DETERMINATION OF PLANT PHOSPHORUS NUTRITIONAL STATUS USING SPECTRAL RESPONSE

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Bachelor of Science

Oklahoma Baptist University

Shawnee, Oklahoma

1997

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1999

DETERMINATION OF PLANT PHOSPHORUS

NUTRITIONAL STATUS USING

SPECTRAL RESPONSE

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ACKNOWLEDGMENTS

I wish to express my gratitude to Oklahoma State University and the Department of Plant and Soil Sciences for allowing me the opportunity to pursue this degree. I would like to extend my sincere appreciation to my advisor, Dr. William Raun, for his wisdom, guidance, and friendship. I would also like to acknowledge my other committee members, Dr. Gordon Johnson, Dr. Mark Rockley, and Dr. Marvin Stone. Also, I would like to express my sincere appreciation to all the individuals involved in the Soil Fertility Project; especially Drew Conkling, Amy Conkling, Doug Cossey, Jeremy Dennis, Darin Drury, LorreLyn Fox, Tina Johnston, Olga Kachurina, Joanne LaRuffa, Heather Lees, Cory Lively, Erna Lukina, Jerry Moore, Billy Mullen, Shawn Norton, Darin Paxton, Steve Phillips, Celine Popoff, Hasile Sembiring, Wade Thomason, Jennifer Tommy, Curt Woolfolk, and Kathie Wynn.

I would like to thank my parents and sister that have prayed for me and encouraged me to always do better, and to Jennifer Glaze that has prayed with me and stood by me. Finally to my Lord, Jesus Christ for allowing me the opportunity to pursue this degree so that I can use it to glorify His name in all the earth through service to others.

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NOMENCLATURE

UV	Ultraviolet
P	Phosphorus
PSI	Photosystem I
PSII	Photosystem II
Pi	Inorganic phosphorus
N	Nitrogen
ATP	Adenosine tri-phosphate
ADP	Adenosine di-phosphate
K	Potassium
NIR	Near infrared reflectance
NDVI	Normalized difference vegetative index

DETERMINATION OF PHOSPHORUS NUTRITIONAL STATUS USING SPECTRAL RESPONCE

ABSTRACT

Sensor – based methods of determining the phosphorus (P) status of plants have not been developed. The objective of this research was to determine the feasibility of measuring in-situ P levels in winter wheat (*Triticum aestivum L.*) using spectral data. Spectral irradiance measurements were taken and investigated from wheat that was grown with different nitrogen (N) and P rates on a soil low in soil test P. Total P in wheat plant tissue and forage P uptake were correlated with various wavelengths but not always consistent across growth stages or years. However, there was some consistency for correlation between P tissue concentration and spectral irradiance from wavelengths 705 – 725 (numerators) to 505 – 515 (denominators). Grain yield was correlated with spectral irradiance readings near 755 nm using the UV light at night for both years from Feekes growth stages 4 through 7. Improvements in data collection and data processing need to be addressed for further research.

INTRODUCTION

Light is absorbed by plants and turned into chemical energy. The initial process occurs in the chloroplast through photosystem I (PS I) and photosystem II (PS II). Phosphorus is an essential part of the transformation of this energy in the plant. This study focused on finding an indirect method to determine the P

nutritional status of winter wheat (*Triticum aestivum* L.). It would be ideal if P deficiencies could be detected before levels were low enough to produce externally visible symptoms, such as purple coloration on the older leaves, fewer tillers, and dark green young leaves (Bollons and Barraclough, 1997).

Increased yields could possibly be achieved if the P nutrient needs were treated early on in the growing season. Miller et al. (1994) reported that P uptake peaked near the stage of flag leaf emergence, which is late in the season, thus showing that P deficiency might be corrected if detected early on. However, it should be noted that some work has shown that P application at anathesis can increase yield (Sherchand and Paulsen, 1985). Alternatively the majority of all fertility work has shown that P must be applied early in the season in order to impact grain yields (Smith, 1969). A sensor application system could be developed to determine P level and immediately apply the needed amount of fertilizer for optimum yields. This may also reduce the adverse impact on the environment from high P sediment runoff into streams and lakes.

LITERATURE REVIEW

P uptake method

Phosphorus is taken up by plants as an anion, $H_2PO_4^-$ or HPO_4^{2-}, at the plasma membrane of the root cell via a proton-anion co-transport (Dunlop, 1989). Another probable way for P uptake is with an OH^-/phosphate counter transport as reported by Liu (1979). For the plant to be able to assimilate P by either of these methods its roots need to be close enough for these chemical

reactions to take place. Fohse and Jungk (1983) noted that root hairs were abundant in soil that was low in available P, while no hairs were observed when P was readily available. In low available P soils, root exudates like citrate and phenolics, allow the bound-up inorganic P to come into solution by binding with the cation half (Parfitt, 1979; Gerke 1992). In soils where P is abundant but most of it is tightly bound, the plant will show yield reductions due to low P availability. Thus total soil P is not a good indicator of P availability for the plant. In this regard numerous of different extracting solutions have been evaluated, in an attempt to simulate plant available P.

Methods of soil and tissue P analysis

Total soil P analysis is an unreliable indicator of plant available P since most of the P is tightly bound thus making it unavailable for plant uptake. For organic P extraction, acids, bases or both are added to the soil so the orthophosphates can be determined from the extract before and after the oxidation of organic matter (Page et al. 1990). Other methods of extracting P from the soil that resemble the P available to the plants include Bray and Kurtz (1945), Mehlich III (1984), Olsen et al. (1954), and Nelson et al. (1953). These methods are time consuming, require lab analysis and correlation for different types of soils.

Shchurina (1990) reported that x-ray fluorescence could be used for P determination in soil and plant tissue. Their procedure required about one minute per sample giving an error of 3.4% for plant matter; however, if not sufficiently ground the error can rise to 80%. Valdes and Leeson (1989), and

Ruiz and Córdoba (1991) reported using x-ray fluorescence spectroscopy to analyze P concentration in poultry feeds and flours respectively. Treeby et al. (1987) used electron probe x-ray microanalysis to estimate the P concentration in *Lupinus luteus*, but this method required extensive sample preparation. Therefore the present methods for extracting and determining P levels in soil require that the soil be taken from the field and sent to a lab which involves time and introduces errors due to sampling techniques and soil P variability as found by Raun et al. (1998). Total P analysis in forage is subject to analytical error, but is an accurate measure of the P availability in the area from which it was taken. In extreme deficiencies plants can show characteristic vegetative symptoms.

Low P effect on wheat

Yield is reduced when there is low P availability in the soil; total leaf P is reduced when there is low P availability in the soil and thus total P in the leaf is positively correlated with yield (Hargrove et al. 1984). Purpling of the edge of the older leaves is associated with P deficiency along with retarded growth. Inside the leaf the effect of low P on wheat (*Triticum aestivum* L.) has been shown by Jacob and Lawlor (1991) to severely hinder the mesophyll capacity for photosynthesis. They ruled out the possibility of lower CO_2 assimilation being caused by lower stomatal conductance. They did find smaller cells overall, but there were more cells per leaf. They also found that the total protein content was negatively affected, while the chlorophyll content in wheat was not. Rao et al. (1986) reported more light scattering and a change in fluorescence due to the

incapability of the Calvin cycle to transform the light energy into chemical energy of the sugar beet leaf (*Beta vulgaris* L. cv. F58-554H1). Robinson and Walker (1981) found that the low P availability in the chloroplast hindered photosynthesis by inhibiting 3-PGA (3-phosphoglycerate) production and sugar phosphates while excessive inorganic phosphorus (Pi) availability can hinder photosynthesis by increasing the export of trios phosphates (glyceraldehyde-3-phosphate and dihydroxyacetone phosphate). Lower concentration of Pi in the leaves reduced the rate of photosynthesis, and resulted in a lower sucrose to starch ratio (Foyer and Spencer, 1986). They concluded that P concentration in the leaf is not a good indicator for P deficiency since the vacuole can act as a buffer for the cytoplasmic P concentration.

Fluorescence

Lauer et. al. (1989) reported that low P nutrition stimulated greater chlorophyll fluorescence in soybeans (*Glycine max*. L.) and reduced crop yields. They proposed that Pi stress would have more effect on the Calvin cycle products than the phosphorylation of the enzymes. Phosphorus deficiency lowered the concentration of ATP and ADP in the leaves of both *Zea mays* L. and *Helianthus annuus* L.. Phosphorus deficiencies were correlated with a change in chlorophyll-a fluorescence, indicating that a low Pi concentration lowered the efficiency of excitation capture by open PSII reaction centers (Jacob and Lawlor, 1993). Alternatively, Abadia et. al. (1987), indicated that decreased P status increased PSI chlorophyll-protein complexes compared to PSII, and that there was little affect on chlorophyll fluorescence of sugar beet leaves (*Beta*

vulgaris L. cv. F58-554H1). A saturating light on barley (*Hordeum vulgare* L.) and spinach (*Spinacia oleracea* L.) leaves caused chlorophyll fluorescence quenching when carbon assimilation was limited. This provides evidence that there is surplus electron transport capacity which is not being used (Stitt and Schreiber 1988). Similar work by Sivak and Walker (1986) indicated that some of the excitation energy that is not converted is dissipated as red fluorescence, and the lower concentration of orthophosphate in the chloroplast can limit photosynthesis in spinach leaves. Sun et. al. (1989) reported that N, P, and K nutrient deficiencies in hard red spring wheat (*Triticum aestivum* L.) did cause a decline in chlorophyll fluorescence but concluded that diagnosing individual nutrient deficiencies would not be feasible since they had similar effects.

Spectrometer and Sensing

Gamon et. al. (1990) used a spectroradiometer suspended 4 m above the canopy of a sunflower field, to pick up signals and shifts that reflected the chlorophyll fluorescence quenching and de-epoxidation of violaxanthin to zeaxanthin, respectively. They found that they could detect the reflectance change in the green, red, and near-infrared regions of the spectra due to quenching. Recently, Stone et al. (1996) found that spectral readings in the red and NIR regions of the spectra were highly correlated with in-season forage N uptake and that this information could be used to adjust for topdress N needs.

OBJECTIVE

The objective of this research is to determine the feasibility of measuring in-situ P levels in winter wheat using daytime spectral data and fluorescence spectral data from night readings produced using an UV illumination source.

MATERIALS AND METHODS

Pot Studies

Pot and field studies were conducted to evaluate the use of spectral irradiance measurements (with and without a UV lamp) for detecting plant P deficiencies in winter wheat at early stages of growth. The soil for both pot and field studies was a Teller sandy loam; fine-loamy, mixed, thermic Udic Argiustoll that was known to be low in soil test P. Each pot contained 5 kg of this soil. Complete soil test data for both the pot and field studies are reported in Table 1. Planting, harvest, spectral reading dates and growth stages evaluated are reported in Table 2.

The 1997 pot experiment employed a completely randomized experimental design with three replications and that included a factorial arrangement of treatments. Rates of Nitrogen (N) and P included 0, 56, 112, and 168 kg N ha^{-1} and 0, 7.3, 14.7, and 22.0 kg P ha^{-1}. Nitrogen and P were applied as ammonium nitrate, 33% N, and triple super phosphate, 22% P, solutions 5 days after the wheat had sprouted since it was not pre-plant incorporated. More seeds were planted during the second week of the experiment to ensure that there would be enough leaf density for spectral

readings. The second pot study, conducted in 1999, evaluated only two N levels, 0 and 112 kg N ha^{-1} and seven P rates, 0, 9.8, 19.6, 29.3, 39.1, 48.9, and 58.7 kg P ha^{-1}. P was applied in a KH_2PO_4 solution, and KCL was applied of adjust for the K differences caused by the P treatments. All fertilizing was done previous to planting.

All pots were placed in controlled environment growing chambers, with temperature settings at 30°C day and 25°C night. Sixteen hours of light was provided by 30 fluorescent tubes and 45 incandescent bulbs, giving a klux of 77.5 (960 micromoles/m^2/s). The pots were watered so that they were maintained at field capacity. The pots were weighed every two weeks and water was added to bring them up to field capacity. On a daily basis, 200 to 400 ml of water was added to ensure no moisture stress between the weighing times. Plates were put under the pots so that if there was water percolation, it could be re-circulated into the pot. Following spectral readings, plants were harvested, weighed and then dried at 75°C for at least one week following which they were weighed again. Forage was ground to pass a 1 mm screen on a Udy Cyclone Sample Mill for further processing. Total N in wheat forage was determined using a Carlo Erba NA 1500 dry combustion analyzer (Schepers, 1989). Total forage P was determined using a HNO_3 - $HClO_4$ digest on 0.5 g of ground plant tissue (Barton, 1942 and Bolim and Stamberg, 1944). Concentration was subsequently determined on the digest, with an Inductive Coupled Plasma (ICP) spectrometer.

