American Journal of Agricultural and Biological Sciences 8 (3): 222-229, 2013
ISSN: 1557-4989

doi:10.3844/ajabssp.2013.222.229 Published Online 8 (3) 2013 (http://www.thescipub.com/ajabs.toc)

Evaluation of Phosphorus Application with Avail on Growth and Yield of Winter Wheat in Southeastern Coastal Plains

Pawel Wiatrak

School of Agricultural, Forest and Environmental Sciences, Clemson University, Edisto REC, Blackville, USA

Received 2013-09-01, Revised 2013-09-13; Accepted 2013-09-16

ABSTRACT

Phosphorus (P) application with Avail may affect plant growth and grain yields of winter wheat (*Triticum aestivum* L.) under dryland conditions. The objective of this study was to determine the effects of two P application rates (45 and 90 kg ha^{-1}) with and without Avail polymer on growth and yields of dryland winter wheat near Blackville, SC from 2010 to 2012. Plant growth measurements included plant biomass, P uptake, Normalized Difference Vegetation Index (NDVI), plant height and grain weight, yield and nutrient uptake. Application of P significantly improved wheat biomass production, plant Normalized Difference Vegetation Index (NDVI) at 8, 10 and 12 weeks after planting and grain yields of winter wheat. Plant biomass production improved with addition of Avail polymer by 6.3% at P rate of 45 kg ha^{-1} and by 4.3% at P rate of 90 kg ha^{-1}. Additionally, Avail application increased P uptake by 8% in biomass and improved plant NDVI at high P rates. Compared to untreated control, higher grain yields were obtained from treatments with P application at 90 kg ha^{-1} with and without Avail and P rate at 45 kg ha^{-1} with Avail application. Avail improved wheat grain yields by 5.1% at 45 kg P ha^{-1} and 2.0% at 90 kg P ha^{-1} and increased grain P uptake by 2.6% at P rate of 45 kg ha^{-1}. Based on significant linear regression at 20 weeks after planting, increasing plant NDVI by 0.1 increased grain yield by 0.88 Mg ha^{-1}. Phosphorus and Avail polymer applications did not affect plant height, grain mass and grain nitrogen uptake compared to the untreated control. Results from this study indicate that growth and yields of winter wheat grown may increase with P application and Avail polymer under dryland conditions with insufficient rainfall in Southeastern Coastal Plains.

Keywords: Wheat Grain, Phosphorus (P), Avail, Normalized Difference Vegetation Index (NDVI), Wheat Growth

1. INTRODUCTION

Worldwide soils are generally deficient in Phosphorus (P) (McLaughlin *et al*., 2011) and growers may not apply recommended rates due to high price of phosphate fertilizers (Afzal *et al*., 2010). Wang *et al*. (2012) noted that P utilization efficiency is very low in soils due to its low solubility and mobility. Phosphorus accumulates in soil mostly in inorganic forms under cropping systems and accumulate in both inorganic and organic forms under pastures (McLaughlin *et al*., 2011). Afzal *et al*. (2010) reported that soil P availability to plants is often low, because P reacts with iron (Fe), Aluminum (Al) and Calcium (Ca) in soil to form insoluble phosphates. Nadeem *et al*. (2012) emphasized that P is the least mobile nutrient in the soil compared to other macronutrients and frequently limits crop growth. Low soil P availability to plants is the primary limiting factor in soybean production in southern China (Liu *et al*., 2010), insufficient P fertilizer in Brazil is detrimental to fresh mass production and grain yield of soybean (Guareschi *et al*., 2011) and many food production systems in western Kenya depend on P (Kihara *et al*., 2010). Kihara *et al*. (2010) showed that continuous cereal systems need P application every second season, but P application in one out of three seasons could be sufficient in rotation systems with soybean.

To optimize fertilizer management, growers need to better understand factors affecting grain yield and quality (Anthony *et al*., 2012a). Anthony *et al*. (2012b) emphasized that accurate fertilizer recommendations depend on estimation of nutrients supplied and immobilized by soil. Additionally, understanding variation in these processes over space and time is critical for site-specific nutrient management. Using solution P-31 Nuclear Magnetic Resonance (NMR) spectroscopy, the main forms of P detected in stem and chaff were orthophosphate (25-75%), phospholipids (10-40%) and RNA (5-30%) (Noack *et al*., 2012). They reported that majority of residue P in aboveground plant residues may be delivered to soil in a form readily available to plants and soil microorganisms.

