Published online August 10, 2007

In Celebration of 100 Years of ASA

The Magruder Plots: Untangling the Puzzle

Kefyalew Girma, Starr L. Holtz, Daryl B. Arnall, Brenda S. Tubaña, and William R. Raun*

ABSTRACT

Long-term experiments play a vital role in revealing dynamic soil and weather processes that directly influence sustainable crop production and ecosystem health. The objective of this review paper is to present one of the oldest long-term continuous winter wheat (*Triticum aestivum* L.) experiments, the Magruder Plots, and their contribution to the scientific community regarding questions of yield response to amendments, yield stability, percentage organic matter (OM) lost over time, soil nutrient status, microbial activity, weed population, and information on the economic return from winter wheat production. Alexander C. Magruder initiated the experiment in 1892 and is in progress to date. The original plot was started to evaluate wheat production on native prairie soils without fertilization. After 6 yr the principal investigator split the initial plot into two and fertilized one half with cattle manure. The experiment was then modified to include 10 treatments in 1930 by Dr. Horace J. Harper to answer several soil fertility related questions. Since 1947, six treatments have remained intact that evaluate simple combinations of manure, and inorganic N, P, K, and lime. Following 114 yr of continuous winter wheat production under conventional tillage, the check plot that has never received any fertilizer addition continues to produce wheat grain yields of >1 Mg ha^{-1}. Despite the decline in soil organic matter from 4 to 1% during this time period, wheat grain yields continue to show slight increases with time, likely due to improved genetics. While continuous wheat without rotation is not recommended, this 114-yr study documents the feasibility.

Long-term experiments play a vital role in revealing dynamic soil and weather processes that directly influence sustainable crop production and ecosystem health. They are valuable repositories of information in understanding nutrient dynamics and balances along with understanding changes in yield (Davis et al., 2003; Regmi et al., 2002; Mitchell et al., 1991). The importance of long-term experiments lies in their ability to observe trends which may only be seen over long periods of time such as changes in soil OM. Weather, one of the most important factors in crop production, is highly variable and cannot be predicted over a short period of time. According to Grandstedt and Kjellenberg (1997) and Witt et al. (2004), it is not possible to determine with any degree of certainty trends in soil processes or weather changes with short-term studies.

Typical rationale of having long-term experiments would be evaluating changes in soil chemical and physical properties that can be reflected through changes in crop yields. For example, Ladha et al. (2003) were able to track a decline in rice yield at an average rate of 23 kg ha^{-1} each year using data from 33 long-term experiments. This yield decline was attributed to the loss of OM, the decrease of nutrient supply, and climate fluctuations. While this trend was not universal for all 33 long-term experiments examined, it does indicate that further investigation is needed to develop improved production practices. Similarly, in India during the 1980s, long-term data was used to evaluate the rice–wheat production system efficiency (Bhandari et al., 2002). Based on a 14-yr study in Punjab, it was noted that rice yields declined even when the recommended rates of N, P, and K were applied. This decline was attributed to loss of total soil N and OM. For this reason the continued examination of these long-term experiments is needed to determine if the implementation of these findings can improve yields for these systems. In this review paper we discuss the brief history and procedural evolution of the Magruder Plots, and their significant contribution in untangling several research questions including changes in soil chemical properties and variations in yields; soil microbial and weed dynamics; and varietal performance in relation to fertility gradients on a long-term basis.

HISTORY AND TREATMENT STRUCTURE OF THE MAGRUDER PLOTS

The Magruder Plots, located just off the Oklahoma State University campus in Stillwater, OK, were initiated in 1892 by Alexander C. Magruder to evaluate wheat production on native prairie soils without fertilization (Magruder, 1892, 1893). The land was tilled for the first time in the fall of 1892 with the initiation of the experiment. Since its inception the experiment has experienced several threats of destruction. In the early and late 1930s, campus expansion projects attempted to destroy the Magruder Plots. This effort was culminated thanks to the dedication of researchers responsible for the experiment. In 1947, another expansion project necessitated by increased student numbers threatened the Magruder Plots. The researcher in charge at that time, Dr. Horace J. Harper, fought intensely and the experiment was saved once again; but this time, selected treatments were relocated 1.6 km west of its original location to what is known today as the Agronomy Research Station. The detail of relocation of this experiment in 1947 is documented elsewhere (Chester, 1947; Harper, 1953, 1959). Noteworthy was the physical movement of the

Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078. Contribution from the Oklahoma Agricultural Experiment Station. Received 4 Jan. 2007. *Corresponding author (bill.raun@okstate.edu).

Published in Agron. J. 99:1191–1198 (2007).
Centennial Papers
doi:10.2134/agronj2007.0008

Abbreviations: NPKL, sodium nitrate + superphosphate + potash + lime; OM, organic matter.

Table 1. Treatment modifications and plot management for the Magruder Plots, OK, 1892 to present.

Year	No. of treatments	Nitrogen source	N rate	Manure N rate	P source (N–P–K–S)†	Spacing	Seed rate	Location	Seed type‡
			kg ha^{-1}			cm	kg ha^{-1}		
1892–1898	1	–	–	–	–	17.8	84	old	SRWW
1899–1912	2	Manure only	–	–	–	17.8	84	old	SRWW
1913–1929	2	Manure only	–	134**	–	17.8	84	old	HRWW
1930–1933	10	$NaNO_3$ (16–0–0)	37	134**	OSP (0–20–0–12)	17.8	84	old	HRWW
1934–1945	10	$NaNO_3$ (16–0–0)	37	134**	OSP (0–20–0–12)	35.6	56	old	HRWW
1946–1947	10	NH_4NO_3 (33.5–0–0)	37	134**	OSP (0–20–0–12)	35.6	56	old	HRWW
1948	6	NH_4NO_3 (33.5–0–0)	37	134**	OSP (0–20–0–12)	17.8	84	new	HRWW
1949–1957	6	NH_4NO_3 (33.5–0–0)	37	134**	OSP (0–20–0–12)	35.6	56	new	HRWW
1958–1967	6	NH_4NO_3 (33.5–0–0)	37	134**	OSP (0–20–0–12)	25.4	67	new	HRWW
1968–1993	6	NH_4NO_3 (33.5–0–0)	67	269**	TSP (0–46–0–0)	25.4	67	new	HRWW
1994–2003	6	NH_4NO_3 (33.5–0–0)	67	269**	TSP (0–46–0–0)	19.1	67	new	HRWW
2004–present	6	Urea (46–0–0)	67	269**	TSP (0–46–0–0)	19.1	67	new	HRWW

