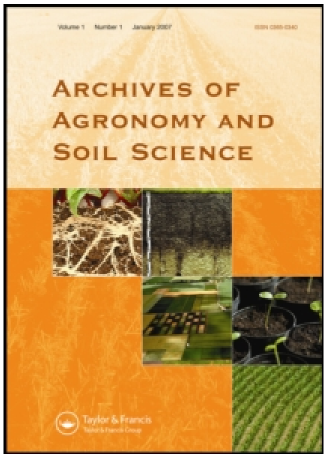

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Analysis of yield variability in winter wheat due to temporal variability, and nitrogen and phosphorus fertilization

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Abstract
Field average based recommendations have been a common practice for recommending the major crop nutrients nitrogen (N) and phosphorus (P). The problem is yield will not be the same from year to year with application of the same amount of recommended rate of fertilizer. The objectives of this study were to demonstrate how recommendations generated using nutrient response experiments were dynamic; and to assess the relative contribution of temporal variability, N and P fertilizers on winter wheat grain yield and N concentration. Twelve factorial combinations of four N (0, 56, 112, and 168 kg ha^{-1}) and three P (0, 14.5, and 29 kg P ha^{-1}) rates were evaluated in a randomized complete block design with three replications at Perkins, Oklahoma. To address the first objective, ANOVA and orthogonal polynomial contrasts were used. To address the second objective, a ten predictor variable multiple linear regression model with two quantitative variables and their interaction (N, P and N $\times$ P) and seven-year variables was evaluated and a reduced model containing seven variables was generated. Wheat grain yield showed three distinct responses to N rates: Linear, quadratic and no response. These individual year data show that it is not always appropriate to use results of nutrient response experiments to estimate next year's N fertilizer requirement due to apparent temporal variability in the results. Wheat only responded to P during the first two years of the study. The reduced model from the regression analysis revealed that most of the variability in grain yield was accounted for by five individual indicator years and N only. High variability across years in grain yield and fertilizer (N and P) response, even between years of similar grain yield, is an indication of a given season's production dependence on factors other than N and P.

Keywords: *Winter wheat, temporal variability, nitrogen, phosphorus*

Introduction

Oklahoma is one of the major winter wheat (*Triticum aestivum* L.) producing states in the United States (US). All winter wheat is produced under dryland rainfed production system. This system is characterized by very high year to year variability which in turn makes difficult

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predicting grain yield and crop nutrient requirement. Temporal and spatial variability are the reasons for evolutionary arrival of precision agriculture. Crop management practices that did not attempt to control or minimize the effects of both temporal and spatial variabilities are incomplete and mostly has economic catastrophe to producers.

Temporal variation is variation in precipitation, soil moisture, nutrient status, disease and pests in time and is very difficult to predict (Machado et al. 2000; 2002). The significance of temporal variability was assessed by a few research studies. Huggins and Alderfer (1995) found that temporal variability explained 50% of crop yield variability across years in corn. Several researchers have reported that managing temporal variability was more important than spatial variability. In a long-term study designed to assess the effect of management and temporal variability in yields of several crops, Eghball and Varvel (1997) found that temporal variability was more important than management (i.e. N fertilizer and cropping sequences). According to Mamo et al. (2003) the economic optimum N rate in corn was significantly influenced by temporal variability through its influence on spatial variability. Additionally, the results indicated the strong dependence of management of corn on temporal variability.

Likewise, Flowers et al. (2004) found that in-season optimization of N rate through management of temporal variability was more important than site-specific management. According to their results a large reduction in N inputs (up to 48.6%) was attributed to an in-season N rate optimization while a further reduction in N inputs (up to 19.6%) was possible through site-specific application. The authors also reported that N use efficiency was improved by site-specific N application compared with either field-specific or typical growers' practices. Their results clearly showed the significance of managing temporal variability that is a function of several factors.