Legumes have been shown to increase P uptake of the following wheat crop, but underlying mechanisms of this effect are unclear (Wang *et al*., 2012). Results showed that rotation with legumes increased P uptake of 6 week-old wheat and suggested that previous crops may enhance P uptake of wheat also in the later stages of growth. Qiao (2012) pointed out the amounts of P removed from soil was affected by N source, which may increase P uptake and crop yield. Nunes *et al.* (2011) also showed that management of phosphate fertilization affects P availability in the soil and crop yields. They reported that distribution of soil-extractable P after 14 years of cultivation was influenced by the source and application form of phosphate fertilizer down to a depth of 10 cm in no-till and to 20 cm in conventional tillage. Under no-till system, P accumulates in few centimeters of the topsoil layer and plant residues left on the soil surface release P and organic acids, which may improve P availability and fertilizer efficiency (Olibone and Rosolem, 2010).

Surveys showed that soybean yield variability was mainly influenced by soil available and applied P, which explained the yield variation (Zheng *et al*., 2010). They reported that P application could improve yields under drought stress. Under low P status, it is important to apply P to the soil at the beginning of the wheat growth cycle to provide essential P for early growth and to replace P removed with previous crops (McBeath *et al*., 2011). They showed that low P added at planting may provide sufficient P until tillering, but increase in yield potential my require additional P. The P Use Efficiency (PUE) of fertilizers is generally low in the year of application (McLaughlin *et al*., 2011). They noted that slow release P products may help improve PUE in soils where leaching is a problem. Modification of soil chemistry around the fertilizer granule and better placement of P also offers promise to increase PUE (McLaughlin *et al*., 2011).

Technology based on nondestructive light reflectance can be used to monitor nutrient deficiencies of plants (Blackmer *et al*. 1994). Wiegand *et al*. (1991) stated that the Normalized Difference Vegetation Index (NDVI) optical sensing technology measures the photosynthetic area of the crop canopy. The NDVI, calculated as (NIR-Red/NIR + Red), where NIR and Red are canopy reflectance of near-infrared light and red light, respectively. Higher positive NDVI values indicate higher proportion of green vegetation, which are associated with greater nutrient uptake and yields (Raun *et al*., 2002).

Relatively little research focuses on P utilization with Avail polymer under dryland environments and there are no conclusions regarding the effect of Avail on wheat crop under limited rainfall. Researcher De Figueiredo *et al.* (2012) emphasized that there is a need to evaluate the effect of polymer-coated phosphate fertilizer to improve efficiency due to low availability of P. In the Southeastern Coastal Plain, wheat is mostly grown under dryland conditions, where soils have low water and nutrient holding capacity and precipitation is unpredictable and mostly deficient. Therefore the objective of this study was to evaluate P application rates with Avail polymer on wheat growth and yield under dryland conditions in Southeastern Coastal Plains.

2. MATERIALS AND METHODS

2.1. Site Preparation

This study was initiated on Faceville loamy sand (Fine, kaolinitic, thermic Typic Kandiudults) at Clemson University, Edisto Research and Education Center (REC) near Blackville, SC (33° 21' N, 81°18' W) under dryland conditions in the fall of 2010. These are well drained soils with moderate permeability and soil pH was 6.6. Treatments consisted of 2 rates of P (45 and 90 kg P_2O_5 ha^{-1}) with and without Avail applied to wheat prior to planting and an untreated control.

Prior to planting winter wheat following soybean (*Glycine max* L.) previous crop, all treatments with Diammonium Phosphate (DAP) (18-46-0 of N-P_2O_5-K_2O fertilizer with and without Avail) were applied separately in each plot using a handheld spreader. The nitrogen in each plot was balanced with urea (46-0-0 of N-P_2O_5-K_2O fertilizer) application to a uniform Nitrogen

(N) rate across treatments of 18 kg ha^{-1}. Wheat cv. 'Pioneer 26R12' was planted at 59 seeds per 1 m of row and 19 cm row spacing using a GreatPlains no-till drill (Great Plains Ag, Salina, KS) on 15 November 2010 and 9 December 2011. The plot size was 9.1 m long by 4.0 m wide. Wheat was sidedressed with broadcast application of N at 33.6 kg ha^{-1} in the form of liquid urea-ammonium sulfate (25-S fertilizer with 25% N and 3.5% S) on 21 January 2011 and 25 January 2012 and again at 67.2 kg ha^{-1} on 4 March, 2011 and 23 February 2012.

