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Long-term agro-economic and environmental assessment of adaptive nutrient management on cropland fields with established structural conservation practices

D.R. Smith, R.D. Harmel, and R.L. Haney

Abstract: On-farm adoption of agricultural conservation practices or management alternatives depends on conservation ethic, social pressure, regulatory attention, and perceived impact on yield and economic return. Although agro-economic and environmental impacts are assumed to conflict, little research has been conducted to address potential tradeoffs and provide a scientific basis for decision-making. Thus, this 16-year evaluation of adaptive nutrient management was conducted in the Texas Blackland Prairies ecoregion on six fields with structural conservation practices already in place. Each field was randomly selected to receive either commercial fertilizer or poultry litter at rates of 4.5 to 13.4 Mg ha^{-1}. Two major nutrient management adaptations were made (i.e., soil test nitrogen [N] rate recommendations in 2009, and reduction of fallow period length and cover cropping during prolonged fallow periods in 2013). Important results included (1) soil test recommendations that consider historical crop yields reduced N application 25% to 38% for low rates of poultry litter, but did not reduce profits; (2) interannual variability of economic and weather conditions contributed to the lack of statistically significant differences in profit, although profit reduction for high nutrient rate treatments was clear; and (3) litter application, especially at rates in excess of crop phosphorus (P) needs, also increased runoff P losses by 1 to 1.4 kg ha^{-1} indicating the need for careful management of organic nutrient sources. Results of this long-term study showed that maintaining or increasing economic return does not have to be sacrificed to improve environmental impacts, which is an important consideration as producers make on-farm management decisions.

Key words: economics—nitrogen—phosphorus—poultry litter—water quality

Agriculture is known to contribute to sediment and nutrient loadings to streams, lakes, and estuaries (Smith et al. 2008; Jarvie et al. 2015). Conservation practices are used to decrease these loadings from agriculture (Smith et al. 2015; Her et al. 2016; Jarvie et al. 2017); however, producers do not make decisions on practice adoption in isolation (Reimer et al. 2012; Wilson et al. 2014; Smith et al. 2018). On-farm adoption of agricultural conservation practices or management alternatives depends on factors such as conservation ethic, social pressures, and yield and/or economic impact (Hoag et al. 2012; Perry-Hill and Prokopy 2014).

Most of the literature on the biophysical impacts of conservation practices in agricultural landscapes focuses on environmental parameters, such as soil health (Ashworth et al. 2018; VeVerka et al. 2019), runoff water quality (Thapa et al. 2018; Cober et al. 2019; Plach et al. 2019), and soil erosion (Acharya et al. 2019), and are either of short duration (Smith et al. 2016, 2017) or do not include metrics (i.e., economics of practice adoption [Feyereisen et al. 2015; Baker et al. 2018]). Producers need to not only know the environmental impact of conservation adoption, but also how adoption might affect their bottom line. Other studies in the literature report on the economics of practice alternatives (Harmel et al. 2008), but not on the environmental aspects in cultivated annual cropping systems for the United States. It is important that long-term studies consider both economic and environmental components, insofar as possible.

It is rare that cropping systems management is static over extended periods due to changing weather patterns, economic factors, consumer preferences, etc. Producers respond to economic pressures (i.e., lower commodity prices or higher fertilizer prices), incentives lead to adoption of new conservation measures (i.e., cover crops), or other drivers result in producers responding through adaptive management to optimize their operation to these external pressures (McIsaac et al. 2002; Morton et al. 2015). In the United States, high profile instances of nitrogen (N) and phosphorus (P) enrichment in the Gulf of Mexico, Chesapeake Bay, and Lake Erie have increased public awareness and thus pressure on farmers to reduce nutrient runoff. Thus, it is important that long-term studies offer some adaption during the life of the study, but not change course so quickly that results are masked by inherent interannual variability that exists in cropping systems (Kleinman et al. 2018).

This study was conducted to evaluate 16 years of adaptive nutrient management on six cultivated fields at the Riesel watersheds in central Texas, United States. It is important to note that the study fields have had structural conservation practices in place (i.e., terraces and grassed waterways) for decades; therefore, the study was designed not to evaluate the effects of those practices but to evaluate the next iteration of management evolution. Adaptive nutrient management was intensified every four to six years (i.e., reduce the N fertilization rate to more closely match crop requirements, then addition of cover crops). While individual studies at Riesel have compared inorganic fertilizer and poultry litter applied as a soil amendment and nutrient source for crop and forage production (e.g., soil microbiology [Acosta-Martinez and Harmel 2006], runoff water quality [Harmel et al. 2004, 2009, 2013, 2014], on-farm economics [Harmel et al. 2008], and nutrient cycling [Vadas et al. 2007; Harmel et al. 2011]), the present study

Douglas R. Smith and **Rick L. Haney** are research soil scientists at the USDA Agricultural Research Service (ARS) Grassland Soil and Water Research Laboratory in Temple, Texas. **R. Daren Harmel** is center director for the USDA ARS Center for Agricultural Resources Research, Ft. Collins, Colorado.

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Table 1
Land management and watershed characteristics of cultivated fields.