† OSP, ordinary superphosphate; TSP, triple superphosphate.
‡ HRWW, hard red winter wheat; SRWW, soft red winter wheat.

surface 40.6 cm of soil from six 30.5- by 6.1-m plots to the new site, comprising >450 metric tons of soil to accomplish the task, and to ensure long-term biological integrity of the experiment. After the relocation, researchers were concerned with a potential threat to the Magruder Plots specifically due to a rumor of the creation of an athletic center where the Plots are located. To preserve the Magruder Plots, researchers in charge in the mid to late 1970s campaigned to enter this long-term experiment into the National Registry of Historic Places and this was successful on 29 Aug. 1979 (Delaporte, 1979).

Only one plot was used to evaluate native wheat production without the application of organic or inorganic fertilizers from 1893 to 1898. The initial objective was to track the productivity of the prairie soils without the addition of any form of fertility reclamation. From 1899 to 1929, half of the experimental area was fertilized with cattle manure while the other half received no fertilization after observing a decline in performance of wheat in the check plot versus the adjacent field (apparently receiving some form of organic fertilizer in the past). In 1930, Dr. Horace J. Harper established 10 separate fertilization treatments on these plots which continued until 1947. Although details are given in the literature (Harper, 1959; Murphy, 1929; Westerman, 1992), it is important to mention how Dr. Harper came up with the new treatment sets which helped in making decisions during the relocation. Dr. Harper had analyzed the soil chemical properties of the Magruder Plots in 1926 and he discovered that P was deficient in the check plots. Additionally, Dr. Harper learned that at the same experiment station, another short-term study revealed that P was the deficient nutrient. He also anticipated that N, K, and lime would be required at some point in the life of the experiment, which was in fact correct. He divided the unfertilized check into five plots and applied superphosphate (P), sodium nitrate + superphosphate (NP), sodium nitrate + superphosphate + potash (NPK), and sodium nitrate + superphosphate + potash + lime (NPKL) in the four plots, each receiving only one treatment set. Similarly, the cattle manure plot was divided into five subplots, of which four were fertilized with P, rock phosphate, PK, and NPK. This treatment structure was continued until 1947. The timeline for changes that occurred in the Magruder Plots and the monthly average rainfall and temperature across 36 yr are given in Table 1 and Fig. 1. All nonexperimental plot management activities such as weed control and varietal selection have been accomplished as per Oklahoma State University Extension Service recommendation.

Because of a university construction decision for a new dormitory, plots from six of the 10 treatments were moved (surface 0–40.6 cm) following wheat harvest in 1947 to their present location at the Agronomy Research Station (Table 2, Fig. 2). The subsoil at the new location was noted to be very similar to that of the original site (Boman et al., 1996; Harper, 1953). The treatments were cattle manure (from the cattle manure only treatment before relocation), unfertilized check, P, NP, NPK, and NPKL (all from the originally unfertilized check treatment). Manure has been applied every 4 yr since the inception of the experiment at two rates based on N need (to deliver 134 kg ha^{-1} N between 1899 and 1967 and 269 kg ha^{-1} N since 1968). Between 1930 and 1967, N was applied at 37 kg ha^{-1} as sodium nitrate (16% N). Nitrogen was applied at 67 kg ha^{-1} N in the form of ammonium nitrate (34% N) from 1968 until 2004 and as urea (46% N) since 2005. Phosphorus was applied as ordinary superphosphate between 1930 and 1967 at 14.6 kg ha^{-1} P and the source was changed to triple superphosphate (TSP, 20% P) in 1968. Potassium has been applied at 28.8 kg K ha^{-1} as muriate of potash since the inception of the treatment in 1930. Lime was applied only twice during the life of the Magruder Plots (1929 and 1954),

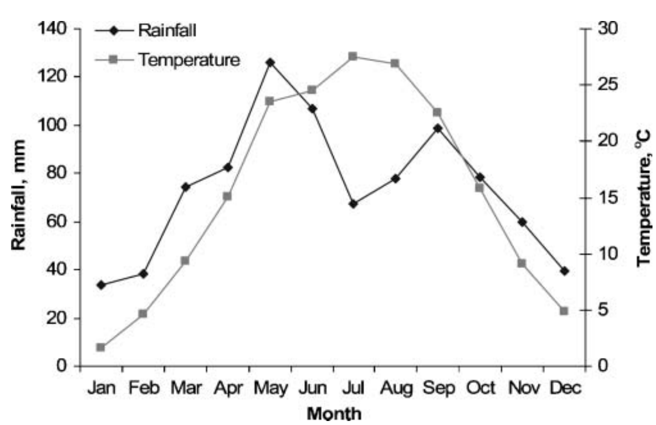

Fig. 1. Monthly average temperature and rainfall (summed over days of the month) averaged over 36 (1969–2006) years at the Agronomy Research Station, Stillwater, OK.

Table 2. The Magruder Plots treatment structure since 1930.

Treatment no.	Composition	Description
1	manure	Cattle manure applied every 4 yr
2	–	no nutrients applied
3	P	P applied each year
4	NP	N and P applied each year
5	NPK	N, P, and K applied each year
6	NPKL	N, P, and K applied each year + lime applied when soil pH < 5.5. (limed in 1929 and 1954)

when the pH in NPKL treatment dropped below 5.50. The first application was as coarse limestone screenings at a rate of 6720 kg ha^{-1}, while the second was applied at 4480 kg ha^{-1} as ground limestone.

The changes introduced into the treatment structure in 1930 marked an essentially new era in the value of the experiment. This treatment structure, while not perfect, enabled the comparison and estimation of yield, soil chemical properties, microbial activity, and weed population dynamics among treatments. The estimation of different nutrient effects is shown in Table 3.