2.2. Sample Collections and Analyses

On 1 February 2011 and 9 February 2012, plant tissue samples were collected from above the ground for biomass production and P uptake. Normalized Difference Vegetation Index (NDVI) was measured in the center of each plot using handheld GreenSeeker™ (NTech Industries, Inc. Ukiah, CA) instrument once a week starting in late January. Plant height was measured from the ground to the tip of the grainhead based on 10 randomly selected plants in each plot prior to wheat harvest. Weed control was based on the South Carolina Extension recommendations.

Wheat was harvested from the entire length of the plot using Kinkaid 8XP small plot combine (Kinkaid Equip. Mtg, Haven, KS) on 16 May 2011 (about a week earlier that normally due to possibility of the hailstorm damage in the area) and 24 May 2012. All plots were harvested at the same time, because there was no visible and measured (using the GreenSeeker) difference in wheat maturity between plots.

Grain Samples from all harvested plots were evaluated for weight and tested for moisture using a Burrows Model 750 Digital Moisture Computer (Seedburo Equip. Co., Chicago, IL). Seed weight was determined after counting seeds using the Agriculex electronic seed counter model ESC-1 (Agriculex Inc., Guelph, Ont., Canada). Grain yield was converted to 135 g kg^{-1} moisture content. Additionally, weather data (air temperature and rainfall) were recorded during wheat vegetation using a weather station located at Edisto REC.

2.3. Statistical Analysis

The study design was a Randomized Complete Block with eight replications. Data were analyzed using the general linear models in SAS (SAS Institute Inc., Cary, NC) by analysis of a variance and means were separated using Fisher's Least Significant Difference Test at $p \leq 0.05$. Single degree-of-freedom contrasts were used to evaluate linear and quadratic effects of NDVI on wheat yield parameters. When a contrast indicated that there was a significant ($p \leq 0.05$) linear or quadratic response, a linear or quadratic regression model was fit using PROC REG (SAS Institute Inc., Cary, NC).

3. RESULTS

3.1. Weather Conditions

Monthly mean temperature, total precipitation and average from the 20-yr average are shown in **Table 1**. The mean air temperature during the wheat growing seasons in each year was mostly similar to the 20-yr average, except for March 2012 when temperature was 3.3°C higher and December 2010 and January 2011 when temperature was 6.0 and 3.2°C lower, respectively.

Monthly and total precipitation in the growing season varied between years and affected plant growth. Total precipitation was 182 mm lower in 2010/2011 season and 145 mm lower in 2011/2012 season. Deficit of precipitation was recorded for November, December, January and April in both seasons and also May in the first growing season and February in the second season. Slightly higher precipitation was observed in February in the first season, March in both seasons and May in the second season.

3.2. Biomass Production and Nutrient Uptake

Table 2 shows that P nutrient application with and without Avail increased biomass production and nutrient uptake. Compared to the control, application of P with and without Avail significantly improved biomass production, especially with higher P applications. Avail combination with P fertilizer improved wheat biomass production by 6.3% at 45 kg P ha^{-1} and by 4.3% at 90 kg P ha^{-1}.

Highest P uptake in plant biomass was observed with highest rates of P fertilizer with and without Avail. Addition of Avail to high P rate increased nutrient uptake in plant biomass by 8% compared to P fertilizer without Avail. Wheat from the control plots had the lowest P uptake in plant biomass.

3.3. Plant Normalized Difference Vegetation Index (NDVI)

Compared to untreated control, P fertilizer application with and without Avail significantly increased plant NDVI at 8, 10 and 12 weeks after planting (**Table 3 and 4**). Additionally, highest plant NDVI were observed with fertilizer application at 45 kg P ha^{-1} without Avail and 90 kg P ha^{-1} with and without Avail at 7 and 15 weeks after planting. Application of P fertilizer at 45 kg ha^{-1} with and without Avail and 90 kg ha^{-1} with Avail also improved plant NDVI compared to other treatments at 9 weeks after planting.

