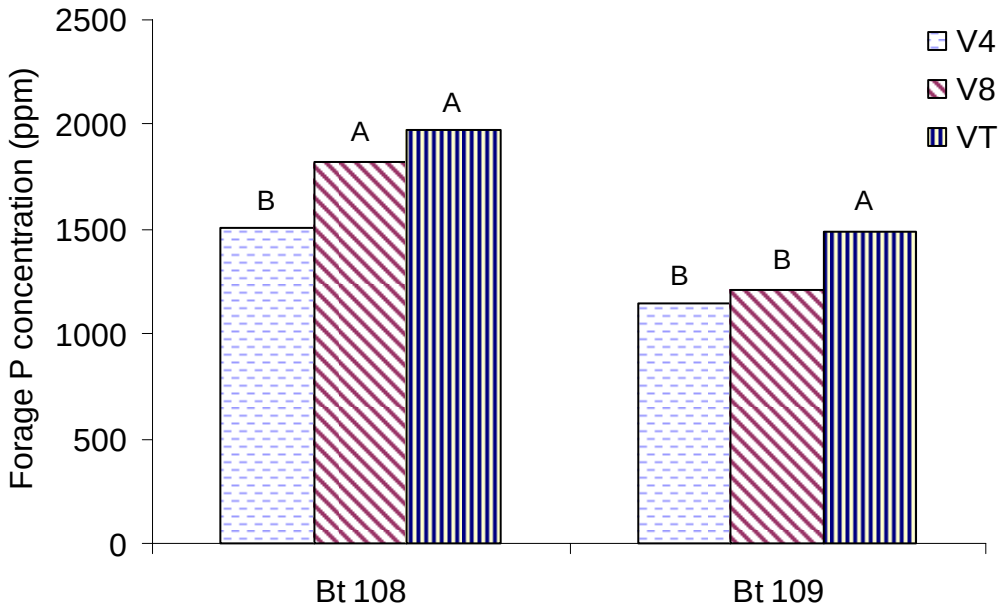
Appendix 15. Grain P concentration of plots treated with foliar P rates of 2, 4 and 8 kg ha^{-1} at VT growth stage of corn at Lake Carl Blackwell (LCB) and Perkins in 2003.



Appendix 16. Forage P concentration as affected by interaction of foliar P rates (kg ha^{-1}) and growth stage at Efaw, Lake Carl Blackwell (LCB) and Goodwell in 2003. within location, bars followed by common letter are not significantly different at $p<0.05$ using least significant difference (LSD) procedure.



Appendix 17. Forage P concentration of different corn plant parts evaluated at three growth stages. Means followed by the same letter for plant part are not significantly different at $p<0.05$ based on least significant difference (LSD) procedure.



Appendix 18. Forage P concentration in leaf for foliar P applied at different growth stages of corn at Perkins for hybrid Bt corn 108 and 109. Bars followed by the same letter are not significantly different at P<0.05 based on least significant difference (LSD) procedure.

VITA

Kefyalew Girma Desta

Candidate for the Degree of

Doctor of Philosophy

Thesis: I. IDENTIFICATION OF OPTICAL SPECTRAL SIGNATURES FOR DETECTING CHEAT AND RYEGRASS IN WINTER WHEAT
II. DETERMINATION OF OPTIMUM RATE AND GROWTH STAGE OF FOLIAR APPLIED PHOSPHORUS IN CORN

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Name: Desta, Kefyalew G. Date of Degree: July, 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: IDENTIFICATION OF OPTICAL SPECTRAL SIGNATURES FOR DETECTING CHEAT AND RYEGRASS IN WINTER WHEAT, AND DETERMINATION OF OPTIMUM RATE AND GROWTH STAGE OF FOLIAR APPLIED PHOSPHORUS IN CORN

Pages in Study: 93 Candidate for the Degree of Doctor of Philosophy

Major Field: Soil Science

Abstract:

Site specific weed management requires the identification of crop and weed species in a mixture. Reflectance spectra were used for the detection of cheat and ryegrass in winter wheat under greenhouse conditions. The three plant species and two nitrogen levels were arranged in a completely randomized design with three replications. Spectral readings were taken at Feekes 3 and 5 wheat growth stages using SD2000 spectrometer. Data were analyzed using a discriminant analysis procedure. The discriminant function with the band combinations 515/675, 555/675 and 805/815 resulted in the best overall correct classification (94%) of observations at Feekes 3 while for spectral data at Feekes 5 the discriminant function with the band combinations 755 and 855/675 resulted in 66.7% overall correct classification of observations. In several instances, ryegrass was classified as either cheat or wheat while cheat was classified as rye. Cheat was not classified as wheat in most of the instances. This suggests that it is possible to identify cheat in wheat using wavelength ratios developed from spectral readings in 10 nm bands between 500 and 860 nm.

Foliar applications of fertilizer phosphorus (P) could improve use efficiency by minimizing soil applications. Nine experiments were conducted at Efaw, Goodwell, Guymon, Lake Carl Blackwell, Perkins and Stillwater, OK in 2002 and 2003 to determine foliar phosphorus rates and appropriate application growth stages. Treatments comprised of ten factorial treatments combinations of three foliar P application timings and four rates of foliar P. Foliar application times were V4, V8 and VT corn growth stages. Foliar P rates were 0, 2, 4 and 8 kg P ha^{-1}. Foliar P applied at VT growth stage improved grain and forage P concentration which was reflected in increased grain yield in some of the experiments. Foliar P rate of 8 kg ha^{-1} improved to some extent yields and largely forage and grain P concentration of corn more than the smaller rates although phosphorus use efficiency was high only with low foliar P rates. The results suggest that foliar P could be used as efficient P management tool in corn when applied at the appropriate growth stage and rate.

ADVISER'S APPROVAL: ___Dr. William R. Raun_____