WINTER WHEAT GRAIN YIELD RESPONSE TO MANURE, NITROGEN, PHOSPHORUS, POTASSIUM, AND LIMING

Boman et al. (1996) and Mullen et al. (2001) summarized Magruder Plots yield results in different categories based on changes made throughout the history of the experiment. The yield trend in different treatments was grouped into five categories (1893–1898, 1899–1929, 1930–1957, 1958–1994, and 1995–2006) since the treatment effects were consistent during each of these time periods. The response of winter wheat to treatments since 1995 was consistent with the data averaged for years 1958 to 1994, except the higher yield level for manure, NP, NPK, and NPKL treatments during this period (Fig. 3).

The check plot had an average grain yield of 1.1 Mg ha^{-1} after 114 yr of continuous wheat without any fertilizer input. The yield in the check plot fluctuated from year to year, but was >1 Mg ha^{-1} since 1958; and showed an increasing trend (Westerman et al., 1989, 1992). Johnson and Raun (2003) plotted the yield of continuous winter wheat over 34 yr and found that failure to apply N fertilizer did not show continuous yield reduction; the authors attributed this to compensation from the environment. Albeit the contribution from the environment maintained yield in the check plot, the increasing trend would not be possible without additional crop management intervention. In this line, the continuous change of cultivars would partly explain this increase. For all varieties sown since 1958, the average yield exceeded 1.5 Mg ha^{-1} for fertilized and unfertilized plots (Fig. 4). Girma et al. (2006) also observed similar results in an analysis conducted on two long-term continuous winter wheat experiments in Oklahoma.

The effect of applied N was determined for two scenarios, P limiting and nonlimiting (Table 3). Nitrogen effect with P nonlimiting was apparent (although magnitude was small) for all the three periods since 1930. The difference in yield was 0.7, 0.78, and 1.26 Mg ha^{-1} for 1930 to 1957, 1958 to 1994, and 1995 to 2006 time periods, respectively (Fig. 5). The depletion of soil total N and OM could be the reason for this outcome. Boman et al. (1996) documented that for the time period 1930 to 1957, effect of N was negative with P limiting but was positive and significantly high for the later periods. However, the magnitude was slightly lower (P limiting) than when P was nonlimiting. When P was the principal deficient nutrient for the period 1930 to 1957, no N effect was observed; however, the decreased P response due to P accumulation from fertilization led to a shift toward N. From yield and soil analysis results, Boman et al. (1996) explicitly showed that the first deficient nutrient in this continuous winter wheat experiment was P. Thus, the increase in yield due to the application of cattle manure was attributed to the alleviation of P deficiency and not N (Harper, 1953).

The effect of applying K (difference in yield of NPK and NP treated plots) was observed only for data averaged between 1995 and 2006 (Fig. 5). This effect was higher than P and lime effects in the same period. The effect of liming was apparent for all three periods, but

Fig. 2. The Magruder Plots at their current location at the Agronomy Research Station, Stillwater, OK. The experiment was initiated in 1892 and has been repository of scientific information.

Table 3. The treatment combinations used to estimate the response to applied N, P, K and lime in the Magruder Plots since 1930.

Treatment combination	Estimated effect
4 − 3	Response to applied N (P not limiting)
3 − 2	Response to applied P (in the absence of N)
5 − 4	Response to applied K (N and P not limiting)
6 − 5	Response to applied lime (N, P, and K not limiting)
(4 − 3) − (3 − 2)†	Response to applied N (P limiting)

† Assumes that effects were orthogonal, and that only N or P was limiting (Source: Boman et al., 1996).

the largest difference was observed for the 1958 to 1994 period, after the second lime application in 1957.The relatively higher response to liming during this time could be in response to the continuous application of ammonium nitrate fertilizer that tended to reduce the soil pH. With time, response to lime was decreased as a consequence of the slow, yet continuous release of Ca from the lime that presumably offset the added acidity.

GRAIN YIELD STABILITY IN THE MAGRUDER PLOTS

Stability analysis was initially developed using the dynamic concept (Eberhart and Russell, 1966), in which simple regression is used to assess genotype yield stability from location to location and from year to year. In 1984, this concept was applied to an on-farm variety × N rate experiment in Malawi where the focus was to compare local and composite corn (*Zea mays* L.) variety performance in different environments (Hildebrand, 1984). Raun et al. (1993) used the concept to evaluate the fertilizer treatment yield stability from year to year, given the large variability observed in the plots. According to Raun et al. (1993) and Guertal et al. (1994), the environment (yearly) mean yield was obtained by averaging yield of all treatments for each year while the mean for each treatment was calculated from subplots. Raun et al. (1993) revealed that when environmental means were <2 Mg ha^{-1}, the cattle manure treated plots performed poorly while the NPK-treated plots had slightly higher yields. The opposite was reported with higher environmental means (>2 Mg ha^{-1}), that is, cattle manure plots had steady yield when growing conditions were optimal

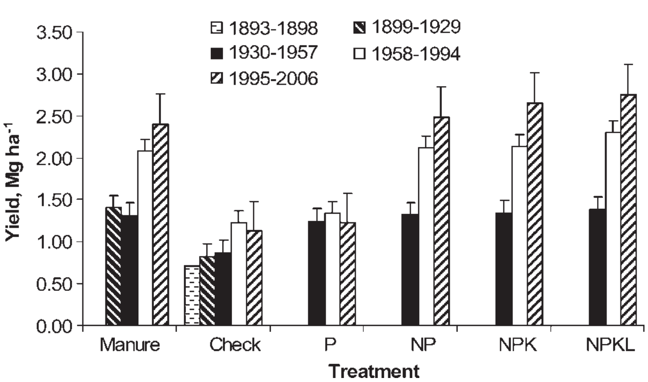

Fig. 3. Winter wheat grain yield averaged over several years based on treatment response in selected time periods for each of the treatments. Each period denotes average yield with similar yield response due to treatments (Modified from Boman et al., 1996).

