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Maize yields from manure and mineral fertilizers in the 100-year-old Knorr–Holden Plot

Bijesh Maharjan | **Saurav Das** | **Rex Nielsen** | **Gary W. Hergert**

Dep. of Agronomy & Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA

Correspondence
Bijesh Maharjan, Dep. of Agronomy & Horticulture, Univ. of Nebraska-Lincoln, Lincoln, Nebraska 68583, USA
Email: bmaharjan@unl.edu

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Abstract

It takes years, if not decades, before measurable changes in crop productivity and soil properties due to management practices can be detected. The objective of this experiment was to evaluate the effects of long-term cattle manure and inorganic fertilizer applications on irrigated continuous maize grain yield, yield stability and reliability, nitrogen use efficiency (NUE), and soil properties. The experiment was conducted at the Knorr–Holden Plot in Scottsbluff, NE, from 1912–2012. Maize received no fertilizer in the first 30 yr of the experiment, and yields declined as nutrient supply from the native prairie was used. In 1942–1952, there were two cattle manure rates (0 and 27 kg ha^{-1} yr^{-1}), and yield significantly increased in the manure treatment. In 1953, second replication and six inorganic N treatments were added effectively, making the study a randomized complete block with manure as the main and inorganic N as subplot factor with two replications. Linear regression of yield against years in manured plots had similar slopes across N rates. There was a gradual increase in slope with increasing N rates in non-manured plots. Yield response to inorganic N rates in the non-manured plot had a significantly greater slope but lower intercepts than the manured plot. Manure provided greater yield stability and reliability and significantly increased soil organic matter, nitrate-N, and P accumulation in soil. Optimized manure and inorganic fertilizer N management are necessary to provide a stable and reliable yield and help establish an economically and environmentally sustainable maize production system.

1 | INTRODUCTION

Long-term field experiments (LTFE) are excellent resources to understand the sustainability of agricultural practices and crop productivity and stability. Long-term studies can also account for the inter-annual variability in crop yield influenced by environmental factors, pathogenic pressure, and management practices (Grover et al., 2009). Understanding yield responses under different agronomic management over many years helps define conditions for a stable production system and sustainability . However, maintaining LTFEs requires consistent and committed management from generations of dedicated scientists. Many practices may lose their relevance over time (Aref & Wander, 1997). Revisions to LTFEs to address relevant and emerging questions with the

Abbreviations: AE, agronomic efficiency; AONR, agronomic optimum nitrogen rate,; AOY, agronomic optimum yield; LTFE, long-term field experiment; NUE, nitrogen use efficiency; PFP, partial factor productivity; SOM, soil organic matter; UNL, University of Nebraska-Lincoln.

development of new technologies are sometimes needed. The Knorr–Holden Plot in Scottsbluff, NE, established in 1910, is an LTFE where fertility treatments have been revised twice over the last 100 yr. The Knorr–Holden Plot has stayed true to the original question of determining the sustainability of continuous maize production in the U.S. High Plains (Anderson & Peterson, 1973).

Only a few LTFE have studied soil fertility management with continuous crop production under organic or inorganic fertilizer management practices, which were also established and maintained over a century. They include Sanborn Field in Missouri, started in 1888; the Magruder Plots in Oklahoma started in 1892; the Old Rotation Plots in Alabama began in 1896; and the Morrow Plots in Illinois started in 1876 (Aref & Wander, 1997). The Sanborn and Morrow plots share maize (*Zea mays* L.) as the primary crop in the Knorr–Holden (Scofield & Holden, 1927). The Knorr–Holden was enlisted in the U.S. National Register of Historic Places in 1992 for its unique role in educational research and historic property worthy of preservation.

Maize production and productivity have increased considerably in the last few decades with improved cultivars and efficient agronomic management practices (Nielsen, 2017). Transitioning from open-pollinated varieties to hybrids and transgenics coupled with the adoption of fertilizers and enhanced crop protection practices have significantly improved maize yield in the United States (Johnston & Poulton, 2018). Increasing yield potential and demand for maize have also increased fertilizer use, especially nitrogen (N). Since inorganic fertilizer N became readily available for agriculture following World War II (Kurt et al., 1984), crop yields have significantly increased with increasing amounts of applied fertilizer N (Johnston & Poulton, 2018).

Cattle manure has historically been a significant source of nutrients for crop production. The oldest agricultural experiment at Rothamsted Experimental Station in England demonstrated the effectiveness of farmyard manure on producing continuous wheat (*Triticum aestivum* L.) (Johnston & Poulton, 2018). The sustainability of fertilizer uses in agricultural production systems and a mono-cropping system can be challenging considering <50% of nitrogen use efficiency (NUE) in the U.S. maize hybrids (Kucharik and Ramankutty, 2005; Varvel and Peterson, 1990).

Sustainable production requires high NUE crops that give maximum biomass and grain yield for every unit of fertilizer N input. Various indices are used in agronomic research to assess NUE (Cassman et al., 2002). Another important metric to determine a sustainable system is yield stability, which measures consistency under different management practices (Tollenaar and Lee, 2002). Dynamic yield stability accounts for increasing yield potential over the years and simultaneously determines consistency in yield and yield gain (Lin et al., 1986). In some instances, high stability may correspond to stable but low-mean yields. The yield reliability index provides a measure of high-mean yield and the consistency in yield over the years (Annicchiarico, 2002).

Core Ideas

- Manured plots provided a more reliable and stable yield than the non-manured.
- Manure increased soil organic matter but also N and P accumulation in the soil profile.
- Linear regression of yield against years in manured plots had similar slopes across N rates.
- Slopes of linear regression of yield against years increased with N rates in non-manured plots.
- Management of fertilizer should account for yield potential to ensure environmental safeguard.

The Knorr–Holden Plot has been planted to continuous maize since 1912 and maintained with organic and inorganic fertilizers. It presents a historical dataset that provides unique insights into fertility management in maize as no other single experiment does. The objective of this historic experiment was to evaluate the effects of long-term cattle manure and inorganic fertilizer application on irrigated continuous maize grain yield, NUE, yield stability and reliability, and soil properties.

2 | MATERIALS AND METHODS

This experiment was conducted at the University of Nebraska-Lincoln (UNL) Panhandle Research and Extension Center, Scottsbluff, NE, and later became known as the Knorr–Holden Plot in honor of the first two superintendents of the experiment station. It was initiated in 1910 in the North Platte Valley of western Nebraska during the state's first large-scale irrigation project. It is the oldest irrigated maize plot and the third-oldest maize research plot in North America after the Morrow Plots at the University of Illinois and the Sanborn Field at the University of Missouri (Blanco-Canqui et al., 2015). It was developed in response to a need to determine the best-irrigated farming method for continuous maize in the early 1900s for western Nebraska, where the mean annual precipitation is 396 mm. The soil at the experiment site is a Tripp very fine sandy loam soil (coarse-silty, mixed, superactive, mesic Aridic Haplustoll).