Cultivated watersheds	Y6	Y13	Y10	W12	W13	Y8
Area (ha)	6.6	4.6	7.5	4.0	4.6	8.4
Slope (%)	3.2	2.3	1.9	2.0	1.1	2.2
Litter rate (Mg $ha^{-1} y^{-1}$)	0.0	4.5	6.7	9.0	11.2	13.4
Year	Land use/crop					
2001	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow
2002	Corn	Corn	Corn	Corn	Corn	Corn
2003	Corn	Corn	Corn	Corn	Corn	Corn
2004	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
2005	Corn	Corn	Corn	Corn	Corn	Corn
2006	Corn	Corn	Corn	Corn	Corn	Corn
2007	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
2008	Corn	Corn	Corn	Corn	Corn	Corn
2009	Corn	Corn	Corn	Corn	Corn	Corn
2010	Hay	Hay	Hay	Hay	Hay	Hay
2011	Hay	Hay	Hay	Hay	Oats	Oats
2012*	Oats, hay	Oats, hay	Oats, hay	Oats, hay	Oats, hay	Oat hay, hay
2013	Hay	Cover†	Cover†	Cover†	Cover†	Cover†
2014	Corn	Corn	Corn	Corn	Corn	Corn
2015	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat
2016	Hay	Hay	Hay	Hay	Hay	Hay
2017	Wheat	Wheat, hay‡	Wheat, hay	Wheat, hay	Wheat, hay	Wheat, hay

*Double crop.

†Incorporated as "green manure," not harvested.

‡Summer legume planted as cover crop, harvested for hay.

is the first comprehensive analysis of the agro-economic and environmental effects.

Materials and Methods

Site Description. In August of 2000, six cultivated fields were selected as the experimental units for a long-term study of the agro-economic and environmental impacts of land applying poultry litter as a nutrient source. These homogeneous land use areas are best described as field-scale watersheds. Litter application rates from 0.0 to 13.4 Mg ha^{-1} were chosen to encompass and exceed the typical range of application rates in the region, were determined a priori, and then were randomly assigned to each of the six cultivated fields (table 1). The litter was obtained from turkey or broiler chicken houses near the study site, and the bedding material in litter was either wood shavings or rice hulls. Each cultivated field had broad-base terraces on the contour and grassed waterways at the terrace outlets.

All of the study fields were located at the USDA Agricultural Research Service Grassland Soil and Water Research Laboratory near Riesel, Texas (31°28′38.65″ N, 96°53′14.97″ W; figure 1). The research site is dominated by Houston Black clay soil (fine, smectitic, thermic, udic Haplustert), which is widely recognized as a classic Vertisol. These highly expansive clays, which shrink and swell with changes in moisture content, have a typical particle size distribution of 17% sand, 28% silt, and 55% clay. These soils are very slowly permeable when wet (saturated hydraulic conductivity ≈ 1.5 mm h^{-1}); however, preferential flow associated with soil cracks contributes to high infiltration rates when the soil is dry (Arnold et al. 2005; Allen et al. 2005).

Land Management. Management consisted of tillage, planting, harvest, and application of inorganic fertilizer, litter, and pesticides. In 2001, the cultivated fields were kept fallow and no fertilizer or litter was applied to establish baseline conditions. Beginning in 2001 and in each following year, each field received the same annual litter application rate each year (0 to 13.4 Mg ha^{-1}). Three distinct study periods followed in which differing management strategies were evaluated (table 2). In Period 1, the effect of nutrient source was evaluated at traditional rates. In Period 2, the effects of nutrient source and rate were evaluated with supplemental N rates based on soil test results (Haney et al. 2004, 2012; Haney and Haney 2010). The soil test results were coupled with appropriate crop yield goals based on historical production and nutrients required per unit production to determine the N required. In Period 3, the effect of nutrient source and rate with supplemental N based on soil test results with appropriate yield goals and utilization of cover crops was evaluated. Throughout the study, the control field (Y6) received inorganic fertilizer at traditional rates. For the litter applied fields, it was assumed that the litter N and P available in the year of application increased from 40% initially to 50% and in the year following application increased from 5% initially to 10% as soil microbial communities were enhanced and better able to mineralize organic amendments (Acosta-Martinez and Harmel 2006).

Economic Data. Throughout the study, detailed management records including date and activity details were collected for each field along with agronomic and economic data (e.g., crop yield; commodity price; seed price; fertilizer type, rate, and cost; and herbicide type and rate). Data on each tillage, planting, harvest, pest control, and weed control operation were also collected, but the cost of these operations was not tabulated because they did not vary across treatments. On-farm economic throughput was determined as the difference of revenue and variable production cost. Revenue was a function of commodity price as determined by market factors and crop yield as affected by numerous factors (e.g., climate, rainfall, soil conditions, and nutrient availability). Total variable costs were based on fertilizer costs including purchase and application. In the last study period, costs also included cover crop seed.

Hydrology and Water Quality Data. Runoff and seepage data were collected from the outlet of each field as described subsequently. Each field was equipped with a flow control structure (v-notch weir or a flume and weir combination), and flow data were recorded continuously at 5 to 15 minute intervals depending on watershed size. Runoff water quality samples were collected with automated sampling strategies designed to sample intensively and thus minimize uncertainty based on Harmel et al. (2006a, 2006b). Runoff water quality samples were