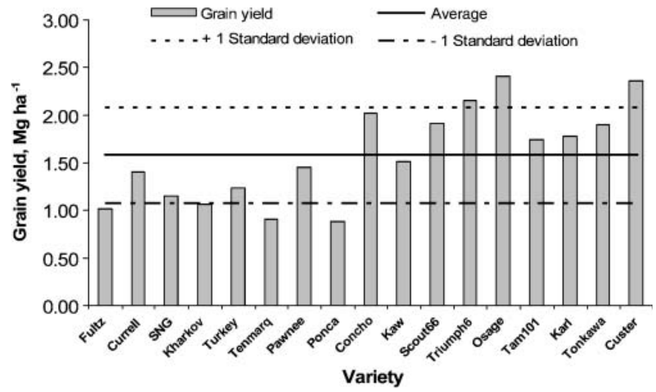

Fig. 4. Winter wheat grain yield by variety in the Magruder Plots, Stillwater, OK. Cultivars Fultz, Currell, SNG, Kharkov, Turkey, Tenmarq, Pawnee, Ponca, Concho, Kaw, Scout66, Triumph6, Osage, Tam101, Karl, Tonkawa, Custer, and Endurance were planted in 1893 and 1895–1907, 1894, 1908–1911, 1912–1916, 1917–1942, 1943–1945, 1946–1953, 1954–1957, 1958–1963, 1964–1968, 1969–1973, 1974–1977, 1978–1979, 1980–1992, 1993–1994, 1995–1999, 2000–2005, and 2006, respectively.

(Raun et al., 1993). The check and P plots had the lowest slope coefficients (0.66 and 0.62, respectively), which signifies less-stable yield than the rest of the treatments (Fig. 6). The overall lesson was that cattle manure and N fertilizer receiving plots tended to buffer the effect of environmental variability. The practical significance of this analysis is its capacity to reveal treatment effects by reducing the confounding effect of year to year variability that is not evident in conventional ANOVA.

TRACKING ORGANIC MATTER IN CONTINUOUS WINTER WHEAT

Recent work by Davis et al. (2003) on the Magruder Plots found that OM decreased 55 to 67% in the last 110 yr, largely a result of cultivation. The highest reduction was in the check (2.41%) and NP (2.61%) plots, while the lowest reduction was in cattle manure (1.85) plots (Table 4). Boman et al. (1996) reported that OM decreased from 4 to 1% in the check plot since the experiment was initiated. The rate of OM decline per year was 0.0151 and 0.0168% in the cattle manure and check plots, respectively (Fig. 7). The OM reduction of this magnitude was apparently associated with loss of productivity of arable land; there are some reports that the reduction in OM forced farmers to abandon farming (Wright et al., 2004). Long-term experiments like the

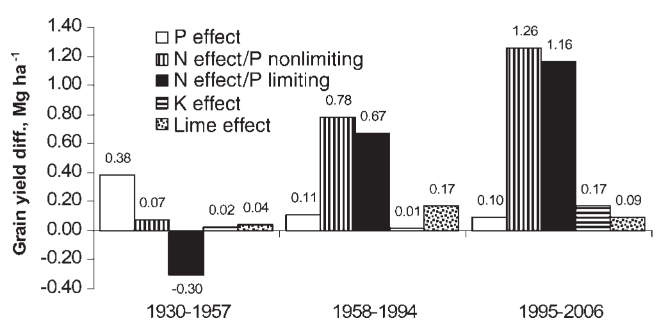

Fig. 5. Effect of applied N, P, K, and lime in the Magruder Plots for three selected time periods (1930–1957, 1958–1994, and 1995–2006).

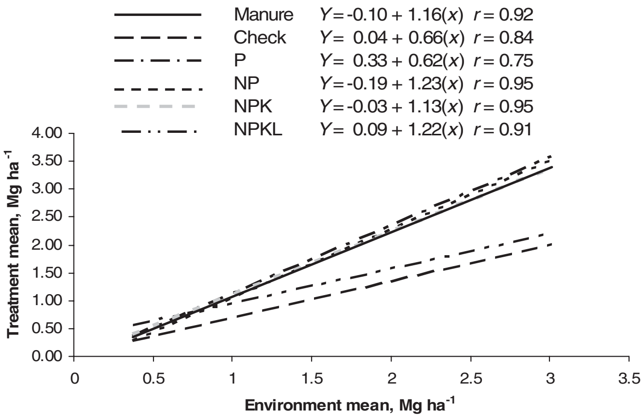

Fig. 6. Regression lines of stability (winter wheat grain yield vs. environment mean) for all treatments at the Magruder Plots, Stillwater, OK, for data compiled over 76 yr (Modified from Raun et al., 1993). NPKL = sodium nitrate + superphosphate + potash + lime.

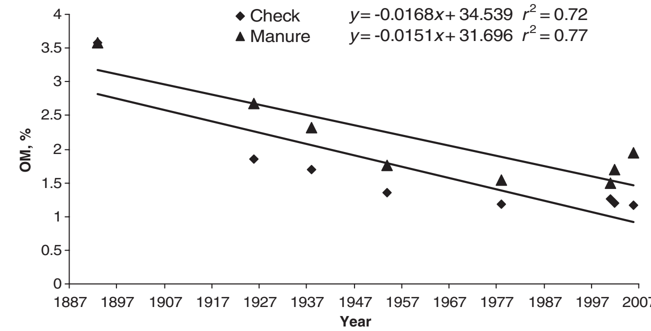

Fig. 7. Decrease in soil organic matter [OM = organic C × 1.8 + 0.35 (Ranney, 1969)] for data gathered in selected years in the Magruder Plots, Stillwater, OK (Raun, 2006).

Magruder Plots can serve as a warning system by predicting possible changes in the soil ahead of time. One obvious observation in the long-term analysis of soil OM of the Magruder Plots was the reduction of OM level in cattle manure and inorganic NPK plots. This is presumably related to conventional tillage used throughout the life of this long-term experiment. Conventional tillage has been known to deplete soil OM (Wilhelm et al., 2004; Katsvairo et al., 2006). This justification is plausible because researchers showed that turning under and exposing the subsurface soil can break down soil aggregates (Willis, 1955; Hadas, 1990, Edwards, 1991; Beare et al., 1994), indirectly affecting OM level. Destruction of soil aggregates as a result of cultivation alters soil conditions (i.e., temperature, moisture, and aeration), hastening microbial activity and decomposition rate of OM (Rovira and Greacen, 1957; Cambardella and Elliott, 1993). This in turn lowers levels of soil OM that have direct relationships with increased erosion, nutrient leaching, and reduction in biological diversity. Additionally, conventional tillage is known to reduce water use efficiency and decrease water holding capacity of the soil due to decreased OM.