Field Trials

A field study was conducted at Perkins OSU Agronomy Field Station (Teller sandy loam; fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma. Initial surface soil test levels are reported in Table 1. Planting, harvest, and growth stages at the time spectral readings were taken are reported in Table 2. The experimental design was a randomized complete block with three replications using individual plots measuring 3.1 m x 9.1 m. A factorial arrangement of treatments for N and P rates (0, 56, 112, and 168 kg N ha^{-1} with 0, 14.7, and 29.3 kg P ha^{-1}) was evaluated. Nitrogen and P rates were surface applied and incorporated prior to planting. Spectral irradiance readings were collected from an area of (0.91 x 0.91m) in 1998, and (0.61 x 0.61) in 1999 from within each plot. Once all spectral irradiance readings were collected, wheat forage was clipped at ground level from the specified area, weighed and dried in a forced air oven. Following drying, wheat forage was ground to pass a 106 μm (No. 140 sieve) screen and analyzed for N and P.

Spectrometer Readings

Spectral readings and forage yields were collected at Feekes growth stages 5 (leaf structure strongly erect) from the pot studies. The field studies also included readings from Feekes growth stages, 7 (second node visible), and 10.5 (post flowering), see figure 1, (Large, 1954). A wide range of spectral irradiance measurements were obtained from the first pot study in 1997 using a PSD-1000 portable dual spectrometer manufactured by Ocean Optics Inc.. The spectrometer had two overlapping bandwidths, 300-850nm and 650-1100nm.

The PSD 1000 was connected to a portable computer through a Personal Computer Memory Card International Association (PCMCIA) slot using a PCMDAS 16D/12 A/D converter manufactured by Computer Boards Inc.. The fiber optic spectrometer has a spectral resolution as low as 1nm +/- 6nm. From the pot studies, the hemispherical lucite™ lens, was extended approx. 0.5m above the rim of the pot, see figure 2.

The readings for field studies and the second pot studies were taken with a S2000 portable spectrometer manufactured by Ocean Optics Inc., that had a spectral range of 328 to 1040 nm. The connection to the computer was provided by a PCMCIA slot using a data acquisition card (analog to digital DAQCard-700 A/D) manufactured by National Instruments. This fiber optic spectrometer has a 400 um diameter fiber entrance slit and a grating of 600 lines blazed at 500 nm with a coated array, and a 50 nm slit, and that gives a spectral resolution as low as 1 nm. A UV lamp manufactured by Tracerline TP-1200P that emits primarily at 365 nm wavelength signal was used. The spectrometer readings were calibrated by taking a dark reading as a reference. The UV light was placed at a 90° angle to the wheat pots and the lens of the spectrometer was aimed at approx. 45° relative to the wheat pots. Wheat pots were placed in a holder that ensured all the pots were read from the same angle, see figure 2. White lights were turned off during the readings, allowing the UV lamp to be the only source of light. Four readings from each pot were taken, turning the pots 90° each time. In the field studies, readings were recorded using a tripod mounting so that height variation would be negligible across the different plots, see figure 3.

Individual wavelengths and combinations of wavelengths were used to predict biological responses, including the Normalized Difference Vegetation Index (NDVI). Various combinations of these wavelengths were evaluated to determine the proper indices for predicting wet biomass, dry biomass, total N uptake, total N concentration, total P uptake, and total P concentration in winter wheat forage, (Table 3).

At each stage of growth the readings were taken from the exact area used for the forage clipping. Three readings were collected; 1) during the day; 2) dark readings at night using a UV source 30 minutes after the sun had set to ensure dark adaptation, 3) the following day using an enclosed box (shielding outside light) whereby the plant was not dark adapted (1998); 4) and with a grow light at night (1999). Statistical analyses were performed using SAS (SAS institute, 1990).

RESULTS

Field Study:

For both 1997-98 and 1998-99 crop years, applied P significantly increased grain yields and grain P concentration (Tables 4 and 5). Similarly, N applications increased grain yields and grain N concentration levels for both crop years (Tables 4 and 5).

For the 1997-98 crop year, applied P increased forage yields at Feekes growth stages 5 and 7 but did not effect forage yields at Feekes growth stage 10.5 (Tables 6, 7,and 8). With only one exception (Feekes 5), applied P did not

alter tissue P concentration (Tables 6, 7, and 8). It is important to note that the one exception was at an early stage of growth where increased P uptake was also detected (Table 6). Although no differences in forage yield were detected at the two late forage sampling dates (7 and 10.5) the tissue P deficiencies that were reflected in 1st forage harvest at Feekes 5 also impacted final grain yields. Early P nutrition was therefore important for early forage harvest and final grain yields but which did not alter mid-season forage production to such a large extent. Applied N resulted in increased forage yields and forage N concentration at Feekes 5, but had relatively less effect at the later stages of growth (Tables 6, 7, and 8).

In 1998-99, applied P had no effect on the forage yields at the early stages of growth (Feekes 4, Table 9) but significantly increased forage yields at all late stages of growth (Tables 10 – 12). Applied P resulted in increased forage P concentration and forage P uptake at all stages of growth (Tables 9 – 12) in 1999.

Applied N resulted in increased forage yields, forage N concentration and forage N uptake at all stages of growth (Tables 9 – 12). No N*P interaction was detected at any growth stage for either P concentration or for P uptake (Tables 6 – 12).

Feekes 5 Perkins 1997-98

In general, higher correlation was found for forage P uptake and grain yield with individual wavelength data collected during the day versus night at Feekes growth stage 5 for 1997-98 (Table 13).

Limited significance was found for spectral irradiance readings collected at any wavelength or using alternative indices when evaluating simple correlation coefficients with P tissue concentration. With or without the UV light (day), forage P uptake was significantly correlated with spectral irradiance in the 424 to 445 nm region. It was equally important to find that even at these early stages of growth, daytime spectral irradiance readings from the 382 to 393 nm region ended up being highly correlated with final grain yield (Table 13).

Feekes 7 Perkins 1997-98

Limited significance was found for single wavelength spectral readings correlated with P tissue concentration. Forage P uptake was slightly correlated with some indices but no single wavelength was significant. Grain yield was highly correlated with several single wavelengths and with several indices when spectral irradiance was recorded during the day, but not at all the same wavelengths as was reported for Feekes 5 (Table 14).

Feekes 10.5 Perkins 1997-98

No single wavelength was significantly correlated with P tissue concentration and only limited significance was noted for the indices reported. Forage P uptake was highly correlated using night readings for both single wavelengths and indices. Spectral irradiance reading from the 730 to 765 nm region during the night and 393 to 403 nm region during the day were significantly correlated with grain yield. Indices with a 705 nm numerator and a 526 to 546 nm denominator were also highly correlated for daytime readings (Table 15).

Feekes 4 Perkins 1998-99

For P tissue concentration, daytime readings were limited in significance in the 725 and 729 nm spectral region. Spectral irradiance from 413 to 434 nm was significantly correlated with forage P uptake using daytime readings. Individual wavelength data showed limited correlation with grain yield in the spectral region of 711 to 758 nm (Table 16).

Feekes 5 Perkins 1998-99

Phosphorus tissue concentration was correlated with several indices compiled from dark readings. The spectral region of 459 to 469 nm for single wavelengths and several indices were significantly correlated with forage P uptake during daytime readings. The spectral region of 744 to 753 nm showed slight correlation for both forage P uptake and grain yield during the night readings (Table 17).

Feekes 8 Perkins 1998-99

Phosphorus tissue concentration was correlated with spectral irradiance in the 530 to 540 nm spectral region for daytime readings. Forage P uptake was significantly correlated with spectral irradiance readings in the 398 to 418 nm region for daytime readings, the 744 to 753 nm region using the UV night readings and several indices. The spectral irradiance readings in the 739 to 758 nm region, using the UV night readings, and at this stage of growth, were significantly correlated with grain yield (Table18).

Feekes 11.1 Perkins 1998-99

In general spectral irradiance from nighttime readings were more highly correlated with the dependant variables analyzed using single wavelengths while the daytime readings had higher significant correlation using the computed indices.

Spectral irradiance readings in the 413 to 449 nm region were positively correlated with P concentration for daytime readings (Table 19). Forage P uptake was highly correlated with spectral irradiance readings in the 744 to 753 nm region for nighttime readings. Daytime readings in the 398 to 408 nm region and growlight readings in the 525 to 540 nm region were also highly correlated with forage P uptake. Grain yield was significantly correlated with spectral irradiance readings in the 744 to 758 nm range when collected at night using UV light (Table 19).

DISCUSSION

Some thought should be given as to why we are developing indirect measures for plant nutrient status. Detecting P deficiencies in-season will unlikely lead to an in-season treatment, largely because others have shown limited yield response from in-season applied P in either foliar or granular form. However, some work has shown that foliar applied P at anathesis can be beneficial (Sherchand and Paulsen, 1985). Paulsen (1985) stated that foliar applied P is typically used in China to protect the plant against hot, dry winds that cause desiccation, which in turn causes lower yields. Barber (1977) showed

that uptake of P by roots decreases as much as 100 fold per meter between 20 and 80 days, so as the plant ages there is less of a possibility to utilize applied P fertilizer. Even though in-season response to applied P is unlikely, it would be important to identify lowered yield potential due to P deficiency. This is largely because in-season N-fertilization based on a lowered yield potential has been shown to be beneficial when individual $1m^2$ areas were sensed and treated independently (OSU VRT project 1999). Thus by detecting lower yield potential areas due to P deficiency, in-season N application to this area would be corrected. This information could be used to create a field map of the P deficient areas and then integrating this with a global positioning system (GPS); P fertilizer could be applied to those areas, which had been P deficient the previous year. In this regard any index capable of identifying altered or lowered yield potential could be extremely useful as it relates to in-season treatment of wheat.

Phosphorus deficiencies are generally visible early in the life cycle of cereal crops; therefore, sensing techniques should target early stages of growth. In addition treatment of P stress early on, may result in increased yields, and that are unlikely from late-season applied P.

CONCLUSIONS

Many individual wavelengths and indices were correlated with P tissue concentration, some consistency was found at early growth stages though not always consistent over the different growth stages or years. However, there was

some consistency to find correlation between P tissue concentration and spectral irradiance from wavelengths 705 – 725 (numerator) to 505 – 515 (denominator). Some consistency was found between forage P uptake and wavelengths around the 430nm region. Grain yield was correlated with spectral irradiance readings near 755 nm at early stages of growth (Feekes 4 – 7), for both years, when readings were collected at night using UV illumination.

Finding that early-season spectral irradiance from wheat canopies at specific wavelengths were correlated with grain yield was considered important since this information could be used to adjust in-season fertilization. However, our experience suggests that improvement needs to be made when processing the initial data. The collection of light from samples needs to be increased for the UV night readings in order to enhance signals to raise ratios. At this time, the feasibility of using this technology to determine in-situ P levels of winter wheat using spectral data is limited, largely due to problems with data collection. The potential for this technology to be used is great.

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Table 1. Initial surface (0 – 15cm) soil test characteristics from the Teller sandy loam soil used in both field and pot studies, 1996

Characteristics	Method	Unit	Soil test level	Critical level
pH	1:1 soil:H_2O	-	5.9	5.7
Organic Carbon†	Dry Combustion	g kg^{-1}	5.336	
Total Nitrogen†	Dry Combustion	g kg^{-1}	0.504	
NH_4-N‡	2 M KCl extract	mg kg^{-1}	3.0	
NO_3-N‡	2 M KCl extract	mg kg^{-1}	2.8	40
Phosphorus§	Mehlich-3	mg kg^{-1}	8.9	32.5
Potassium§	Mehlich-3	mg kg^{-1}	133.0	125

†Schepers et al. (1989)
‡Lachat instruments (1989)
§Mehlich (1984)

Table 2. Experiment Location, year, planting date, spectral reading date and growth stage at that reading.

Experiment	Year	Planting date	Spectral reading	Growth stage
Perkins- field	1997	10/21/97	02/24/98	Feekes 4
			04/01/98	Feekes 5
			04/21/98	Feekes 7
			05/07/98	Feekes 10.5
Perkins- field	1998	10/15/98	02/23/99	Feekes 4
			03/09/99	Feekes 5
			04/06/99	Feekes 8
			05/08/99	Feekes 11.1
Perkins- pot	1997	10/06/97	11/07/98	Feekes 5
Perkins- pot	1999	06/04/99	06/29/99	Feekes 5

Table 3. Combinations of multi-wavelength indices tested for winter wheat forage spectral irradiance readings collected for both field and pot studies, 1997, 1998, and 1999.