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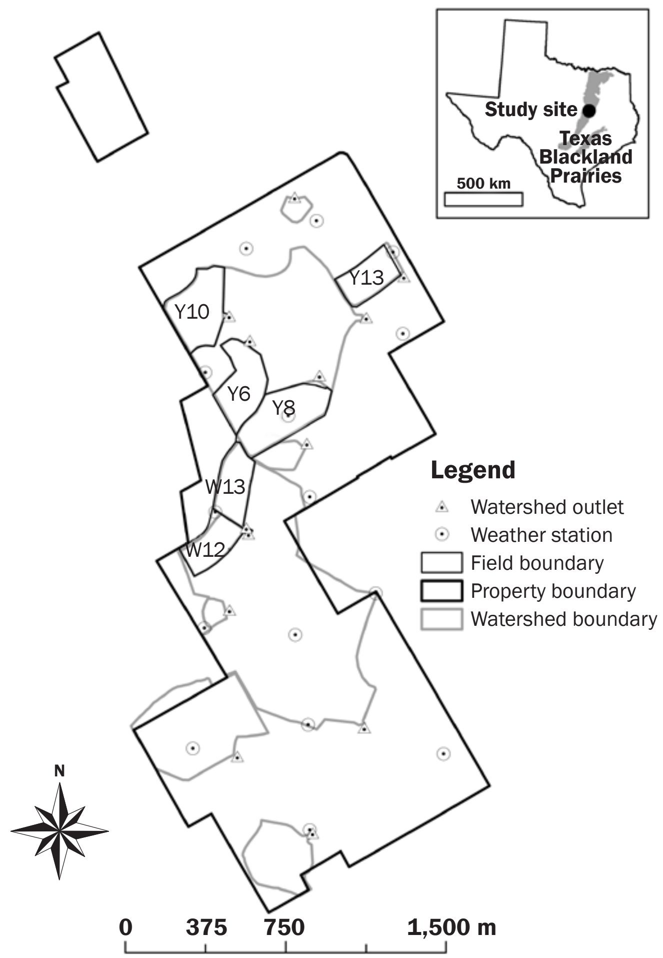
Figure 1
Map of the Riesel watersheds used for this study.



collected from the field within 48 hours of each event. Baseflow water quality samples were collected manually from all sites at the end of storm events when storm runoff samples were retrieved from the field and each subsequent week as long as flow persisted.

At each field, rainfall depth and intensity data were also collected using a Hydrologic Services tipping bucket rain gauge (Hydrologic Services PTY, Ltd., Sydney, Australia) connected to Campbell Scientific CR10X datalogger (Campbell Scientific, Inc., Logan, Utah). A standard rain gauge was also used at each field as a backup and calibration device.

All water quality samples were stored at 4°C prior to analysis and analyzed for dissolved nitrate and nitrite N (NO_3+NO_2-N), ammonium nitrogen (NH_4-N), and dissolved reactive phosphorus (DRP) concentrations using colorimetric methods (Technicon 1976) with a Technicon Autoanalyzer IIC (Bran-Luebbe, Roselle, Illinois) or a Flow IV Rapid Flow Analyzer (O.I. Analytical, College Station, Texas). Results for NO_3+NO_2-N in runoff are reported as nitrate N (NO_3-N) because the NO_3-N form dominates. The sediment (total settleable solids) concentration was determined by mass after settling for three to five days, decanting off a majority of the solution, and drying at 116°C for 18 to 24 hours. The concentrations of N and P in the particulate form (TKN and TKP) were determined by a salicylic acid modification of a semimicro-Kjeldahl digestion procedure

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Table 2
Summary of land management for the three study periods.

Dates	Conservation practices	Rotation	Between cash crops	Control field nitrogen rate	Other fields nitrogen rate
Period 1, 2002 to 2008	Contour terraces, water ways, reduced tillage	Corn–corn–wheat	Fallow	Traditional rates*: corn (170 kg ha^{-1}); wheat (67 kg ha^{-1})	Amount in litter at 4.5 to 13.4 Mg ha^{-1} + supplemental N if needed to reach traditional rate
Period 2, 2009 to 2012	Contour terraces, water ways, reduced tillage	Various crops	Fallow	Traditional rates: corn (170 kg ha^{-1}); oats (67 kg ha^{-1}); hay (135 kg ha^{-1})	Amount in litter at 4.5 to 13.4 Mg ha^{-1} + supplemental N if needed based on Haney test† and appropriate yield goal
Period 3, 2013 to 2017	Contour terraces, water ways, reduced tillage	Various crops	Minimized fallow period length, cover crop during prolonged fallow periods (not on control field)	Traditional rates: corn (170 kg ha^{-1}); wheat (67 kg ha^{-1}); hay (135 kg ha^{-1})	Amount in litter at 4.5 to 13.4 Mg ha^{-1} + supplemental N if needed based on Haney test and appropriate yield goal

*Based on Gass (1987).
†Summarized in Haney et al. (2018).

(Technicon Industrial Systems 1976). The NO_3-N and DRP concentrations presented represent event mean concentrations. The uncertainty of measured runoff concentrations was estimated with the method of Harmel et al. (2006a). Runoff loads for each runoff event were determined by multiplying concentrations by corresponding flow volumes.

Litter Properties. Litter samples (four replicates) were collected for analysis each year immediately prior to application. Moisture content was determined by drying at 116°C for 24 hours. Water extractable NO_3+NO_2-N, NH_4-N, and DRP concentrations were determined with extraction methodology described in Self-Davis and Moore (2000) and subsequent colorimetric analysis. Total N and total P were determined by Kjeldahl digestion and colorimetric analysis. Organic carbon (C) was determined using a total C analyzer with temperature of the primary sample ignition furnace reduced to 650°C (McGeehan and Naylor 1988; Schulte and Hopkins 1996).

