Received: 24 March 2019 | Accepted: 22 December 2019

DOI: 10.1002/agg2.20017

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Agrosystems

Effect of winter wheat cultivar on grain yield trend under different nitrogen management

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Abstract

In many developing countries, crop production is achieved with little or no application of fertilizer N. Understanding grain yield trends as new winter wheat cultivars (*Triticum aestivum* L.) are released and grown under different N management is important for crop yield improvement. This study evaluated grain yield trends of winter wheat cultivars over time in a crop production system with and without N application. Yield data was obtained from two long-term experiments; 502 (E502) and 222 (E222) between 1969 and 2018. Results showed a mean annual grain yield increase of 12 and 30 kg ha^{-1} yr^{-1} as new cultivars were released and grown under adequate N management in E222 and E502, respectively. However, without N application, yield declined annually by 2.4 kg ha^{-1} yr^{-1} in E222 and increased marginally by 0.6 kg ha^{-1} yr^{-1} in E502. Nonetheless, the yield increase or decrease was only significant for E502 at 112 kg N ha^{-1} ($r^2 = .145$; $p = .01$) and its slope was significantly different from that of control treatment ($p = .02$). In both experiments, yield was significantly influenced by cultivar and N interaction ($p < .01$), an indication that yield changed according to the level of N applied. In general, when N was applied, grain yields were high as well. New cultivars released over time improved grain yield with adequate N management.

1 | INTRODUCTION

The past decades have seen the release of several new winter wheat (*Triticum aestivum* L) cultivars by crop breeders around the world to increase crop yield and quality (Foulkes, Sylvester-Bradley, & Scott, 1998; Fufa et al., 2005). This has been driven by the continuous growth in human population (Vitousek et al., 1997), and a fixed land area under cultivation (Lambin & Meyfroidt, 2011). Grain yield and qualities for winter wheat are a result of the interaction between crop genetics and the environment. Modern cultivars have been observed to achieve higher grain yield than those released before them (Fufa et al., 2005). The same study revealed that the newly released cultivars consistently yielded higher than older cultivars across all environments in which they were grown. Foulkes et al. (1998) attributed the yield increase of 1.9 Mg ha^{-1} to the release of new cultivars with high-yielding genes over a 20-yr period. During the same period, the study showed an annual increase of 2.8 kg ha^{-1} in fertilizer N requirement. However, the peak performance of modern cultivars is best achieved in high yielding environments

Abbreviations: E, experiment; NUE, nitrogen use efficiency.

and may also yield higher than old cultivars in low yielding environments (Brancourt-Hulmel et al., 2003). De Vita et al. (2007) observed a similar result where there was a yield difference between modern and old cultivars evaluated under different N rates of at least 45 kg ha^{-1}. Ortiz-Monasterio, Sayre, Rajaram, and McMahon (1997) showed that genetic yield gains occurred at all the N rates for the modern cultivars and was higher at high N rates compared to the old cultivars which were more affected by lodging. They further reiterated that the modern cultivars perform equally and, in some cases, better than old cultivars in low yielding environments and that modern cultivars are more responsive to N compared to old ones. Because of the good performance of modern cultivars, annual grain yield increase has been reported in past studies. In a study that spanned from 1962–2000, Zhou et al. (2007) found winter wheat grain yield to increase annually at a rate of 0.48–1.23%. Sayre, Rajaram, and Fischer (1997) also found genotypes to contribute to an annual yield gain of about 0.9% per year. Foulkes et al. (1998) found that newly released wheat genotypes contributed to an annual grain yield improvement of approximately 96 kg ha^{-1}.

Several studies have documented the evidence of N contribution to improved crop yields (Mohammed et al., 2013; Omara, Macnack, Aula, & Raun, 2017; Phillips & Mullins, 2004; Yi, He, Zhang, Yang, & Xiong, 2015). Stewart, Dibb, Johnston, and Smyth (2005) estimated yield increases due to fertilizer N and P to be between 40 and 60%.