NPCI1 = (W685 – W435)/(W685 + W435)	NPCI2 = (W675 – W425)/(W675 + W425)
NPCI = (NPCIX1 + NPCIX2)/2	WBI1 = W975 – W905
WBI2 = W695 – W895	WBI = (WBI1 + WBI2)/2
PRI1 = (W555 – W535)/(W555 + W535)	PRI2 = (W545 – W525)/(W545 + W525)
PRI = (PRI1 + PRI2)/2	GR = (W515 + W525 + W535 + W545)/4
NDVI = (W805 – W695) / (W805 + 695)	PNSI = (W805 + W695)/(W805 – W695)
NIRGI = W795 /(1/W545)	NR = W805/W695
PFR = W725/W655	PFR2 = W725 / W655
W735_665 = W735/W665	W405_635 = W405/W635
W805_415 = W805/W415	W795_735 = W795/W735
W735_655 = W735/W655	W705_505 = W705/W505
W705_515 = W705/W515	W705_525 = W705/W525
W705_535 = W705/W535	W705_545 = W705/W545
W715_505 = W715/W505	W715_515 = W715/W515
W715_525 = W715/W525	W715_535 = W715/W535
W715_545 = W715/W545	W725_505 = W725/W505
W725_515 = W725/W515	W725_525 = W725/W525
W725_535 = W725/W535	W725_545 = W725/W545
W735_505 = W735/W505	W735_515 = W735/W515
W735_525 = W735/W525	W735_535 = W735/W535
W735_545 = W735/W545	W725_715 = W725/W715
W735_715 = W735/W715	W785_505 = W785/W505
W695_405 = W695/W405	W405_635 = W405/W635

W_ wavelength in nm used either alone or with other combinations of spectral data.

Table 4. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for grain yield, N concentration, and P concentration in the grain, Perkins, OK, 1997-98 crop year.

Source of Variation	df	Grain Yield		
		Yield	N	P
		Mg ha^{-1}	*g kg^{-1}*	*g kg^{-1}*
		----------mean squares----------		
Rep	2	0.44	0.36	0.12
N rate	3	2.04***	18.09**	0.99*
P rate	2	0.59*	3.43	0.81*
N rate * P rate	6	0.04	0.94	0.10
MSE	22	0.14	2.90	0.21
Contrast				
N rate linear	1	5.85***	50.82***	2.61**
N rate quadratic	1	0.23	0.02	0.32
P rate linear	1	1.18**	6.39	0.95*
P rate quadratic	1	0.00	0.46	0.66
		Treatment means		
N rate kg ha^{-1}				
0		1.15	20.6	3.88
56		1.60	21.2	3.51
112		2.06	23.1	3.17
168		2.20	23.5	3.19
SED		0.18	0.80	0.21
P rate kg ha^{-1}				
0		1.53	22.7	3.14
14.5		1.74	22.0	3.63
29		1.98	21.7	3.54
SED		0.15	0.69	0.18
CV, %		21	8	13

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 5. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for grain yield, N concentration, P concentration, in the grain, Perkins, OK, 1998-99 crop year.

Source of Variation	df	Grain Yield		
		Yield	N	P
		Mg ha^{-1}	*g kg^{-1}*	*g kg^{-1}*
		mean squares		
Rep	2	0.29†	2.6	0.09
N rate	3	2.11***	75.1***	2.40***
P rate	2	0.72**	21.9*	0.79*
N rate * P rate	6	0.11	5.6	0.05
MSE	22	0.10	3.8	0.17
Contrast				
N rate linear	1	5.74***	198.3***	6.28***
N rate quadratic	1	0.50*	26.3*	0.64†
P rate linear	1	1.39**	25.2*	1.08*
P rate quadratic	1	0.05	18.5*	0.49
Treatment means				
N rate kg ha^{-1}				
0		0.83	21.5	4.76
56		1.34	21.7	3.96
112		1.83	24.2	3.82
168		1.86	27.7	3.56
SED		0.15	0.9	0.20
P rate kg ha^{-1}				
0		1.20	25.3	3.73
14.5		1.52	22.8	4.19
29		1.68	23.2	4.16
SED		0.13	0.8	0.17
CV, %		21	8	10

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 6. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 5, 1997-98 crop year.

Source of Variation	df	Feekes 5				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		mean squares				
Rep	2	224742	14.6	0.08	122	1.53
N rate	3	849226†	97.4**	0.13	1163**	3.27
P rate	2	2870079**	129.2**	0.39†	910*	29.70**
N rate * P rate	6	58582	8.3	0.03	72	0.59
MSE	22	331026	6.9	0.16	162	4.21
Contrast						
N rate linear	1	2098440†	288.7**	0.35	3125**	5.98
N rate quadratic	1	270192	7.4	0.03	70	2.49
P rate linear	1	5714382***	209.0**	0.78	1741**	58.20**
P rate quadratic	1	25776	57.3**	0.00	53	0.65
Treatment means						
N rate kg ha^{-1}						
0		1231	22.8	2.53	27.3	3.1
56		1494	24.4	2.40	34.6	3.7
112		1900	27.2	2.29	49.5	4.5
168		1816	30.3	2.27	53.6	4.4
SED		271	1.2	0.19	6.0	1.0
P rate kg ha^{-1}						
0		1141	29.9	2.18	32.8	2.4
14.5		1572	24.4	2.37	38.9	3.7
29		2117	24.1	2.55	50.3	5.6
SED		235	1.1	0.16	5.2	0.8
CV, %		36	10	17	31	52

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 7. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 7, 1997-98 crop year.

Source of Variation	df	Feekes 7				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		mean squares				
Rep	2	575977	0.13	0.00	104.2	2.79
N rate	3	235599	24.70**	0.68***	280.0†	1.33
P rate	2	54561	24.70**	0.09	117.4	0.60
N rate * P rate	6	687422†	1.72	0.05	173.9	4.84
MSE	22	333141	2.99	0.09	98.2	2.44
Contrast						
N rate linear	1	349396	71.66***	1.76***	776.3*	2.04
N rate quadratic	1	140650	1.89	0.22	0.1	0.18
P rate linear	1	5594	40.53**	0.17	216.2	0.97
P rate quadratic	1	103527	8.86†	0.00	18.6	0.22
Treatment means						
N rate kg ha^{-1}						
0		2070	11.0	2.50	22.7	5.2
56		2144	11.6	2.07	24.6	4.5
112		2441	13.2	1.98	32.3	4.8
168		2265	14.7	1.87	34.0	4.4
SED		272	0.8	0.14	4.7	0.7
P rate kg ha^{-1}						
0		2177	14.3	2.03	31.9	4.4
14.5		2306	11.9	2.09	27.4	4.8
29		2208	11.7	2.20	25.9	4.8
SED		236	0.7	0.12	4.0	0.6
CV, %		26	14	14	35	33

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 8. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 10.5, 1997-98 crop year.

Source of Variation	df	Feekes 10.5				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		----------mean squares----------				
Rep	2	657481†	0.93	0.04	75	1.91*
N rate	3	564422	8.93**	0.16*	216**	0.29
P rate	2	64194	9.82**	0.01	84	0.45
N rate * P rate	6	547823†	1.88	0.05	48	0.71
MSE	22	245844	1.58	0.05	38	0.48
Contrast						
N rate linear	1	1501429*	23.69***	0.44**	643***	0.22
N rate quadratic	1	188023	2.60	0.00	2	0.32
P rate linear	1	58282	18.39**	0.00	150†	0.14
P rate quadratic	1	70106	1.24	0.01	18	0.77
		Treatment means				
N rate kg ha^{-1}						
0		2431	7.4	1.14	17.4	2.7
56		2740	7.8	1.09	21.1	3.0
112		2950	8.2	0.89	24.3	2.7
168		2970	9.6	0.87	29.0	2.6
SED		233	0.6	0.10	2.9	0.3
P rate kg ha^{-1}						
0		2755	9.2	1.00	26.0	2.8
14.5		2710	8.0	0.97	21.9	2.5
29		2853	7.5	1.02	21.0	2.9
SED		202	0.5	0.09	2.5	0.3
CV, %		18	15	22	27	25

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 9. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 4, 1998-99 crop year.

Source of Variation	df	Feekes 4				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		---mean squares---				
Rep	2	62328	2.7	0.14	72	0.11
N rate	3	1164003*	89.5***	0.19	1426**	3.48
P rate	2	775589	2.1	0.73**	546	5.78†
N rate * P rate	6	204320	3.5	0.12	160	0.96
MSE	22	359520	4.9	0.10	285	1.99
Contrast						
N rate linear	1	2499386*	261.5***	0.51*	3683**	5.74
N rate quadratic	1	133736	1.1	0.02	59	1.14
P rate linear	1	1547876*	4.0	1.38**	1090†	11.52*
P rate quadratic	1	3302	0.2	0.08	1	0.04
Treatment means						
N rate kg ha^{-1}						
0		677	24.1	2.04	16.2	1.39
56		758	27.5	2.03	20.9	1.54
112		1409	28.9	1.84	40.3	2.74
168		1246	31.7	1.74	39.9	2.17
SED		283	1.0	0.15	8.0	0.66
P rate kg ha^{-1}						
0		762	28.5	1.64	22.4	1.29
14.5		1036	27.9	1.98	29.6	1.91
29		1269	27.7	2.12	35.9	2.68
SED		245	0.9	0.13	6.9	0.57
CV, %		59	8	16	58	71

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 10. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 5, 1998-99 crop year.

Source of Variation	df	Feekes 5				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		mean squares				
Rep	2	566600	31.9***	0.05	427	1.87
N rate	3	2093654**	129.4***	0.43*	2094*	5.15
P rate	2	3051929**	2.1	1.08***	1282	22.51**
N rate * P rate	6	451873	7.5	0.12	253	2.17
MSE	22	405308	5.7	0.10	530	2.93
Contrast						
N rate linear	1	6220399***	380.2***	1.27***	6195**	13.55*
N rate quadratic	1	45518	0.4	0.00	55	1.53
P rate linear	1	5885848**	1.9	2.06***	2473*	43.91***
P rate quadratic	1	218009	2.1	0.10	91	1.11
		Treatment means				
N rate kg ha^{-1}						
0		846	20.4	2.27	17.2	1.93
56		1253	24.4	2.09	29.7	2.71
112		1679	26.2	1.98	43.9	3.53
168		1944	29.4	1.75	51.5	3.48
SED		300	1.0	0.15	10.8	0.81
P rate kg ha^{-1}						
0		990	25.7	1.69	26.6	1.68
14.5		1321	24.9	2.10	33.3	2.66
29		1981	24.4	2.28	46.9	4.39
SED		260	0.9	0.13	9.4	0.70
CV, %		44	9	16	65	59

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 11. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 8, 1998-99 crop year.

Source of Variation	df	Feekes 8				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		----------mean squares----------				
Rep	2	2467644	1.3	0.16	780	9.69
N rate	3	18548471***	88.8***	0.71**	13362***	43.77**
P rate	2	14383546***	8.7	0.48*	5367**	87.66***
N rate * P rate	6	2940670†	3.3	0.12	1754†	10.40
MSE	22	1327469	3.7	0.12	786	6.57
Contrast						
N rate linear	1	53104319***	262.2***	1.81***	38805***	124.91***
N rate quadratic	1	41141	2.4	0.17	752	0.35
P rate linear	1	26784388***	12.3†	0.89*	9177**	167.11***
P rate quadratic	1	1982704	5.1	0.07	1558	8.21
		Treatment means				
N rate kg ha^{-1}						
0		1666	15.0	2.48	24.3	4.00
56		3156	16.5	2.02	51.3	6.60
112		3535	19.5	2.00	70.4	7.17
168		5160	22.1	1.82	115.8	9.37
SED		543	0.9	0.16	13.2	1.2
P rate kg ha^{-1}						
0		2489	19.3	1.86	50.5	4.48
14.5		3047	17.8	2.14	56.1	6.11
29		4602	17.8	2.24	89.6	9.76
SED		470	0.8	0.14	11.4	1.05
CV, %		34	10	16	43	38

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 12. Analysis of variance, single-degree-of-freedom-contrasts, and treatment means for dry matter, N concentration, P concentration, total N uptake, and total P uptake, Perkins, OK, Feekes growth Stage 11.1, 1998-99 crop year.

Source of Variation	df	Feekes 11.1				
		Dry Matter *Mg ha^{-1}*	N *g kg^{-1}*	P *g kg^{-1}*	N uptake *kg ha^{-1}*	P uptake *kg ha^{-1}*
		mean squares				
Rep	2	33746535**	0.4	0.06	2727	23.29
N rate	3	55559511***	14.4**	0.72***	8063***	22.16*
P rate	2	22630852*	5.1	0.16*	795	25.68*
N rate * P rate	6	4126205	1.8	0.07	334	2.72
MSE	22	4865741	2.5	0.04	602	6.38
Contrast						
N rate linear	1	161334721***	31.1**	1.55***	23649***	65.26**
N rate quadratic	1	2641708	11.8*	0.43**	358	1.19
P rate linear	1	38236077*	10.3†	0.18†	1060	49.71*
P rate quadratic	1	7025626	0.0	0.13†	530	1.64
Treatment means						
N rate kg ha^{-1}						
0		3034	8.0	1.52	23	4.32
56		5960	7.5	0.99	43	5.84
112		7118	8.6	0.99	60	7.12
168		8960	10.4	0.90	93	7.91
SED		1040	0.7	0.10	12	1.19
P rate kg ha^{-1}						
0		5318	9.3	0.97	51	5.01
14.5		5643	8.6	1.18	50	6.00
29		7842	8.0	1.14	64	7.89
SED		900	0.6	0.08	10	1.03
CV, %		35	18	19	45	40

†, *, **, ***-significant at the 0.10, 0.05, 0.01, and 0.001 probability levels, respectively.
SED- standard error of the difference for two equally replicated means.
CV- coefficient of variation.