Soil Properties. Soil samples for each field were taken annually in the winter with a manual soil probe (2.54 cm diameter) and a depth of 15 cm. Samples were collected at a frequency of at least one core per 0.4 ha with a random sampling scheme, which was stratified so that samples were collected in the top, middle, and bottom portion of each field. Then, the cores were composited to create one sample for each field. Beginning in 2009, soil samples were analyzed to determine total plant available N and P in the soil (Haney et al. 2004, 2006, 2012; Haney and Haney 2010). Previous analyses of soil N and P levels in these fields can be found in Harmel et al. (2011).

Statistical Analyses. The six fields were the experimental units for this study. All statistical tests were conducted with Minitab software (Minitab 2000) according to procedures described in Helsel and Hirsch (1993) or Haan (2002). For the analyses, an a priori significance level of α = 0.05 was used; however, p-values were also presented when appropriate.

The analysis conducted in the present study (i.e., profitability and environmental tradeoffs as measured by runoff water quality) represent only a fraction of analyses possible with the Riesel watersheds legacy database; therefore, it is important to note that data are publicly available for use in further analyses (www.ars.usda.gov/plains-area/temple-tx/grassland-soil-and-water-research-laboratory/docs/hydrologic-data) and from the Sustaining the Earth's Watersheds, Agricultural Research Data System (STEWARDS) database (Steiner et al. 2008, 2009) at https://data.nal.usda.gov/dataset/stewards-data-delivery-application-usdaars-conservation-effects-assessment-project.

Results and Discussion

The following sections present 16 years of results for fertilizer (application rate, type), economics (fertilizer cost, revenue, and profit), soil nutrient levels (N, P), hydrology (runoff, rainfall), and water quality (N, P, sediment load). Comprehensive, multiyear data sets such as this are quite rare, as most studies evaluating the environmental and economic impact of cropping systems management and/or conservation practices generally span from less than a year to three to five years (Harmel et al. 2008; Smith et al. 2015; Cober et al. 2019; Plach et al. 2019; VeVerka et al. 2019). Agronomic, economic, and environmental (e.g., water quality) results are presented individually, but the interactions, which are paramount to on-farm decision-making and resulting environmental impact, are also discussed.

Fertilizer. Nutrient application rate and source were the sole treatment variables in study Period 1 to 2, thus the differences in total N and P application rate between fields were intentional as per study design (table 3). Fields Y6, Y10, Y13, and W12 represent the most realistic, agronomic comparison of fertilizer rate and type. The higher litter rate fields with >9 Mg ha^{-1} (W12, W13, and Y8) received excess N and P by any reasonable criteria, but these annual rates were chosen to assess the environmental impacts of excess litter application in a waste disposal not agronomic mindset.

For the control field (Y6), traditional N and P rates were used throughout the study (table 2); however, crops with lower nutrient requirements (hay in 2013 and 2016) along with not applying fertilizer in 2013 reduced mean N application in Period 3. For Y13 and Y10, N rate management based on soil test results instead of traditional rates contributed to significant trends (reductions) in N application (table 3). The reductions in N applied were not as pronounced for the high litter rate fields (W12, W13, Y8) because N was applied in excess of traditional rate recommendations at these litter rates; therefore, soil test recommendations did not have as great an impact since supplemental N was not necessary in either case. Temporal trends in P application were an artifact of differing interannual litter P levels (table 3), as supplemental P was not necessary.

The effectiveness of reducing N application rates when moving from traditional rate recommendations (Period 1) to soil test recommendations and reasonable yield goals based on historical production (Period 2 to 3) is an important result confirming that previously recommended rates were excessive. As expected, no significant differences in median N rates were observed for the control field (Y6); however, N rate management based on soil test results contributed to significant reductions in N rate for Y13 and Y10 where supplemental N was needed but not for the high litter rate fields (W12, W13, Y8) where litter supplied excess N eliminating the ability to manage supplemental N rates.

Economics. In each of the three study periods, fertilizer cost was significantly different between fields, but revenue and profit throughput were not (table 4). Although statistical analyses did not indicate significant differences due to annual variability, practical differences in profit were certainly evident. The overriding influence of interannual variability on both statistical analysis and real-world decisions and outcomes was evident throughout the present study (and in most such studies). From a practical standpoint Y10 (US$157), Y13 (US$182), and Y6 (US$152) certainly had the highest profits (table 4). For two of the study periods and the overall study, these three fields had the highest profits. Each of the other fields had annual average profits <US$145 when assessed for the entire 2002 to 2017 study.

From 2002 to 2008, which was a relatively wet period with annual average rainfall 11% greater than the long-term (30-year) average, profit for the 4.5 Mg ha^{-1} litter rate field (Y13) exceeded all the others by at least US$7.30 ha^{-1}. The revenue generated by all the fields with applied litter exceeded that of the inorganic fertilizer field (Y6) by at least US$9.70 ha^{-1}, indicating possible benefits of additional C, potassium (K), and micronutrient inputs. In 2009 to 2012, with annual rainfall 7% less than the long-term average, the profits for all fields increased because increases in revenue exceeded those of fertilizer costs (figure 2). As in Period 1, Y13 had the highest average profit because it had the lowest organic fertilizer cost but maintained revenue; however, the 13.4 Mg ha^{-1} field (Y8) had the second highest profit, which is interesting because

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Table 3
Total annual nutrient application rates. The control field (Y6) received only inorganic nitrogen (N) and phosphorus (P). The other fields all received poultry litter, a portion of which was available, and supplemental inorganic N if needed.