It is, therefore, important to note that the higher yields achieved today can be attributed to improved genetics, N application, and other environmental factors (Ortiz-Monasterio et al., 1997). Recent technological advances to improve nitrogen use efficiency (NUE) used active normalized difference vegetation index (NDVI) sensor readings taken mid-season to estimate plant biomass, and project nutrient needs and demands (Raun et al., 2002). Further progress has been made through breeding programs directed to improve cultivar production in terms of grain yield but also NUE. This is expected to ensure maintenance of the integrity of the environment (Raun & Johnson, 1999).

However, in many developing countries, crops are grown with little or no application of fertilizers particularly N and this is coupled with declining soil fertility (Ehui & Pender, 2005; Taddese, 2001). The low soil fertility problem, which has persisted around the world and was documented more than two centuries ago, contributed to the development of fertilizers that are widely used today particularly in developed countries (Foster & Magdoff, 1998). With the inadequate application of plant nutrients, it may be possible that over the years, new cultivars have not offered a substantial yield increase for smallholder farmers in developing countries. This makes it important to understand and document the yield trend as new winter wheat cultivars are released in agronomic environments with and without sufficient N. Long-term experiments present a unique opportunity to study how yields have changed as new cultivars are released and grown under varying N regimes in a winter wheat monocropping system. The superiority of modern cultivars over the old cultivars of winter wheat would be expected to increase grain yield over time in all environments including infertile soils common in developing countries. Although some studies have demonstrated this genetic superiority across all crop growing environments, it is important to further evaluate and document winter wheat yield trends using long-term winter wheat fertility trials subjected to a range of N rates.

This study evaluates trends in winter wheat yields as influenced by cultivar and N application.

Core Ideas

- New cultivars improved grain yield in Experiment 502 at 112 kg N ha^{-1}.
- No significant yield change at zero N rate at both sites.
- Reaping full benefit of high yielding cultivars requires fertilizer N input.

2 | MATERIALS AND METHODS

Two long-term winter wheat fertility trials; Experiment 502 (E502) and Experiment 222 (E222) were used to establish trends for winter wheat grain yields over time as influenced by cultivar and N fertilization.

Experiment 222 was established in 1969 in Stillwater, OK, while E502 was established in 1970 at Lahoma, OK. The E502 site soil is a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustoll), while the E222 soil is a Kirkland silt loam (fine-silty, mixed, thermic Udic Paleustoll). The experimental design for E222 and E502 was a randomized complete block design with four (0, 45, 90 and 135 kg ha^{-1}) and six (0, 22, 45, 67, 90 and 112 kg ha^{-1}) N treatments, respectively. Each N treatment was replicated four times. Additional description of these experiments was reported by Aula, Macnack, Omara, Mullock, and Raun (2016). For this study, yield data were obtained from plots that received 0 and 135 kg N ha^{-1}; and 0 and 112 kg N ha^{-1} for E222 and E502, respectively. Winter wheat cultivars planted every fall for each experiment during this study period are reported in Table 1. Key features for each of the cultivars were described on the Oklahoma State University (OSU, 2019) website for winter wheat. For all sites, varieties

TABLE 1 Wheat cultivars grown at Experiments 222 (E222) and 502 (E502) between 1969 and 2018

	Period	
Cultivar	**E222**	**E502**
Scout 66	1969–1973	×
Nicoma	×	1971–1974
Triumph 64	1974–1977	1975–1976
Osage	1978–1980	1977–1977
Triumph 64	×	1978–1978
TAM 101	1981–1992	1979–1992
Karl	1993–1994	1993–1994
Tonkawa	1995–1999	1995–1999
Custer	2000–2004	2000–2004
Overley	×	2 005–2008
P2174	2005–2005	×
Endurance	2006–2007	2009–2009
Bullet	×	2010–2011
Billings	×	2012–2013
Ruby Lee	×	2014–2014
OK Field	2008–2009	×
GoLead	2010–2010	×
Centerfield	2011–2011	×
Endurance	2012–2012	×
OK9935C	2013–2013	×
Doublstop-CL	2014–2014	×
Iba	2015–2018	2015–2018

Note. × Indicates that the cultivar was not grown at the time reflected in other trials in the same row.

in these long-term trials were periodically changed because perceived genetic benefits were expected. Grain yield was collected annually at harvest using a self-propelled experimental combine and the data was stored on an Oklahoma State University website (OSU, 2018). The downloaded winter wheat grain yield covered the period between 1969 and 2018 (Table 1).