Table 13. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 5, Perkins, OK. 1997-98.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake			Grain Yield		
Daytime	W335	W940		W435	W440	W445	W705	W701	W696
No diode	0.36	0.28		-0.52	-0.52	-0.52	-0.50	-0.50	-0.50
	0.035	0.099		0.001	0.001	0.001	0.002	0.002	0.002
Daytime	W429	W388	W440	W429	W424	W445	W382	W388	W393
diode	-0.37	-0.37	-0.36	-0.55	-0.55	-0.55	-0.62	-0.60	-0.60
	0.029	0.031	0.035	0.001	0.001	0.001	0.001	0.001	0.001
Box	W738	W742	W893	W605	W536	W615	W571	W576	W536
	-0.44	-0.43	-0.43	-0.35	-0.34	-0.33	-0.57	-0.56	-0.56
	0.008	0.010	0.010	0.038	0.047	0.049	0.001	0.001	0.001
UV light							W761	W806	W756
night							0.29	0.29	0.28
							0.084	0.086	0.097
UV light	W1001	W993	W728	W429	W440	W435	W345	W361	W356
day	-0.47	-0.47	-0.46	-0.57	-0.57	-0.57	-0.67	-0.62	-0.62
	0.005	0.005	0.006	0.001	0.001	0.001	0.001	0.001	0.001
Indices									
Daytime	W705_506	W806_414	W715_506	W705_506	W715_506	W806_414	W797_733	W733_715	NDVI
No diode	0.36	0.31	0.30	0.60	0.56	0.56	0.54	0.50	0.50
	0.035	0.070	0.082	0.001	0.001	0.001	0.001	0.002	0.002
Daytime	W696_403	W705_506	W806_414	W705_506	W715_506	W806_414	W705_536	W705_546	W705_526
Diode	0.49	0.42	0.40	0.59	0.55	0.54	-0.58	-0.58	-0.57
	0.003	0.012	0.020	0.001	0.001	0.001	0.001	0.001	0.001
Box	NIRGI	GR	W696_403	W797_733	W696_403	W715_506	W797_733	PNSI	GR
	-0.38	-0.37	-0.32	0.45	-0.42	-0.33	0.56	-0.55	-0.53
	0.026	0.027	0.063	0.006	0.011	0.054	0.001	0.001	0.001
UV light	W733_546	W724_546	W733_536				W733_536	W733_715	W724_536
night	-0.37	-037	-0.35				-0.40	-0.39	-0.38
	0.028	0.028	0.042				0.014	0.018	0.023
UV light	W705_506	NIRGI	PRI	W705_506	W715_506	W806_414	GR	W733_715	W705_536
day	0.46	-0.43	0.40	0.62	0.58	0.57	-0.59	0.56	-0.56
	0.006	0.011	0.020	0.001	0.001	0.001	0.001	0.001	0.001

W – wavelength in nm used either alone or with other combinations of spectral data.
No diode – the fiber optic cable that was used did not have the diode on the end, thus the field of view was reduced to 7°.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Box – this reading was taken using a box to cover the reading area during the day so as to provide a dark reading.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 14. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 7, Perkins, OK. 1997-98.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake		Grain Yield		
Daytime Diode	W792	W765	W783			W366	W361	W1005
	-0.39	-0.38	-0.38			-0.65	-0.65	-0.64
	0.020	0.021	0.022			0.001	0.001	0.001
Box						W629	W581	W531
						-0.60	-0.60	-0.60
						0.001	0.001	0.001
UV light Night						W747	W751	W756
						0.52	0.50	0.50
						0.001	0.002	0.002
Indices								
Daytime Diode	WBI2	WBI	WBI1	W696_403		W806_414	W783_506	NR
	0.37	0.36	0.35	0.33		0.62	0.58	0.58
	0.028	0.031	0.037	0.050		0.001	0.001	0.001
Box	WBI2					GR	NPCI1	NPCI
	-0.29					-0.57	0.44	0.42
	0.087					0.001	0.007	0.010
UV light Night	W705_506			WBI1	W724_715	W797_733	NPCI2	W733_516
	0.32			0.47	-0.33	0.51	0.43	-0.42
	0.056			0.004	0.047	0.002	0.008	0.012

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Box – this reading was taken using a box to cover the reading area during the day so as to provide a dark reading.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 15. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 10.5, Perkins, OK. 1997-98.

Reading Conditions	Crop Property						
	——P tissue concentration ——		——— Forage P uptake ———			——— Grain Yield ———	
Daytime Diode			W335	W382	W377	W403	W393	W398
			0.35	0.33	0.33	-0.63	-0.62	-0.62
			0.035	0.046	0.048	0.001	0.001	0.001
UV light Night			W910	W521	W377	W742	W765	W733
			-0.43	-0.42	-0.42	0.69	0.69	0.68
			0.009	0.010	0.011	0.001	0.001	0.001
Indices								
Daytime Diode	PRI	W715_536				W705_526	W705_546	W705_536
	-0.31	-0.28				-0.69	-0.69	-0.68
	0.066	0.099				0.001	0.001	0.001
UV light Night	NPCI2		W724_526	W733_526	W724_516	NIRGI	W797_733	GR
	-0.28		0.48	0.40	0.38	0.59	0.52	0.46
	0.094		0.003	0.016	0.024	0.001	0.001	0.005

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 16. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 4, Perkins, OK. 1998-99.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake			Grain Yield		
Daytime Diode	W729	W725	W345	W429	W434	W413	W725	W720	W729
	-0.36	-0.34	0.33	-0.61	-0.60	-0.60	-0.48	-0.46	-0.46
	0.029	0.044	0.051	0.001	0.001	0.001	0.003	0.005	0.005
UV light Night							W748	W758	W753
							0.39	0.38	0.38
							0.018	0.021	0.024
Grow light Night	W725	W715		W677	W691	W643	W720	W711	W715
	-0.30	-0.29		-0.58	-0.57	-0.57	-0.39	-0.37	-0.36
	0.075	0.091		0.001	0.001	0.001	0.018	0.026	0.032
Indices									
Daytime Diode	NIRGI			W804_413	PFR	W706_505	NIRGI	W695_403	GR
	-0.40			0.69	0.68	0.67	-0.46	-0.37	-0.34
	0.015			0.001	0.001	0.001	0.005	0.025	0.045
UV light Night	W715_545	W725_545	W403_634	W795_734	W403_634	PFR2	W725_505	W795_734	W725_715
	-0.33	-0.31	0.30	0.32	0.32	-0.31	-0.45	0.44	-0.43
	0.052	0.064	0.072	0.056	0.058	0.066	0.006	0.007	0.009
Growlight Night	PRI2			W795_734	NR	PFR	PRI1	GR	W795_734
	0.29			0.67	0.67	0.64	-0.38	-0.28	0.28
	0.088			0.001	0.001	0.001	0.067	0.096	0.098

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Growlight – white light that has enhanced output in the spectral region for plant photosynthesis.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 17. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 5, Perkins, OK. 1998-99.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake			Grain Yield		
Daytime Diode				W459	W469	W464	W691	W696	W687
				-0.87	-0.86	-0.86	-0.66	-0.66	-0.66
				0.001	0.001	0.001	0.001	0.001	0.001
UV light Night				W753	W748	W744	W748	W753	W744
				0.53	0.53	0.50	0.54	0.54	0.52
				0.001	0.001	0.002	0.001	0.001	0.001
Grow light Night	W711			W744	W767	W748	W677	W696	W663
	0.28			0.84	0.84	0.83	-0.62	-0.62	-0.62
	0.08			0.001	0.001	0.001	0.001	0.001	0.001
Indices									
Daytime Diode	W706_505	PRI	W706_515	W715_505	W725_505	W804_413	W706_525	W706_535	W705_545
	0.49	0.47	0.44	0.92	0.91	0.90	-0.75	-0.74	-0.74
	0.003	0.004	0.009	0.001	0.001	0.001	0.001	0.001	0.001
UV light Night	W403_634	W695_403	W715_515	PRI1			W795_734	PRI1	PRI
	0.44	-0.43	0.32	0.29			0.37	0.35	0.34
	0.006	0.009	0.06	0.09			0.02	0.03	0.04
Grow light Night	W715_535	W715_545		W734_715	WBI	WBI2I	W725_715	NDVI	W734_715
	-0.30	-0.28		0.82	0.80	0.79	0.70	0.68	0.68
	0.07	0.09		0.001	0.001	0.001	0.001	0.001	0.001

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Growlight – white light that has enhanced output in the spectral region for plant photosynthesis.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 18. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 8, Perkins, OK. 1998-99.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake			Grain Yield		
Daytime	W535	W540	W530	W418	W398	W408	W392	W387	W398
Diode	0.52	0.51	0.51	-0.79	-0.79	-0.79	-0.67	-0.67	-0.67
	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
UV light	W729	W361		W753	W748	W744	W758	W748	W739
Night	0.40	0.37		0.86	0.86	0.84	0.71	0.71	0.70
	0.01	0.03		0.001	0.001	0.001	0.001	0.001	0.001
Grow light	W495	W580	W590	W677	W672	W687	W687	W672	W682
Night	0.49	0.49	0.48	-0.83	-0.83	-0.83	-0.71	0.71	0.71
	0.003	0.003	0.003	0.001	0.001	0.001	0.001	0.001	0.001
Indices									
Daytime	GR	NIRGI	W715_545	W725_715	NDVI	PFR2	W706_545	W706_535	NDVI
Diode	0.51	0.51	-0.45	0.88	0.87	0.87	-0.72	-0.70	-0.69
	0.001	0.001	0.006	0.001	0.001	0.001	0.001	0.001	0.001
UV light	W715_535	W795_734		NR	NDVI	W795_734	W795_734	NR	NDVI
Night	0.37	-0.33		0.65	0.63	0.62	0.46	0.45	0.44
	0.03	0.05		0.001	0.009	0.019	0.004	0.006	0.007
Grow light	GR	PRI1	W795_734	PFR2	PFR	W734_653	W725_515	NDVI	W734_715
Night	0.44	0.37	-0.37	0.91	0.91	0.90	0.71	0.71	0.69
	0.006	0.03	0.03	0.001	0.001	0.001	0.001	0.001	0.001

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Growlight – white light that has enhanced output in the spectral region for plant photosynthesis.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Table 19. Wavelengths, correlation coefficients and significance of independent spectral readings with tissue P concentration, forage P uptake, and grain yields, from spectral data collected at Feekes growth stage 11.1, Perkins, OK. 1998-99.

Reading Conditions	Crop Property								
	P tissue concentration			Forage P uptake			Grain Yield		
Daytime Diode	W444	W413	W449	W398	W403	W408	W408	W403	W418
	0.64	0.65	0.65	-0.78	-0.78	-0.78	0.69	0.69	0.69
	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
UV light Night	W748	W795	W734	W753	W744	W748	W744	W753	W758
	-0.43	-0.41	-0.40	0.82	0.82	0.81	0.67	0.66	0.65
	0.009	0.01	0.06	0.001	0.001	0.001	0.001	0.001	0.001
Grow light Night	W1017	W1013	W366	W535	W525	W540	W530	W545	W550
	-049	-0.48	-0.48	0.84	0.84	0.84	0.83	0.83	0.82
	0.002	0.003	0.003	0.001	0.001	0.001	0.001	0.001	0.001
Indices									
Daytime Diode	GR	NIRGI	PRI1	W706_545	PRI	W706_535	PRI1	NDVI	W725_715
	0.64	0.61	0.50	-0.84	-0.84	-0.83	-0.71	-0.67	0.65
	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
UV light Night	PFR2	W734_653	W695_403	NIRGI	GR	W795_734	W795_734	NIRGI	GR
	0.38	0.37	-0.36	0.64	0.50	0.49	0.53	0.47	0.33
	0.02	0.02	0.03	0.001	0.001	0.002	0.001	0.004	0.05
Grow light Night	W706_535	NDVI	W734_715	GR	NIRGI	WBI	GR	NIRGI	WBI1
	0.55	-0.54	-0.51	0.84	0.82	-0.80	0.82	0.76	-0.75
	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001

W – wavelength in nm used either alone or with other combinations of spectral data.
Lucite lens - the fiber optic cable was fitted with a Lucite lens that increased its field of view.
Growlight – white light that has enhanced output in the spectral region for plant photosynthesis.
GR, NDVI, NIRGI, NPCI, NPCI1, NPCI2, NR, PFR, PFR2, PNSI, PRI, PRI1, PRI2, WBI, WBI1, WBI2 – see Table 3.

Figure 1. Feekes growth stages for cereals.