In 1910, native short grass prairie sod was broken, and the land was seeded to oat (*Avena sativa* L.) in spring 1911. The plot was 33 by 25 m. Open-pollinated maize was planted from 1912 through 1940. Different Nebraska experimental station hybrid and commercial hybrid varieties were used

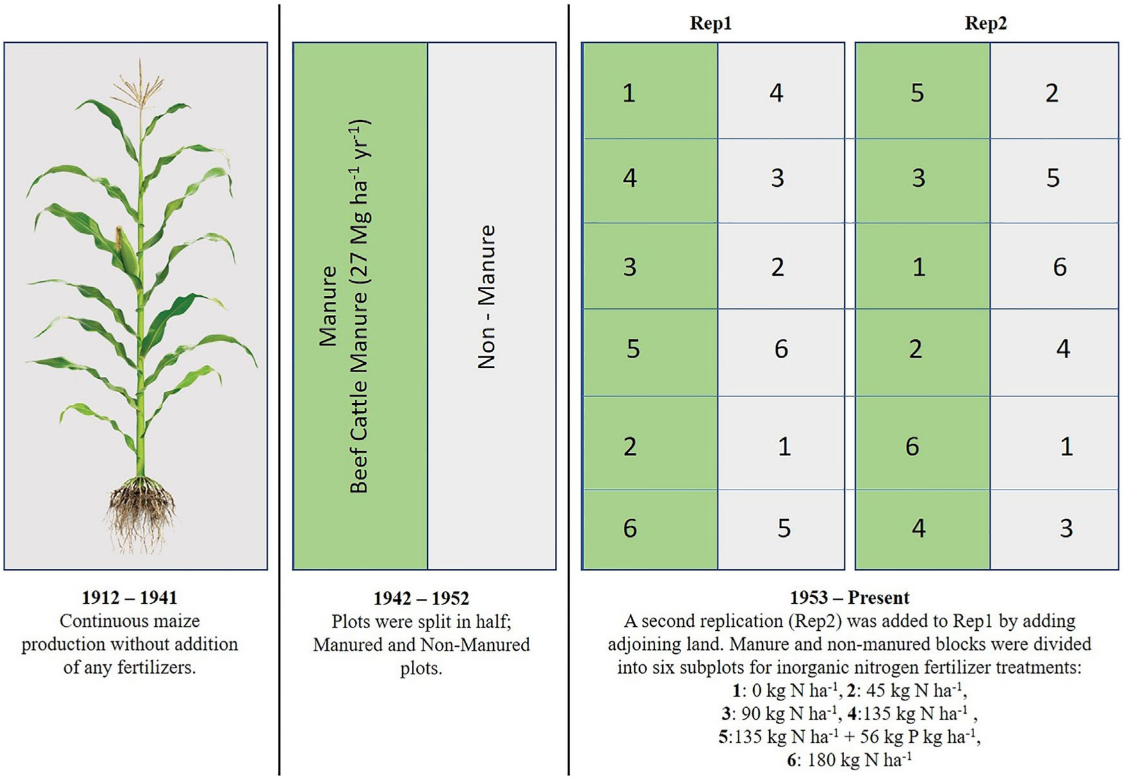

FIGURE 1 Dynamic plot design of the Knorr–Holden Plot

from 1940 to 2012. Top-yielding varieties adapted to the area were selected based on the UNL variety testing program. From 1912 through 1941, the plot received no fertilizer (Figure 1). In 1942, the plot was split in half to include a beef cattle manure treatment (0 and 27 Mg ha^{-1} yr^{-1}). In 1953, a second replication was added by expanding into the adjoining plot area. The second replication soil had a manure history of 27 Mg ha^{-1} yr^{-1} since 1942. Hereafter, the first replication (Rep 1) is referred to as "old" and the second replication (Rep 2) "new." The manure treatment blocks were split into subplots in the same year to include six inorganic fertilizer N treatments: 0, 45, 90, 135, 135 (+ 56 kg P ha^{-1}), and 180 kg N ha^{-1}. Thus, in 1953, the experiment design was effectively made into a split-plot design with manure treatment as the main factor and inorganic fertilizer N treatments as a subplot and with two replications. It is important to remember that this historic experiment was designed before the modern statistical design was developed.

Beef feedlot manure was scraped and stockpiled during the previous year from the UNL research cattle feedlot. It was transported and spread with a small manure spreader in early April each year and incorporated by plowing to about a 25-cm depth. The amount of manure (27 Mg ha^{-1}) applied was on a wet weight basis. The manure moisture content at spreading varied from 114–276 g kg^{-1} among years. The pH of the manure has ranged from 6.4 to 8.5. The organic C concentration of the manure range from 81 to 251 g kg^{-1} (Table 1).

TABLE 1 Characteristics of the feedlot manure used in the Knorr–Holden Plot (adapted from Blanco-Canqui et al., 2015)

Property	Value
Moisture, g kg^{-1}	114–276
pH	6.4–7.9
Total N, g kg^{-1}	9.2–28.5
Organic N, g kg^{-1}	8.6–26.4
Total C, g kg^{-1}	86.0–270.7
Organic C, g kg^{-1}	81.5–193.8
P, g kg^{-1}	3.8–12.3
K, g kg^{-1}	12.3–33.1
S, g kg^{-1}	2.0–6.1
Zn, g kg^{-1}	0.11–0.20
Fe, g kg^{-1}	1.3–12.1

The initial inorganic N source was ammonium nitrate which was hand-applied before plowing every year. Urea was substituted for ammonium nitrate in 2005 due to changes in fertilizer availability. Soil samples from each plot were analyzed every 2 or 3 yr to monitor soil P and Zn concentration levels. If P and Zn in the non-manured plot decreased below critical levels, about 18–22 kg ha^{-1} of P and 1.4 to 2.3 kg ha^{-1} of Zn as $ZnSO_4$ were added. Early in the experiment, cultivation was the sole method of weed control. Maize was planted from late April to early May. The irrigation furrows were formed in mid-June each year. At physiological maturity, maize ears were harvested from all plants from 6.1-m sections of each plot's middle two rows. Ears were dried, shelled, and weighed. Grain yields are reported at 15.5% moisture.

In 2013, at the turn of the century for the experiment, two 5-cm diam. soil cores (0–150 cm) were composited from all treatment plots using a hydraulic probe. Cores were divided into 0–20-, 20–60-, 60–90-, 90–120-, and 120–150-cm sections. All soil samples were analyzed for pH (Thomas, 1996), soil organic matter (SOM) (Nelson & Sommers, 1996), Olsen P (Olsen et al., 1954), S, nitrate-N (NO_3^-–N) (Mulvaney, 1996), sulfate-S (Johnson, 1987), and DTPA-extractable Zn, Fe, Mn, and Cu (Lindsay & Norvell, 1978).

An asymptotic segmented linear regression fit was used to determine the yield trend from 1912–2012 in the control plot (no manure or inorganic fertilizer) in R using package segmented. Linear regression of yield against year for each inorganic N treatment in both manured and non-manured plots was determined using R-stat (package: ggplot2 and ggpmisc) separately for each replication to determine the yield dynamics over the years. Each replication was considered as a discrete variable in statistical models to account for the past manure history in the new replication. Yield response to applied inorganic N rates in manured and non-manured plots was evaluated yearly from 1953–2012 using a linear regression model. Model-generated slopes and intercepts were regressed against years to determine the effects of applied inorganic N rate on grain yield in manured and non-manured plots over the years. The year is considered an independent variable in the analysis to capture the yield responses accounting for interannual variations. In this experiment, the interannual variation will constitute several factors, including weather, crop genetics, and agronomic practices.

Nitrogen use efficiency was estimated as partial factor productivity (PFP) and agronomic efficiency (AE) for different inorganic fertilizer N rate treatments in the non-manured plots and only AE in the manured plots. Partial factor productivity and AE were calculated as,

$$\mathrm{PFP} = Y_{\mathrm{N}} / F_{\mathrm{N}}$$

$$\mathrm{AE} = \left(Y_{\mathrm{N}} - Y_0\right) / F_{\mathrm{N}}$$

where

Y_{N} is crop yield in a given treatment plot (Mg ha^{-1})

Y_0 is crop yield in the control treatment (0 N) (Mg ha^{-1})

F_{N} is the amount of fertilizer N applied (kg ha^{-1})

Effects of manure on crop yield over the years and pairwise comparisons of other variables were determined using a *t* test in SAS. Crop yields by inorganic N treatments in the non-manured plot were averaged over consecutive 10-yr periods (1953–1962, 1963–1972, 1973–1982, 1983–1992, 1993–2002, and 2003–2012). A quadratic plateau model was fitted against decadal crop yields at different N rates in the non-manured plots in SAS (SAS, 2012) to determine agronomic optimum nitrogen rates (AONR) and corresponding agronomic optimum yield (AOY).