Year	Y6	Y13	Y10	W12	W13	Y8	Y6	Y13	Y10	W12	W13	Y8
	N (kg ha^{-1})						P (kg ha^{-1})					
Period 1												
2002	162	228	265	282	316	373	0	101	158	184	236	324
2003	74	245	291	310	341	367	17	143	235	276	335	393
2004	67	158	221	208	316	445	15	81	113	106	161	227
2005	174	206	221	225	254	274	15	82	118	126	192	241
2006	174	218	237	241	277	294	15	81	116	124	189	222
2007	94	113	161	216	263	308	20	58	84	112	136	160
2008	174	205	218	234	254	307	24	59	85	113	148	213
Average	131	196	231	245	289	338	15	87	130	149	200	254
Median*	162a	206a	221a	234a	276a	308a						
Period 2												
2009	175	151	188	198	268	378	23	61	100	105	143	201
2010	134	129	183	219	202	256	15	22	33	40	42	53
2011	134	186	201	294	270	324	20	63	95	126	158	190
2012	67	107	161	214	268	321	15	67	101	134	168	202
Average	128	143	183	231	252	320	18	53	82	102	128	161
Median	135a	140b	185b	216a	268a	323a						
Period 3												
2013	0	103	155	206	258	309	0	76	114	152	190	229
2014	180	167	233	289	326	391	25	71	107	143	178	214
2015	78	128	164	210	227	273	17	65	97	129	161	194
2016	108	148	195	242	235	282	24	60	89	119	149	179
2017	94	108	163	217	271	325	21	72	108	143	179	215
Average	92	131	182	233	264	316	17	69	103	137	172	206
Median	94a	128b	165ab	217a	258a	309a						
Average change (kg y^{-1})	−2.8	−6.8	−5.8	−1.9	−3.7	−3.8	+0.5	−2.7	−4.3	−2.9	−4.9	−7.3
p-value	0.350	0.003	0.003	0.339	0.066	0.185	0.193	0.045	0.058	0.285	0.134	0.054

*For each row, median nutrient rates followed by the same letter are not significantly different (α = 0.05).

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that litter rate would be judged excessive by all other criteria. In 2013 to 2017, profits dropped dramatically for all fields despite good yields. This resulted from increased fertilizer cost, addition of cover crop seed costs, and decreased revenue from low commodity prices, which affected many farmers nationally. Increased fertilizer cost regionally was associated with increased demand for poultry litter, whereas commercial fertilizer costs decreased during Period 3 compared to the previous period (2009 to 2012).

When digging deeper into the annual economic data and factors that affect differences between the fields, it was interesting to note that rainfall was negatively correlated to revenue (p <0.001, r = –0.416) and profit (p < 0.001, r = –0.375). It was presumed that drought would have a larger impact on revenue in this subhumid region; however, excess annual rain seemed to have a larger impact. Late-spring rains in years when wheat (*Triticum aestivum* L.) is grown (i.e., 2015) can diminish grain quality resulting in discounted prices. Further, while 2017 was a dry year relative to the others for the duration of this study, late spring rains prevented portions of fields from being harvested, thereby decreasing revenues. Also, N fertilizer rate was correlated with revenue but was not correlated to profit (data not shown). This challenges the traditional belief that increasing fertilizer increases profit up to a point, which was likely true in the past when fertilizer represented a very low input cost. In multiple regression analysis of profit (r^2 = 0.99, p < 0.001), N fertilizer rate, rain, fertilizer cost, and revenue were all significant (p < 0.05), but P fertilizer rate was not. This is most likely because for the duration of this study, particularly in the poultry litter–amended fields, the rate of P application exceeded crop requirements. Although N fertilizer rate was a significant variable, rain, fertilizer cost, and revenue explained most of the profit variability (r^2 = 0.99, p < 0.001, for multiple regression with these three variables).

Comparing poultry litter to commercial fertilizer applications to sorghum (*Sorghum bicolor* [L.] Moench) during a three-year period, Penn et al. (2014) found that there was no significant difference in crop yield, but the lower cost of poultry litter resulted in greater profitability than commercial fertilizers. In a two-year comparison of poultry litter and inorganic fertilizers in potato (*Solanum tuberosum* L.) cropping, there was no significant difference in crop yield

Table 4
Mean annual fertilizer cost, revenue, and profit throughput results for each field in each study period.

Dates	Average inorganic fertilizer cost (US\$ ac^{-1})	Average litter cost (US\$ ac^{-1})	Average fertilizer cost (US\$ ac^{-1})	Average revenue (US\$ ac^{-1})	Average profit (US\$ ac^{-1})
Period 1 2002 to 2008	Poultry litter rate versus traditional rate inorganic N and P				
Y8	3c	121a	124a	231a	108a
W13	11bc	101b	112ab	230a	118a
W12	19bc	81c	100abc	232a	132a
Y10	21b	61d	82bcd	237a	155a
Y13	27b	40e	67cd	240a	173a
Y6	61a	0f	61d	206a	144a
Period 2 2009 to 2012	Poultry litter rate and supplemental N, P based on the Haney test* versus traditional rate inorganic N and P				
Y8	0b	179a	179a	370a	191a
W13	0b	149ab	149a	325a	175a
W12	20b	119abc	139ab	303a	164a
Y10	15b	90bc	105bc	266a	161a
Y13	24b	60cd	84c	280a	197a
Y6	93a	0d	93c	258a	166a
Period 3 2013 to 2017	Poultry litter rate and supplemental N, P based on the Haney test* versus traditional rate inorganic N and P; all under continuous cropping†				
Y8	17b	258a	275a	189a	–76a
W13	17b	215b	232b	191a	–32a
W12	29b	172c	201b	181a	–9a
Y10	30b	129d	159c	159a	12a
Y13	31b	86e	117d	154a	51a
Y6	74a	0f	74e	154a	80a
Entire study 2002 to 2017					
Y8	5d	139a	144a	282a	138a
W13	8cd	118ab	126a	264a	139a
W12	18bc	96bc	114ab	258a	144a
Y10	18bc	72cd	90bc	248a	157a
Y13	23b	50d	73c	255a	182a
Y6	73a	0e	73c	245a	152a

