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4 **Integrated Crop-Livestock System Effects on Soil N, P, and pH in a Semiarid Region**
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18 **Abbreviations:** ICLS, integrated crop-livestock system.
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Abstract

Integrated crop-livestock systems (ICLS) represent a potential means to sustainably intensify agriculture. Developing ICLS that concurrently achieve production and environmental goals is contingent upon efficiently managing plant nutrients in time and space. In this study, we sought to quantify residue management and field-zone effects on soil $\text{NO}_3\text{-N}$, available P, and soil pH over a 12 year period for an ICLS experiment near Mandan, ND USA. From 1999 to 2011, soil $\text{NO}_3\text{-N}$ and available P were measured in three residue management treatments (grazed, mechanically harvested, and no residue removal) every third year across a 122 cm soil depth, while soil pH was measured prior to deploying ICLS treatments in 1999 and again in 2011. Residue management did not affect soil $\text{NO}_3\text{-N}$ or available P at any depth for any year ($P>0.1$), implying no accumulation of available N and P under grazing compared to cropping. Similarly, no differences in available N and P were observed across grazed sampling zones. Soil nutrients, however, increased or fluctuated greatly over the 12 year period, suggesting a need for adaptive nutrient management. Soils became more acidic between 1999 and 2011, with the greatest decreases in soil pH at 0-8 cm under grazing (0.74 pH unit decline; $P=0.0581$) and mechanical harvest (0.86 pH unit decline; $P=0.0138$). Management interventions targeting nutrient conservation may serve to mitigate N and P loss and soil acidification in ICLS.

Keywords: Livestock; Rainfed cropping systems; Soil acidification; Soil nitrate.

1. Introduction

Integrating livestock into cropping systems can improve economic returns, thereby providing a more profitable means to sustainably intensify agriculture (Russelle et al., 2007; Soussana and Lemaire, 2014). Integrated crop-livestock systems (ICLS) combine livestock and cash crops at the farm level (Ryschawy et al., 2012), whereby crops and crops by-products in ICLS are used to feed livestock, which return excreta to fertilize crops (Schiere et al., 2002). Such integration provides opportunities to reduce intensive inputs, while recoupling nutrient cycles and improving soil quality (Hendrickson et al. 2008; Krall and Schuman, 1996).

Research on ICLS globally has identified a diversity of management approaches to achieve production and environmental goals through the integration of agricultural enterprises. In France, Ryschawy et al. (2012) found ICLS using diversified ley-cereal rotations achieved positive environmental and economic outcomes when integrated with livestock. Coquil et al. (2013) found mixed crop-dairy farms in Europe became more self-sufficient and profitable through the incorporation of temporary grasslands in crop rotation. In the Amazonian region of Brazil, Bonaudo et al. (2014) found ICLS that coupled enterprise diversification with small chemical inputs improved agricultural production, reversed degradation of grazing land, and limited deforestation. Incorporation of interseeded grasses or legumes in row crops in the U.S. Corn Belt was found to increase forage availability in late fall and early spring without compromising crop production, thereby reducing livestock feeding costs and increasing profitability (Sulc et al., 2007). In southern Australia, dual-purpose use of cereals and canola (*Brassica napus* L.) for forage and grain increased crop and livestock productivity by 25-75% with minimal increases in external inputs (Bell et al., 2014). Collectively, emergent findings

1 from research on ICLS suggest reconstructing linkages among specialized production enterprises
2 can serve to improve agricultural sustainability.

3 Efficient use of plant nutrients serves as a defining attribute to concurrently achieve
4 production and environmental goals in ICLS through the recoupling of carbon and nitrogen
5 cycles (Soussana and Lemaire, 2014). Nutrient recycling through ruminant livestock can
6 decrease dependence on synthetic crop inputs (Powell et al., 1996), but excess nutrients from
7 livestock on cropland can threaten water quality (Chang and Entz, 1996). Accordingly,
8 achieving an optimal balance of plant nutrients in time and space is of paramount importance in
9 ICLS (Hochman et al., 2013).

10 Designing ICLS to maximize efficient use of nutrients relies on an understanding of
11 nitrogen (N) and phosphorus (P) dynamics in the soil profile. Unfortunately, there is a paucity of
12 published findings on soil nutrient dynamics for ICLS. Use of tillage increased soil NO₃-N,
13 while grazing and/or no-tillage served to moderate soil NO₃-N accumulation in ICLS
14 (Franzluebbers and Stuedemann, 2013; Lenssen et al., 2013). High grazing intensity in ICLS
15 was found to increase soil N loss compared to treatments with moderate and light grazing
16 intensities, underscoring the importance of identifying optimal grazing pressure in ICLS
17 (Assmann et al., 2014). Grazing of cover crops and crops grown for winter forage were found to
18 increase or have no effect on near-surface total and labile P stocks in ICLS (Costa et al., 2014; da
19 Silva et al., 2014; Liebig et al., 2012). Soil acidification, an indirect indicator of nutrient-use
20 efficiency (Smith and Doran, 1996), was less severe under treatments including livestock
21 regardless of grazing intensity compared to no grazing due to greater retention of divalent cations
22 (i.e., exchangeable Ca²⁺ and Mg²⁺) in the former (Martins et al., 2014; da Silva et al., 2014).

There is a need to better understand management effects on soil nutrient stocks over time within ICLS, particularly in semiarid regions where soil attributes change slowly in response to management due to limited biomass production. The objective of this study was to determine management and field-zone effects on soil NO₃-N, available P, and soil pH for an ICLS experiment conducted in a semiarid region. Three hypotheses guided the study: 1) soil NO₃-N and available P would not be elevated under ICLS management compared to cropping alone, 2) soil acidification would be mitigated by livestock integration, and 3) soil nutrient and pH responses to livestock integration would be intensified with increased proximity to shelter/water.

2. Materials and methods

2.1. Site and treatment description

The study site was located approximately 5 km south of Mandan, ND USA (46°46', -100°54, 593 m elevation). The site is within the temperate steppe ecoregion (Baily, 1995), with long-term (1914-2010) mean annual precipitation of 416 mm. Mean annual temperature is 4°C, and the average frost-free period is 131 days. Topography at the site is gently rolling (0-3% slope), and soils are a mix of Temvik-Wilton silt loams (Fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls) (USDA, 2016).

The experiment was initiated in 1999 by spraying two 6.0 ha crested wheatgrass [*Agropyron desertorum* (Fisch. ex. Link) Schult.] pastures with glyphosate [N-(phosphonomethyl) glycine; 0.7 kg a.i. ha⁻¹] twice in mid-May and converted to a three-year crop rotation designed to meet the nutritional needs of dry bred cows during winter. Initially, the rotation consisted of oat/pea (*Avena sativa* L./*Pisum sativum* L.), triticale/sweet clover (*Triticum aestivum* x *Secale cereale*/ *Melilotus officinalis* L.), and corn (*Zea mays* L.) following no-till planting techniques (Fig. 1). Beginning in 2006, the crop rotation was changed to oat/alfalfa

(*Medicago* spp.)/hairy vetch (*Vicia villosa* Roth)/red clover (*Trifolium pratense* L.), proso millet (*Panicum milaceum* L.)/sweet clover/red clover, and corn. In 2007 and every year thereafter, brown midrib sorghum-sudangrass (*Sorghum bicolor* L. Moench) replaced proso millet. Each phase of the three year crop rotation was present in both pastures, which were used as replicates. Fertilizer was applied during seeding every year in all crop phases as urea (70 kg N ha⁻¹ for all crops from 1999 to 2006; 35 kg N ha⁻¹ for oat and sorghum crop mixtures and 70 kg N ha⁻¹ for corn from 2007 to 2011) and monoammonium phosphate (6 kg N ha⁻¹ and 11 kg P ha⁻¹ for all crops in all years). Weeds were controlled using herbicides based on practices used by local producers.

Each phase of the crop rotation was split into three residue management treatments including no residue removal (CONTROL), residue removal with a baler (REMOVED), and residue removal by grazing with livestock (GRAZED) (Fig. 1). The CONTROL and REMOVED treatments were randomly assigned within each crop phase and were not grazed, whereas crop phases in the GRAZED treatment were randomly assigned within each pasture. For the GRAZED treatment, the crop residues from the crop rotation represented winter forage for ten 4-6 year old non-lactating cows, due to calve in late March. Plot areas within a crop phase were 27 m x 23 m (0.06 ha) for the CONTROL and REMOVED treatments, and 54 m x 312 m (1.68 ha) for the GRAZED treatment. Stocking rate within a crop phase for the GRAZED treatment was 0.2 ha cow⁻¹ (5.9 cows ha⁻¹), corresponding to winter grazing practices used by local producers.

Between 1999 and 2001, the oat and triticale crop mixtures were grazed standing during winter, whereas from 2002 through 2005, the mixtures were cut in mid-August to early-September, swathed, baled, and grazed in place during winter. Beginning in 2006, the oat,

1 millet, and/or sorghum crop mixtures were cut and swathed for winter grazing. From 1999
2 through 2005, corn was cut and swathed for forage in mid- to late-September. In 2006, corn was
3 not swathed, but was grazed standing during winter. From 2007 onward, corn was harvested for
4 grain with the straw spreader removed from the combine, thereby creating a crop residue swath
5 for winter grazing.

6 Cattle breeds included Hereford (1999-2004) and Angus (2005-2011). From 1999-2008,
7 grazing started in mid-November and ended in mid-February, with the oat crop mixture grazed
8 first, corn last, and triticale, millet, or sorghum crop mixtures intermediate. Beginning in 2009,
9 grazing started in September and ended in December, with the oat mixture grazed first, corn
10 intermediate, and sorghum mixture last. Access to crop swaths was controlled using electric
11 fences oriented at right angles to the swaths. Fences were moved daily to provide access to fresh
12 forage. Supplementary feed was provided only in the winter of 2000-2001 due to extremely cold
13 weather in the form of an oat, pea, and triticale grain mixture at 1.6 kg d⁻¹ (Karn et al., 2005). A
14 shelter and stock water source were located on the end of each pasture within the GRAZED
15 treatment and were not moved during the study (Fig. 1). Accordingly, cattle were not
16 backfenced during the grazing period, but allowed to re-graze previously grazed areas within
17 each crop phase. Additional details about the experimental treatments can be found elsewhere
18 (Karn et al., 2005; Tanaka et al., 2005).

19 2.2. *Soil sample collection and laboratory analyses*

20 Soil samples were collected in spring of 1999, 2002, 2005, 2008, and 2011 prior to
21 planting crops. Samples were collected in eight locations within each crop phase, with six
22 locations in the GRAZED treatment and one location each in the CONTROL and REMOVED
23 treatments. Locations within each crop phase were established on a grid pattern to represent

distinct zones differing in relative animal impact based on distance from shelter/water (Fig. 1). Zone I was closest to shelter/water, while Zone VII was furthest from shelter/water. No grazing occurred in Zone VII. Individual sampling zones within a crop phase were rectangular in shape with dimensions of 54 m x 52 m for GRAZED treatments (Zones I-VI) and 27 m x 23 m for CONTROL and REMOVED treatments (Zone VII). Within a location, three cores were collected to 122 cm in increments of 0-8, 8-15, 15-31, 31-61, 61-91, and 91-122 cm. Collected cores within a location were composited by depth, placed in a double-lined plastic bag, and transferred to cold storage at 5°C until processing.

Soil samples were processed by drying at 35°C for 4-5 d and then mechanically ground to pass a 2.0 mm (No. 10) sieve. Ground samples were then split for soil chemical analyses and air-dry water content determination. Soil pH was estimated from a 1:1 soil-water mixture (Watson and Brown, 1998), soil NO₃-N was determined from 1:10 soil-KCl (2 M) extracts using cadmium reduction (Mulvaney, 1996), and plant-available soil P was estimated by bicarbonate extraction (Kuo, 1996). Soil NO₃-N and P was analyzed in all years, while soil pH was analyzed in 1999 and 2011 only. Air-dry water content was determined for each sample using a 15 to 20 g subsample by measuring the difference in mass before and after drying at 105°C for 24 hr (Gardner, 1986). Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density from the 2011 sampling (Blake and Hartge, 1986), which did not differ among residue management treatments or sampling zones at any depth (data not shown). All data were expressed on an oven-dry basis.

2.3. *Data analyses*

Prior to data analyses, mean values of soil pH, NO₃-N, and P were expressed for four soil depths within each sampling location: near-surface (0-8 cm), primary rooting (0-31 cm), subsoil

(31-122 cm), and whole profile (0-122 cm). Analysis of variance was conducted using PROC MIXED in SAS (Littel et al., 1996) to evaluate effects of residue management and sampling zones on soil attributes. Residue management treatment was considered a fixed effect, while replicate and replicate x treatment were random effects. Similarly, sampling zone was considered a fixed effect, while replicate and replicate x sampling zone were random effects. Only sampling zones subjected to grazing were included in analysis (Zones I-VI). The effect of sampling year was evaluated for soil attributes using a mixed repeated-measures model. The PDIFF option of the LSMEANS statement was used to document differences between means using a significance criteria of $P < 0.10$.

3. Results

3.1. Precipitation and temperature

Weather conditions during the 12-yr study were characterized as wetter than normal during the growing season, but drier than normal during the dormant season, with seasonal air temperatures similar to long-term means. Growing season precipitation exceeded the long-term mean in eight seasons, and the long-term annual precipitation mean in four seasons (1999, 2001, 2007, 2010) (Table 1). Precipitation received during dormant periods in Jan-Mar and Oct-Dec were less than the long-term means during seven years. Conversely, significant snowfall events in 2000, 2008, and 2009 resulted in more than twice the expected precipitation received in Jan-Mar (2000 and 2009) and Oct-Dec (2000 and 2008). Air temperatures during the study ranged from -10.2 to -3.6°C, 14.5 to 17.2°C, and -3.6 to 1.2°C during Jan-Mar, April-Sep, and Oct-Dec, respectively (Table 1).

3.2. Soil NO₃-N and P responses to residue management and sampling zone

Residue management and sampling zone did not affect soil NO₃-N and P in any year (Tables 2 and 3). Accordingly, available N and P were homogenous among GRAZED, REMOVED, and CONTROL treatments in this study. Moreover, proximity to shelter/water within grazed areas did not prove to be a relevant factor influencing soil NO₃-N and P levels.

Despite the absence of treatment effects, soil NO₃-N and P did change over the 12-yr study period within residue management treatments. Soil NO₃-N within GRAZED and REMOVED treatments was greatest in 2011 compared to previous sampling years for all depths (Table 4). A similar trend was observed for the CONTROL treatment, but only for the 31-122 and 0-122 cm depths. Soil P was greatest among years in 2008 and 2011 at 0-8 cm, in 2002, 2008, and 2011 for 0-31 and 0-122 cm, and in 2002 for 31-122 cm (Table 4). Soil P tended to be lowest in all residue management treatments and depths in 1999 and 2005, corresponding to the first and sixth years of the study.

Differences in soil NO₃-N across years were evident in all sampling zones and depths except for Zone II (0-8 cm) and Zones V and VI (0-8 and 0-31 cm) (Table 5). Soil NO₃-N was greatest in 2011 compared to other years for most zones and depths, corresponding to residue management outcomes for the GRAZED treatment. Soil NO₃-N at 31-122 cm for Zones I, II, and IV in 2002 were intermediate between 2011 (higher) and 2005 and 2008 (lower), suggesting elevated levels of subsoil NO₃-N could be episodic over time. Changes in soil NO₃-N between 1999 and 2011 were numerically greatest in Zone I compared to other zones, with differences of 32.6, 44.2, 37.6, and 81.8 kg N ha⁻¹ for 0-8, 0-31, 31-122, and 0-122 cm depths, respectively. In contrast, differences in soil NO₃-N between 1999 and 2011 for Zones II through VI were 28-79% less than differences observed for Zone I across depths.

Year effects on soil P were observed in all zones except Zone IV (Table 6). At 0-8 cm, soil P generally increased over time in all zones, with values ranging from 4.9-7.5 kg P ha⁻¹ in 1999 to 10.8-18.1 kg P ha⁻¹ in 2011. Gradual increases in soil P at 0-31 cm were less apparent than in the near-surface depth, as the highest level of soil P varied by year depending on zone. In Zones I and III, soil P at 0-31 cm was greater in 2002, 2008 and 2011 than in 1999 and 2005, whereas in Zones II, V, and VI soil P was greater in 2008 or 2011 than other years. Trends in subsoil P over time also differed by zones. Significantly higher subsoil P was observed in 2002, 2008, and 2011 compared to 1999 and 2005 in Zone I. In Zone II, subsoil P was greatest in 2002, intermediate in 1999, 2008, and 2011, and lowest in 2005. In Zones III, V, and VI, subsoil P was greatest in 2002, intermediate in 2008 and 2011, and lowest in 1999 and 2005. Across the entire soil profile (0-122 cm), soil P was either greater in 2002, 2008 and 2011 compared to 1999 and 2005 (Zones I, II, and V) or greatest in 2002, intermediate in 2008 and 2011, and lowest in 1999 and 2005 (Zones III and VI).

3.3. *Soil pH responses to residue management and sampling zone*

Residue management and sampling zone had no effect on soil pH in 2011 (Tables 7 and 8). Soil conditions, however, became more acidic between 1999 and 2011 within near-surface (0-8 cm) and primary rooting (0-31 cm) depths in select treatments and zones (data for 31-122 cm and 0-122 cm depths not shown). Soil pH at 0-8 cm decreased significantly under GRAZED and REMOVED treatments between 1999 and 2011, with declines of 0.74 and 0.86 pH units over the 12 year period, respectively. At 0-31 cm, soil pH decreased over time only within the REMOVED treatment (0.31 pH unit decline) (Table 7).

Soil pH declined numerically in all grazed sampling zones between 1999 and 2011 at 0-8 and 0-31 cm (Table 8). At 0-8 cm, significant decreases in soil pH between 1999 and 2011 were

observed in Zones I, II, V, and VI, corresponding to reductions of 0.65, 1.17, 0.79, and 0.69 pH units, respectively. At 0-31, soil pH decreased significantly only in Zone VI (0.29 pH unit decline).

4. Discussion

Integrated crop-livestock systems offer unique opportunities to capitalize on potential production synergies derived from incorporating livestock in cropping systems (Soussana and Lemaire, 2014). This report provided a summary of grazing and residue management effects on stocks of available N and P and soil pH in an ICLS over a 12 year period at a semiarid location. As such, this report was not an inclusive assessment of nutrient-use efficiency of ICLS management, but instead provided inferences of efficiency through comparison of treatments. Among hypotheses developed to guide data analyses, two of three hypotheses were rejected by reported data (e.g., soil acidification would be mitigated by livestock integration, and soil nutrient and pH responses to livestock integration would be intensified with increased proximity to water/shelter). The remaining hypothesis (e.g., soil NO₃-N and available P would not be elevated under ICLS management compared to cropping alone) was not rejected.

At no time during the evaluation period did grazing result in greater soil NO₃-N and available P when compared to two residue management treatments excluding grazing. This finding was important, as accumulation of available N and P have been observed in ICLS studies, but in warmer and more humid regions (Franzluebbers and Stuedemann, 2003; Costa et al., 2014). Input of N and P from cattle feces and urine during winter months, when air temperatures rarely exceed 0°C, may limit nutrient mineralization and thereby potential loss (Eghball and Power, 1993). Moreover, cool spring temperatures would temper rapid transformation of N and P to forms available for plant uptake. Accordingly, climate-based

factors may have influenced treatment outcomes associated with soil NO₃-N and available P in this study.

Though nutrient stocks did not differ among residue management treatments or grazed sampling zones, there was considerable variation in soil NO₃-N and available P within treatments and zones over time. There was a clear trend toward increased soil NO₃-N as the study progressed, particularly in the last three years of the study, when values more than doubled between 2008 and 2011. Increased available P over time was also observed, though there were substantial fluctuations over the 12 year study, with values peaking in 2002, decreasing in 2005, and then returning to near-2002 levels in primary rooting, subsoil, and whole-profile soil depths in 2008 and 2011. Tempering soil nutrient fluctuations while mitigating their accumulation over time could be achieved with adjustments of synthetic fertilizer rates based on annual assessments of available N and P in the soil profile. If applied, an adaptive approach to nutrient management would serve to optimize crop yield and nutrient inputs, thereby maximizing economic returns while minimizing deleterious environmental impacts (Pierce et al., 1994). Moreover, further production and environmental synergies may be realized in ICLS through the adoption of dynamic crop sequencing (Tanaka et al., 2002), where crops are sequenced in rotation to take advantage of market opportunities based on available soil water and nutrients at planting.

While outcomes from this study suggest the need for adaptive nutrient management, elevated levels of available N and P in subsoil highlighted the potential for nutrient loss by leaching in this semiarid region. Should climatic changes in the Northern Plains region of the USA materialize (i.e., increase in winter and spring precipitation) (Shafer et al., 2014), managing agroecosystems to mitigate N and P loss by leaching will become increasingly important. In addition to adaptive nutrient management, additional interventions to reduce nutrient loss from

cropping systems in this region include the use of late-summer seeded cover crops, which have been found effective at scavenging available N to a depth of 90 cm (Liebig et al., 2015).

Observed changes in soil pH were driven by use of acidifying synthetic fertilizers, nutrient input from cattle, and residue management. Soil pH changes found in this study corresponded to findings elsewhere for rainfed cropping systems in the Great Plains (Bowman and Halvorson, 1998; Schroder et al., 2011; Sainju et al., 2015). Nitrogen inputs from synthetic fertilizer and cattle feces and urea are well known for their acidifying effects on soil in the absence of lime addition (Tarkalson et al., 2006). Among residue management treatments, mechanical harvesting resulted in the largest decrease in soil pH at 0-8 and 0-31 cm. Presumably, removal of basic cations in crop residue served to exacerbate soil acidification (Stewart et al., 2015). Current trajectory of soil pH in this study suggest lime addition may eventually be required to maintain soil solution chemistry ideal for nutrient cycling and plant growth (Smith and Doran, 1998). This management intervention could be delayed by minimizing leaching losses of NH_3 -derived $\text{NO}_3\text{-N}$ by matching N inputs with crop requirements and capturing excess soil $\text{NO}_3\text{-N}$ with cover crops. Continued monitoring of soil chemical attributes in this study will be necessary to track the evolution of acidification under the residue management treatments.

5. Conclusions

A 12-yr study of ICLS management effects on soil nutrients and pH found no accumulation of available N and P under grazing compared to cropping nor differences in N and P among grazed sampling zones. Soil nutrient levels over time, however, increased or were subject to wide fluctuations between sampling dates, suggesting the need for an adaptive approach to nutrient management. Increased soil acidification over the 12 year period was

1 observed in near-surface and primary rooting soil depths, and occurred in areas where crop
2 residue was either grazed or mechanically harvested. For conditions inherent to this ICLS study,
3 management interventions targeting nutrient conservation would serve to concurrently mitigate
4 N and P loss and soil acidification.
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1 **FIGURE CAPTIONS**

- 2 Figure 1. Diagram of crop rotation, residue management treatments, and sampling zones (I-VII)
- 3 within one replicate of an integrated crop-livestock experiment near Mandan, ND, USA.
- 4 Grazed and ungrazed sampling zones are specified to the right of the diagram.

1 Table 1. Precipitation and air temperature for dormant and growing season periods near study site, 1999-2010.

2

Year	----- Dormant season ----- (Jan-Mar)		----- Growing season ----- (April-Sep)		----- Dormant season ----- (Oct-Dec)	
	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)
1999	36 [†]	−5.0	556	15.0	15	2.4
2000	81	−4.0	385	15.5	86	−3.6
2001	32	−7.4	464	16.2	24	1.2
2002	20	−6.1	243	15.5	30	−0.7
2003	21	−8.6	317	16.2	42	−0.5
2004	51	−7.2	381	14.6	23	1.2
2005	15	−6.1	411	16.1	63	0.7
2006	15	−3.6	195	17.2	59	−0.2
2007	46	−6.6	457	16.1	19	−0.7
2008	23	−7.6	305	15.0	185	−2.4
2009	72	−10.2	412	14.5	74	−1.4
2010	26	−7.9	440	15.6	26	−1.9
Long-term (1914-2010)	36 ± 2	−8.4 ± 0.3	331 ± 10	15.4 ± 0.2	49 ± 3	−1.2 ± 0.4

3 [†] Precipitation and air temperature data summaries obtained from Global Historical Climatology Network-Daily (GHCN-D), National Oceanic Atmospheric
4 Administration, National Climatic Data Center (<http://www.ncdc.noaa.gov/cdo-web>; accessed 14 November 2016). Long-term values reflect mean ± 1 standard
5 error.

1 Table 2. Summary of P-values from analysis of variance for residue management effects
 2 on soil NO₃-N and P for four depth increments in 1999, 2002, 2005, 2008, and 2011.

3

Year	Depth (cm)	Soil NO ₃ -N	Soil P
1999	0-8	0.6417	0.9113
	0-31	0.8016	0.7320
	31-122	0.5456	0.9169
	0-122	0.7513	0.8907
2002	0-8	0.7587	0.7237
	0-31	0.7840	0.7095
	31-122	0.7914	0.4476
	0-122	0.7874	0.6554
2005	0-8	0.7033	0.2306
	0-31	0.4064	0.2455
	31-122	0.1347	0.8082
	0-122	0.1222	0.5855
2008	0-8	0.9247	0.8924
	0-31	0.8031	0.9058
	31-122	0.6152	0.9241
	0-122	0.2944	0.9127
2011	0-8	0.8057	0.5469
	0-31	0.7890	0.4183
	31-122	0.6237	0.6912
	0-122	0.8872	0.8880

1 Table 3. Summary of P-values from analysis of variance for grazed sampling zone
2 effects on soil NO₃-N and P for four depth increments in 1999, 2002, 2005, 2008, and
3 2011.

Year	Depth (cm)	Soil NO ₃ -N	Soil P
1999	0-8	0.9911	0.5615
	0-31	0.9997	0.6122
	31-122	0.9212	0.8501
	0-122	0.9994	0.7436
2002	0-8	0.8142	0.2548
	0-31	0.5717	0.5708
	31-122	0.1205	0.7169
	0-122	0.2705	0.8106
2005	0-8	0.4115	0.5436
	0-31	0.6290	0.5892
	31-122	0.1815	0.4428
	0-122	0.1853	0.4905
2008	0-8	0.3054	0.6252
	0-31	0.6983	0.7250
	31-122	0.4961	0.4907
	0-122	0.6631	0.5842
2011	0-8	0.4029	0.5845
	0-31	0.3131	0.5690
	31-122	0.1048	0.5605
	0-122	0.1085	0.6847

5

1 Table 4. Mean values of soil NO₃-N and P for residue management treatments by year. Values organized by depth increment.

2

Depth (cm)	Year	----- Residue management -----					
		GRAZED	REMOVED	CONTROL	GRAZED	REMOVED	CONTROL
		----- Soil NO ₃ -N (kg N ha ⁻¹) -----			----- Soil P (kg P ha ⁻¹) -----		
0-8	1999	7.0 (0.9) b [†]	9.1 (3.1) b	8.4 (3.0)	6.2 (0.5) c	6.3 (1.1) c	5.8 (0.8) c
	2002	7.0 (1.6) b	4.6 (1.6) b	8.7 (5.0)	8.8 (0.5) bc	7.8 (0.5) bc	8.7 (1.3) bc
	2005	11.9 (0.8) b	10.8 (1.4) b	10.5 (1.6)	10.2 (0.9) b	7.2 (1.0) c	7.5 (1.7) c
	2008	5.7 (0.6) b	5.7 (1.3) b	6.3 (1.4)	15.8 (1.5) a	14.1 (1.3) ab	15.4 (3.4) ab
	2011	26.8 (3.1) a	29.1 (5.0) a	31.1 (8.2)	14.6 (1.3) a	18.1 (3.9) a	16.3 (2.1) a
0-31	1999	16.9 (2.1) b	20.3 (7.0) b	19.4 (7.1)	13.5 (0.8) b	13.5 (2.1) bc	15.1 (1.6) b
	2002	14.9 (3.3) b	9.3 (1.8) b	15.2 (6.3)	23.1 (1.0) a	23.8 (2.2) ab	25.2 (2.6) a
	2005	20.1 (1.2) b	17.7 (2.5) b	16.5 (2.1)	16.4 (1.9) b	10.2 (1.1) c	11.1 (2.7) b
	2008	12.0 (1.0) b	12.8 (2.4) b	13.8 (3.5)	28.1 (2.0) a	25.8 (1.8) a	27.9 (2.9) a
	2011	44.0 (6.7) a	48.9 (7.5) a	49.5 (10.4)	24.9 (1.5) a	30.3 (6.1) a	26.5 (2.9) a
31-122	1999	7.3 (0.6) e	9.0 (2.3) cd	7.7 (2.1) b	20.5 (2.9) c	17.3 (7.8) c	21.0 (4.1) d
	2002	25.6 (1.5) b	24.0 (1.7) b	23.5 (2.5) ab	62.6 (4.0) a	58.5 (5.2) a	50.6 (4.0) a
	2005	20.6 (1.5) c	14.5 (1.1) c	15.8 (1.2) b	15.9 (5.1) c	9.6 (2.1) c	8.9 (1.2) e
	2008	16.5 (1.3) d	19.8 (3.1) bc	23.5 (4.1) ab	48.7 (5.0) ab	44.6 (0.9) b	45.9 (2.2) b
	2011	35.4 (1.6) a	35.3 (2.4) a	31.5 (3.0) a	46.1 (4.3) b	40.6 (2.4) b	38.6 (2.3) c
0-122	1999	24.2 (2.6) c	29.3 (9.3) b	27.2 (9.2) b	33.9 (3.4) b	30.8 (8.1) b	36.1 (4.8) b
	2002	40.4 (4.2) b	33.3 (3.4) b	38.7 (8.6) b	85.6 (4.5) a	82.4 (6.4) a	75.8 (5.0) a
	2005	40.6 (2.2) b	32.2 (2.9) b	32.3 (2.4) b	32.3 (6.9) b	19.8 (2.4) b	20.0 (3.6) c
	2008	28.5 (2.1) bc	32.6 (4.2) b	37.2 (7.1) b	76.8 (6.9) a	70.3 (1.3) a	73.8 (2.8) a
	2011	79.4 (4.3) a	84.3 (9.0) a	80.9 (12.2) a	80.0 (5.1) a	70.9 (7.2) a	65.1 (4.8) a

3 [†] Values within a depth and residue management treatment with unlike letters differ (P≤0.10). Values in parentheses reflect the standard error of the mean.

1 Table 5. Mean values of soil NO₃-N within grazed sampling zones by year. Values organized by depth increment.

2

Depth (cm)	Year	----- Soil NO ₃ -N (kg N ha ⁻¹) by sampling zone [†] -----					
		I	II	III	IV	V	VI
0-8	1999	6.8 (2.0) b [‡]	7.9 (2.4) b	7.6 (2.8)	5.9 (1.7) c	7.1 (2.0)	6.6 (2.4)
	2002	9.8 (7.4) b	6.7 (2.9) b	6.8 (3.2)	3.2 (1.0) d	10.3 (4.8)	4.9 (2.4)
	2005	9.4 (1.5) b	12.6 (2.6) b	10.9 (1.4)	11.0 (1.3) b	15.1 (2.3)	12.2 (1.9)
	2008	8.3 (1.5) b	5.7 (1.1) b	5.1 (0.7)	4.4 (1.0) d	4.3 (1.1)	6.5 (2.2)
	2011	39.4 (6.5) a	27.1 (7.7) a	24.2 (6.7)	12.7 (1.4) a	30.7 (11.0)	26.8 (6.8)
0-31	1999	16.5 (5.0) b	18.3 (6.1) b	16.9 (5.9) b	15.8 (4.5) b	17.5 (5.6)	16.7 (5.9)
	2002	28.4 (17.9) b	11.0 (3.3) b	15.7 (5.2) b	7.8 (1.5) c	15.3 (5.3)	11.0 (4.2)
	2005	16.7 (2.0) b	19.9 (4.2) b	19.1 (2.8) b	19.2 (2.1) b	24.1 (3.3)	21.4 (2.9)
	2008	14.3 (2.1) b	12.5 (2.1) b	11.7 (1.4) b	8.9 (2.2) c	10.6 (3.0)	13.9 (4.0)
	2011	60.7 (8.4) a	43.8 (9.1) a	42.2 (6.5) a	25.0 (2.6) a	47.2 (11.7)	45.2 (9.6)
31-122	1999	8.3 (1.5) c	7.2 (2.1) d	6.7 (1.2) d	6.8 (1.4) d	7.8 (1.5) d	6.6 (1.3) c
	2002	34.9 (7.0) b	23.7 (1.3) b	23.8 (1.0) b	22.5 (1.7) b	23.9 (1.7) b	24.5 (3.2) ab
	2005	15.4 (1.3) c	18.2 (2.4) c	22.4 (3.4) b	16.6 (2.3) bc	24.2 (3.4) b	26.5 (6.1) ab
	2008	14.5 (1.6) c	14.9 (2.3) c	18.8 (2.9) c	13.5 (2.4) c	15.9 (2.9) c	21.5 (5.7) b
	2011	45.9 (4.4) a	33.4 (3.4) a	34.0 (3.5) a	31.2 (2.9) a	34.8 (4.4) a	33.0 (3.5) a
0-122	1999	24.8 (6.4) c	25.5 (8.0) b	23.6 (7.0) c	22.6 (5.7) c	25.3 (6.8) c	23.3 (7.2) b
	2002	63.3 (21.9) b	34.7 (34.7) b	39.5 (5.9) b	30.3 (3.1) bc	39.2 (5.5) bc	35.5 (6.6) b
	2005	32.1 (2.4) c	38.1 (5.8) b	41.5 (4.7) b	35.8 (3.5) b	48.3 (6.2) b	47.9 (6.8) ab
	2008	28.8 (3.3) c	27.4 (3.9) b	30.5 (2.2) bc	22.4 (4.3) c	26.5 (5.8) bc	35.4 (9.5) b
	2011	106.6 (9.9) a	77.2 (10.2) a	76.2 (6.3) a	56.2 (5.1) a	82.0 (10.3) a	78.2 (11.7) a

3 [†] Increasing numerical values represent greater distance from water source and shelter (52 m between sampling zones).

4 [‡] Values within a depth and sampling zone with unlike letters differ (P≤0.10). Values in parentheses reflect the standard error of the mean.

5

1 Table 6. Mean values of soil P within grazed sampling zones by year. Values organized by depth increment.

2

Depth (cm)	Year	----- Soil P (kg P ha ⁻¹) by sampling zone [†] -----					
		I	II	III	IV	V	VI
0-8	1999	4.9 (0.9) b [‡]	7.5 (0.9) c	5.5 (1.0) c	7.4 (1.8)	6.7 (0.8) d	5.4 (0.8) d
	2002	11.7 (1.8) b	7.0 (0.7) c	7.7 (0.7) bc	10.6 (1.5)	8.2 (0.6) cd	7.8 (0.6) c
	2005	8.1 (1.2) b	11.8 (1.4) b	9.5 (1.8) b	13.8 (4.5)	8.9 (0.8) c	9.2 (1.4) c
	2008	17.0 (1.7) a	16.5 (1.7) a	13.6 (0.8) a	20.1 (7.6)	11.3 (1.7) b	16.2 (4.0) a
	2011	18.1 (5.1) a	13.1 (1.9) ab	10.8 (2.4) ab	14.7 (3.1)	17.3 (3.8) a	13.4 (1.2) b
0-31	1999	12.0 (2.0) b	13.6 (1.2) d	13.1 (2.3) b	16.7 (3.0)	13.6 (1.6) c	11.8 (1.4) c
	2002	27.3 (3.9) a	20.7 (2.2) bc	21.8 (1.1) a	26.1 (2.8)	21.3 (1.8) b	21.3 (1.5) b
	2005	11.7 (2.0) b	16.7 (2.3) c	15.8 (2.7) b	25.2 (10.5)	14.1 (1.7) c	15.2 (2.2) c
	2008	28.7 (1.8) a	28.2 (1.8) a	25.7 (1.4) a	35.3 (11.0)	22.5 (2.1) ab	28.5 (4.4) a
	2011	29.8 (5.9) a	22.2 (2.0) b	21.7 (2.5) a	25.2 (4.2)	27.5 (3.9) a	23.1 (1.5) b
31-122	1999	17.4 (3.9) b	27.1 (4.8) b	15.8 (4.0) c	28.8 (16.1)	14.4 (3.0) c	19.4 (2.4) c
	2002	51.5 (4.0) a	58.9 (6.6) a	62.2 (6.3) a	76.9 (20.2)	58.5 (6.2) a	67.6 (6.4) a
	2005	11.4 (2.1) b	8.5 (1.4) c	12.6 (3.8) c	43.6 (29.5)	7.6 (1.0) c	11.9 (3.3) c
	2008	42.8 (4.1) a	40.2 (2.0) b	43.6 (2.7) b	77.1 (28.8)	45.0 (1.3) b	43.2 (3.1) b
	2011	43.3 (3.3) a	40.0 (1.7) b	48.8 (7.9) b	64.2 (24.2)	41.4 (3.3) b	38.9 (3.2) b
0-122	1999	29.1 (4.6) b	40.6 (5.3) b	28.9 (5.2) c	45.5 (18.4)	28.0 (3.8) b	31.2 (2.4) c
	2002	78.8 (6.5) a	79.6 (7.1) a	84.0 (6.9) a	102.9 (22.7)	79.8 (7.4) a	88.8 (7.6) a
	2005	23.2 (3.3) b	25.2 (3.4) b	28.4 (4.6) c	68.7 (40.0)	21.7 (2.3) b	27.1 (4.5) c
	2008	71.5 (4.6) a	68.4 (2.1) a	69.3 (3.9) b	112.4 (39.8)	67.5 (3.1) a	71.7 (5.6) b
	2011	73.0 (8.9) a	62.1 (1.2) a	70.5 (10.1) b	89.4 (27.3)	68.9 (5.7) a	61.9 (4.4) b

3 [†] Increasing numerical values represent greater distance from water source and shelter (52 m between sampling zones).

4 [‡] Values within a depth and sampling zone with unlike letters differ (P≤0.10). Values in parentheses reflect the standard error of the mean.

5

1 Table 7. Residue management effects in 1999 and 2011 on soil pH for two depth
 2 increments.

3

----- Residue management -----				
Year	GRAZED	REMOVED	CONTROL	P-value
----- 0-8 cm -----				
1999	6.80 (0.04) [†]	6.83 (0.04)	6.95 (0.17)	0.2923
2011	6.06 (0.06)	5.97 (0.10)	6.23 (0.13)	0.4235
P-value	0.0581	0.0138	0.1839	
----- 0-31 cm -----				
1999	6.82 (0.04)	6.83 (0.04)	6.88 (0.09)	0.7948
2011	6.56 (0.04)	6.52 (0.05)	6.65 (0.06)	0.7314
P-value	0.3597	0.0403	0.2988	

4 [†] Values in parentheses reflect the standard error of the mean.

1 Table 8. Grazed sampling zone and year effects on soil pH for two depth increments.

2

Year	----- Sampling zone [†] -----						P-value
	I	II	III	IV	V	VI	
1999	6.80 (0.08) [‡]	6.84 (0.16)	6.79 (0.12)	6.81 (0.12)	6.79 (0.10)	6.76 (0.11)	0.9944
2011	6.15 (0.08)	5.67 (0.13)	6.37 (0.23)	6.10 (0.11)	6.00 (0.05)	6.07 (0.06)	0.2538
P-value	0.0293	0.0201	0.4342	0.1032	0.0628	0.0790	
1999	6.95 (0.10)	6.78 (0.11)	6.88 (0.13)	6.79 (0.12)	6.77 (0.08)	6.75 (0.04)	0.4977
2011	6.75 (0.09)	6.32 (0.09)	6.70 (0.18)	6.61 (0.05)	6.55 (0.04)	6.46 (0.05)	0.3486
P-value	0.4988	0.1355	0.7257	0.5811	0.3300	0.0845	

3 [†] Increasing numerical values represent greater distance from water source and shelter (52 m between sampling zones).

4 [‡] Values in parentheses reflect the standard error of the mean.

1 Figure 1