Table 1. Monthly mean air temperature and total precipitation near Blackville, SC from 2010 to 2012

	Month							
Year	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Average/ total
Temperature (°C)								
2010/2011	12.6	3.9	5.2	10.9	13.4	19.1	22.3	12.5
2011/2012	13.2	10.8	9.9	11.3	17.3	18.5	23.2	14.9
20-yr avg.	12.5	9.9	8.3	10.3	14.1	17.8	21.8	13.5
Precipitation (mm)								
2010/2011	22.0	34.0	49.0	124.0	123.0	57.0	59.0	468.0
2011/2012	49.0	37.0	41.0	42.0	119.0	44.0	173.0	505.0
20-yr avg.	69.0	93.0	114.0	102.0	105.0	80.0	87.0	649.0

Table 2. Influence of Phosphorus (P) and Avail on wheat dry matter production and P uptake in early spring near Blackville, SC from 2010 to 2012

P rate (kg ha^{-1})	Dry matter (kg ha^{-1})	P uptake (kg ha^{-1})
Control	359.2	1.42
45	416.2	2.11
45+ Avail	442.5	2.21
90	448.5	2.49
90+ Avail	467.6	2.69
$LSD_{(0.05)}$	61.7	0.38

Table 3. Influence of Phosphorus (P) and Avail on wheat Normalized Difference Vegetation Index (NDVI) near Blackville, SC from 2010 to 2012

P rate	Plant NDVI (week after planting)					
(kg ha^{-1})	6	7	8	9	10	11
Control	0.3682	0.5096	0.4952	0.5653	0.5636	0.7174
45	0.4177	0.5516	0.5833	0.6680	0.6396	0.7392
45 + Avail	0.3797	0.5441	0.5602	0.6315	0.6317	0.7587
90	0.3949	0.5623	0.5809	0.6260	0.6238	0.7409
90 + Avail	0.4002	0.5746	0.5771	0.6372	0.6269	0.752
$LSD_{(0.05)}$	NS	0.0264	0.0529	0.0390	0.0387	NS

Table 4. Influence of Phosphorus (P) and Avail on wheat Normalized Difference Vegetation Index (NDVI) near Blackville, SC from 2010 to 2012 (cont.)

P rate	Plant NDVI (week after planting)					
(kg ha^{-1})	12	13	14	15	16	17
Control	0.6447	0.7215	0.7579	0.7497	0.8136	0.8351
45	0.6708	0.7385	0.7660	0.7901	0.8164	0.8353
45 + Avail	0.6767	0.7444	0.7776	0.7783	0.8257	0.8448
90	0.6844	0.7548	0.7965	0.8019	0.8291	0.8358
90 + Avail	0.6957	0.7616	0.7905	0.8112	0.8336	0.8442
$LSD_{(0.05)}$	0.0274	NS	NS	0.0244	NS	NS

Plant NDVI was not affected by treatment application at 6, 11, 13, 14, 16 and 17 weeks after winter wheat planting. On average, Avail combination with higher rates of P fertilizer improved plant NDVI, while Avail polymer did not increase plant NDVI at low P fertilizer application rates.

3.4. Plant Height and Yield Components

Table 5 shows the influence of P fertilizer with and without Avail on plant height prior to harvest and grain weight, yield, N and P content. Significantly higher grain yields were obtained from treatments with P fertilizer application at 90 kg ha^{-1} for both combinations with and without Avail and fertilizer rate at 45 P kg ha^{-1} with Avail compared to untreated control.

Combination of Avail with 45 kg P ha^{-1} fertilizer improved grain yield by 5.1% while Avail in combination with higher rate of P fertilizer improved yield by 2.0%. The P uptake in grain was significantly higher with fertilizer application at 90 kg P ha^{-1} with and without Avail compared to all other treatments.

At low P fertilizer rate, combination of P fertilizer with Avail improved P uptake in grain by 2.6% while Avail did not affect grain P uptake at high P fertilizer rate of 90 kg ha^{-1}. Treatment application with P fertilizer and Avail did not affect plant height, grain weight and nitrogen uptake compared to the untreated control.

Significant relationship was obtained between plant NDVI at 20 weeks after planting and grain yield and moisture (**Fig. 1 and 2**). Based on the linear regression, grain yield increased by 0.88 Mg ha^{-1} for increase in plant NDVI by 0.1 across all treatments. As for the grain moisture, it increased by 8.2% for every 0.1 change in plant NDVI.