Notes: N = nitrogen. P = phosphorus.

*Haney soil test recommendations are dependent on yield goals. Average yields based site-specific historical production data are recommended.

†Continuous cropping indicates that the fallow period between crops is minimized. The fertilizer cost in Period 3 included cover crop seed.

between fertilizer source when P application rates were similar; however, interannual variability in crop yield was greater than any fertilizer treatment effects (Collins et al. 2016). Similarly, in a three-year study of corn (*Zea mays* L.), there were no significant differences in grain yield between commercial fertilizer and poultry litter when applied at similar rates of N (Tewolde et al. 2013).

Soil Nutrients. Nutrient rate management practices were implemented in 2009. Specifically, supplemental N rates (in addition to that applied with litter) were determined by soil tests and yield goals based on historical production data. As shown in table 5, several interesting temporal patterns occurred in changes of soil N and P. Inorganic soil N decreased in each field with rates of change increasing as litter (fertilizer) rate increased (although these rates were not significant based on the a priori $\alpha = 0.05$ level). In contrast organic soil N increased in each field, but rates of change also increased as litter (fertilizer) rate increased. The decreasing inorganic soil N and increasing organic soil N would be expected with cover crops and conservation tillage, as the transient NO_3-N and NH_4-N pools are utilized by plants and microbes and transformed into organic N pools. However, this also occurred for the commercial fertilized Y6 field. One factor in this unexpected result for Y6 was the inadvertent skipping of N application in 2013, which contributed to lower inorganic soil N the following year.

Soil P levels indicated no clear temporal patterns. The fields fertilized at 4.5, 9, and 13 Mg ha^{-1} resulted in slightly increasing temporal trends in soil P, whereas fields with inorganic fertilizer and 6.7 and 11 Mg ha^{-1} litter rates showed decreasing P trends. Although consistent temporal trends were not observed, buildup of soil P levels, especially at high litter application rates, has been shown previously for these fields (Harmel et al. 2011; Waldrip et al. 2015). During a 10 year study of poultry litter application, it was observed that soil P concentrations increased more than 200% during the study period (Schomberg et al. 2009).

Hydrology and Water Quality. The environmental impact of management, represented by the runoff of nutrients and sediment in this study, is another important consideration. The hydrologic drivers of water impacts—rainfall (data not shown) and runoff (table 6)—exhibited no temporal trends. Similarly, sediment losses exhibited no temporal trends. However, the lowest N and P rate fields (Y6 and Y13) did have higher erosion than the other fields in 2015 and 2016, which produced multiple runoff events >75 mm. The cause for increased sediment loss on these two fields was terrace breaks and increased erosion within grassed waterways, which was understandable on Y6 with no cover crops (but Y13 also experienced similar erosion).

Nitrogen loss in runoff tended to decrease over the 16 year study for all fields (table 7), although few of these trends were significant due to highly variable precipitation and runoff patterns. When assessing N concentrations in runoff, significant decreasing trends in NO_3-N concentrations occurred for most of the fields, which corresponded to decreasing N application trends (table 3). In contrast to N loads, which tended to decrease over time, P loads tended to increase for all the fields (table 7); however, the trends were not significant due to rainfall and runoff variability. Phosphate P (PO_4-P) concentrations also

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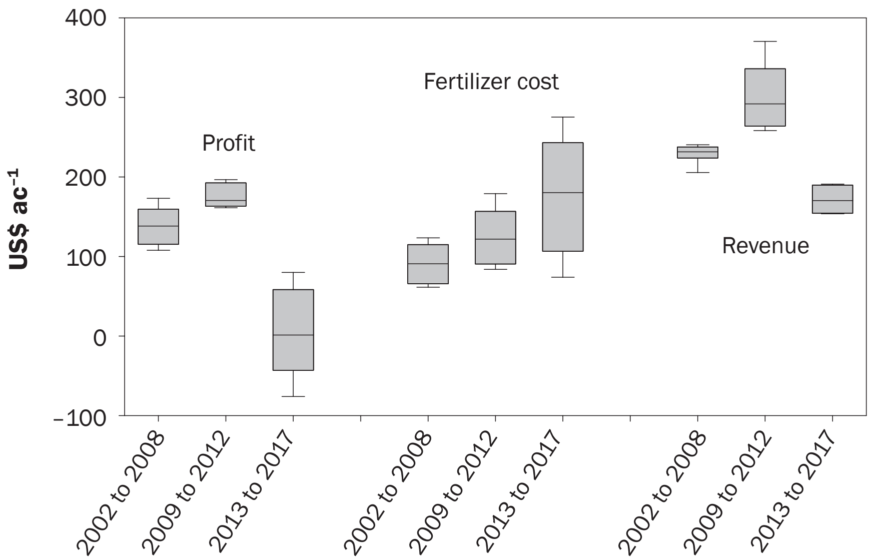
Figure 2

Distribution and temporal trends in key economic data across all treatments.



increased (tables 8 and 9) over time on the litter application fields. Although consistent temporal trends in soil P levels were not observed, fields with excessive litter application have been shown to have high soil P levels (Harmel et al. 2011). If these were production fields instead of research fields with intentional application of excessive litter, management changes (e.g., reduced annual rates or skip application years) would be recommended to reduce P losses and improve environmental sustainability.