Nelson (1990) reported that in US about 30–50% of crop yield obtained is attributed to application of the major nutrients N and P. In another study, Oklahoma State University (2000) reported that when averaged over 71 years, N and P fertilizers explained 40% of wheat yield. In their report Stewart et al. (2005) indicated that in wheat, elimination of N fertilizer caused a reduction of at least 16% in grain yield on average. Nitrogen and P management based on soil test results and nutrient response trials did not address temporal variability. Partly this was attributed to the mobile nature of N in the soil and fast transformation of both nutrients from one form to another. However, as it is known, N is required abundantly by wheat and it has also several loss mechanisms making it more unpredictable as compared to P.

It has been stressed from the research perspective to synchronize nutrient supply with crop demand in order to ensure optimum crop yield and quality while avoiding deleterious impacts on the environment (Grant et al. 2002) by managing temporal variability. Given the importance of temporal variability in the dryland winter wheat production system, the relative contribution of temporal variability and management (N and P) was not quantified. There was not much data documented in the literature that shows how certain management decisions, such as nutrient response trials are misleading unless temporal variability is considered in due process. In this study we sought: (i) To demonstrate how recommendations generated using nutrient response experiments were dynamic; and (ii) assess the relative contribution of temporal variability, N and P fertilizers on winter wheat grain yield and N concentration.

Materials and Methods

Experiment description

A long-term field experiment was initiated in 1996 at Perkins (Teller sandy loam, fine-loamy, mixed, thermic Udic Argiustoll), Oklahoma, USA. Initial soil characteristics are reported in Table I. Twelve factorial combinations of four N (0, 56, 112, and 168 kg ha^{-1}) and three P (0, 14.5, and 29 kg P ha^{-1}) levels were evaluated in a randomized complete block design with three replications. Nitrogen and P were broadcast and incorporated to 5 cm depth as urea (46% N) and triple super phosphate (46% P_2O_5), respectively, in late August to mid-September depending on soil moisture status. Plots are permanent from year to year and received fixed rates of N and P every year. The plot size was 3.1 × 9.1 m. The winter wheat variety 'Tonkawa' was used during the 1996–1999 cropping seasons. This variety was replaced by 'Custer' from 2000–2002. Wheat was planted between October and November in 25.4 cm wide rows at a seeding rate of 98 kg ha^{-1}. All other crop management practices were carried out as per the Oklahoma State University recommendation for the Perkins site.

Wheat was harvested from the centre of each plot in June with a Massey Ferguson 8XP plot combine with a yield-monitoring computer (Harvest Master^{TM}) to record grain weight and moisture levels, removing an area of 2 × 9.1 m from the centre of each plot. Grain harvested from the net plot was used to determine grain yield after adjusting to a 13% moisture level. Grain sub-samples collected for total N analysis were dried in a forced-air oven at 66°C, ground to pass a 140 mesh sieve (100 μm), and analysed for total N concentration using a Carlo-Erba (Milan, Italy) NA-1500 dry combustion analyser (Schepers et al. 1989).

Data analysis

Grain yield and N concentration data since 1998 were subjected to analysis of variance (ANOVA) for each year using SAS (SAS institute 2001). A multiple regression analysis conformed to a model with one quantitative variable and six-year indicator variables. A qualitative variable with *i* classes is represented by *i*-1 indicator variables (Kutner et al. 2004). One year (2001) was used as a reference group (i.e. the slope coefficients of the years included in the model would be compared to the reference group) to obtain unique estimators of the regression coefficients for the rest of the indicator variables representing years. The regression equation for grain yield (GY) was:

$$\begin{aligned} GY_i = {} & \beta_0 + \beta_1 N_i + \beta_2 P_i + \beta_3 N_i P_i + \beta_4 Y_{1i} + \beta_5 Y_{2i} + \beta_6 Y_{3i} + \beta_7 Y_{4i} \\ & + \beta_8 Y_{5i} + \beta_9 Y_{6i} + \beta_{10} Y_{7i} + \varepsilon_i \end{aligned}$$

where GY_i = expected grain yield (kg ha^{-1}) of the ith treatment mean; i = 1, 2,...n; n = number of treatment means (= 84 in the study); N and P are nitrogen and phosphorus; Y = 1, 2,... 7 denote year variables for years 1998 through 2004 in that order; β_0 = intercept;