For yield stability analysis, dynamic, that is, type 2 yield stability index (Lin et al., 1986) was calculated to determine yield stability by the treatments over the years. Dynamic yield stability for the different N rate and manure treatments was quantified using several measures that included Wricke's ecovalence (We) (Piepho, 1994), Shukla's stability variance (Ss) (Shukla, 1972), and Finlay and Wilkinson's regression coefficient (Finlay and Wilkinson, 1963). The treatment's yield stability ranking was performed by calculating mean yield stability indices (MYSI) averaged over three estimated stability measures. In dynamic yield stability, a given treatment is considered stable when the yield response in each year is parallel to all the experiment's mean responses (Lin et al., 1986). Yield reliability was also calculated based on mean yield and yield stability index to reduce Type II error in the cases where high stability corresponds to the stable but low-mean yield (Annicchiarico, 2002). The yield reliability index (YRI) was measured by calculating Kang's rank-sum (Kang, 1988). Yield stability and reliability were calculated in R adopting the stabilitysoft programming source codes (Pour-Aboughadareh et al., 2019).

Effect of manure and inorganic N treatments on soil chemical variables was determined using Proc Mixed in SAS, where manure and inorganic N treatments were fixed factors and rep was a random factor. Statistical significance of models and all the tests were determined at $\alpha < .05$.

3 | RESULTS

3.1 | Weather

There were several years where grain yield was either reduced or completely lost due to severe weather conditions. There are no grain yield data for 1952 and 1968 when yields were reportedly lost to severe hail damage. There were other years (1971, 1987, and 1999) that reported low yields due to hail damage. Considerable yield losses due to drought and low irrigation water supply were reported for eight different years in 100 yr. The yield was considerably reduced due to severe weed infestation in 1951. Rootworm caused a significant yield loss in 1974. This problem was corrected with the application of rootworm insecticides after 1976, then the use of genetic modifications in the 1990s replaced insecticides.

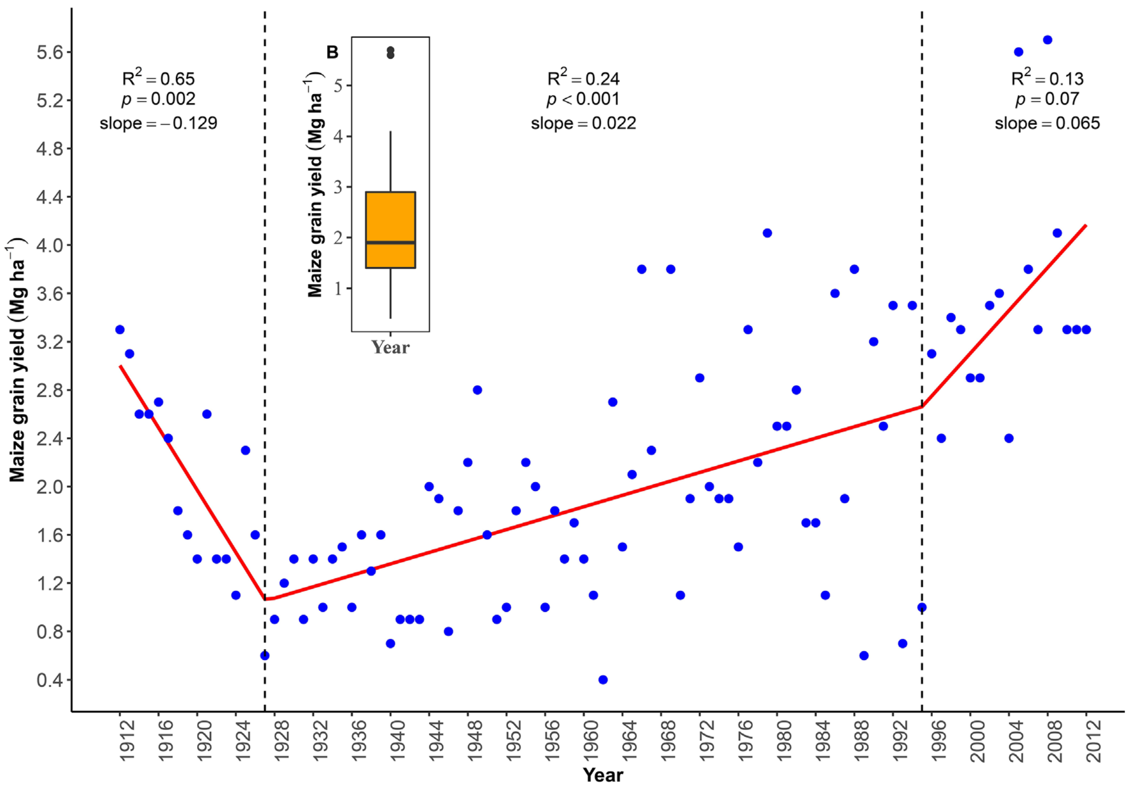

FIGURE 2 Maize grain yield in the control plot (no manure or inorganic N) from 1912 to 2012 with an asymptotic segmented linear regression fit with two break points at 1927 and 1995. Embedded plot B shows the quartile distribution of maize yield from 1912 to 2012 with two outliers in 2005 and 2008

3.2 | Crop grain yield

3.2.1 | Control plot (1912–2012)

Maize yields were 3.3 Mg ha^{-1} in 1912 and 3.1 Mg ha^{-1} in 1913 without any N input (Figure 2). Over time, grain yield showed a significant and gradual decrease (slope = –0.129, $R^2 = .65$), and by 1927, it was reduced to 0.6 Mg ha^{-1} (reduced by >300% from 1912) (Figure 2). There was a significant linear increase in grain yield in 1928–1995 (slope = 0.022). From 1996–2012, there was a greater increase in the grain yield with a slope of 0.065 at $p = .07$. Most of the years, grain yields were in the range of 0.4–4.1 Mg ha^{-1} with two exceptions of 5.6 Mg ha^{-1} in 2005 and 5.7 Mg ha^{-1} in 2008. The mean yield from 1912–2012 was 2.18 Mg ha^{-1} with a minimum of 0.4 Mg ha^{-1} in 1962 and a maximum of 5.7 Mg ha^{-1} in 2008.

3.2.2 | Manured vs. non-manured treatments (1942–1952)

In 1942, the 1st year of manure application, yield increased to 2.13 Mg ha^{-1} from 0.86 Mg ha^{-1} in 1941. By 1949, grain yield increased to 7.47 Mg ha^{-1}, which was >700% increase from 1941 and 126% increase from 1912. The mean yield for the manured plot in 1942–1952 was 3.09 Mg ha^{-1} with a maximum of 7.47 Mg ha^{-1} in 1949 and a minimum of 2.13 Mg ha^{-1} in 1942. Grain yield was in the range of 0.76–2.82 Mg ha^{-1} in the non-manured plot during the same time.

In the first decade since manuring began (1942–1952), and when there was only one replication, maize grain yields linearly increased ($R^2 = .36$, $p = .03$) over the years in the manured plot. In 1942–1952, grain yield in the manured plot was significantly greater than in the non-manured plot (Figure 3).