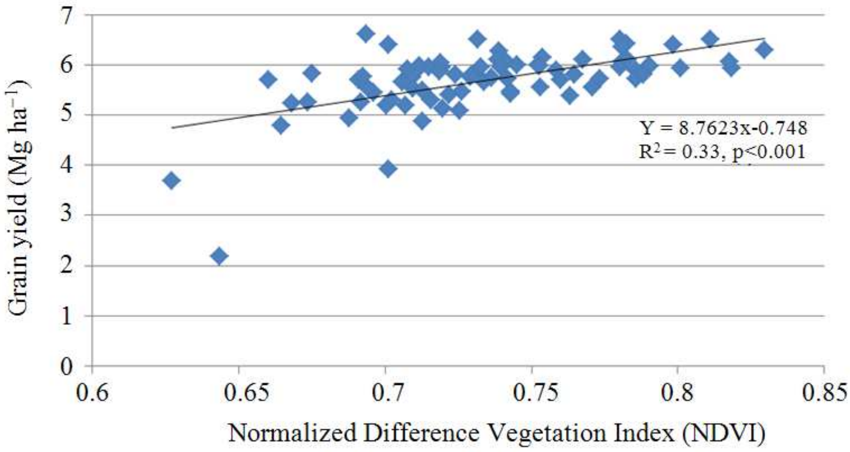

Fig. 1. Relationship between Normalized Difference Vegetation Index (NDVI) at 20 weeks after planting and grain yield of winter wheat near Blackville, SC from 2010 to 2012

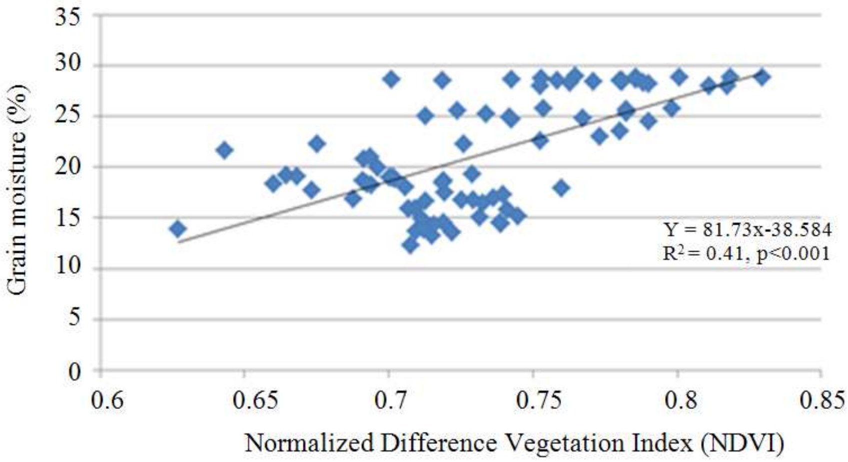

Fig. 2. Relationship between Normalized Difference Vegetation Index (NDVI) at 20 weeks after planting and grain moisture of winter wheat near Blackville, SC from 2010 to 2012

Table 5. Influence of Phosphorus (P) and Avail on plant height prior to harvest and grain weight, yield, Nitrogen (N) and P content of wheat near Blackville, SC from 2010 to 2012

P rate (kg ha^{-1})	Plant height (cm)	500 grain weight (gms)	Grain yield (Mg ha^{-1})	Grain N (%)	Grain P (%)
Control	90.0	24.3	5.420	1.92	0.370
45	90.8	24.3	5.450	1.91	0.380
45 + Avail	91.7	24.5	5.730	1.99	0.390
90	91.6	24.9	5.870	1.95	0.410
90 + Avail	89.6	24.2	5.990	1.95	0.410
$LSD_{(0.05)}$	NS	NS	0.398	NS	0.014