Table I. Initial surface (0–15 cm) soil chemical characteristics at Perkins, OK, 1996.

pH	NH_4-N	NO_3-N	P	K	Total N	Organic Carbon
-----------------mg kg^{-1}-----------------					-------g kg^{-1}-------	
5.95	3.04	2.83	8.99	133.0	0.50	5.34

Phosphorus and K were extracted and measured with Mehlich-3 extractant and analysis methods, respectively (Mehlich 1984). Saturated paste extraction of 1:1 soil to deionized water was used for soil pH. Ammonium-N and NO_3-N were extracted using 2M KCl (Bremner 1965) and analyzed using a Lachat QuikChem AE automated flow injection analysis system (Lachat Instruments, Milwaukee, WI, USA). Organic C and Total N were determined using Carlo Erba NA-1500 dry combustion analyser (Milan, Italy).

β_1, β_2, and β_3 are coefficients for N, P, and N × P; β_4, $\beta_5, \ldots$, B_9 and B_{10} are regression coefficients for Y1, Y2,...,Y6 and Y7, respectively; and ε_i = Error term.

The multiple regression analysis initially included all 10 components. Elimination of components exhibiting the least contribution to the regression sum of squares and being non-significant individually ($p > 0.05$) was accomplished using 'Forward Stepwise Regression' automatic model selection procedure. This procedure adds and drops each variable in the model using a *t*-statistic (Neter et al. 1990; Kutner et al. 2004). Ultimately only those components with significant ($p < 0.05$) contribution to the multiple regression (contribute the most variability in the response variable grain yield) were retained in the reduced model. For the reduced model, REG procedure in SAS (SAS institute 2001) was used to determine the partial squared correlation coefficients, PCORR1 and PCORR2 from Type I sequential sum squares and Type III partial sum-squares, respectively. The partial squared correlation coefficients were used to define the contribution of each predictor variable in the final reduced model by removing the effect of the other predictor variables on that predictor variable and the response variable (Cohen et al. 2002). This same procedure was also applied on grain N concentration data.

Results and discussion

Nitrogen, P and N by P interaction

Wheat grain yield responded to N rates in five of seven years (Table II). During the first two years (1998 and 1999), wheat grain yield increased linearly with N rates. Wheat grain yield showed a significant quadratic response to N fertilizer in three years (2000, 2003 and 2004) while in two years (2001 and 2002) wheat did not respond to N fertilizer rates. If we based N fertilizer recommendation on the quadratic response shown above, we would have recommended to producers 56 kg N ha^{-1} in 2000 and 2003 and would have recommended 112 kg N ha^{-1} based on 2004 data. On the other hand, if we base our recommendation on

Table II. Mean wheat grain yield and probabilities of polynomial orthogonal contrasts at Perkins, OK, 1998–2004.

Source	1998	1999	2000	2001	2002	2003	2004
N, kg ha^{-1}	Yield, kg ha^{-1}						
0	1147	584	1654	2306	2769	2744	2087
56	1602	954	2418	2472	2804	3510	3599
112	2063	1233	2297	2316	2683	3493	3877
168	2196	1269	2161	2026	2686	3488	3697
Linear	***	***	$p < 0.1$	NS	NS	***	***
Quadratic	NS	NS	*	NS	NS	***	***
SED	179	101	254	223	249	122	194
P, kg ha^{-1}	Yield, kg ha^{-1}						
0	1535	823	2514	2317	2680	3242	3492
15	1744	1045	2279	2398	2680	3322	3457
30	1978	1163	1593	2130	2847	3362	2996
Linear	***	***	***	NS	NS	NS	***
Quadratic	NS	NS	NS	NS	NS	NS	NS
SED	155	88	220	193	215	106	168

*, ***Significant at the 0.05, 0.01 and 0.001 levels of probability, respectively; NS, not significant; SED, standard error of the difference of two equally replicated means.