3.2.3 | Inorganic N and manure treatments (1953–2012)

Linear regression of grain yield against years in the manured plot had a similar slope (~ 0.10) irrespective of grain yields considered for an individual N rate or all rates together and new, old, or both replications together (Figures 4, 5, and 6). A linear regression of yield against years for different N treatments in the non-manured plots showed a gradual increase in slope with increasing N rates. When averaged across two replications, regression slopes were 0.03, 0.06, 0.08, 0.09,

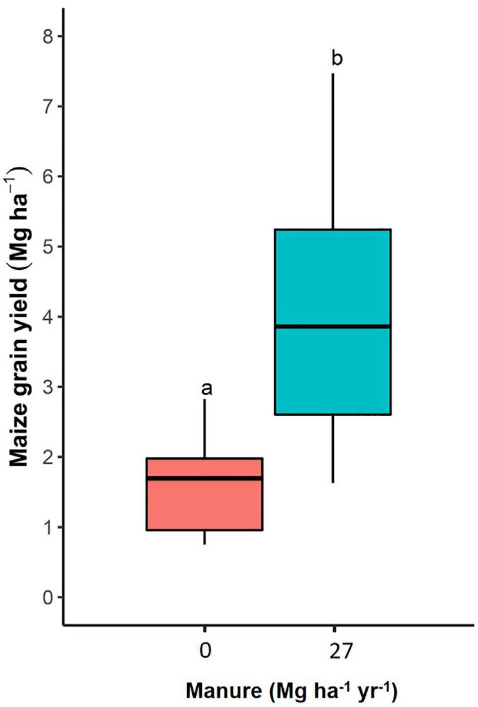

FIGURE 3 Box plot of maize grain yield in manured (27 Mg ha^{-1} yr^{-1}) and non-manured plots in 1942–1952. Different lowercase letters indicate significant difference in mean values at $p < .05$

0.10, and 0.11 for the N treatments at 0, 45, 90, 135, 135 (+56 kg P ha^{-1}), and 180 kg N ha^{-1}, respectively (Figure 6). The second (new) replication had a smaller slope for yield response to N rates than the old replication in the non-manured plot .

Yield responses to applied N rates in individual years during 1953–2012 varied by manure treatment. In contrast to manured plots, maize yields in non-manured plots significantly differed by inorganic N treatments. In non-manured plots, maize yields in the control treatments (0 N) ranged from 0.40 to 5.71 Mg ha^{-1} over the years, whereas they ranged from 2.53 to 15.66 Mg ha^{-1} in the N treatment of 180 kg N ha^{-1}. Slopes of regressions were significantly greater in the non-manured plot than the manured plot (Figure 7). For any given year, the regression slope for yield response to applied N rates in non-manured plots ranged from 0.019 to 0.044 (lower bound) to 0.027 to 0.061 (upper bound) (95% confidence interval). A mean slope of ~0.025 Mg kg^{-1} was persistent from 1953 until 1990. After that, the slope increased over the years to ~0.045 in 2012. In contrast, slope ranged from 0.001 to 0.003 (lower bound) to 0.003 to 0.014 (upper bound) in the manured plot.

Regression of intercepts of yield response to N rates against years were significantly greater in the manured plots than the non-manured (Figure 8). For any given year, the regression intercept for yield response to applied N rates in manured plot ranged from 5.36 to 11.55 (lower bound) to 7.49–14.72 (upper bound) (95% confidence interval). A mean intercept of 7.00 Mg ha^{-1} yr^{-1} was consistent from 1953 until 1980. Intercepts increased over the years to 15.24 in 2012. In contrast, intercepts ranged from 2.85 to 4.63 to 3.92 to 6.60 in the non-manured plots.

3.2.4 | Nitrogen use efficiency

Partial factor productivity (PFP) decreased with the increase in the inorganic N rate from 45 to 180 kg N ha^{-1} in the non-manured plots (Figure 9). The new replication showed significantly higher PFP compared to the old replication. Average PFP across all the inorganic N rates was 70.2 and 77.9 kg grain kg^{-1} N in the old and new replications. For the 45 kg N ha^{-1} treatment, the average PFP from 1953 to 2012 was 111.6 and 134.2 kg grain kg^{-1} N in the old and new replications. Quadratic regression of PFP against years showed improved PFP over the years. Application of P along with the fertilizer N increased NUE as evidenced by average PFP of 62.0 kg grain kg^{-1} N at 135 kg N ha^{-1} with 56 kg P ha^{-1} compared to 58.4 kg grain kg^{-1} N without P.

Average AE decreased as the input N rate increased in the non-manured plots (Figure 10). It dropped from 55.0 kg grain kg^{-1} N at 45 kg N ha^{-1} to 31.69 at 180 kg N ha^{-1} in old plots and 66.9 to 30.6 kg grain kg^{-1} N in new plots. Similarly, the average AE of all the inorganic N rates was higher in the new than the old replication (new plots = 45.4 kg grain kg^{-1} N, old plots = 42.9 kg grain kg^{-1} N). The 135 kg N ha^{-1} treatment with 56 kg P ha^{-1} had AE higher than that without P by 8.4 and 9.3% in the new and old replications. In contrast to the non-manured plots, the AE values for all inorganic N treatments (old or new replication) in the manured plots were <10 kg grain kg^{-1} N, and in many instances, AE was negative (data not shown).

3.3 | Agronomic optimum N rates in non-manured plots

A quadratic plateau model significantly fitted maize yield response averaged every 10 yr (from 1953 to 2012) to inorganic N rates in the non-manured plots (Table 2). There were two instances in the old replication, and one with the new replication where agronomic optimum nitrogen rates (ANOR) was greater than maximum applied N rate (180 kg N ha^{-1}) in the study. When those instances were not considered, there were trends for greater AOY over time with AONR that ranged from 88 to 175 kg N ha^{-1}. The new replication tended to have a lower AONR than the old replication. On average, AONR increased from 142 kg N ha^{-1} in 1953–1962 to 164 in 2003–2012 (15% increase), and AOY increased from 7.0 to 12.3 Mg ha^{-1} at the same time (76% increase).

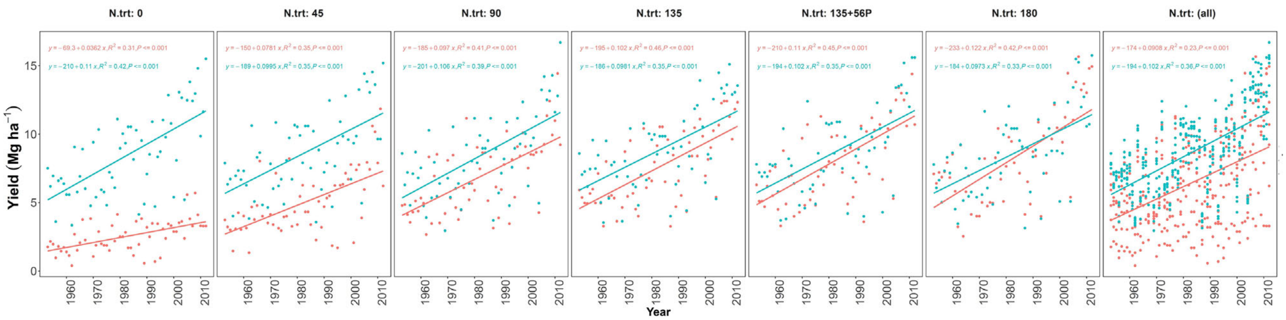

FIGURE 4 Linear regression of grain yield for each inorganic N treatment and all together in manured (blue color) and non-manured (red color) plots in the old replication (Rep 1) against years from 1953 to 2012. Regression equations in manured and non-manured plots are given with coefficients and *p* values in respective colors