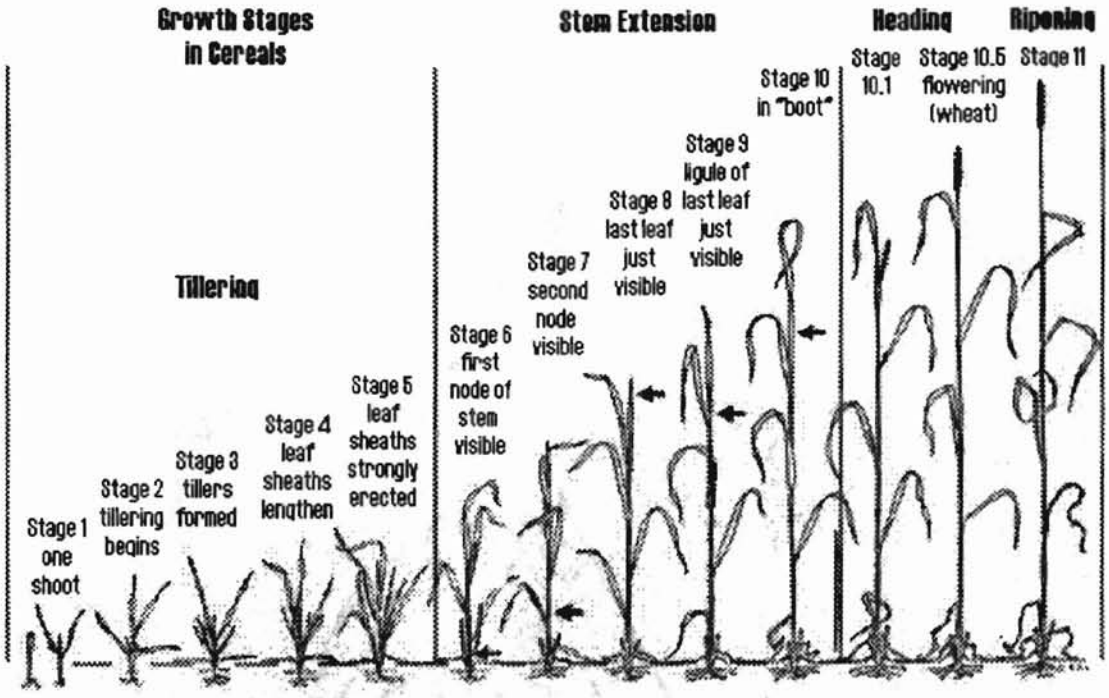
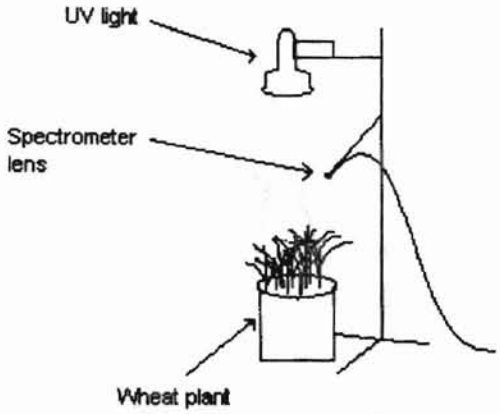


Figure 2. Setup for pot study: UV lamp, fiber optic cable, wheat pot, and holder.



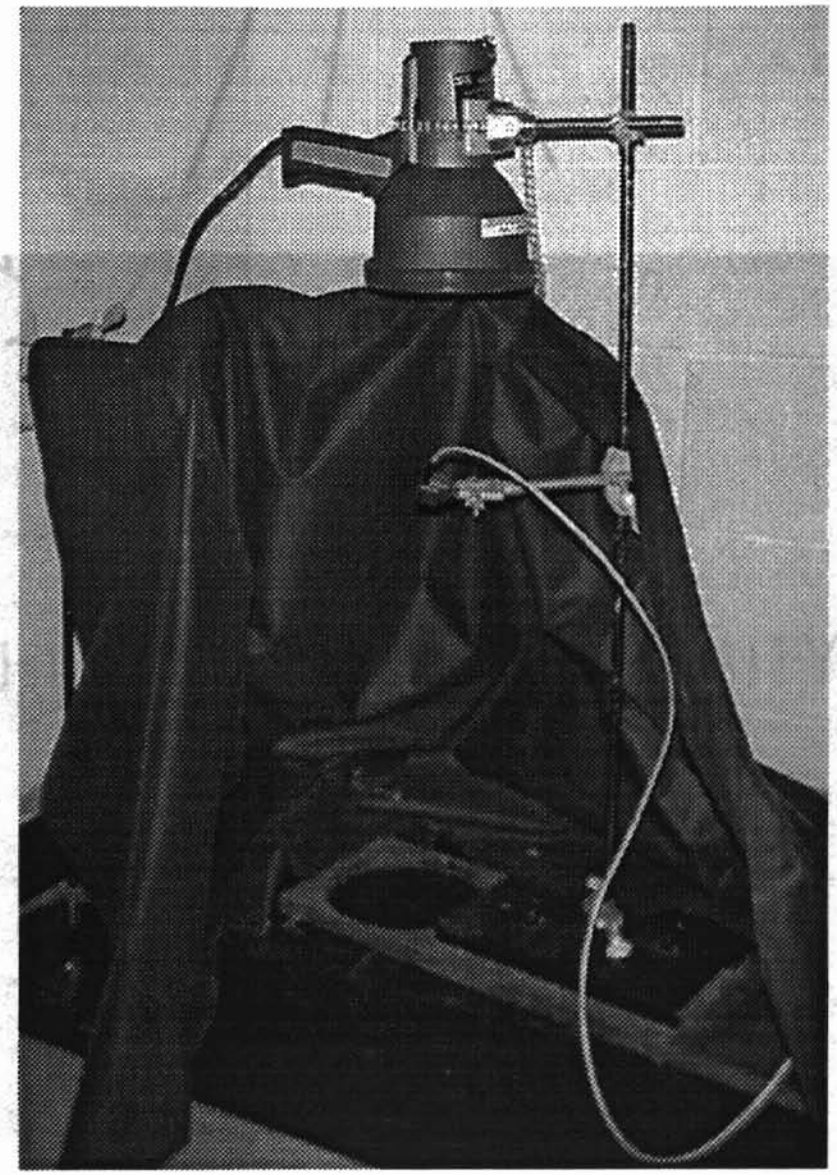
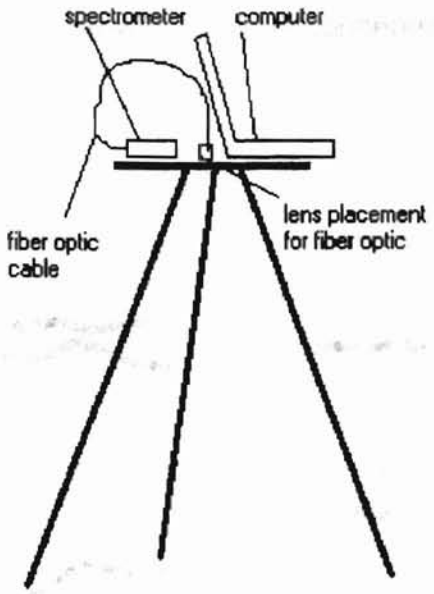
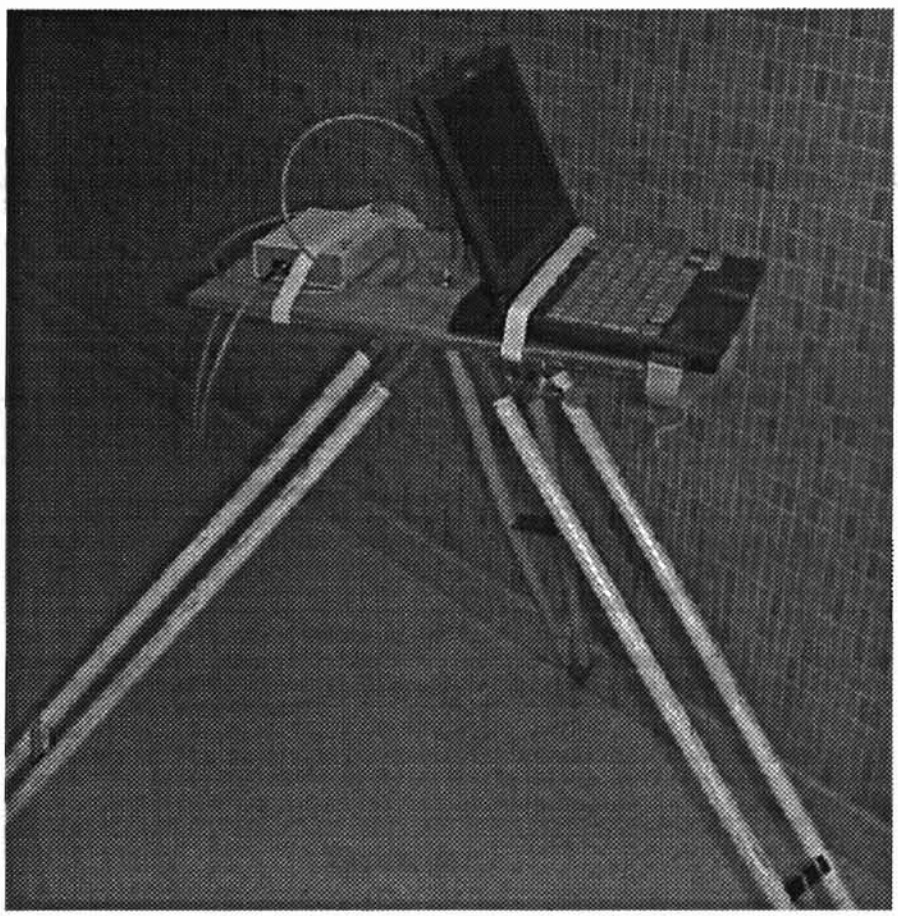


Figure 3. Tripod with computer and spectrometer, ready for daytime readings.





APPENDIX

Figure 1. Daytime correlation with P tissue concentration over stages of growth for 1998.

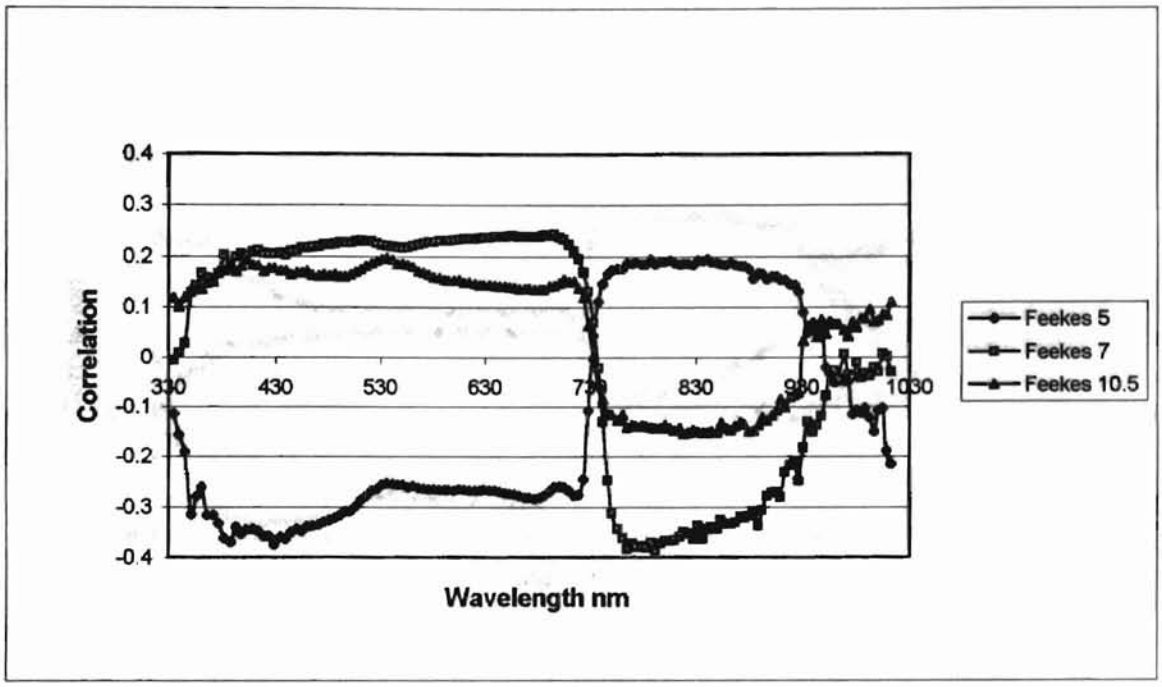


Figure 2. Daytime correlation with P tissue concentration over stages of growth for 1999.