the years where linear response was observed (168 kg N ha^{-1}), we would have applied excess N in the other five years where response was not apparent or was quadratic. Alternatively, if recommendation was based on 2001 and 2002 data we would have recommended no N and virtually misleading producers. These individual year data shows that it is not commendable to use results of nutrient response experiments to estimate next year's N fertilizer requirement due to apparent temporal variability. Despite this however, some researchers still offer this approach as viable option. In the Great Plains, N rates near 70 kg N ha^{-1} or less were generally sufficient to optimize small-grain crops yields in several continuous cropping studies when estimates of yield goals were difficult to obtain and no information on residual soil N concentration was available (Schlegel et al. 2005).

Grain N concentration was affected in six of seven years. Accordingly it was linearly and positively related to N rate for all years except 2001 (Table III). At least for this kind of variable where nutrient response experiments showed a consistent trend over years, it is plausible to use the results for subsequent growing seasons if N concentration in the grain is the variable of primary interest for the producer.

The wheat crop seemed to benefit and respond to P only during the first two years of the study (Table II). Beyond that, wheat showed no response and the application of P resulted in inconsistent trend compounded by other unforeseen factors. The soil test P based recommendation in several states suggests an application of the amount that would equal the amount removed in harvested crops (Dahnke & Olson 1990). Interestingly the experimental results support this approach due to a lack of significance to P that was independent of years. Consequently this shows that variability in years which is, of course, the function of several weather-related factors did not have much influence on P use of the crop. In such cases an in-season crop demand might be satisfied with foliar P supplement. According to recent studies by Mosali et al. (2006) foliar P was recommended to supplement P requirement of wheat versus continuous application of P as blanket preplant recommendation to correct deficiency in case crop requires P at the peak grain filling time. Similarly, P had effect on

Table III. Mean grain N concentration (g kg^{-1}) and probabilities of polynomial orthogonal contrasts at Perkins, OK, 1998–2004.

Source	1998	1999	2000	2001	2002	2003	2004
N, kg ha^{-1}				N concentration, g kg^{-1}			
0	20.6	21.5	19.1	37.7	20.3	19.2	17.6
56	21.2	21.7	21.1	23.6	25.0	22.5	21.0
112	23.1	24.2	22.1	25.2	27.2	24.9	24.8
168	23.5	27.7	25.9	26.0	27.7	27.2	29.1
Linear	***	***	***	NS	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS	NS
SED	0.8	0.9	1.0	4.5	1.0	1.0	1.0
P, kg ha^{-1}				N concentration, g kg^{-1}			
0	22.7	25.3	22.3	24.1	24.8	23.0	23.0
15	21.9	22.8	21.3	37.1	25.4	23.3	22.8
30	21.8	23.2	22.6	25.2	25.0	24.1	23.6
Linear	NS	*	NS	NS	NS	NS	NS
Quadratic	NS	*	NS	*	NS	NS	NS
SED	0.7	0.8	0.9	4.0	0.8	0.9	0.8

*, ***Significant at the 0.05 and 0.001 levels of probability, respectively; NS, not significant; SED, standard error of the difference of two equally replicated means.

grain N concentration only in two instances (1999 and 2001) where a quadratic relationship was observed between grain N concentration and the three levels of P (Table III). The nutrient response experiment approach might work better for P as evidenced by consistent results over years. No significant N and P interaction was observed for any of the years.

Evaluation of grain yield and N concentration variability explained by temporal variability, N and P