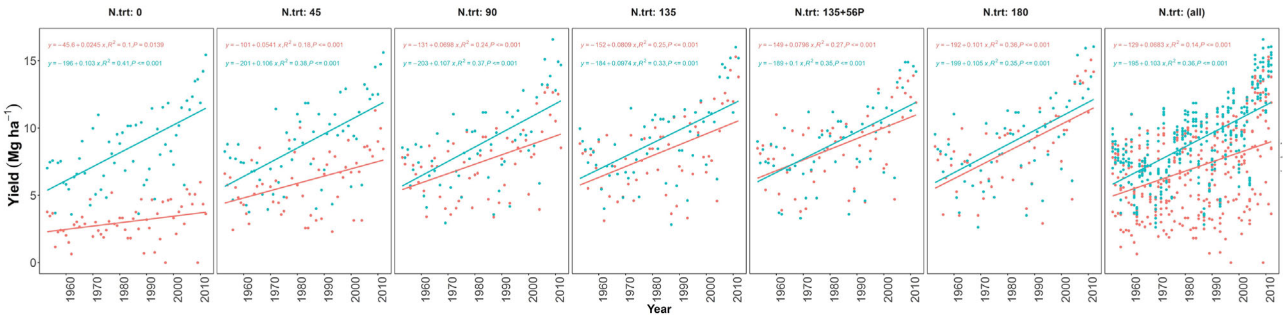

FIGURE 5 Linear regression of grain yield for each inorganic N treatment and all together in manured (blue color) and non-manured (red color) plots in the new replication (Rep 2) against years from 1953 to 2012. Regression equations in manured and non-manured plots are given with coefficients and *p* values in respective colors

3.4 | Yield stability

Relative ranking based on yield reliability index (YRI) showed that 10 out of top 12 treatments with high yield reliability were from the manured plots (Table 3). Two N treatments from the non-manured plots in the top YRI rank included N rate of 135 kg ha^{-1} with 56 kg ha^{-1} P and 180 kg N ha^{-1}, and both were from the second (new) replication of non-manured plots, which had the past manure history.

Relative ranking based on mean yield stability index (MYSI) showed that 7 out of 12 top-ranking treatments in terms of yield stability were from the manured plots. Five N treatments from the non-manured plot in the top ranks included an N rate of 135 kg ha^{-1} with and without 56 kg ha^{-1} P and 180 kg N ha^{-1}. Of these five non-manured plots, three were from the second (new) replication of non-manured plots. The treatments with the least yield stability and yield reliability were 0 and 45 kg N ha^{-1} rate treatments in the non-manured plots.

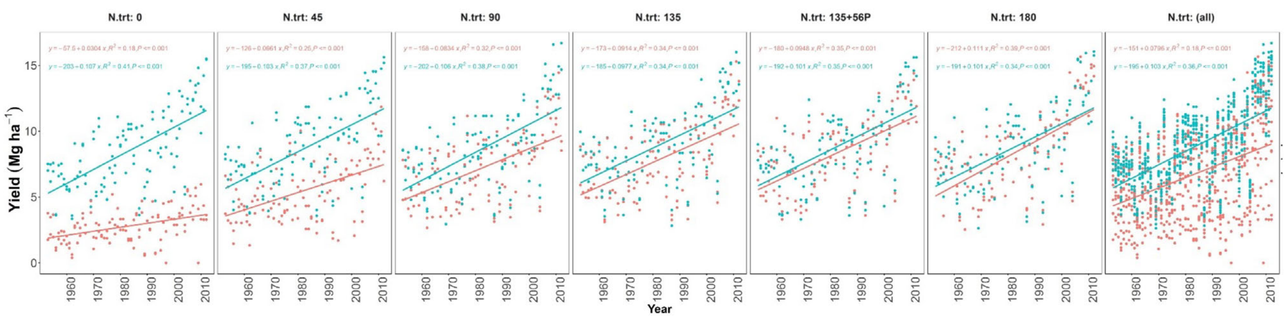

FIGURE 6 Linear regression of grain yield for each inorganic N treatment and all together in manured (blue color) and non-manured (red color) plots in both old and new replications against years from 1953 to 2012. Regression equations in manured and non-manured plots are given with coefficients and *p* values in respective colors

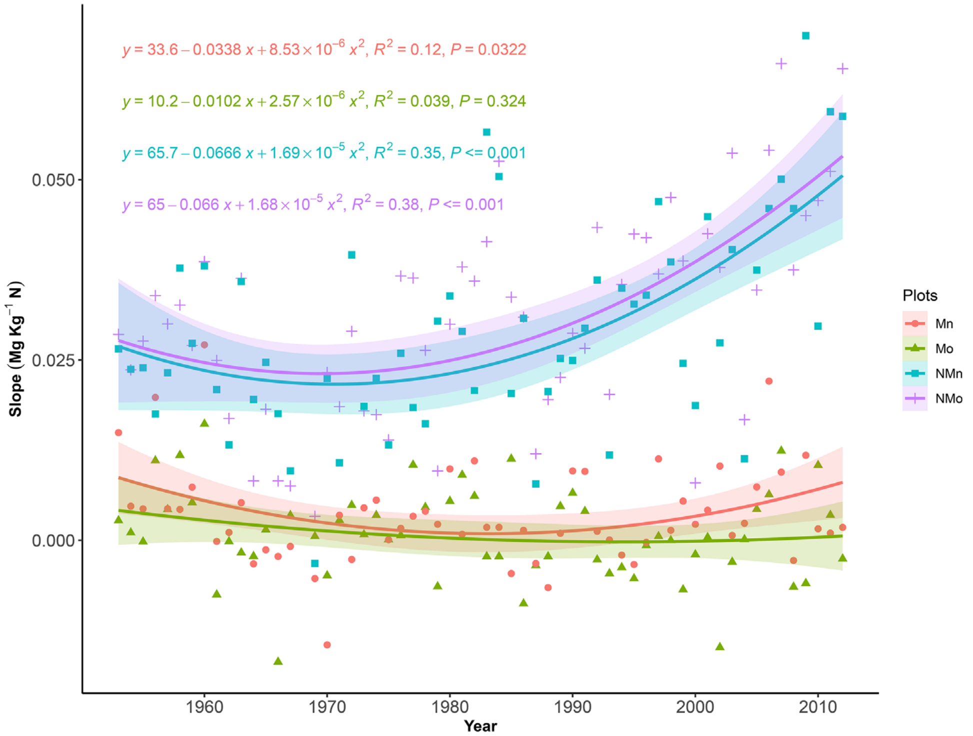

FIGURE 7 Regression of slope of yield response to applied N rates against years in old (o) and new (n) replications of manured (Mo, Mn) and non-manured plots (NMo, NMn). Regression equations with coefficients and *p* values and lower and upper bounds of 95% confidence interval are given in colors corresponding to regression lines

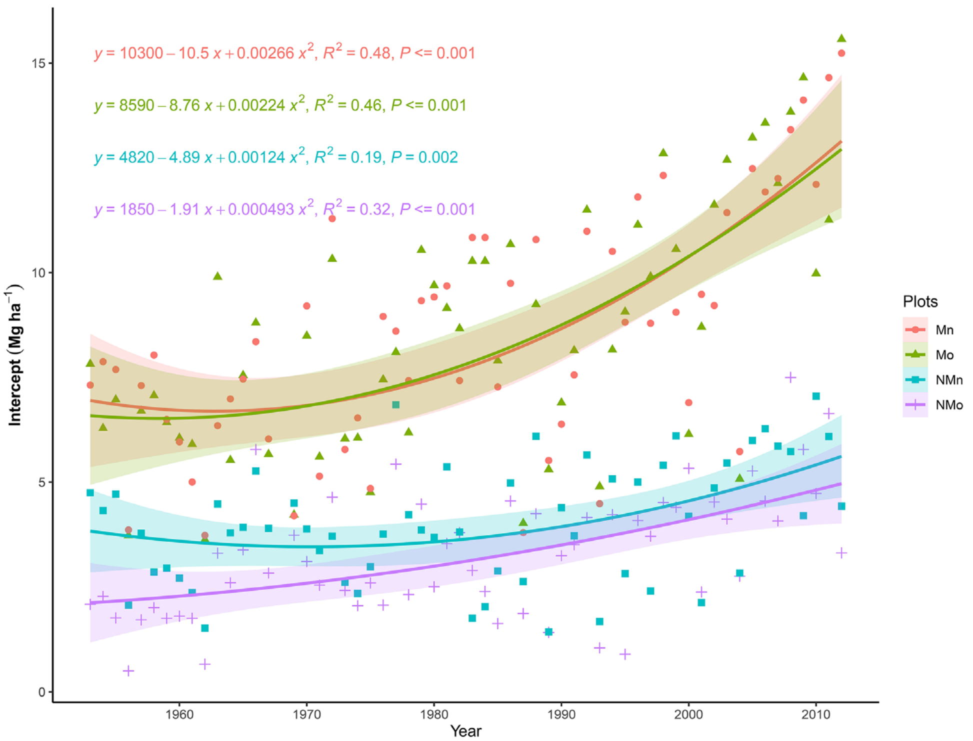

FIGURE 8 Regression of intercepts of yield response to applied N rates against years in old (o) and new (n) replications of manured (Mo, Mn) and non-manured plots (NMo, NMn). Regression equations with coefficients and *p* values and lower and upper bounds of 95% confidence interval are given in colors corresponding to regression lines