4. DISCUSSION

Previous results on biomass production and P uptake with P fertilizer application are not conclusive. Mabapa *et al*. (2010) reported that P fertilizer application did not affect crop biomass of three soybean cultivars over two seasons. However, de Figueiredo *et al*. (2012) showed that polymer-coated P fertilizer improved total corn dry-matter yield when compared to conventional P fertilizer application. Broadcast application of polymer coated P and K fertilizer in Brazil 15 days prior to planting improved soybean dry matter yield, but conventional and coated fertilizers provided similar increases in soybean dry matter when applied at planting (Guareschi *et al*., 2011). Our research showed that P fertilizer application, especially at higher rates, increased plant biomass production and P uptake. Avail in combination with P fertilizer improved biomass production by more than 6% with P fertilizer rate to winter wheat at 45 kg ha^{-1} and by more than 4% with P fertilizer rate at 90 kg ha^{-1}. According to previous research, fertilization with P fertilizer improved P concentration in soybean leaves (Farmaha *et al*., 2011) and soybean fertilization with P and K improved total N, P and K uptake in the plant shoot (Abbasi *et al*., 2012). McBeath *et al*. (2012), based on the isotopic tracer technique, concluded that P fertilizer uptake in wheat was 3-30% from applied P fertilizer and increased with increasing rainfall. Application of P fertilizer stimulated the use of subsoil P, but most crop P uptake was from the topsoil. Germination and early corn growth, seed-phytate hydrolysis and seed-P remobilization is the major P source for developing seedlings (Nadeem *et al*., 2012). They stated that phytate hydrolysis and remobilization of nonphytate P was the main source of P to seedlings and sufficient P nutrition was observed during the first four weeks of growth. In our research, combination of Avail polymer with high P fertilizer rate increased P uptake in early wheat growth by 8% compared to P without Avail.

Phosphorus application in this study significantly increased plant NDVI at 8, 10 and 12 weeks after planting. Combination of Avail polymer with P fertilizer at higher rates improved plant NDVI, but it did not increase plant NDVI at low P fertilizer application rates. Plant NDVI increase with higher P applications was due to increased growth and/or greener plants, because NDVI reflectance in the Near-Infrared (NIR) and red wavelengths is related to plant growth and chlorophyll content (Shanahan *et al*., 2001).

According to De Figueiredo *et al*. (2012), polymer-coated P fertilizer application increased plant height compared to conventional P fertilizer application. Plant height in our study was not affected by combination of P fertilizer and Avail due to most likely low precipitation, which most likely affected uptake of nutrients and plant growth. Significantly higher grain yields in this study were obtained from treatments with high P fertilizer application rates. Combination of Avail polymer with P fertilizer improved grain yield of winter wheat. Previous research results are not conclusive. Some researchers reported that P fertilizer application did not have a significant effect on maize (Kolawole, 2012) and soybean grain yields (Mabapa *et al*., 2010). Other researchers reported higher number of pods per plant and greater soybean yields with P applications (Farmaha *et al*., 2011) or improved soybean grain yields with P and K fertilization (Abbasi *et al*., 2012). Olibone and Rosolem (2010) stated that improved P distribution in soil depth resulted in higher soybean yields. Models of soybean yield indicate that soybean yield can be improved with increasing P levels above the extension recommendations (Anthony *et al*., 2012a). Liu *et al*. (2010) reported decreased soil available P after four seasons of crop growth without P fertilizer application, but adding 80 kg P ha^{-1} increased soybean production. The P fertilizer application was effective in improving soybean production with rates up to 55.7 kg ha^{-1} (Zheng *et al*., 2010).

Karamanos and Puurveen (2011) did not observe a significant effect of treating P fertilizer with Avail on the yield of wheat. Guareschi *et al*. (2011) stated that broadcast application of coated P and K polymer 15 days prior to planting improved soybean grain yields compared to fertilizer without coating, but did not show similar increases with coated fertilizer when applied at soybeans planting.

In our study, P uptake in grain improved with high P fertilizer rates and combination with Avail increased P uptake at low P rate of 45 kg ha^{-1}. Karamanos and Puurveen (2011) did not observe a significant effect of P fertilizer with Avail on wheat grain P uptake. However, Abbasi *et al*. (2012) stated that P and K fertilization improved total N, P and K uptake in the soybean seeds. Based on the significant linear regression between plant NDVI at 20 weeks after planting and grain yield, yield increased by 0.88 Mg ha^{-1} for increase in plant NDVI by 0.1. A positive relationship in this study agrees with results obtained by Raun *et al*. (2001), who stated that plant NDVI of winter wheat had a strong relationship to actual grain yield.