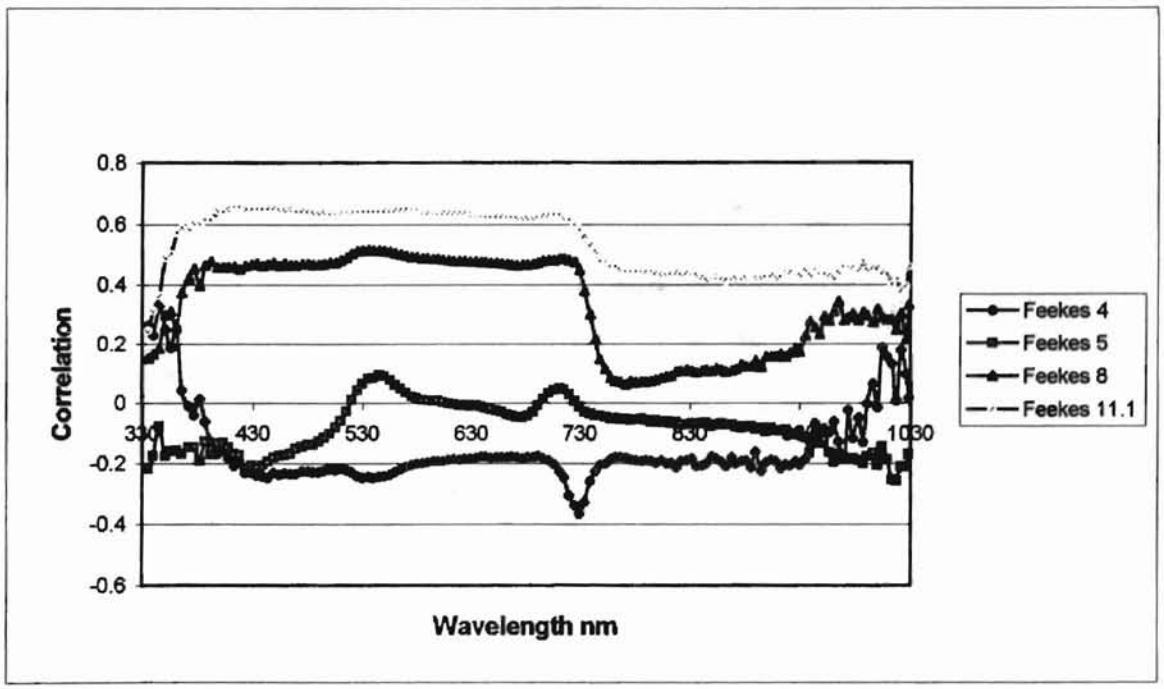


Figure 3. Daytime correlation with forage P uptake over stages of growth for 1998.

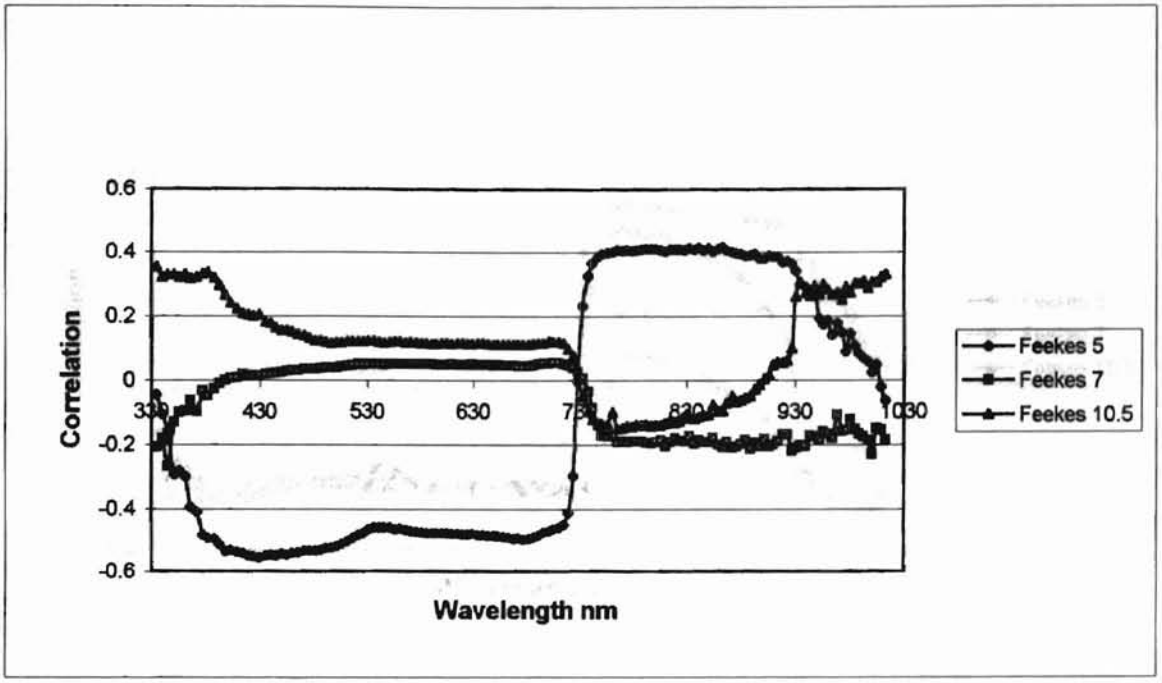


Figure 4. Daytime correlation with forage P uptake over stages of growth for 1998.

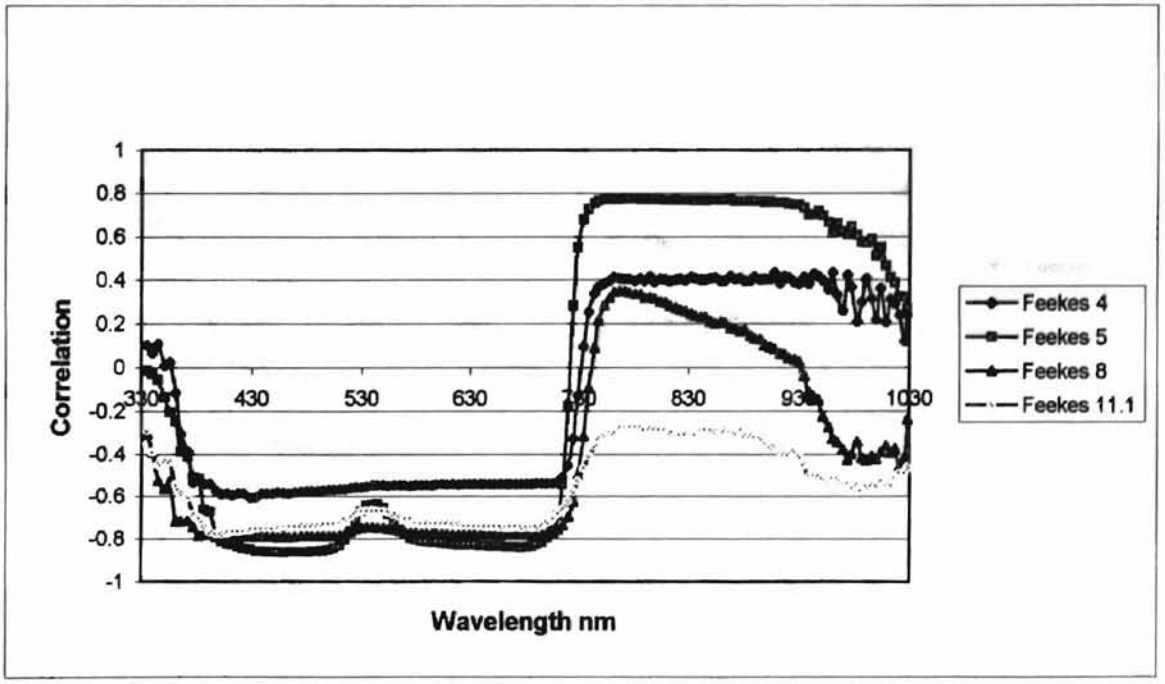


Figure 5. Daytime correlation with Yield over stages of growth for 1998.

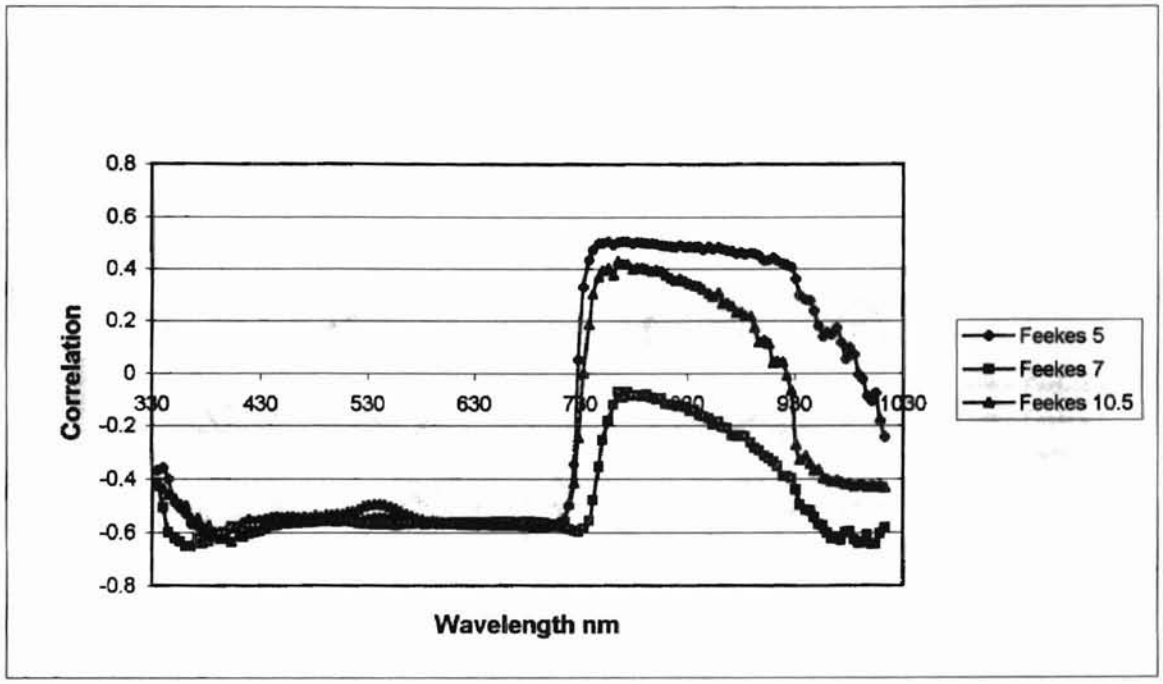


Figure 6. Daytime correlation with Yield over stages of growth for 1999.

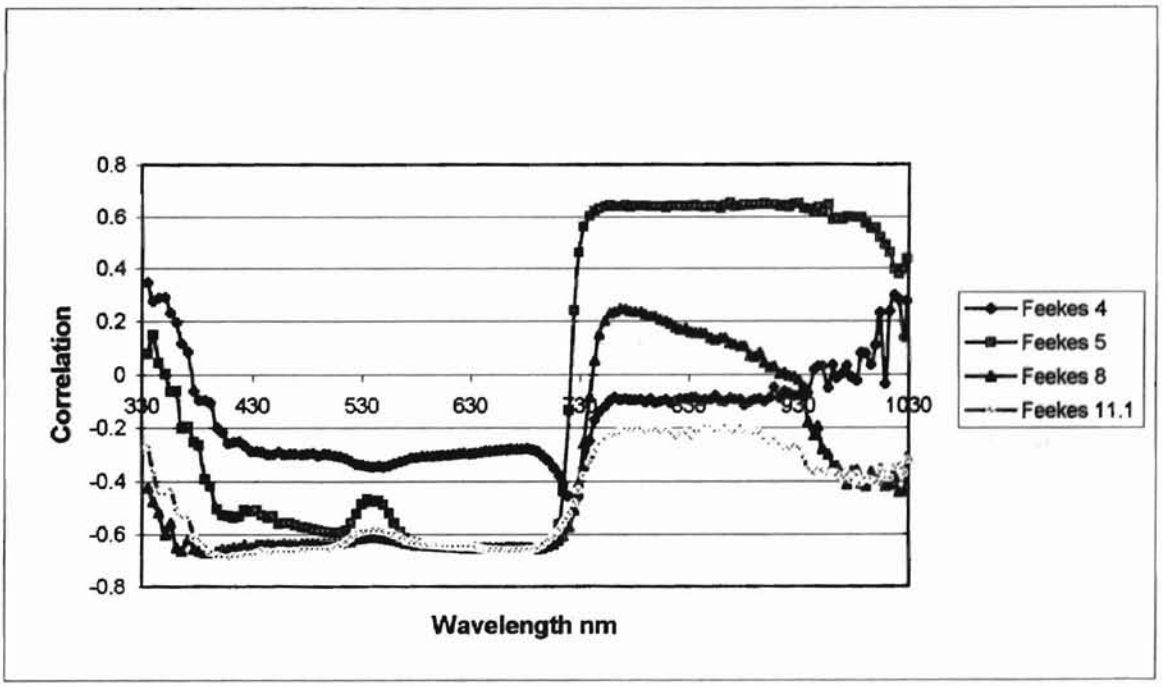


Figure 7. UV correlation with P tissue concentration over stages of growth for 1998.