TABLE 2 Parameters of quadratic plateau model fitted in maize yield response to inorganic N rates in the non-manured plots across every 10 yr from 1953 to 2012

Time Period	*p* value		AONR, kg N ha^{-1}			AOY, Mg ha^{-1}		
	Old rep	New rep	Old rep	New rep	Average	Old rep	New rep	Average
1953–1962	NA	0.006	NA[a]	142.1	142.1	NA	7.0	7.0
1963–1972	0.044	0.002	99.9	87.7	93.8	6.0	6.8	6.4
1973–1982	0.008	0.068	165.4	132.6	149	7.1	7.3	7.2
1983–1992	0.010	NA	175.1	NA*	175.1	7.9	NA	7.9
1993–2002	0.003	0.017	164.9	145.4	155.2	8.9	8.6	8.8
2003–2012	NA	0.002	NA*	163.7	163.7	NA	12.3	12.3

Note. AONR, agronomic optimum nitrogen rate; AOY, agronomic optimum yield; NA, not applicable.
[a]Instances where AONR was greater than the applied N rates in the study and, therefore, not reported.

TABLE 3 Yield stability rank based on mean yield stability index (MYSI) and yield reliability index (YRI) for the different manure and inorganic N treatments at the Knorr–Holden Plot

Manure treatment	Rep	N Rate	We[a]	Ss	Fr	MYSI	Rank	YRI[b]
		kg ha^{-1}						
Manure	2	135	4	4	7	5.0	3	1
Manure	2	135+56P	3	3	8	4.7	1	2
Manure	1	135	2	2	11	5.0	2	3
Non-manure	2	135+56P	1	1	17	6.3	5	4
Manure	2	90	10	10	15	11.7	12	5
Non-manure	2	180	5	5	6	5.3	4	6
Manure	2	180	14	14	9	12.3	14	7
Manure	2	45	12	12	2	8.7	7	8
Manure	2	0	15	15	20	16.7	19	9
Manure	1	45	13	13	5	10.3	10	10
Manure	1	90	11	11	13	11.7	13	11
Manure	1	135+56P	16	16	10	14.0	17	12
Non-manure	1	135	6	6	16	9.3	8	13
Non-manure	2	135	8	8	14	10.0	9	14
Non-manure	1	135+56P	9	9	3	7.0	6	15
Manure	1	0	7	7	18	10.7	11	16
Manure	1	180	18	18	12	16.0	18	17
Non-manure	1	180	20	20	1	13.7	16	18
Non-manure	2	90	17	17	4	12.7	15	19
Non-manure	1	90	19	19	19	19.0	20	20
Non-manure	1	45	21	21	22	21.3	21	21
Non-manure	2	45	22	22	21	21.7	22	22
Non-manure	1	0	23	23	23	23.0	23	23
Non-manure	2	0	24	24	24	24.0	24	24

[a]Yield stability measures included We, Wricke's ecovalence; Ss, Shukla's stability variance; and Fr, Finlay and Wilkinson's regression coefficient. These three measures were averaged to calculate Mean Yield Stability Index (MYSI), which was then used to rank yield stability for treatments.
[b]YRI, Yield reliability index was based on Kang's rank-sum.

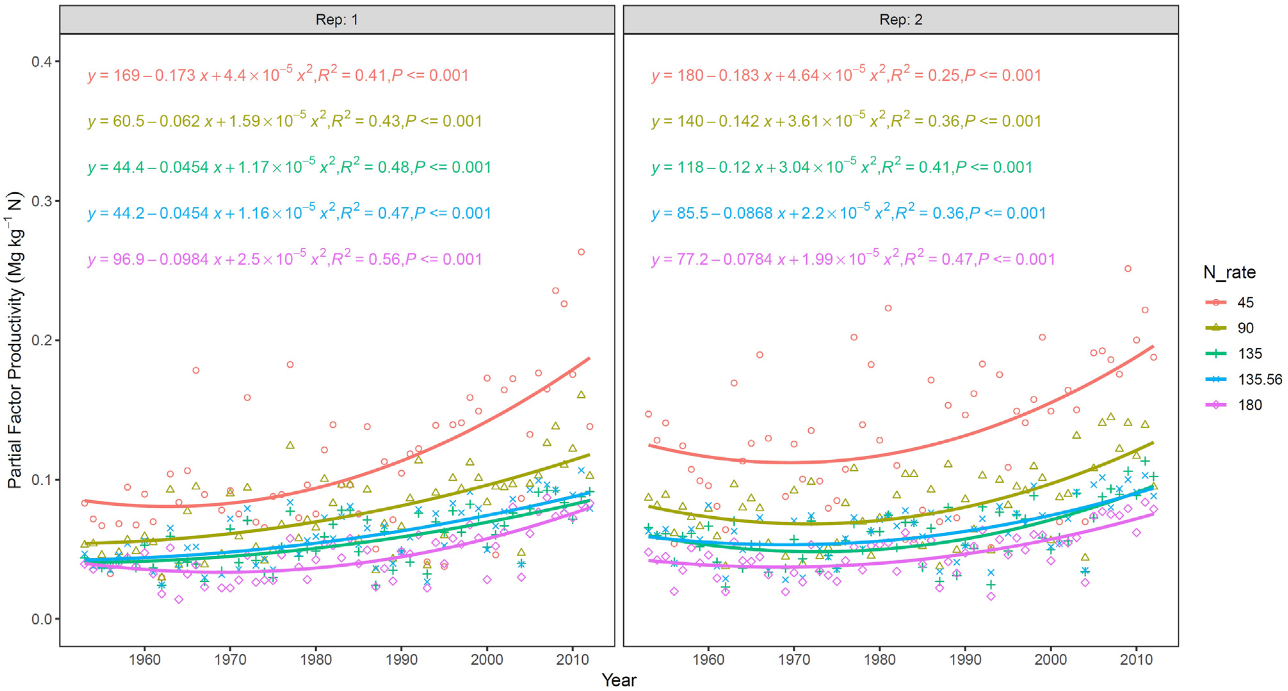

FIGURE 9 Regression of partial factor productivity of different inorganic N rate treatments against years in old (Rep 1) and new (Rep 2) replications of the non-manured plots. Regression equations are given with coefficients and p values in colors corresponding to regression lines