The results of the simultaneous regression of the mean wheat grain yield for the N, P and $N \times P$ treatments and the seven years (2001 as reference group), revealed that six of the 10 regression coefficients used in the model were significant. The parameter estimates, probabilities, partial squared correlation coefficients, i.e. SPCORR1 and SPCORR2 (from both type I and III sum squares, respectively) are given in Table IV. The model that included the six significant components in the multiple regression analysis explained a significant proportion of the variation in wheat grain yield ($R^2 = 0.71$). The coefficients in Table IV showed that very large positive coefficients were associated with most of the indicator variables except years 1998 and 1999, where coefficients were large negatives. The partial squared correlation coefficients clearly indicated the strong effect of year variables on grain yield. Figure 1 also shows this variability across years. The high variability across years and dependency of final grain yield on these years is simply an indication of a given season's production dependence on factors other than N. This has great impact for those recommendations based on yield goal as increased year-to-year yield variability with continuous cropping poses difficulty in accurately estimating yield goals. This year-to-year variability also means it is not appropriate for farmers to fertilize a crop that does not reflect fertilizer response in the final yield. Indeed it has been the challenge of both researchers and farmers to know what is happening over a season as most of the farming practices are dictated by crop growth stage and the need to follow cropping calendar.

Selection of the best model for grain N concentration revealed that N was the only significant component that explained a substantial portion of variability in grain N content (data not shown). Phosphorus and the seven-year indicator variables were excluded from the reduced model. This shows that grain N concentration of wheat is not affected by temporal variability as such for the soil type in this study, indicating that grain protein (derived from grain N concentration) will not fluctuate year-to-year.

Table IV. Parameter estimates, probabilities, and partial squared correlation coefficients for effect of N and year indicator variables on grain yield of winter wheat at Perkins, OK.

Parameter	Variable	Estimate	$Pr > \|t\|$	SPCORR1[†]	SPCORR2[‡]
$\beta 0$		1910	***	.	.
$\beta 1$	N	3.52	***	0.05	0.150
$\beta 2$	1998	−453	***	0.07	0.06
$\beta 3$	1999	−1195	**	0.46	0.33
$\beta 5$	2002	531	***	0.00	0.08
$\beta 6$	2003	1104	***	0.12	0.29
$\beta 7$	2004	1110	***	0.29	0.29

**, ***Significant at the 0.01 and 0.001 levels of probability, respectively; †The squared partial correlation coefficients calculated using Type I sequential sum square; ‡The squared partial correlation coefficients calculated using Type III partial sum square.

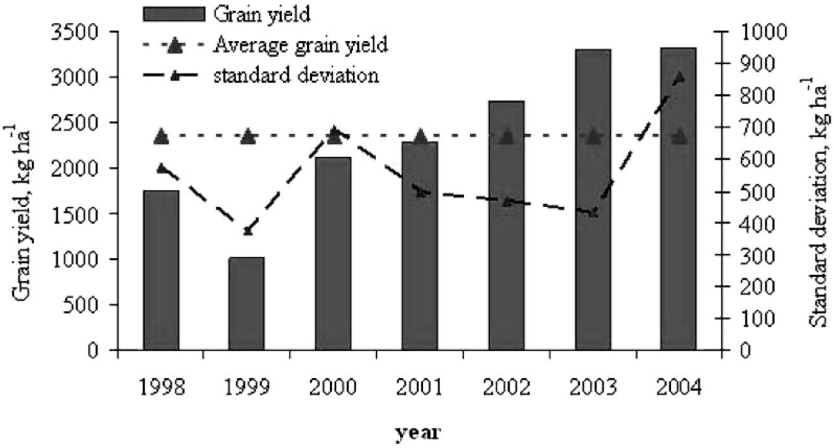

Figure 1. Winter wheat grain yield, overall mean and standard deviation across years at Perkins, OK, USA.

Our results showed that temporal variability due to yield limiting factors other than N is a major factor controlling winter wheat grain yield followed by N fertilizer. Several studies have shown that N fertility was one of the most important factors accounting for variability in corn yield (Varvel 2000). Nitrogen nutrition, whether it is from an inorganic or organic source was found to stabilize winter wheat grain yield despite tremendous year-to-year variability in yield due to temporal variability (Raun et al. 1993).

The results of this study conform to the current notion that 'average based' N recommendation should be avoided. Producers need to shift to alternate strategies that comply with current pressures for both competitiveness and environmental protection in agricultural production. Such alternative methods include the new N rich and ramp calibration strips (Girma et al. 2007) that are easy to use while managing temporal variability.

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