Table 4. Changes in the soil organic matter (OM, %) levels in the Magruder Plots, 1892–2002.†

	OM change					
	Manure	Check	P	NP	NPK	NPKL‡
	%					
1892	**NA**	**3.58**	**NA**	**NA**	**NA**	**NA**
1926	**2.68**	**1.85**	**NA**	**NA**	**NA**	**NA**
1938	**2.32**	**1.69**	**1.77**	**1.65**	**1.64**	**1.70**
1954	**1.76**	**1.35**	**NA**	**NA**	**NA**	**NA**
1978	**1.54**	**1.18**	**NA**	**NA**	**NA**	**NA**
1990	**2.15**	**1.71**	**1.92**	**1.97**	**2.16**	**2.20**
1991	**2.15**	**1.71**	**1.92**	**1.97**	**2.17**	**2.20**
1992	**2.13**	**1.77**	**1.82**	**1.99**	**2.44**	**2.15**
1993	**2.12**	**1.76**	**1.82**	**1.99**	**2.44**	**2.14**
1994	**2.44**	**1.84**	**2.04**	**2.33**	**2.11**	**2.34**
1995	**2.56**	**1.99**	**2.15**	**2.42**	**2.20**	**2.56**
1996	**2.52**	**1.68**	**1.71**	**2.00**	**2.17**	**2.36**
1997	**2.40**	**1.48**	**1.71**	**1.98**	**2.00**	**2.09**
2001	**1.49**	**1.26**	**1.24**	**1.49**	**1.53**	**1.81**
2002	**1.73**	**1.17**	**1.29**	**0.97**	**1.59**	**1.58**
OM lost§	**1.85**	**2.41**	**2.29**	**2.61**	**1.99**	**2.00**

† Crop years in which organic matter levels were recorded. OM = Organic C × 1.8 + 0.35 (Ranney, 1969).
‡ L, lime applied when soil pH < 5.5 (limed in 1929 and 1954).
§ Organic matter lost was calculated by subtracting the OM concentration at present from the OM at initiation of the experiment (Source: Davis et al., 2003).

A slight trend for increased OM has been noted in recent years. In another long-term experiment in the same Kirkland silt loam soil near the Magruder Plots, Raun et al. (1998) observed that applications of N in excess of 67 kg ha^{-1} could lead to increases in soil organic C and a decrease in the C/N ratio. They found that the application of N in excess of maximum yield potential requirements led to steady increases in soil organic C. With optimal weather conditions for maximum biomass production due to large amounts of N released from cattle manure, there was a possibility to have higher levels of organic C from residue accumulation in the Magruder Plots. It is important to note that the cattle manure used in the Magruder Plots was calculated to deliver 269 kg ha^{-1} N (over 4 yr), which is close to the amount that is required for maximum yield (90 kg ha^{-1}) based on the yield goal approach (Dahnke et al., 1988) during this period.

SOIL NITROGEN, PHOSPHORUS, POTASSIUM, AND PH STATUS

Although several research findings were reported on soil N in this study (e.g., Boman et al., 1996; Fell, 1976), the most comprehensive report on the Magruder Plots was published by Davis et al. (2003). In their paper the authors attempted to estimate soil N balance by quantifying additions and losses in the first 30 cm depth of each of the Magruder Plots (Table 5). The additions were N applied from fertilizer, added to the soil through nonsymbiotic fixation, from atmospheric deposition (mainly rainfall), and mineralization from organic pool. The losses were N removed in the grain, gaseous losses from the plant, denitrified from the soil, and leached from the root zone. Grain N removal for years between 1892 and 2001 for different treatments ranged from 2808 (check) to 4186 kg ha^{-1} N (cattle manure) with a corresponding average of 25.7 to 38.4 kg ha^{-1} yr^{-1} N, respectively. The values were obtained by multiplying yield and percentage N in the grain. The unaccounted N in different treatments ranged from 2 to 13 kg ha^{-1} yr^{-1} N after subtracting estimates of losses from additions

Table 5. Estimates of total amounts of N applied and removed from the Magruder Plots from 1892 to 2002, Stillwater, OK.

N source/sink	Manure	Check	P	NP	NPK	NPKL†
	kg ha^{-1}					
Total soil N in organic matter, 1892	6,890	6,890	6,890	6,890	6,890	6,890
N applied from rainfall	545	545	545	545	545	545
N fertilizer applied	4,200	0	0	3,321	3,321	3,321
N from nonsymbiotic N fixation‡	109	218	218	146	146	146
Additions + initial total	11,744	7,653	7,653	10,902	10,902	10,902
N removed by the grain	4,186	2,808	2,944	3,975	3,990	4,091
Estimated plant N loss	1,726	1,252	1,252	1,614	1,614	1,614
Soil denitrification	769	265	265	664	664	664
Nitrate-N leaching losses	470	306	306	436	436	436
Removal (loss) total	7,151	4,631	4,767	6,689	6,704	6,805
Total soil N in organic matter, 2002	3,198	2,411	2,657	3,149	3,247	3,124
Total unaccounted	1,395	611	229	1,064	951	973
	kg ha^{-1} yr^{-1}					
N unaccounted	13	6	2	10	9	9

† L, lime applied when soil pH < 5.5 (limed in 1929 and 1954).
‡ Assumes 2 kg ha^{-1} yr^{-1} N fixed via nonsymbiotic N fixation in the check and P plots, and 1 kg ha^{-1} yr^{-1} N in the N-applied plots including the manure plot; an additional 37 kg ha^{-1} N was added on the NP, NPK, and NPKL plots for the 37 yr (1892–1929) where no N had been applied (Source: Davis et al., 2003).

(Davis et al., 2003). The check had the lowest unaccounted N while the cattle manure treated plots had the highest. Although the objective was to come up with a zero N balance, it did not turn out that way mainly because the inputs for losses and additions were only estimates as reported by the authors. However, the unaccounted N increased as applied N increased regardless of the source (Table 5). Lees et al. (2000) observed similar trends in a study conducted to document unaccounted N using ^{15}N.