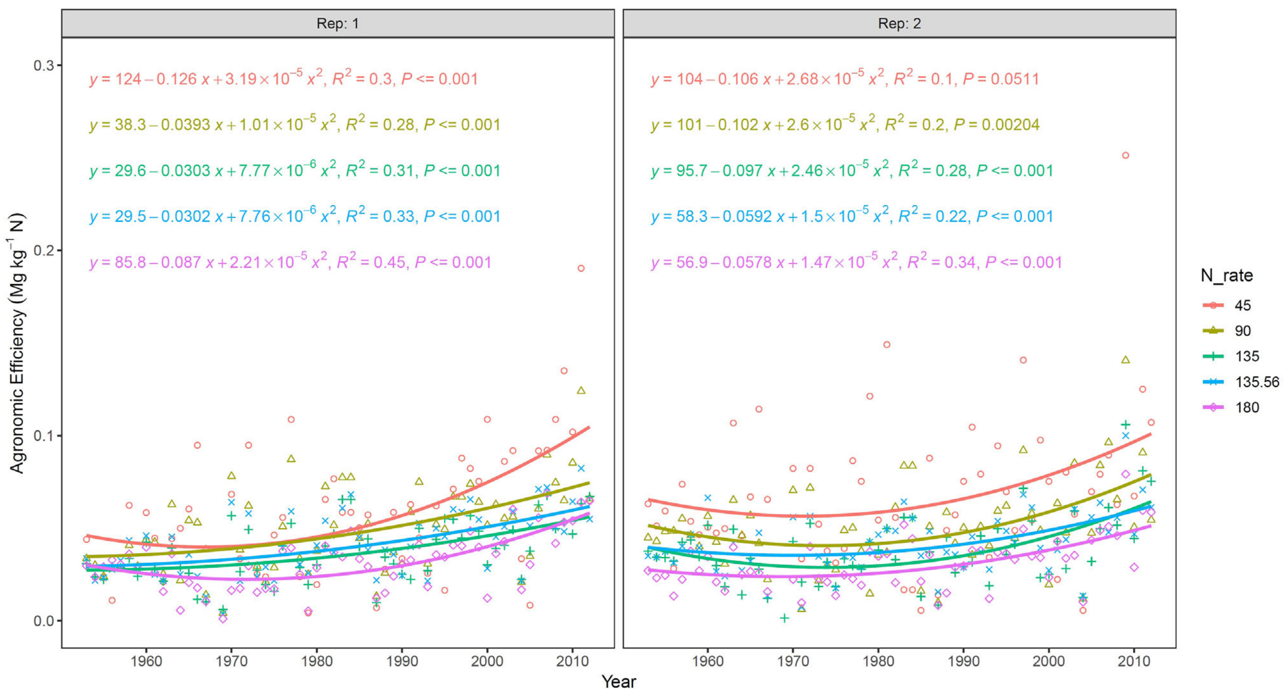

FIGURE 10 Regression of agronomic efficiency of different inorganic N rate treatments against years in old (Rep 1) and new (Rep 2) replications of the non-manured plot. Regression equations are given with coefficients and p values in colors corresponding to regression lines

3.5 | Soil properties

Soil organic matter was about 15 mg kg^{-1} in the top 20 cm in the non-manured plots (Figure 11). Soil organic matter was >20 mg kg^{-1} in the top 20 cm in the manured plots. Soil nitrate-N accumulation in the top 20 cm and through the soil profile (0–150 cm) was greater in the manured plots than in the non-manured. Soil residual nitrate-N in the top 20 cm in

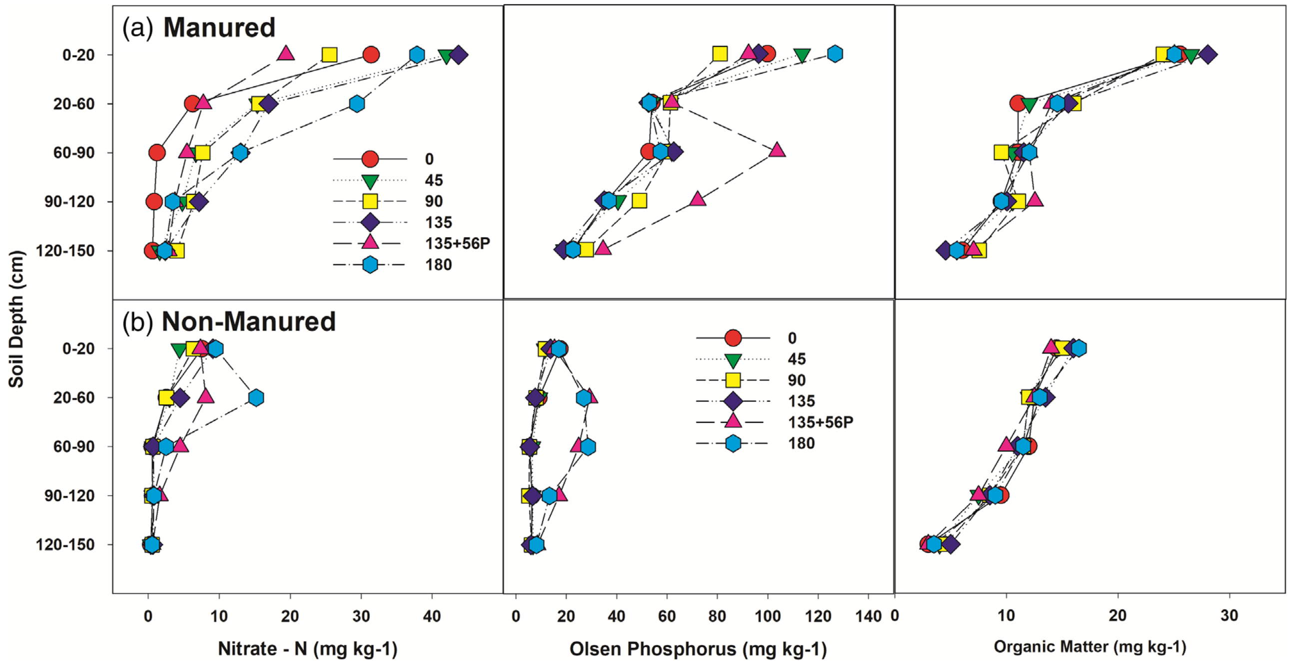

FIGURE 11 Soil nitrate-N, Olsen phosphorus, and organic matter at different sampling depths in different inorganic N rate treatments in the (a) manured and (b) non-manured plots at the Knorr–Holden Plot

the manured plots was between 12–42 mg kg^{-1} compared to 2–12 in the non-manured.

Soil P in the top 20 cm in the non-manured plots was well below 20 mg kg^{-1} compared to >60 in the manured plots. Only one N treatment (135 kg N ha^{-1} + 56 P kg ha^{-1}) in the non-manured plot had >20 mg kg^{-1} in the soil profile deeper than 20 cm. All inorganic N treatments had P > 20 mg kg^{-1} throughout the 0-to-150-cm profile in the manured plot.

4 | DISCUSSION

4.1 | Maize yield with no fertilizer inputs

The U.S. Department of Agriculture started to publish maize yield estimates in 1866. For 70 yr until 1936, the average U.S. maize yield was 1.6 Mg ha^{-1} (Nielsen, 2017). In the Knorr–Holden Plot, the average maize yield was 1.6 Mg ha^{-1} from 1912 to 1941. The yield started at 3.6 Mg ha^{-1} in 1912. Higher soil organic matter from the recently broken native sod vs. longer-term cultivated land in the USDA information resulted in the higher maize yield at Knorr–Holden. As soil nutrients were depleted over the years (Anderson & Peterson, 1973), yield decreased at a rate of 0.13 Mg ha^{-1} yr^{-1} to 0.6 Mg ha^{-1} in 1927 and was at a range of 0.6–1.6 until 1941. In addition to nutrient depletion, the open-pollinated lines used from 1912 to 1941 were lower yielding due to their poor vigor and susceptibility to different pests and diseases (García-Lara & Serna-Saldivar, 2018; Pruitt, 2016). At the Knorr–Holden Plot, a local open-pollinated variety known as Calico maize was grown from 1912 to 1921 and later, a local yellow variety from 1922 to 1942 (Anderson & Peterson, 1973). Introduction of improved double-crossed hybrid varieties in 1942 significantly improved yields. Yield fluctuated between 0.4 and 5.7 Mg ha^{-1} yr^{-1} from 1942 to 2012.