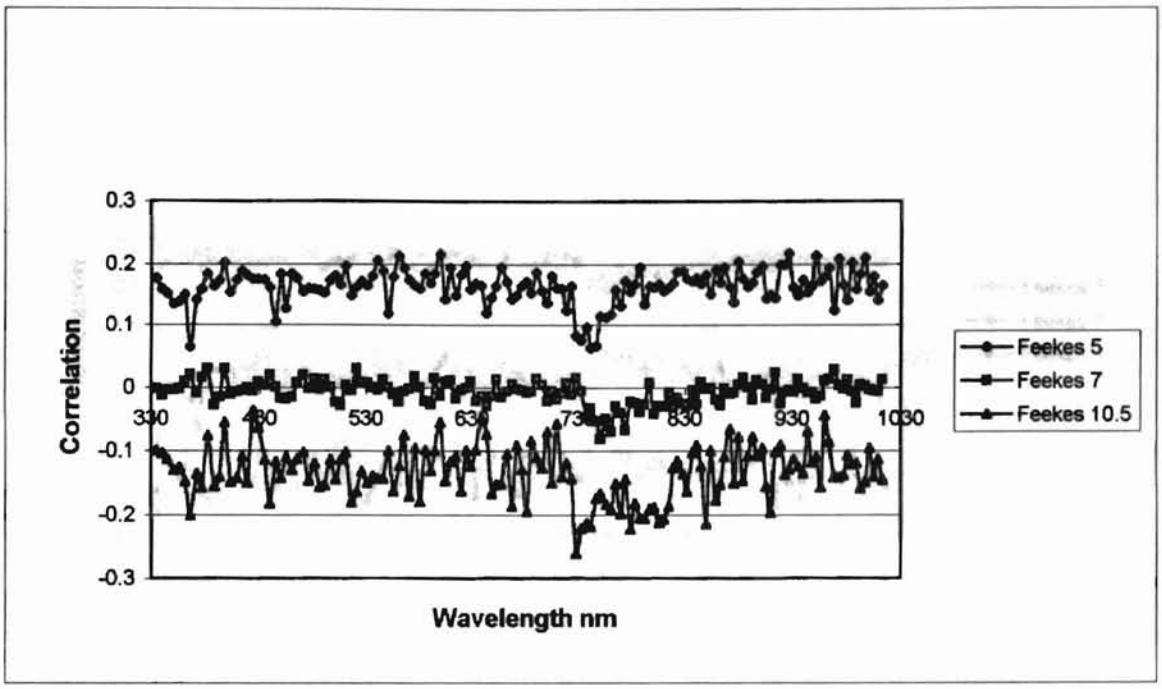


Figure 8. UV correlation with P tissue concentration over stages of growth for 1999.

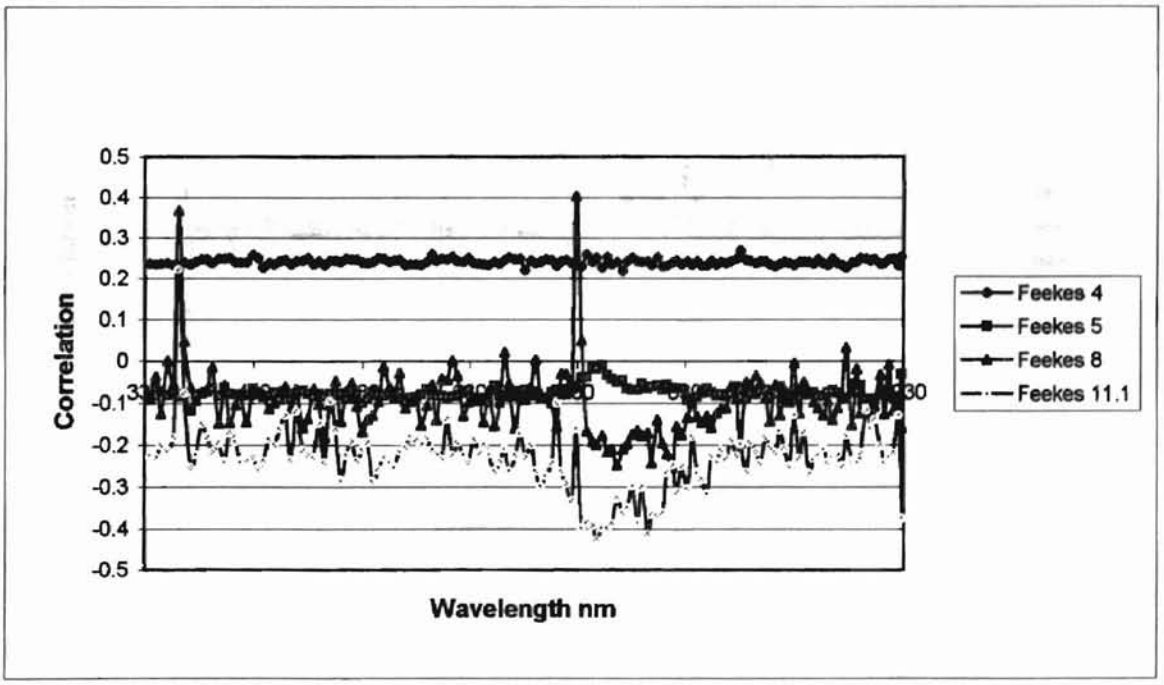


Figure 9. UV correlation with forage P uptake over stages of growth for 1998.

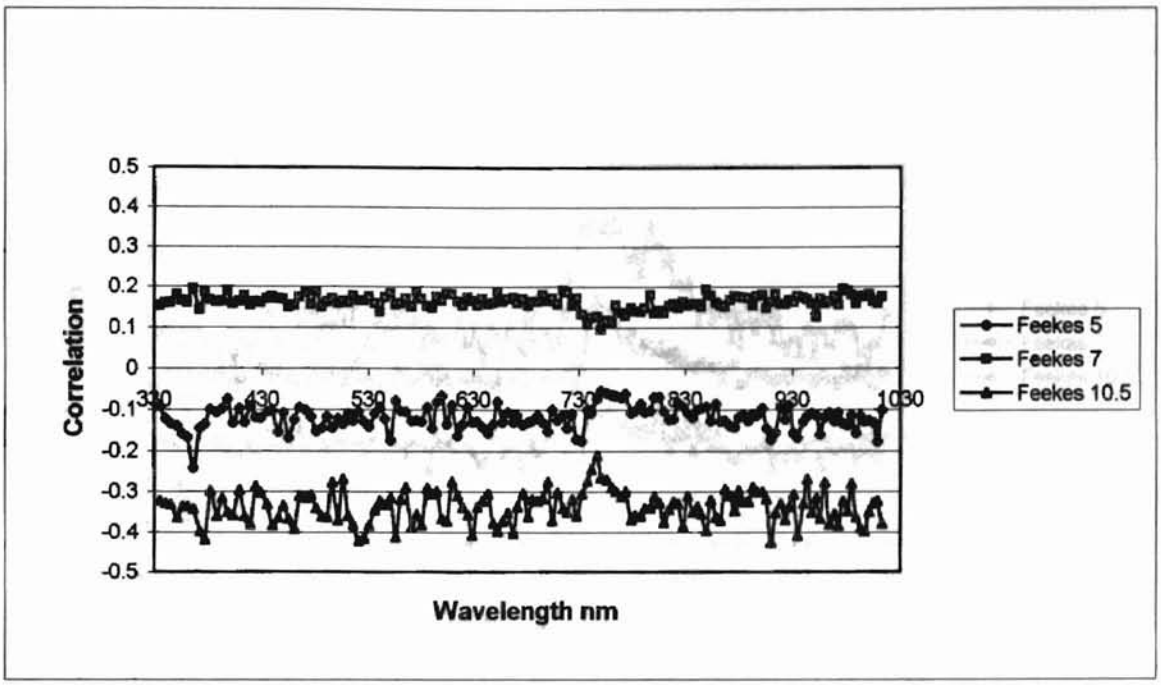


Figure 10. UV correlation with forage P uptake over stages of growth for 1999.

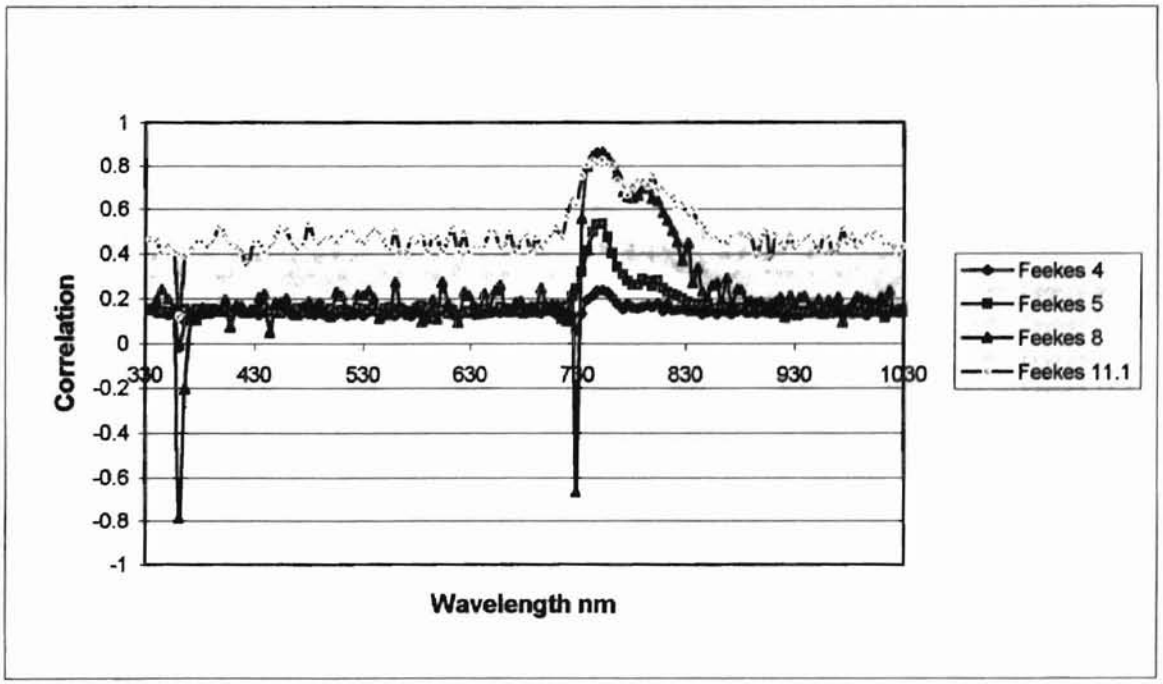


Figure 11. UV correlation with Yield over stages of growth for 1998.

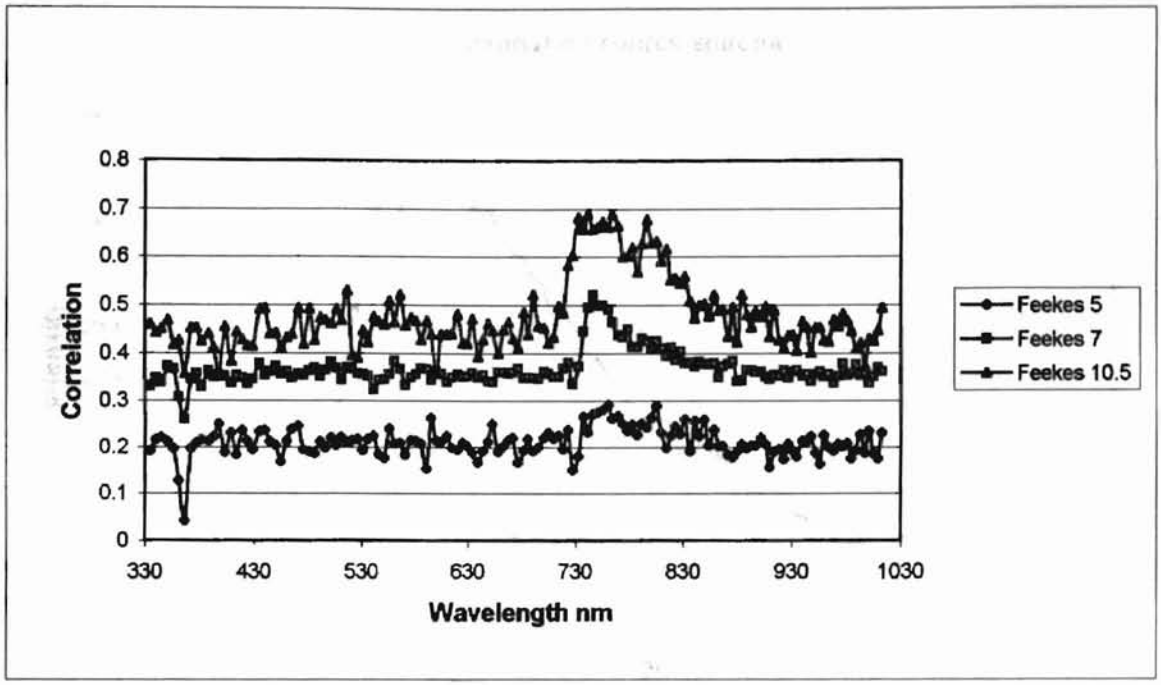


Figure 12. UV correlation with yield over stages of growth for 1998.