Parham et al. (2002) found an interesting result from this long-term experiment on soil P levels in different treatments. Inorganic P treated plots always had the highest level of P, while cattle manure plots exhibited the lowest soil test P. It was reported that 77 to 86% of the inorganic P applied for the last 69 to 71 yr was recovered in the harvested winter wheat grain or remained in the top 30 cm of soil (Parham et al., 2002). In contrast, in the cattle manure plots only 22% of P was recovered. This suggests that cattle manure supplied P was more mobile than that supplied from inorganic fertilizer sources (Parham et al., 2002).

Cattle manure application maintained the pH at the optimum (6.20) level while the application of NP and NPK dropped the pH to 5.10 (Zhang, 1998). Liming, coupled with NPK fertilization, raised the pH to acceptable levels (5.51) although it was not as high as that of the cattle manure treated plots. Apparently, the reduction in pH was associated with N fertilizer; plots that did not receive N fertilizer including the check showed no significant reduction in pH. Information regarding why pH was maintained at optimum levels in the cattle manure plots, even better than the lime-treated plots, was assessed with the data generated from the same experiment. Zhang (1998) attributed this to abundance of basic cations such as Ca found in manure. Parham et al. (2002) indicated that cattle manure enriches some microbial communities that favor higher soil productivity through maintenance of soil pH. Long-term experiments are critical for evaluating the fate of continuous application of organic nutrient sources such as cattle manure, which can contain different concentrations of nutrient and nonnutrient minerals. Edmeades (2003) reviewed 14 field trials of long-term experiments dealing with the use of fertilizers and manures on crop production and soil properties. It was found that fields with cattle manure application had increased levels of OM, P, K, Ca, and Mg in the surface, increased levels of nitrate-nitrogen (NO_3–N), Ca, and Mg in the subsoil, and decreased bulk density.

SOIL MICROBIAL ACTIVITY AND SOILBORNE DISEASES

Crucial soil microbial population and community structure information was generated from the Magruder plots (Parham et al., 2003; Sun et al., 2004). It was found that cattle manure enhanced bacterial populations compared with the check plot. From this study, the authors concluded that "The richness and evenness of the bacterial community were enhanced by cattle manure treatments and treatments that included N and P." In another study that assessed the effect of cattle manure application on microbial biomass C and enzyme activity, Parham et al. (2002) found that cattle manure increased microbial activity and stimulated the activity of several enzymes involved in N and P transformation.

Limited information on soilborne disease status was presented in Boman et al. (1996) using data collected in the 1992–1993 crop season. Specifically, the author surveyed the Magruder Plots for lower internode discoloration (%) and amount of wheat germ infected by *Pythium* spp. The former is essentially an indicator of soilborne disease-causing organisms (Wiese, 1987; Singleton and Russell, 1990). Figure 8 shows that lower internode discoloration, which is a likely symptom of soilborne disease status, was different among the six treatments ranging from 23% in the check plot to 53% in the cattle manure plot (Boman et al., 1996). Alternatively, the *Pythium* spp. infection of wheat germ was significant among treatments, the check, cattle manure, and NPKL plots had the lowest infection level. The results suggested that in the cattle manure treated plot the abundance of soilborne disease-causing organisms other than *Pythium* spp. outcompeted the *Pythium* spp. population. The check had overall lower discoloration and *Pythium* spp. abundance (Fig. 8). Apparently the soil of the check

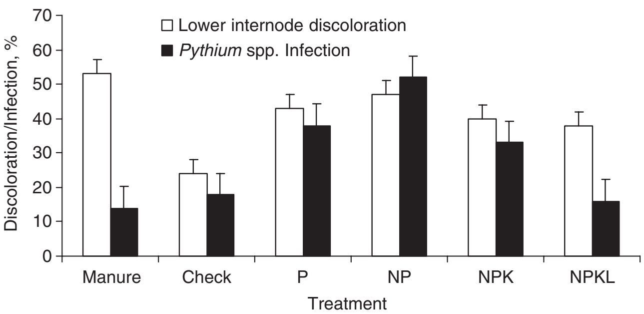

Fig. 8. Effect of treatments on the lower internode discoloration (indicator of the abundance of soilborne disease causing organisms other than *Pythium* spp.) and *Pythium* spp. infection in the Magruder Plots in 1993, Stillwater, OK (modified from Boman et al., 1996).

plot lacked nutrients required by both beneficial and nonbeneficial soil organisms. However, as revealed in the cattle manure plots an increase in beneficial organisms in the soil would likely antagonize and suppress the population of disease-causing pathogens (Hoitink, 1986).

WEED POPULATION DYNAMICS IN MAGRUDER PLOTS

The Magruder Plots also served to evaluate weed species dynamics and abundance (Banks et al., 1976). In this study they showed that weed species and abundance generally were low in the check plot. With the addition of nutrients in each of the other five treatments, weed species type, total population, and individual species abundance increased, reaching the highest level with the application of NPKL. Exceptions were evening primrose (*Oenothera laciniata* Hill), carpetweed (*Mollago vericillata* L.), and henbit (*Lamium amplexicaule* L.). Evening primrose was abundant in the unfertilized plot, with a decrease in population as fertility levels increased with addition of different types of nutrients. Carpetweed and henbit responded to P and NP fertilization where highest abundance was recorded.

In a way, the Magruder Plots enabled researchers to characterize the weed species in Oklahoma in relation to fertility gradient. These plots were good indicators of a succession trend in a continuous winter wheat cropping system. This could assist Oklahoma producers in devising weed management strategies in continuous winter wheat. A followup study would have confirmed or revealed consistency of weed species dynamics.