The transition of open-pollinated to hybrid maize varieties significantly improved the yield in the United States. Uniformity, higher yield potential, and efficient machine harvest were a few of the factors which helped in the adoption of hybrid maize within a few years (Crabb, 1947; Stuber et al., 1992). According to the USDA, maize yield increased at 0.008 Mg ha^{-1} yr^{-1} after introducing maize varieties with improved genetics in the late 1930s. Starting from 1928, maize yield at the Knorr–Holden Plot gradually increased with a slope of 0.022 Mg ha^{-1} yr^{-1} until 1995. Because improved hybrids from the Nebraska variety testing program were used, we assume this played a considerable role in yield increases. A significant increase in yield of 0.036 Mg ha^{-1} yr^{-1} in the control plot from 1953 to 2012 underscores the role of improved varieties, including improved management practices (herbicides, insecticides, irrigation management) and possible atmospheric nutrient deposition. The USDA reported a second significant improvement in maize yield in the mid-1950s due to improved crop genetics, expanded use of mineral N fertilizers, and agricultural mechanization (Nielsen, 2020). This was also observed in the Knorr–Holden Plot. From 1928 to 1949 average maize yield of the control plot was 1.36 Mg ha^{-1} yr^{-1}, which increased to 2.48 Mg ha^{-1} yr^{-1} from 1950 to 2012. Starting at 1995, maize yield at the Knorr–Holden Plot again showed a departure from the yield trend of 1928–1994 with an increment of 0.065 Mg ha^{-1} yr^{-1}, primarily reflecting the adoption of transgenic hybrid varieties during the 1990s. The importance of hybrid varieties in maize yield improvement was reported in several studies (Guo et al., 2014; Shi et al., 2013). The Knorr–Holden control plot (old replication) provided a unique insight into how inter-annual variation, a function of climate and weather, genetic improvement, and agronomic practices, explained about one-third of the yield variation in the last 100 yr.

4.2 | Fertilizer effect on maize yield and N use efficiency

Fertilization is another major agronomic practice that significantly increased maize yield (Egli, 2008). The yield gain in the manured plot can be attributed to enhanced crop essential nutrient supply (Evanylo et al., 2008; Manna et al., 2005; Mundus, et al., 2008; Wang, et al., 2017) and cumulative benefits of manure application on soil properties over the years. Soil organic matter increased by 10mg kg^{-1} following long-term manuring compared to non-manured plots. Blanco-Canqui et al (2015) reported reduced susceptibility to compaction and improved water retention at the Knorr–Holden Plot due to long-term manuring, corroborated in other studies (Shirani, et al., 2002; Wortmann & Shapiro, 2008; Zhang, et al., 2018). Improvement in SOM, water retention, and plant available water with less compaction would support root proliferation and growth and subsequently increase crop yield in the manured plots than the non-manured. A considerably high intercept in yield-response curves in the manured plots over the years underscores the cumulative benefit of annual manure application on crop productivity (Schlegel et al., 2015). In addition, this data suggests that regular manure application can provide for increasing crop yield potential over the years due to factors such as improved cultivar and management practices.

In the Knorr–Holden Plot, application of inorganic N to manured plots did not improve maize yield, as evidenced by a smaller slope in yield response to N rates over the years. Maize yields did not vary much with or without inorganic N in the manured plots. Low or negative NUE in the manured plots suggested economic and environmental disadvantages of unnecessarily supplementing manure with inorganic fertilizer. Similar results were reported from the Rothamsted long-term experiment where the application of 35 Mg ha^{-1} farmyard manure had similar yields with or without inorganic N fertilizers (Johnston & Poulton, 2018).

In the non-manured nutrient-depleted soil, there is always a positive correlation between inorganic N rates and grain yield (Srivastava, et al., 2018; Tamang, et al., 2017). As the crop yield potential increased over the years, yield gain with added inorganic N also increased, as evidenced by increasing slopes of yield-response curves. The USDA annual maize yield estimates showed that inorganic fertilizer N, along with the improved genetics, was the most critical addition back in 1950, which doubled the rate of maize production in the United States. Modern varieties produced more grain per unit of N (Mueller et al., 2019), as evidenced by the increasing NUE over the years in the non-manured plots at the Knorr–Holden Plot. However, unlike manure, inorganic N supplied for crop nutrient needs but did not improve soil properties. Despite comparable crop yields in the high inorganic N rate in the non-manured plot and the manure only plot, the latter benefited from enhanced soil properties such as SOM. Long-term benefits of manuring would explain a higher yield and yield stability and reliability observed in the new replication vs. old in the non-manured plots since the new replication had a manuring history.

4.3 | Yield stability and reliability

Several studies reported that long-term application of manure brought yield stability in different cropping systems (Chen et al., 2018; Knapp and van der Heijden, 2018). Chen et al. (2018) reported manure supplemented with inorganic fertilizer produced stable yields. Yield reliability measures high yield in addition to stable yield. It was evident that manure provided for both yield stability and reliability in most cases. The manured plot with supplemental N (and P) ranked highest in YRI. However, given a small slope for yield response to applied N rates, actual crop N need based on yield potential needs to be accounted for while planning for simultaneous use of manure and inorganic fertilizer.

Yield stability and reliability indices showed that one replication of each of the highest and the lowest N rate (180 and 0 kg N ha^{-1}) in the manured plots was among the treatments with the lowest yield stability and reliability. High inorganic N present in the high C system, such as in manured plot, can be immobilized (Szili-Kovács et al., 2007) depending on weather, soil dynamics, and interannual variability. In another case, crop N need may not be fully met with manure alone at times. One of the major concerns in relying on manure alone is difficulty determining the timing and amount of N mineralization (Tarkalson et al., 2012) and high manure salt levels (Eghball et al., 2004; Horneck et al., 2007). Therefore, yield-goal-oriented stable and reliable treatments with an optimized combination of manure and inorganic fertilizer can bring sustainability to maize production in the United States and the world.

4.4 | Optimizing fertilizer management

In the Knorr–Holden Plot, applied manure and some inorganic N rates were higher than those required for observed crop yields, particularly until 2000. Such excessive input was regular in the past in the United States and can have considerable environmental implications. Phosphorus level >20 mg kg^{-1} recorded at 120–150 cm in the manured plots attested to it. Following a more moderate manure application for 119 yr, Pasket et al (2020) observed P leaching down to 90 cm. Campbell and Racz (1975) showed elevated P levels at 120–150 cm below a beef cattle feedlot in a calcareous soil. Several studies reported P enrichment at variable depths in soils manured for over-extended periods (Kuo & Baker, 1982; Liu et al., 2019; Mozaffari & Sims, 1994; Sharpley, et al., 1984). A large P accumulation in soil is concerning as it is susceptible to losses via run-off, erosion, and leaching to water bodies downstream. Similarly, excessive inorganic N input is responsible for greenhouse gas emissions and nitrate leaching. Therefore, manure and inorganic N management need to be optimized, accounting for yield potential and considering environmental safeguard.

5 | CONCLUSION

The 100-yr continuous maize grain yield data from a single experiment illustrated annual variation and long-term trends in maize yield under varying fertilizer treatments. This historic dataset underscores the role fertilization and improved genetics and production technologies played in improving maize yield. Maize yield increased over the years with an increasing inorganic N rate in the non-manured plot. If appropriately managed, manure can be an effective sustainability tool as it recycles nutrients, improves soil properties, and sustains crop production. Optimized manure supplemented with inorganic fertilizer can provide a stable and reliable yield and help establish an economically and environmentally sustainable maize production system.

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AUTHOR CONTRIBUTIONS

Bijesh Maharjan: Conceptualization; Data curation; Formal analysis; Investigation; Project administration; Resources; Software; Supervision; Writing-original draft; Writing-review & editing. Saurav Das: Formal analysis; Software; Visualization; Writing-original draft; Writing-review & editing. Rex Nielsen: Data curation; Resources; Writing-review & editing. Gary W. Hergert: Conceptualization, Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing-original draft; Writing-review & editing

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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