Application of poultry litter has been well-documented to increase P loss in runoff water. Menjoulet et al. (2009) found that P losses roughly doubled when poultry litter was applied compared to an unfertilized control soil where natural precipitation was used to generate runoff. The impact of poultry litter application on N and P losses via runoff can occur very quickly (Kleinman and Sharpley 2003; Smith et al. 2007).

When digging deeper into the annual data, it was surprising that N rate and N load were not correlated, and neither were P rate and P load. In the multiple regression analysis of N loads, rain, runoff, and sediment load were significant descriptors. This relationship between N loads and rain, runoff, and sediment load was significant ($p \leq 0.001$), but there was considerable variability ($r^2 = 0.28$). In the multiple regression of P loads, runoff and sediment load were significant descriptors, and the resulting relationship was significant ($p \leq 0.001$) and explained much of the variability ($r^2 = 0.74$).

Summary and Conclusions

Studies such as the present evaluation of adaptive nutrient management scenarios using organic amendments and inorganic fertilizers on fields with conservation practices are needed to guide conservation decision-making. This study evaluated a robust adaptive management scheme, in which fertility management evolved over the 16-year study with enhanced scientific understanding of soils and fertility concurrent with dramatic shifts in economic patterns. Results from this long-term evaluation of the agronomic, environmental, and economic impacts indicated that N application was reduced when rate recommendations were based on soil test recommendations and historical yield data compared to traditional rate recommendations. More importantly, although N rate was correlated with revenue, it was not correlated to profit, challenging the traditional view that more fertilizer increases profit up to a point. Conclusions include the following:

1. The overriding influence of interannual variability on outcomes was evident throughout the present study. Because of interannual variability of factors such as yields and commodity prices, statistical analyses did not indicate significant differences in profit between treatments; however, the practical differences in profits were clear. The traditional treatment (Y6), along with the two lowest rate adaptive management treatments (Y13, Y10) had mean annuals profits from US\$152 to US\$187 y^{-1} while the other fields averaged between US\$138 to US\$144 y^{-1}.
2. Rainfall was negatively correlated to both revenue and profits. This observation is counterintuitive to the presumption that drought would have a larger impact on dryland farming in this subhumid region, when in fact excess annual rain diminished wheat crop quality or prevented harvest in portions of fields.
3. Nitrogen loads and NO_3-N concentrations in runoff tended to decrease over the 16-year study, but P loads and PO_4-P concentrations tended to increase; however, few of these trends were significant due to highly variable precipitation and runoff.

Table 5

Annual rates of change (kg ha⁻¹) from 2009 to 2016 for plant available nitrogen (N) and phosphorus (P) in the soil following implementation of nutrient rate management practices (supplemental N based on soil test recommendations).

Field	Inorganic N	*p*-value	Organic N	*p*-value	Inorganic P	*p*-value
Y6	−4.35	0.12	+0.82	0.61	−1.10	0.16
Y13	−5.63	0.13	+0.62	0.78	+0.15	0.92
Y10	−7.52	0.14	+0.56	0.82	−4.52	0.45
W12	−7.11	0.09	+0.91	0.66	+0.31	0.88
W13	−12.23	0.15	+2.09	0.56	−0.46	0.83
Y8	−10.95	0.12	+2.82	0.30	+0.28	0.91

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Table 6
Annual runoff and sediment loads.

Year	Y6	Y13	Y10	W12	W13	Y8	Y6	Y13	Y10	W12	W13	Y8
	Runoff (mm)						Sediment (kg ha^{-1})					
2002	147	176	226	108	168	136	1,620	1,950	1,340	1,810	1,610	1,490
2003	117	84	119	84	92	78	684	567	407	726	462	529
2004	384	378	377	257	362	305	2,130	2,030	1,810	907	1,860	1,420
2005	60	94	100	72	63	75	891	1,260	1,280	936	473	1,110
2006	57	63	57	66	67	51	613	1,150	497	1,367	935	483
2007	461	591	589	441	469	461	332	1,390	646	141	145	270
2008	39	52	69	28	26	29	355	468	888	496	483	433
Average	181	205	220	151	178	162	946	1,260	981	911	853	820
2009	142	195	256	132	133	179	584	838	1,260	745	698	711
2010	54	84	123	46	47	91	160	508	729	42	114	210
2011	16	30	29	21	26	22	50	137	195	63	880	281
2012	66	90	105	49	67	55	47	73	641	18	24	36
Average	69	100	128	62	69	87	210	389	705	217	429	309
2013	76	69	111	62	65	47	175	333	202	114	134	86
2014	66	49	73	41	29	39	258	246	242	242	127	181
2015	586	817	737	483	436	523	10,600	21,000	1,920	2,470	1,910	1,390
2016	316	323	371	256	216	283	10,300	1,710	1,410	792	854	709
2017	9	13	23	3	4	0	286	12	27	5	7	0
Average	211	254	263	169	150	179	4,320	4,650	760	725	607	473
Average change (y^{-1})	+1.2	+3.6	+2.4	+1.1	+3.6	+0.8	+274	+252	−29	−39	−40	−49
p-value	0.907	0.780	0.839	0.896	0.673	0.932	0.144	0.378	0.392	0.328	0.265	0.072

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Table 7
Total annual nitrogen (N) and phosphorus (P) runoff loads.

Year	Y6	Y13	Y10	W12	W13	Y8	Y6	Y13	Y10	W12	W13	Y8
	N (kg ha^{-1})						P (kg ha^{-1})					
2002	14.7	28.5	34.7	13.0	7.18	14.4	0.36	1.33	1.44	1.16	1.21	1.42
2003	38.8	29.3	50.3	16.0	24.7	21.7	0.47	0.88	2.07	0.78	2.10	1.59
2004	8.06	14.6	14.1	6.51	18.6	17.1	1.41	3.08	2.87	2.15	4.65	4.41
2005	2.90	5.05	5.24	3.08	1.86	6.95	0.52	0.70	0.73	0.69	0.46	0.42
2006	12.0	14.0	12.9	8.95	6.23	5.83	0.31	0.61	0.40	0.70	0.62	0.40
2007	2.91	6.17	5.55	5.78	9.06	5.36	0.76	3.33	2.89	1.83	3.35	3.65
2008	8.19	15.7	21.7	5.22	4.71	3.53	0.41	0.75	1.17	0.72	0.78	0.66
Average	12.5	16.2	20.6	8.4	10.3	10.7	0.6	1.5	1.7	1.1	1.9	1.8
2009	2.26	2.97	3.71	2.68	3.38	3.04	0.97	1.80	2.56	1.52	1.96	2.20
2010	4.69	15.2	43.4	14.6	11.8	25.1	0.44	1.84	4.13	1.11	1.28	2.42
2011	0.40	2.04	1.44	1.20	2.25	0.83	0.07	0.34	0.38	0.23	1.46	0.54
2012	0.52	0.26	0.95	0.14	0.22	0.44	0.19	0.22	0.74	0.17	0.54	0.40
Average	2.0	5.1	12.4	4.7	4.4	7.4	0.4	1.0	2.0	0.8	1.3	1.4
2013	0.58	3.25	2.59	1.29	1.93	1.59	0.21	1.58	1.75	0.82	1.20	0.89
2014	11.3	10.3	13.5	7.51	5.28	7.05	0.26	0.56	0.89	0.60	0.47	0.67
2015	20.9	50.3	8.33	11.0	8.54	10.5	6.85	27.7	12.5	11.8	12.1	13.7
2016	24.3	13.5	16.7	9.52	4.12	6.80	5.83	4.06	5.48	3.72	4.16	5.37
2017	0.30	0.02	0.18	0.01	0.04	0.00	0.16	0.13	0.37	0.13	0.09	0.00
Average	11.5	15.5	8.3	5.9	4.0	5.2	2.7	6.8	4.2	3.4	3.6	4.1
Average change (kg ha^{-1} y^{-1})	−0.44	−0.48	−1.56	−0.40	−0.78	−0.77	+0.18	+0.42	+0.20	+0.18	+0.13	+0.18
p-value	0.470	0.526	0.061	0.160	0.027	0.062	0.117	0.265	0.245	0.269	0.462	0.359

Table 8
Linear annual trends for event mean nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and phosphate phosphorus (PO_4-P) concentrations.

	NO_3-N (mg L^{-1})		NH_4-N (mg L^{-1})		PO_4-P (mg L^{-1})	
Field	Trend y^{-1}	*p*	Trend y^{-1}	*p*	Trend y^{-1}	*p*
Y6	−0.70	0.015	−0.01	0.206	−0.00	0.149
Y13	−0.42	0.046	0.00	0.997	+0.37	0.000
Y10	−0.68	0.004	−0.00	0.786	+0.06	0.000
W12	−0.20	0.190	0.00	0.819	+0.07	0.000
W13	−0.24	0.046	0.00	0.432	+0.08	0.000
Y8	−0.47	0.001	0.00	0.450	+0.07	0.000

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Table 9
Event mean nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and phosphate phosphorus (PO_4-P) concentrations for each study period.

Field	NO_3-N (mg L^{-1})	NH_4-N (mg L^{-1})	PO_4-P (mg L^{-1})
Period 1: 2002 to 2008			
Y6	10.92	0.24	0.16
Y13	7.79	0.10	0.36
Y10	10.18	0.24	0.53
W12	4.80	0.11	0.44
W13	4.63	0.10	0.67
Y8	6.51	0.17	0.77
Period 2: 2009 to 2012			
Y6	3.37	0.19	0.29
Y13	4.26	0.27	0.68
Y10	5.97	0.43	0.99
W12	8.07	0.27	0.82
W13	4.32	0.26	0.92
Y8	4.56	0.28	0.93
Period 3: 2013 to 2017			
Y6	1.50	0.10	0.14
Y13	1.60	0.08	0.88
Y10	1.69	0.12	1.27
W12	1.37	0.11	1.34
W13	1.32	0.11	1.82
Y8	1.72	0.10	1.78

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