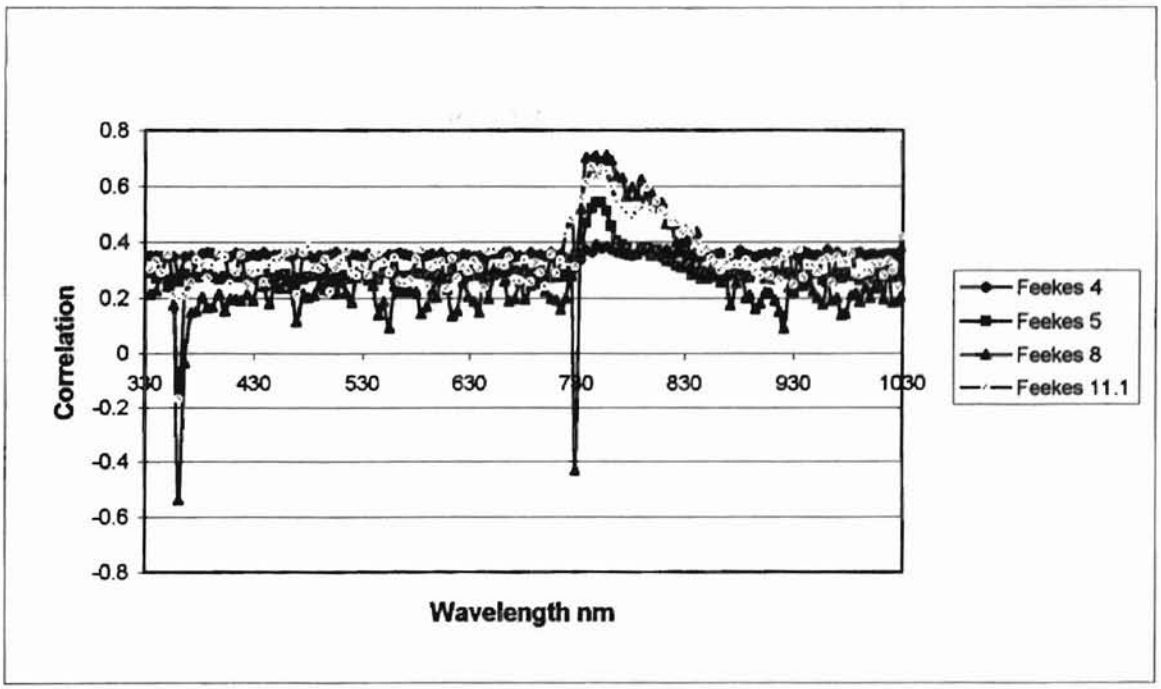


Figure 13. Daytime reading, the irradiance of the sun 1998.

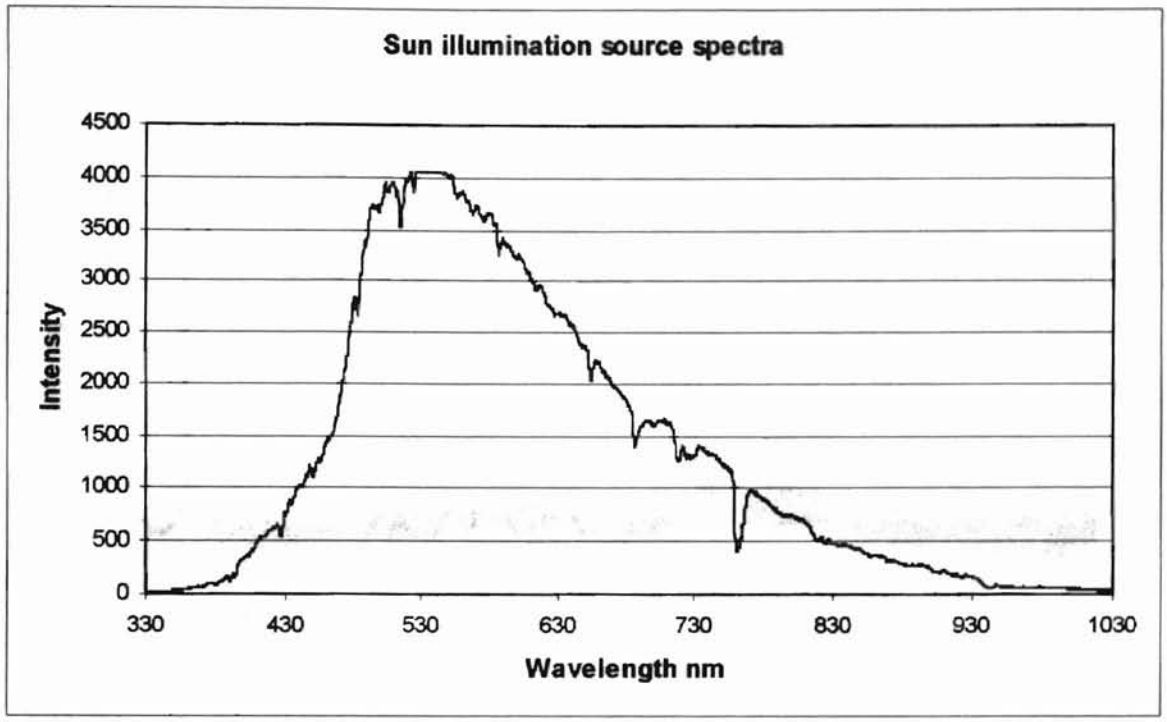


Figure 14. UV nighttime reading, the irradiance of the UV illumination source 1998.

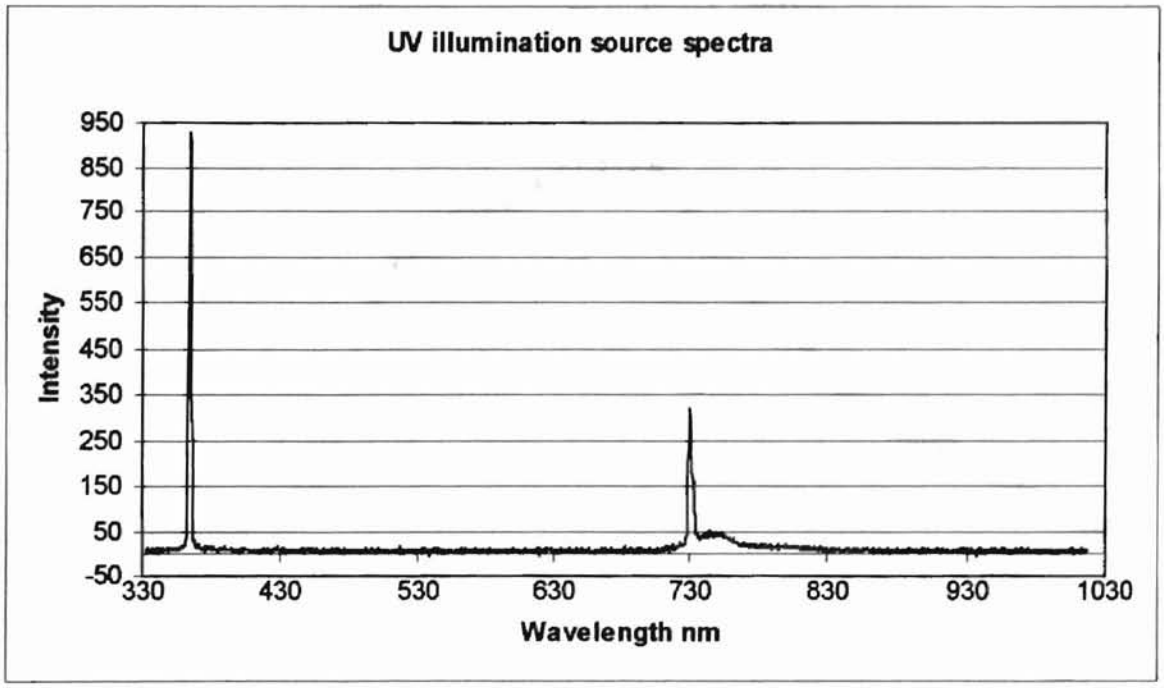


Figure 15. UV box reading, 1998.

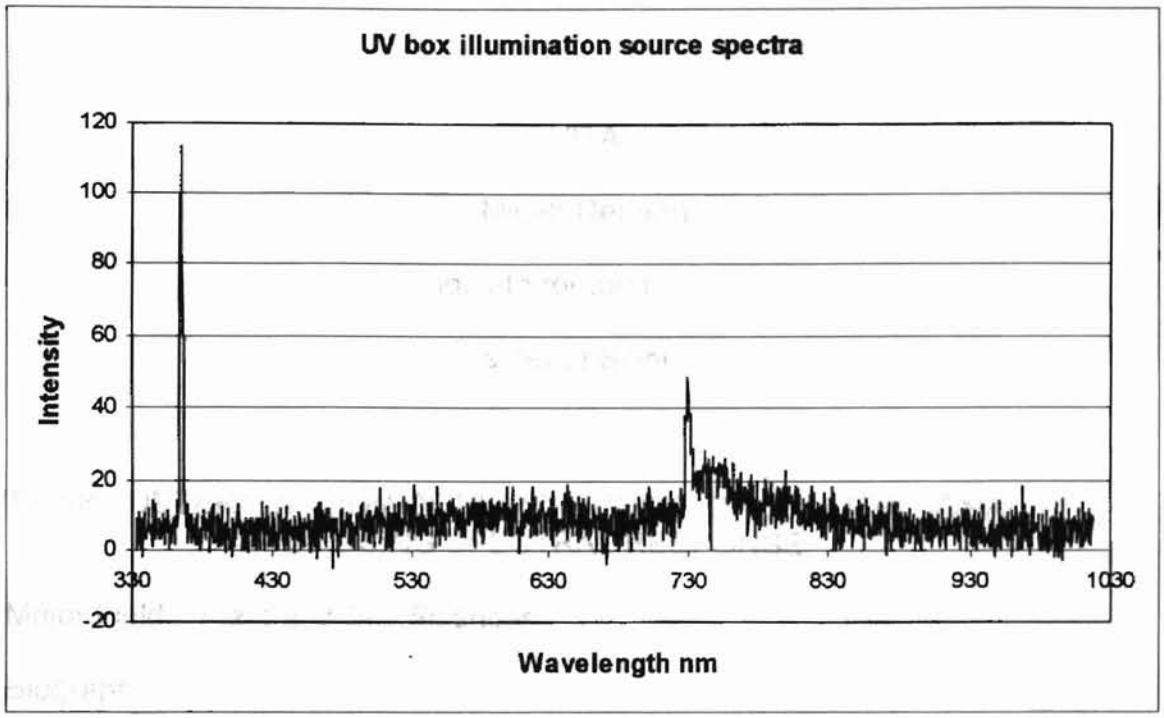
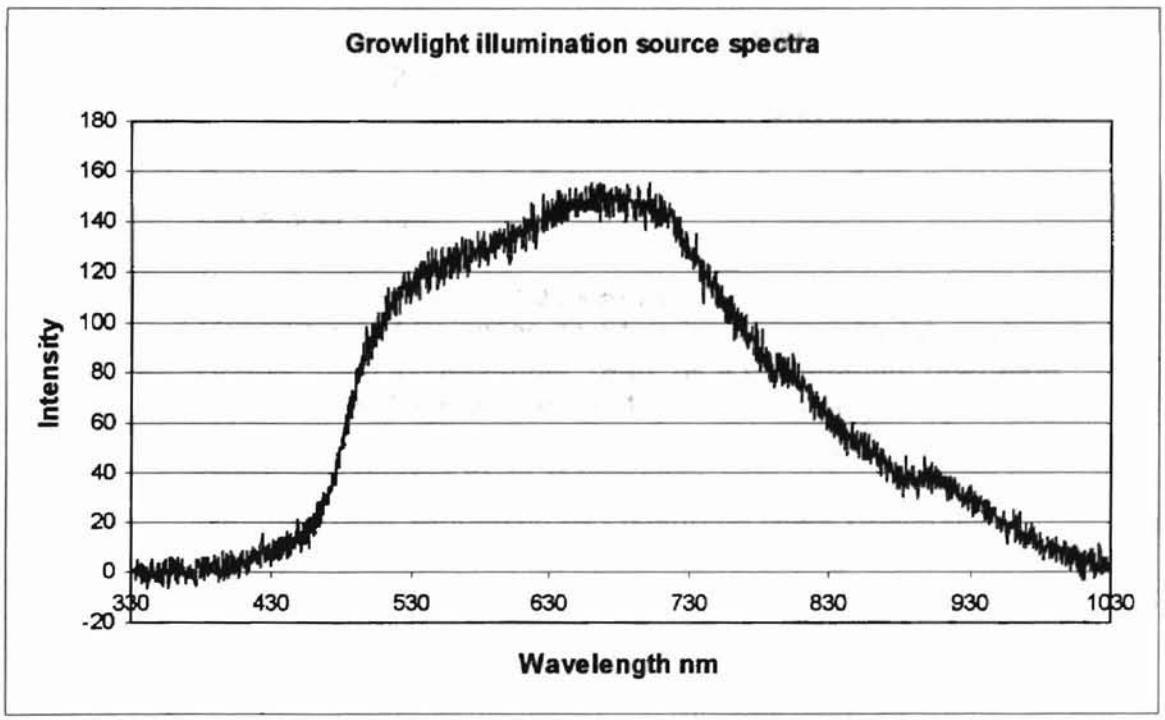


Figure 16. Growlight sample of the spectra for 1999.



VITA

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