The data for each experimental site was analyzed independently using PROC MIXED model in SAS (SAS Institute, 2016). The fixed effects of cultivars, N rates, and the interaction between cultivars and N rates were examined across years. Replication was treated as a random effect. The fixed effects were tested for significance using Kenward–Roger approximation with DDFM = KR specified in the model statement of PROC MIXED. Treatment means (Least Significant Means) were separated using the Bonferroni procedure at a .05 probability level. Simple regression analysis was also accomplished using PROG MIXED to determine the change in yield over time under two N rates for each trial.

3 | RESULTS AND DISCUSSION

3.1 | Trends in grain yield

Results showed that the release of new winter wheat cultivars over time resulted in an increase in grain yield for a management approach that integrated external N inputs in E502 (p = .0100; r^2 = .145) (Table 2). During the study period in E502, there was a linear increase in yield as new cultivars were released and grown in an environment with N application (Figure 1). Over time, the slight increase in yield as new cultivars were released and grown under adequate N management in E222 was not significantly different from zero, potentially indicating that yield did not change by substantial margin during the study period (p = .205; r^2 = .0350) (Table 2). The slope components showed that for treatments receiving 135 and 112 kg N ha^{-1}, grain yield increased annually at the rate of 12 and 30 kg ha^{-1} in E222 and E502, respectively (Figures 1 and 2). This represented 0.34 and 0.79% annual grain yield increase in E222 and E502, respectively.

With no N applied, genetic yield gains experienced a slight annual yield increase of 0.56 kg ha^{-1} yr^{-1} or 0.02% yr^{-1} in E502 (Figure 1). This yield increase was not substantially different from zero (p = .921; r^2 = .0100) (Table 2). Meanwhile, in E222, the introduction of new cultivars without inorganic N application over the years resulted in an annual grain yield reduction of 2.4 kg ha^{-1} (.07%) (Figure 2). The lack of significance in yield decline indicates that the slope was not different from zero (p = .732; r^2 = .0100) (Table 2).

These results suggest that in the absence of N fertilizer inputs, the introduction of new wheat cultivars in a continuous wheat monoculture cropping system have not led to yield increases. However, since soil and climatic conditions have likely changed with time and cultivars are confounded with time in these experiments, direct comparisons of cultivar performance cannot be made. We can only conclude that the combination of time and the introduction of new cultivars resulted in yield increases in fertilized plots, but not unfertilized plots.

Further analyses showed that the slopes for yield trends at 0 and 135 kg N ha^{-1} in E222 were not significantly different from each other (p = .217) (Table 2). This indicates that the rate of change in yield was similar at both N rates of 0 and 135 kg N ha^{-1}. In E502, the slopes at 0 and 112 kg N ha^{-1} were significantly different from each other (p = .02) (Table 2). This shows that the annual rate of yield increase (30 kg ha^{-1} yr^{-1}) at 112 kg N ha^{-1} was significantly greater than the rate of increase (.56 kg ha^{-1} yr^{-1}) at 0 kg N ha^{-1}. Other researchers have demonstrated that new cultivars introduced over time resulted in an improvement in winter wheat grain yield. For instance, Ortiz-Monasterio et al. (1997) reported that the introduction of new cultivars over time has led to an improvement in grain yield under both

TABLE 2 Regression analysis for winter wheat grain yield vs. years of wheat production in Experiments 222 (E222) and 502 (E502)

			SE				*p* value	
N rates kg ha^{-1}	Intercept	Slope	Intercept	Slope	CV %	r^2	Intercept	Slope
E222								
0	6,100	–2.4	14,000	6.9	50.5	.0100	.662	.732
135	–22,000	12	19,000	9.5	44.3	.0350	.246	.205
Slope at 0 vs. Slope at 135								.217[a]
E502								
0	630	0.56	1,100	5.6	30.1	.0100	.956	.921
112	–56,000	30	21,000	11	33.0	.145	.0120	.0100
Slope at 0 vs. Slope at 112								.0182

Note. CV, Coefficient of variation.