THE MAGRUDER PLOTS AS REPOSITORIES OF ECONOMIC RETURN INFORMATION

One aspect of the use of the Magruder Plots was the evaluation of economic returns and reliability of economic yield increases due to treatments. Boman et al. (1996) reported the moving average net return and reliability of economic yield as a function of N, P, and K fertilizer for each 10-yr period. They showed that there was a wide discrepancy in net return due to N fertilization, but mostly positive ranging from \$49 to 185 USD ha^{-1} since 1958. For earlier years, the moving average increase in net return was <0. In contrast, for P the net return was positive for averages computed between 1920 and 1957, and was negative thereafter. Positive increase in net return due to K fertilization was observed only for the moving average computed between 1988 and 1994. This coincided with the apparent response of winter wheat to K fertilization during this period. The peak (>0.8) reliability of obtaining an economic yield increment in response to N, P, and K fertilization was somehow consistent with the increase in net return (Boman et al., 1996).

CONCLUSIONS

The Magruder Plots have proven to be a source of scientific information in sustainable soil fertility management and cereal production. This experiment has helped scientists to monitor long-term changes in soil chemical properties and variations in yields in relation to weather. The information extracted from this experiment on soil microbial and weed dynamics helped researchers and producers to understand possible changes in their farming and ecosystem for better resource management and sustainability. The Magruder Plots have also helped breeders and agronomists to assess varietal performance in relation to fertility gradients and will continue to guide them in future breeding work. The only pitfall of this long-term experiment is the lack of replication, as at its inception the concept of replications and thus statistics was not established. Despite this, measurements taken from the Magruder Plots have contained at least four subsamples, as the plot size is big enough to do so. After all, there are statistical tools today to manage nonreplicated experiments and the issue of replication becomes less important when 100+ years of data are available. The Magruder Plots will continue to be repositories of valuable information for developing sustainable and environmentally friendly winter wheat production systems in Oklahoma and elsewhere. As issues of sustainability and environmental safety become increasingly more important, long-term experiments such as the Magruder Plots will be further explored.

REFERENCES

Banks, P.A., P.W. Santelmann, and B.B. Tucker. 1976. Influence of long-term soil fertility treatments on weed species in winter wheat. Agron. J. 68:825–827.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58:777–786.

Bhandari, A.L., J.K. Ladha, H. Pathak, A.T. Padre, D. Dawe, and R.K. Gupta. 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Sci. Soc. Am. J. 66:162–170.

Boman, R.K., S.L. Taylor, W.R. Raun, G.V. Johnson, D.J. Bernardo, and L.L. Singleton. 1996. The Magruder Plots: A century of wheat research in Oklahoma. Div. of Agric. Sci. and Natural Resources, Oklahoma State Univ., Stillwater.

Cambardella, C.A., and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071–1076.

Chester, K.S. 1947. They moved field 'O'. Farm J. 71(10):66.

Dahnke, W.C., L.J. Swenson, R.J. Goos, and A.G. Leholm. 1988. Choosing a crop yield goal. North Dakota State Ext. Ser. SF-822. North Dakota Univ., Fargo.

Davis, R.L., J.J. Patton, R.K. Teal, Y. Tang, M.T. Humphreys, J. Mosali,

K. Girma, J.W. Lawles, S.M. Moges, A. Malapati, J. Si, H. Zhang, S. Deng, G.V. Johnson, R.W. Mullen, and W.R. Raun. 2003. Nitrogen balance in the Magruder plots following 109 years in continuous winter wheat. J. Plant Nutr. 26:1561–1580.

Delaporte, C.T. 1979. Congressional notification of acceptance of Magruder Plots into National Register of Historic Places. U.S. Department of the Interior Heritage Conservation and Recreation Service, 29 Aug. 1979.

Eberhart, S.A., and W.A. Russell. 1966. Stability parameters for comparing varieties. Crop Sci. 6:36–40.

Edmeades, D.C. 2003. The long-term effects of manure and fertilizers on soil productivity and quality: A review. Nutr. Cycling Agroecosyst. 66:165–180.

Edwards, L.M. 1991. The effect of alternate freezing and thawing on aggregate stability and aggregate size distribution of some Prince Edward Island soils. J. Soil Sci. 42:193–204.

Fell, G.T. 1976. Nitrogen mineralization potential of some key Oklahoma soils in relation to nitrogen treatment, sample depth, and wheat yields. M.S. thesis. Oklahoma State Univ., Stillwater.

Girma, K., K.L. Martin, R.H. Anderson, D.B. Arnall, K.D. Brixey, M.A. Casillas, B. Chung, B.C. Dobey, S.K. Kamenidou, S.K. Kariuki, E.E. Katsalirou, J.C. Morris, J.Q. Moss, C.T. Rohla, B.J. Sudbury, B.S. Tubana, and W.R. Raun. 2006. Mid-season prediction of wheat grain yield potential using plant, soil, and sensor measurements. J. Plant Nutr. 29:873–897.

Grandstedt, A., and L. Kjellenberg. 1997. Long-term field experiment in Sweden: Effects of organic and inorganic fertilizers on soil fertility and crop quality. p. 79–90. *In* W. Lockeretz (ed.) Agricultural Production and Nutrition. Proc. Int. Conf., Boston, MA. 19–21 Mar. 1997. Tufts Univ., Boston, MA.

Guertal, E.A., W.R. Raun, R.L. Westerman, and R.K. Boman. 1994. Applications of stability analyses for single-site, long-term experiments. Agron. J. 86:1016–1019.

Hadas, A. 1990. Directional strength in aggregates as affected by aggregate volume and by a wet/dry cycle. J. Soil Sci. 41:85–93.

Harper, H.J. 1953. A study of phosphate fertilization and legume rotations for small-grain winter pastures. Bull. B-414. Oklahoma Agricultural Exp. Stn., Stillwater.

Harper, H.J. 1959. Sixty-five years of continuous wheat. Bull. B-531. Oklahoma Agric. Exp. Stn., Stillwater.

Hildebrand, P.E. 1984. Modified stability analysis of farmer managed, on-farm trials. Agron. J. 76:271–274.

Hoitink, H.A. 1986. Basis for the control of soilborne plant pathogens with composts. Annu. Rev. Phytopathol. 2:93–114.

Johnson, G.V., and W.R. Raun. 2003. Nitrogen response index as a guide to fertilizer management. J. Plant Nutr. 6:249–262.