5. CONCLUSION

This study investigated the effects of two P fertilizer application rates with and without Avail polymer on winter wheat growth and yield under dryland conditions. Application of P fertilizer significantly improved biomass production, plant NDVI at 8, 10 and 12 weeks after planting and grain yields of winter wheat. Combination of Avail polymer with P fertilizer improved winter wheat biomass production by 6.3% at 45 kg P ha^{-1} and by 4.3% at 90 kg P ha^{-1}, increased nutrient uptake by 8% for combination of Avail polymer with high P rate and generally improved plant NDVI at higher P fertilizer rates. Highest winter wheat grain yields were obtained with fertilizer application at 90 kg P ha^{-1} in treatments with and without Avail and at 45 kg P ha^{-1} in combination with Avail compared to the untreated control. Combination of Avail with P fertilizer improved wheat grain yields by 5.1% at 45 kg P ha^{-1} and 2.0% at 90 kg P ha^{-1}. At low P fertilizer rate, combination with Avail improved grain P uptake by 2.6%. Based on significant linear regression, grain yield increased by 0.88 Mg ha^{-1} with 0.1 increase in plant NDVI across all treatments. The P fertilizer and Avail polymer applications did not affect plant height, grain weight and nitrogen uptake compared to the untreated control.

6. ACKNOWLEDGEMENT

I greatly appreciate a financial support from Specialty Fertilizer Products (SFP) for conducting field research.

7. REFERENCES

Abbasi, M.K., M.M. Tahir, W. Azam, Z. Abbas and N. Rahim, 2012. Soybean yield and chemical composition in response to phosphorus-potassium nutrition in kashmir. Agron. J., 104: 1476-1484. DOI: 10.2134/agronj2011.0379

Afzal, A., A. Bano and M. Fatima, 2010. Higher soybean yield by inoculation with n-fixing and p-solubilizing bacteria. Agron. Suist. Dev., 30: 487-495. DOI: 10.1051/agro/2009041

Anthony, P., G. Malzer, M.C. Zhang and S. Sparrow, 2012b. Soil nitrogen and phosphorus behavior in a long-term fertilization experiment. Agron. J., 104: 1223-1237. DOI: 10.2134/agronj2012.0020

Anthony, P., G. Malzer, S. Sparrow and M. Zhang, 2012a. Soybean yield and quality in relation to soil properties. Agron. J., 104: 1443-1458. DOI: 10.2134/agronj2012.0095

Blackmer, T.M., J.S. Schepers and G.E. Varvel, 1994. Light reflectance compared with other nitrogen stress measurement in corn leaves. Agron. J., 86: 934-938. DOI: 10.2134/agronj1994.00021962008600060002x

De Figueiredo, C.C., D.V. Barbosa, S.A. de Oliveira, M. Fagioli and J.H. Sato, 2012. Polymer-coated phosphate fertilizer and liming on the production and morphological parameters of corn. Rev. Cienc. Agron., 43: 446-452. DOI: 10.1590/S1806-66902012000300005

Farmaha, B.S., F.G. Fernandez and E.D. Nafziger, 2011. No-till and strip-till soybean production with surface and subsurface phosphorus and potassium fertilization. Agron. J., 103: 1862-1869. DOI: 10.2134/agronj2011.0149

Guareschi, R.F., P.R. Gazolla, A. Perin and J.M.K. Santini, 2011. Antecipated fertilization on soybean with triple superphosphate and potassium chloride coated with polymers. Cienc. Agrotecnol., 35: 643-648. DOI: 10.1590/S1413-70542011000400001

Karamanos, R.E. and D. Puurveen, 2011. Evaluation of a polymer treatment as enhancer of phosphorus fertilizer efficiency in wheat. Can. J. Soil Sci., 91: 123-125. DOI: 10.4141/cjss10071

Kihara, J., B. Vanlauwe, B. Waswa, J.M. Kimetu and J. Chianu *et al*., 2010. Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in western Kenya. Exp. Agric., 46: 35-52. DOI: 10.1017/s0014479709990810

Kolawole, G.O., 2012. Effect of phosphorus fertilizer application on the performance of maize/soybean intercrop in the southern Guinea Savanna of Nigeria. Arch. Agron. Soil Sci., 58: 189-198. DOI: 10.1080/03650340.2010.512723

Liu, J., K.Z. Cai, S.M. Luo, L.X. Zhu and J.E. Zhang *et al*., 2010. Soil phosphorous status and phosphorus cycling as influenced by soybean genotypes on an acidic low-phosphorus soil of southern China. Commun. Soil Sci. Plant Anal., 41: 1838-1849. DOI: 10.1080/00103624.2010.492441

Mabapa, P.M., J.B.O. Ogola, J.J.O. Odhiambo, A. Whitbread and J. Hargreaves, 2010. Effect of phosphorus fertilizer rates on growth and yield of three soybean (*Glycine max*) cultivars in limpopo province. Afr. J. Agric. Res., 5: 2653-2660.

McBeath, T.M., M.J. McLaughlin and S.R. Noack, 2011. Wheat grain yield response to and translocation of foliar-applied phosphorus. Crop Pasture Res., 62: 58-65. DOI: 10.1071/cp10237

McBeath, T.M., M.J. McLaughlin, J.K. Kirby and R.D. Armstrong, 2012. The effect of soil water status on fertiliser, topsoil and subsoil phosphorus utilisation by wheat. Plant Soil, 358: 337-348. DOI: 10.1007/s11104-012-1177-8

McLaughlin, M.J., T.M. McBeath, R. Smernik, S.P. Stacey and B. Ajiboye *et al*., 2011. The chemical nature of p accumulation in agricultural soils-implications for fertiliser management and design: An Australian perspective. Plant Soil, 349: 69-87. DOI: 10.1007/s11104-011-0907-7

Nadeem, M., A. Mollier, C. Morel, A. Vives and L. Prud'homme *et al*., 2012. Seed phosphorus remobilization is not a major limiting step for phosphorus nutrition during early growth of maize. J. Plant Nutr. Soil Sci., 175: 805-809. DOI: 10.1002/jpln.201200369

Noack, S.R., M.J. McLaughlin, R.J. Smernik, T.M. McBeath and R.D. Armstrong, 2012. Crop residue phosphorus: Speciation and potential bio-availability. Plant Soil, 359: 375-385. DOI: 10.1007/s11104-012-1216-5

Nunes, R.D., D.M.G. de Sousa, W.J. Goedert and L.J. Vivaldi, 2011. Phosphorus distribution in soil as affected by cropping systems and phosphate fertilization management. Rev. Brasileira Cienc. Do Solo, 35: 877-888.

Olibone, D. and C.A. Rosolem, 2010. Phosphate fertilization and phosphorus forms in an oxisol under no-till. Scientia Agricola, 67: 465-471. DOI: 10.1590/s0103-90162010000400014

Qiao, S.M.Y., 2012. Distribution of inorganic and organic phosphorus fractions in two phosphorus-deficient soils as affected by crop species and nitrogen applications. Commun. Soil Sci. Plant Anal., 43: 631-644. DOI: 10.1080/00103624.2012.644004

Raun, W.R., J.B. Soile, G.V. Johnson, M.L. Stone and E.V. Lukina *et al*., 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J., 93:131-138. DOI: 10.2134/agronj2001.931131x

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone and R.W. Mullen *et al*., 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J., 94: 815-820. DOI: 10.2134/agronj2002.0815

Shanahan, J.F., J.S. Schepers, D.D. Francis, G.E. Varvel and W.W. Wilhelm *et al*., 2001. Use of remote-sensing imagery to estimate corn grain yield. Agron. J., 93: 583-589. DOI: 10.2134/agronj2001.933583x

Wang, Y., F.S. Zhang and P. Marschner, 2012. Soil ph is the main factor influencing growth and rhizosphere properties of wheat following different pre-crops. Plant Soil, 360: 271-286. DOI: 10.1007/s11104-012-1236-1

Wiegand, C.L., A.J. Richardson, D.E. Escobar and A.H. Gerbermann, 1991. Vegetation indices in crop assessments. Remote Sens. Environ., 35:105-119. DOI: 10.1016/0034-4257(91)90004-P

Zheng, H.F., L.D. Chen, X.Z. Han, Y. Ma and X.F. Zhao, 2010. Effectiveness of phosphorus application in improving regional soybean yields under drought stress: A multivariate regression tree analysis. Afr. J. Agric. Res., 5: 3251-3258. DOI: 10.5897/AJAR10.589,