[a]Since the two slopes for E222 were not significantly different, the common slope was reflected in these two equations; at 0 kg N ha^{-1} yield = –8400 + 4.94x, at 135 kg N ha^{-1} yield = –7700 + 4.94x. The data used for analysis was measured in kg ha^{-1}.

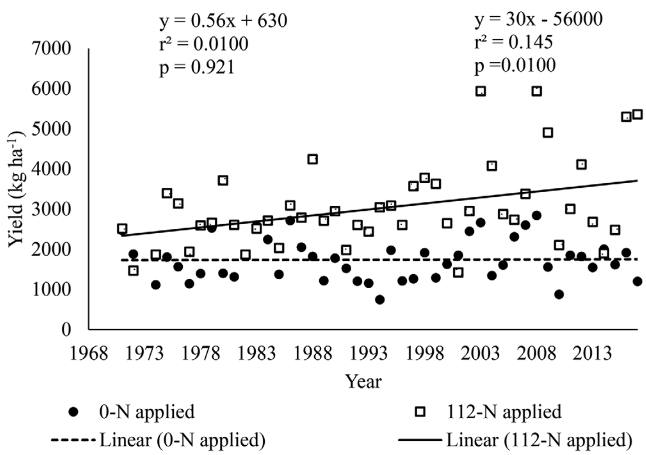

FIGURE 1 Grain yield trends at zero (0-N) and 112 kg N ha^{-1} (112-N) as observed at Experiment 502, 1969–2018. Regression equations on the left and right represent fitted lines at 0-N and 112-N, respectively

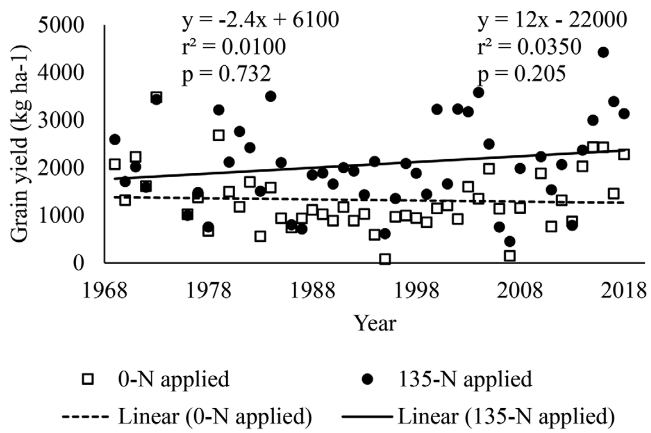

FIGURE 2 Grain yield trends from 1969–2018 at zero (0-N) and 135 kg N ha^{-1} (135-N) as observed in Experiment 222. Regression equations on the left and right represent fitted lines at 0-N and 135-N, respectively

low and high N management with at least a 17.5 kg ha^{-1} yr^{-1} (.3%) annual yield gain. Brancourt-Hulmel et al. (2003) revealed a significant improvement in grain yield with time. They, however, noted that much of the grain yield improvement was due to treatment comprising of N and fungicide. This was demonstrated by a large ratio of explained to unexplained variance (F = 1187.2) for treatment which exceeded that of genotype by 806.7 Brancourt-Hulmel et al. (2003). Sayre et al. (1997) also found an annual yield gain of about 67 kg ha^{-1} yr^{-1} or 0.9% per year. Zhou et al. (2007) examined genetic gains in winter wheat grain yield at 200 kg N ha^{-1} and found that the genetic improvement contributed to an annual grain yield increase of 0.48–1.23%. Lithourgidis, Damalas, and Gagianas (2006) in a 25-yr study of continuous winter wheat, observed a slight decline in grain yield over time. The annual grain yield increase of 0.34 and 0.79% in E222 and E502, respectively were within the range of yield increases reported in other studies (Fischer, 2009; Sadras & Lawson, 2011; Sayre et al., 1997; Zhou et al., 2007).