Ladha, J.K., D. Dawe, H. Pathak, A.T. Padre, R.L. Yadav, B. Singh, Y. Singh, Y. Singh, P. Pingh, A.L. Kundu, R. Sakal, N. Ram, A.P. Regmi, S.K. Gami, A.L. Bhandari, R. Amin, C.R. Yadav, E.M. Bhattarai, S. Das, H.P. Aggarwal, R.K. Gupta, and P.R. Hobbs. 2003. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Res. 81:159–180.

Katsvairo, T.W., D.L. Wright, J.J. Marois, D.L. Hartzog, J.R. Rich, and P.J. Wiatrak. 2006. Sod–livestock integration into the peanut–cotton rotation: A systems farming approach. Agron. J. 98:1156–1171.

Lees, H.L., W.R. Raun, and G.V. Johnson. 2000. Increased plant N loss with increasing N applied in winter wheat observed with 15N. J. Plant Nutr. 23:219–230.

Magruder, A.C. 1892. Tests of varieties of oats, corn, spring wheat, Irish and sweet potatoes. Bull. 4. Oklahoma Agric. Exp. Stn., Stillwater.

Magruder, A.C. 1893. Tests of varieties of wheat. Bull. 8. Oklahoma Agric. Exp. Stn., Stillwater.

Mitchell, C.C., R.L. Westerman, J.R. Brown, and T.R. Peck. 1991. Overview of long-term agronomic research. Agron. J. 83:24–29.

Mullen, R.W., K.W. Freeman, G.V. Johnson, and W.R. Raun. 2001. The Magruder Plots—Long-term wheat fertility research. Better Crops 85(4):6–8.

Murphy, H.F. 1929. Fertility study of Kirkland soil. Bull. 155. Oklahoma Agric. Exp. Stn., Stillwater.

Parham, J.A., S.P. Deng, H.N. Da, H.Y. Sun, and W.R. Raun. 2003. Long-term cattle manure application in soil. II. Effect on soil microbial populations and community structure. Biol. Fertil. Soils 38:209–215.

Parham, J.A., S.P. Deng, W.R. Raun, and G.V. Johnson. 2002. Long-term cattle manure application in soil. I. Effect on soil phosphorus levels, microbial biomass C, and dehydrogenase and phosphatase activities. Biol. Fertil. Soils 35:328–337.

Ranney, R.W. 1969. An organic carbon–organic matter conversion equation for Pennsylvania surface soils. Soil Sci. Soc. Am. Proc. 33:809–811.

Raun, W.R. 2006. Long term soil fertility experiments at Oklahoma State University [online]. Available at http://nue.okstate.edu/Long_Term_Experiments.htm [verified 29 May 2007]. Oklahoma State Univ., Stillwater.

Raun, W.R., H.J. Barreto, and R.L. Westerman. 1993. Use of stability analysis for long-term soil fertility experiments. Agron. J. 85:159–167.

Raun, W.R., G.V. Johnson, S.B. Phillips, and R.L. Westerman. 1998. Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma. Soil Tillage Res. 47:323–330.

Regmi, A.P., J.K. Ladha, H. Pathak, E. Pasuquin, C. Bueno, D. Dawe, P.R. Hobbs, D. Joshy, S.L. Maskey, and S.P. Pandey. 2002. Yield and soil fertility trends in a 20-year rice–rice–wheat experiment in Nepal. Soil Sci. Soc. Am. J. 66:857–867.

Rovira, A.D., and E.L. Greacen. 1957. The effect of aggregate disruption on the activity of microorganisms in the soil. Aust. J. Agric. Res. 8:659–673.

Singleton, L.L., and C.C. Russell. 1990. Wheat root rot nematode research. Ann. Wheat Newsl. 36:203.

Sun, H.Y., S.P. Deng, and W.R. Raun. 2004. Bacterial community structure and diversity in a century-old manure-treated agroecosystem. Appl. Environ. Microbiol. 70:5868–5874.

Westerman, R.L. 1992. Magruder Plots Centennial, 1892–1992, celebrating one hundred years of continuous soil fertility research on wheat. Agronomy Department, Agronomy 92–2. Oklahoma Agricultural Exp. Stn. Stillwater.

Westerman, R.L., B.B. Tucker, B.B. Webb, R.K. Boman, and W.R. Raun. 1992. The Magruder Plots: Efficient use of fertilizes in a 100 year wheat experiment. *In* R.L. Westerman (ed.) Efficient use of fertilizers. Agron. Dep., Agronomy 92-1. Oklahoma Agric. Exp. Stn., Stillwater.

Westerman, R.L., B.B. Tucker, and G.V. Johnson. 1989. The Magruder Plots: Ninety-seven years of continuous wheat. p. 256. *In* 1989 Agronomy abstracts. ASA, Madison, WI.

Wiese, M.V. 1987. Compendium of wheat diseases. 2nd ed. The American Phytopathological Society, St. Paul, MN.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal. Agron. J. 96:1–17.

Willis, W.O. 1955. Freezing and thawing, and wetting and drying, of soils treated with organic chemicals. Soil Sci. Soc. Am. Proc. 19:263–267.

Witt, C., A. Doberman, R. Buresh, S. Abdulrachman, H.C. Gines, R. Nagarajan, S. Ramanathan, P.S. Tan, and G.H. Wang. 2004. Site-specific nutrient management and the sustainability of phosphorus and potassium supply in irrigated rice soil of Asia. p. 360–363. *In* K. Toriyama et al. (ed.) Rice is life: Scientific perspectives for the 21st century. Proc. Int. Conf., Tokyo and Tsukuba, Japan. 4–7 Nov. 2004. The Rice Research Institute, Los Baños, Laguna, the Philippines.

Wright, D., J. Marois, T. Katsvairo, P. Wiatrak, and J. Rich. 2004. Value of perennial grasses in conservation cropping systems. p. 135–142. *In* D.L. Jordan and D.F. Caldwell (ed.) Proc. of the 26th Southern Conservation Tillage Conference for Sustainable Agriculture, Raleigh, NC. 8–9 June 2004. Tech. Bull. TB-321. Available at www.ag.auburn.edu/nsdl/sctcsa/ [verified 29 May 2007]. North Carolina Agric. Res. Service, Raleigh.

Zhang, H. 1998. Cattle manure can raise soil pH. PT 98–7, Vol. 10, No. 7. Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater.