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Integrated crops and livestock in central North Dakota, USA: Agroecosystem management to buffer soil change

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Abstract

Integrated crop–livestock systems have been purported to have numerous agronomic and environmental benefits, yet information documenting their long-term impact on the soil resource is lacking. This study sought to quantify the effects of an integrated crop–livestock system on near-surface soil properties in central North Dakota, USA. Soil bulk density, electrical conductivity, soil pH, extractable N and P, potentially mineralizable N, soil organic carbon (SOC) and total nitrogen (TN) were measured 3, 6 and 9 years after treatment establishment to evaluate the effects of residue management (Grazed, Hayed and Control), the frequency of hoof traffic (High traffic, Low traffic and No traffic), season (Fall and Spring) and production system (integrated annual cropping versus perennial grass) on near-surface soil quality. Values for soil properties were incorporated into a soil quality index (SQI) using the Soil Management Assessment Framework to assess overall treatment effects on soil condition. Residue management and frequency of hoof traffic did not affect near-surface soil properties throughout the evaluation period. Aggregated SQI values did not differ between production systems 9 years after treatment establishment (integrated annual cropping = 0.91, perennial grass = 0.93; $P = 0.57$), implying a near-identical capacity of each system to perform critical soil functions. Results from the study suggest that with careful management, agricultural producers can convert perennial grass pastures to winter-grazed annual cropping systems without adversely affecting near-surface soil quality. However, caution should be exercised in applying results to other regions or management systems. The consistent freeze/thaw and wet/dry cycles typical of the northern Great Plains, coupled with the use of no-till management, modest fertilizer application rates and winter grazing likely played an important role in the outcome of the results.

Key words: integrated agricultural systems, soil change, soil quality

Introduction

Integrated crop–livestock systems may improve agricultural productivity, environmental quality, operational efficiency and economic performance relative to specialized, single-enterprise production systems[1,2]. Benefits from crop–livestock integration stem from production synergies brought about by using crops and crop residues for livestock feed while capturing nutrients from livestock wastes for subsequent crop production[3,4]. To date, many positive agronomic and environmental attributes have been associated with integrated crop–livestock systems[5–7]. However, concerns persist regarding the role of livestock in these systems to adversely affect near-surface soil conditions, with potential negative impacts on long-term sustainability[8].

Adding livestock to annual cropping systems can have variable effects on soil condition under different climatic and edaphic environments. In humid and sub-humid regions, soil organic carbon (SOC) and total nitrogen (TN) have been observed to increase with the inclusion of cattle within annually cropped systems or systems with a perennial grass phase[6,9,10]. Increases in SOC and TN in integrated crop–livestock systems have been associated with

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greater aggregate stability and labile organic matter pools in near-surface soil depths[6,7], thereby conferring potential benefits to erosion resistance and nutrient-cycling potential. Evidence of soil compaction from livestock trampling, however, has been observed in regions where soils are often not frozen and moist from precipitation[11]. In these regions, increased penetration resistance caused by cattle traffic during winter grazing has been observed[6,12], with negligible or negative effects on subsequent crop yield[7,13].

Published information addressing soil responses to integrated crop–livestock systems is especially limited in semiarid regions. System effects on soil condition are difficult to document in these regions[14,15], owing primarily to the fact that soil attributes change slowly in response to management due to limited—and often erratic—production of above- and belowground biomass[16]. Accordingly, long-term research is needed to document effects of integrated crop–livestock systems on soil attributes associated with key soil functions.

In 1999, a research team at the USDA-ARS Northern Great Plains Research Laboratory initiated an integrated crop–livestock study designed to evaluate production, nutritional, and environmental aspects of overwintering dry bred cows on swathed annual crops[17,18]. Unlike other integrated crop–livestock studies in the northern US, this project converted perennial grass pastures to annual cropping, thereby placing emphasis on maintaining soil conditions accrued under perennial vegetation. From 2001 through 2008, a suite of soil attributes were measured, with the intention of quantifying treatment effects on near-surface soil quality. Specific objectives associated with the soils component of this study were to evaluate the effects of residue management, frequency of hoof traffic, season and production system (e.g., integrated annual cropping versus perennial grass) on near-surface soil quality. The postulation that conversion of perennial grass pastures to a winter-grazed annual crop management system could be achieved without adversely affecting soil quality was used as a guiding hypothesis for this research effort.

Materials and Methods

Site and treatment description

The experimental site was located at the USDA-ARS Northern Great Plains Research Laboratory's south research station, approximately 5 km south of Mandan, North Dakota, USA (latitude 46°46′35′, longitude 100°54′20′). The site was on gently rolling uplands (0–3% slope) with a silty loess mantle overlying Wisconsin age till. Predominant soils at the study site were Temvik–Wilton silt loams (FAO: Calcic Siltic Chernozems; USDA: Fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls).

In 1999, two 6.0 ha crested wheatgrass [*Agropyron desertorum* (Fisch. ex. Link) Schult.] pastures were sprayed with glyphosate [*N*-(phosphonomethyl) glycine; 0.7 kg a.i. ha^{-1}] twice in mid-May and converted to an annual cropping sequence of oat/pea (*Avena sativa* L./*Pisum sativum* L.), triticale/sweet clover (*Triticum aestivum* × *Secale cereale*/*Melilotus officinalis* L.), and corn (*Zea mays* L.). Beginning in 2007, the crop sequence was changed to oat/alfalfa (*Medicago* spp.)/hairy vetch (*Vicia villosa Roth*)/red clover (*Trifolium pratense* L.), Brown midrib sorghum–sudangrass (*Sorghum bicolor* L. Moench)/sweet clover/red clover and corn, also using no-till planting techniques. Each phase of the 3-year cropping sequence was present in both pastures, which were used as replicates. Oat and triticale/sorghum crop mixtures were seeded in mid-to-late May, while corn was seeded in early June. All crops were seeded using no-till planting techniques with a John Deere 750 no-till drill in 19 cm rows (John Deere, Moline, IL). 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 in 2007 and 2008) and monoammonium phosphate (6 kg N ha^{-1} and 11 kg P ha^{-1} for all crops in all years). Weeds were managed using herbicides following recommended practices by area producers.

The oat and triticale/sorghum crop mixtures were harvested for grain from mid-August to early September with the straw spreader removed from the combine, which created a swath of straw and chaff to facilitate winter grazing. The corn was swathed for forage in mid-to-late September. Each crop strip was split into three residue management treatments that included no residue removal (CONTROL; 0.05 ha), residue removal with a baler (HAYED; 0.05 ha), and residue removal by grazing with livestock (GRAZED; 1.69 ha) (Fig. 1). The CONTROL and HAYED treatments were randomly assigned within each crop strip. For the GRAZED treatment, the swathed crop residues from the cropping sequence represented winter forage for ten 4- to 6-yr-old dry bred Hereford cows, due to calve in late March. Grazing commenced in mid-November and ended in mid-February, with the oat crop mixture grazed first, triticale/sorghum crop mixture second and corn last. Access to crop swaths was controlled using electric fences oriented at right angles to the swaths. Fences were moved daily to provide cows access to fresh forage. A shelter and 'frost-free' fountain were located on the end of each pasture within the GRAZED treatment.

Two 6.0 ha western wheatgrass [*Pascopyrum smithii* (Rydb.) Love] pastures were used as a perennial grass treatment for comparison with the annually cropped treatments. Similar to GRAZED treatments, swathed grass from the pastures was used as winter forage from 1999 through 2002 for the same number of cows managed similarly as outlined above. Within each perennial pasture a non-grazed strip was split into HAYED and CONTROL treatments as outlined above. Due to a lack of adequate forage from drought in 2002 and 2003, the perennial grass treatment was hayed but not grazed in 2003. From 2004 through 2008, the perennial grass treatment was not swathed but lightly grazed with ten Hereford or Angus cows from mid-October to mid-January. Additional details

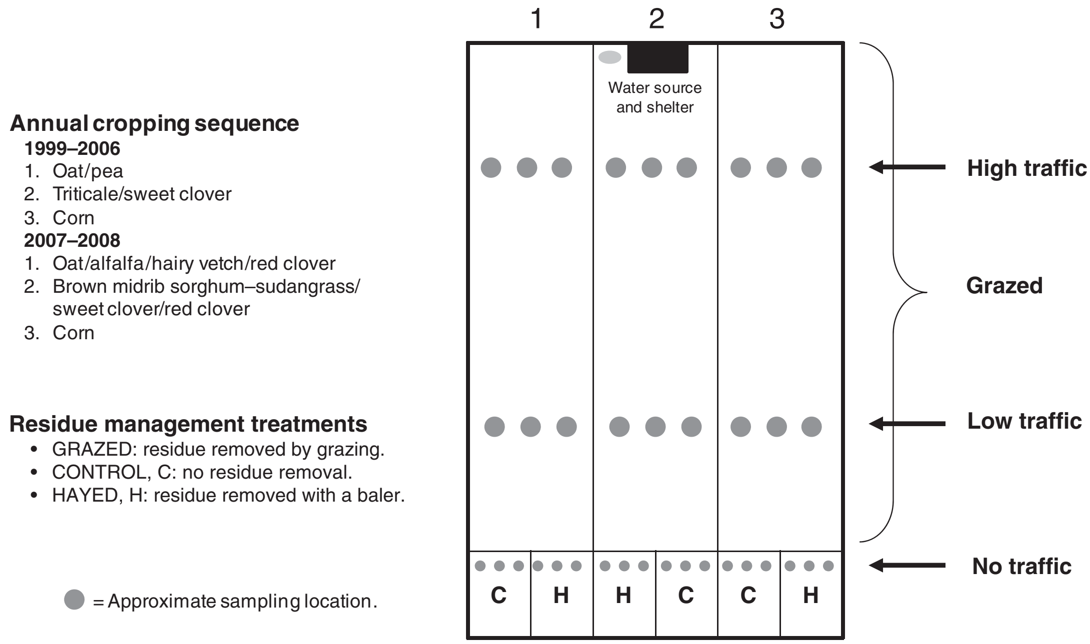

Figure 1. Diagram of residue management and hoof-traffic treatments within an integrated annual cropping pasture near Mandan, ND.

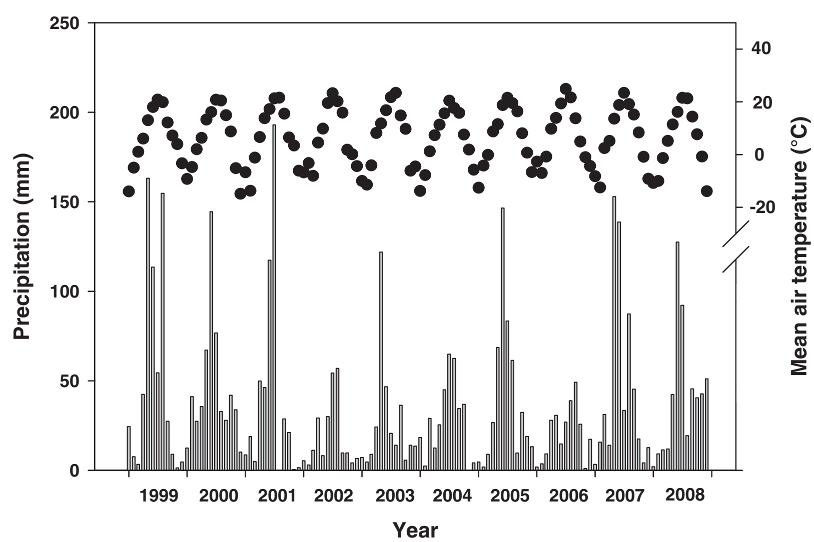

Figure 2. Monthly precipitation and mean monthly air temperature near study site, 1999–2008.

regarding crop and livestock aspects of the experiment are reviewed elsewhere[17,18].

Soil sampling protocol and analysis

Soil samples were collected during the spring (April) and fall (October) of 2001/2002, 2004/2005 and 2007/2008, either after crops had been swathed but not grazed, and after the swathed crops had been grazed but not replanted. Within the annually cropped pastures, samples were collected from nine subplots (three per crop phase) in the CONTROL and HAYED treatments, oriented randomly in each treatment but between crop rows. Samples from the GRAZED treatment were collected from two transects differing in frequency of hoof traffic, also between crop rows. Nine subplots (three per crop phase) were established in each transect perpendicular to crop swaths approximately 100 m (representing high traffic (HT)) and 200 m (representing low traffic (LT)) from the shelter and water source (Fig. 1). Sampling protocol for the western wheatgrass pastures mirrored that in the annually cropped pastures, with the exception of fewer subplots in each treatment (three in the CONTROL, HAYED and GRAZED hoof-traffic transects). Within each subplot, six soil cores were collected from 0 to 7.5 cm depth using a 3.5-cm (i.d.) step-down probe and composited. Each sample was saved in a double-lined plastic bag, placed in cold storage at 5°C, and analyzed within 6 weeks of collection.

Table 1. Effects of grazing and residue management on soil properties at 0–7.5 cm in the spring of 2002, 2005 and 2008 for a winter grazing management system near Mandan, ND.

Year	Grazed	Hayed	Control	*P-value*
	----Soil bulk density ($Mg\,m^{-3}$)------			
2002	1.08 (0.04)[1]	1.06 (0.03)	1.06 (0.03)	*0.95*
2005	1.03 (0.04)	1.10 (0.03)	1.12 (0.03)	*0.77*
2008	1.20 (0.08)	1.11 (0.04)	1.13 (0.07)	*0.57*
P-value	*<0.01*	*0.13*	*0.11*	
	-------Electrical conductivity ($dS\,m^{-1}$)--------			
2002	0.25 (0.04)	0.22 (0.03)	0.25 (0.02)	*0.56*
2005	0.32 (0.04)	0.28 (0.03)	0.28 (0.02)	*0.45*
2008	0.46 (0.03)	0.36 (0.02)	0.45 (0.01)	*0.45*
P-value	*<0.01*	*<0.01*	*<0.01*	
	---------Soil pH ($-\log[H^+]$)--------			
2002	5.88 (0.06)	5.89 (0.08)	5.93 (0.13)	*0.97*
2005	5.92 (0.06)	6.06 (0.08)	6.13 (0.13)	*0.73*
2008	5.83 (0.12)	5.99 (0.23)	6.14 (0.27)	*0.74*
P-value	*0.36*	*0.13*	*0.25*	
	-------Soil nitrate (kg NO_3-N ha^{-1}) --------			
2002	5.4 (2.6)	4.6 (2.1)	6.9 (2.2)	*0.54*
2005	8.0 (2.6)	5.7 (2.1)	6.4 (2.2)	*0.44*
2008	15.2 (1.6)	9.1 (1.8)	11.3 (1.6)	*0.39*
P-value	*<0.01*	*0.12*	*0.08*	
	-------Soil ammonium (kg NH_4-N ha^{-1})--------			
2002	2.0 (1.5)	1.2 (0.5)	1.9 (0.1)	*0.52*
2005	2.1 (1.5)	2.2 (0.5)	2.5 (0.2)	*0.48*
2008	6.3 (1.1)	4.9 (0.5)	4.4 (0.3)	*0.75*
P-value	*0.01*	*<0.01*	*0.01*	
	--------Available P (kg P ha^{-1})--------			
2002	7.8 (1.2)	6.1 (1.1)	6.1 (2.2)	*0.24*
2005	8.1 (1.2)	5.5 (1.1)	8.8 (2.2)	*0.74*
2008	15.7 (2.3)	11.1 (1.1)	11.6 (1.7)	*0.20*
P-value	*<0.01*	*<0.01*	*0.07*	
	-----Potentially mineralizable N (kg N ha^{-1})-----			
2002	63.5 (6.9)	53.7 (6.2)	65.5 (11.6)	*0.40*
2005	65.1 (6.9)	71.8 (6.2)	76.7 (11.6)	*0.62*
2008	75.0 (8.9)	61.1 (4.7)	52.5 (6.7)	*0.27*
P-value	*0.22*	*0.03*	*0.15*	
	--------SOC (Mg C ha^{-1})--------			
2002	23.9 (1.5)	23.2 (1.0)	23.3 (1.9)	*0.89*
2005	20.6 (1.5)	21.9 (1.0)	23.1 (1.9)	*0.15*
2008	25.6 (1.0)	23.8 (1.5)	22.2 (1.8)	*0.54*
P-value	*0.01*	*0.21*	*0.83*	
	--------TN (Mg N ha^{-1})---------			
2002	2.1 (0.1)	2.1 (0.1)	2.1 (0.2)	*0.76*
2005	1.8 (0.1)	1.9 (0.1)	2.0 (0.2)	*0.23*
2008	2.3 (0.1)	2.2 (0.1)	2.1 (0.1)	*0.60*
P-value	*<0.01*	*0.02*	*0.92*	

[1] Values in parentheses represent mean standard error.

Table 2. Effects of frequency of hoof traffic on soil properties at 0–7.5 cm in the spring of 2002, 2005, and 2008 for an integrated annual cropping system near Mandan, ND.