3.2 | Effect of cultivars and nitrogen management on grain yield

Results for E222 and E502 showed that there was a significant interaction effect of cultivars and N rates on winter wheat grain yield (p < .01) (Table 3). This may indicate that the contribution of cultivars to improved crop yield was closely related to N management. Generally, grain yields were higher for treatment combinations that included fertilizer N application. In E502, there were 26 treatment combinations involving 13 cultivars and two levels of N (0 and 112 kg N ha^{-1} denoted as N_0 and N_{112}, respectively). Analysis showed that 160 out of 169 possible pairwise comparisons for treatments

TABLE 3 Analysis of variance *F* and *p* values showing sources of variation for winter wheat cultivars and N rates in Experiments 222 (E222) and 502 (E502)

	E222			E502		
	ANOVA			ANOVA		
SOV	df	*F* value	*p* value	df	*F* value	*p* value
Cultivar	14	19.5	<.01	12	7.2	<.01
N rate	1	49.4	<.01	1	181.3	<.01
Cultivar × N rates	14	4.0	<.01	12	5.1	<.01
	Mean grain yield, Mg ha^{-1}					
Cultivars		Mean[a]	SE	Mean	SE	
Scout 66		2.2	0.1	×	×	
Nicoma		×	×	1.9	.2	
Triumph 64		1.2	.2	2.3	.2	
Osage		1.8	.1	1.5	.3	
TAM 101		1.5	.1	2.3	.1	
Karl		1.3	.2	1.8	.2	
Tonkawa		1.1	.1	2.4	.1	
Cluster		2.1	.1	2.7	.1	
Overley		×	×	3.1	.1	
P2174		2.2	.2	×	×	
Endurance		1.0	.1	3.2	.3	
Bullet		×	×	2.0	.2	
Billings		×	×	2.5	.2	
Ruby Lee		×	×	2.0	.3	
OK Field		1.6	.2	×	×	
GoLead		2.1	.2	×	×	
Centerfield		1.1	.2	×	×	
OK9935C		0.8	.2	×	×	
Doublestop-CL		2.2	.2	×	×	
Iba		2.8	.1	2.8	.1	
N rates						
	N rates, kg ha^{-1}					
0		1.4	.1	1.7	.1	
112 /135[b]		2.0	.1	3.0	.1	
Contrast (0 vs. 112/135)		<.01[c]		<.01[c]		

Note. SOV, source of variation; df, degrees of freedom; SE, standard error.

[a]Average grain yield for wheat cultivars, and N rates.

[b]N rates of 112 and 135 kg ha^{-1} were applied in E502 and E222, respectively.

[c]*p* value due to contrast of yields at 0 vs. 112 kg ha^{-1} (E502) and 0 vs. 135 kg ha^{-1} (E222).

involving cultivar by N_{112} interactions resulted in grain yields that exceeded that of cultivar × N_0 interactions. Furthermore, 54.4% of the possible comparisons of cultivar × N_{112} interaction with cultivar by N_0 interaction was significantly different from each other ($p < .05$).

In E222, 30 treatment combinations that included 15 cultivars, and 2 N levels (0 kg ha^{-1} denoted by N_0; and 135 kg ha^{-1} denoted by N_{135}) existed. Comparison of cultivar × N_0 interactions with cultivar × N_{135} interactions showed that out of the possible 225 pairwise comparisons, 75.1% resulted in higher yields for treatment combinations involving cultivar × N_{135} interactions. However, only 25.3% were statistically different from yield levels of treatment combinations that included cultivar by N_0 ($p < .05$).

The main effect of cultivar was significant at both experimental sites ($p < .01$) (Table 3). This indicated that yield differences existed among cultivars grown at each location. For instance, Iba, a winter wheat cultivar introduced in 2015, had significant yield differences with more cultivars (eight) than any other cultivar grown in E222 ($p < .01$). In E502, Overly, a cultivar introduced in 2005, had substantially higher grain yield differences with more cultivars (four) than any other cultivar ($p < .03$).

The effect of cultivars on grain yield of winter wheat was observed in this study in E222 and E502. This was detected when grain yields were averaged across N rates and years. Souza et al.(2004) reported that cultivars significantly influenced grain yield. However, they noted that location had a greater effect on grain yield than genotypes and that the genotype × N interaction did not influence grain yield. Sayre et al. (1997) further stated that the contribution of cultivars to grain yield improvement may be associated with an increase in the number of kernels per square meter. A study conducted by Kanampiu, Raun, and Johnson (1997) found yield differences among cultivars grown at two different locations. In the same study, interaction between N and cultivars were inconsistent with a significant effect on grain yield in one site and no effect at the second site. Le Gouis, Béghin, Heumez, and Pluchard (2000) did not only detect significant main effects for cultivars and N rates but also found a significant interaction of the two factors on winter wheat grain yield. This was consistent with results from this study which found a significant interaction effect of cultivar and N rates on grain yield. This further showed that cultivars performed differently at variable levels of N, potentially illustrating a yield advantage for wheat grown under adequate N management.

Nitrogen rates, as the main effect, significantly affected winter wheat grain yield at both locations ($p < .01$) (Table 3). Grain yield was highest with addition of external fertilizer N. Grain yield averaged across years and cultivars showed that N application contributed to 42.9 and 76.5% higher yield when compared to no fertilization in E222 and E502, respectively ($p < .01$) (Table 3). The ratio of explained variance to unexplained variance or F distribution, indicated that N application contributed to the largest improvement in winter wheat grain yield (Table 3).

The average yield levels due to fertilization in E222 were consistent with the 40–60% yield increase reported by Stewart et al. (2005). The average yield in E502 was 16.5% higher than the top end of the range. Fertilizer N is vital in the production of food for both animal and human consumption. El-Sirafy, Woodard, and El-Norjar (2006) reported that application of fertilizer N resulted in a much higher yield than yield obtained without inorganic N fertilization or when other N sources were used. This may be due to increased tillering resulting from N applied before anthesis (Peltonen, 1993). In emphasizing the importance of N, Stewart et al. (2005) stated that yield of non-leguminous crops such as wheat could be reduced by as much as 26% without N application. In contrast to this study, Souza et al. (2004) did not detect a significant effect of N on wheat grain yield. They further stated that applying large quantities of N may also lower grain protein concentration. Raun et al. (2002) showed that applying N at the right rate and time improves not only grain yield but also NUE for winter wheat. While N is a limiting factor in cereal production, applying large quantities could lower N utilization efficiency or partial factor productivity (Fischer, 1993; Omara, Aula, Oyebiyi, & Raun, 2019).

4 | CONCLUSION

This study found inconsistent results at the two experimental sites. In E222, the release and growing of new winter wheat cultivars did not lead to a significant grain yield increase or decrease at the two N rates with time. Conversely, the release and growing of new cultivars over the years led to a significant grain yield increase with time for N management that involved application of 112 kg N ha^{-1} in E502. Grain yield was to a large extent influenced by N rate as well as its interaction with cultivars. For producers in developing countries to improve wheat grain yield and meet the food needs of the ever-expanding human population, growing of new cultivars together with N fertilization may need to become an integral part of the farming operation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Aula L, Omara P, Eickhoff E, Oyebiyi F, Dhillon JS, Raun WR. Effect of winter wheat cultivar on grain yield trend under different nitrogen management. *Agrosyst Geosci Environ*. 2020;3:e20017. https://doi.org/10.1002/agg2.20017