Year	High traffic	Low traffic	No traffic	*P-value*
	--------Soil bulk density ($Mg\,m^{-3}$)--------			
2002	1.08 (0.09)[1]	1.03 (0.08)	1.07 (0.03)	*0.93*
2005	1.01 (0.09)	1.08 (0.08)	1.13 (0.03)	*0.79*
2008	1.19 (0.10)	1.16 (0.09)	1.11 (0.05)	*0.37*
P-value	*0.24*	*0.45*	*0.15*	
	------Electrical conductivity ($dS\,m^{-1}$)------			
2002	0.25 (0.15)	0.23 (0.04)	0.24 (0.01)	*0.79*
2005	0.29 (0.15)	0.31 (0.04)	0.27 (0.01)	*0.39*
2008	0.52 (0.10)	0.39 (0.03)	0.41 (0.01)	*0.65*
P-value	*0.20*	*0.14*	*<0.01*	
	--------Soil pH ($-\log[H^+]$)--------			
2002	5.72 (0.07)	5.69 (0.08)	5.88 (0.11)	*0.99*
2005	5.56 (0.07)	5.80 (0.08)	6.07 (0.11)	*0.60*
2008	5.80 (0.07)	5.78 (0.15)	6.03 (0.21)	*0.68*
P-value	*0.04*	*0.46*	*0.25*	
	-----Soil nitrate (kg NO_3-N ha^{-1}) ------			
2002	5.3 (6.7)	5.4 (2.0)	5.3 (0.1)	*0.89*
2005	6.0 (6.7)	7.7 (2.0)	5.5 (0.1)	*0.38*
2008	20.2 (4.7)	11.6 (1.4)	9.7 (0.6)	*0.32*
P-value	*0.10*	*0.17*	*<0.01*	
	-----Soil ammonium (kg NH_4-N ha^{-1}) -------			
2002	2.2 (4.3)	1.4 (1.0)	1.5 (0.2)	*0.70*
2005	2.0 (4.3)	2.3 (1.0)	2.4 (0.2)	*0.35*
2008	9.4 (3.0)	5.4 (0.7)	4.4 (0.2)	*0.48*
P-value	*0.21*	*0.11*	*<0.01*	
	--------Available P (kg P ha^{-1})--------			
2002	9.3 (2.8)	6.8 (2.8)	6.5 (1.8)	*0.17*
2005	6.8 (2.8)	8.6 (2.8)	6.9 (1.8)	*0.97*
2008	16.8 (3.9)	15.2 (2.0)	10.8 (1.7)	*0.42*
P-value	*0.02*	*0.17*	*0.07*	
	---Potentially mineralizable N (kg N ha^{-1})---			
2002	57.2 (11.5)	55.4 (17.7)	59.7 (11.3)	*0.42*
2005	65.9 (11.5)	56.0 (17.7)	70.1 (11.3)	*0.70*
2008	59.4 (8.1)	89.8 (14.0)	56.7 (8.0)	*0.23*
P-value	*0.74*	*0.29*	*0.47*	
	----------SOC (Mg C ha^{-1})----------			
2002	23.0 (1.1)	25.0 (5.6)	23.4 (1.9)	*0.59*
2005	19.0 (1.1)	20.3 (5.6)	22.9 (1.9)	*0.14*
2008	25.8 (1.0)	20.8 (3.9)	21.6 (1.7)	*0.43*
P-value	*<0.01*	*0.70*	*0.63*	
	----------TN (Mg N ha^{-1})----------			
2002	2.1 (0.1)	2.2 (0.5)	2.1 (0.2)	*0.40*
2005	1.7 (0.1)	1.8 (0.5)	2.0 (0.2)	*0.13*
2008	2.4 (0.1)	1.9 (0.3)	2.0 (0.1)	*0.42*
P-value	*<0.01*	*0.74*	*0.89*	

[1] Values in parentheses represent mean standard error.

Soil samples were dried at 35°C for 3–4 days and then ground by hand to pass a 2.0 mm sieve. Identifiable plant material (>2.0 mm diameter, >10 mm length) was removed during sieving. Electrical conductivity and pH were estimated from a 1 : 1 soil–water mixture[19,20]. Soil NO_3-N and NH_4-N were determined from 1 : 10 soil-KCl (2 M) extracts using cadmium reduction followed by a modified Griess–Ilosvay method and indophenol blue reaction[21]. Plant-available soil P was estimated by bicarbonate extraction[22]. Potentially mineralizable N was estimated from the NH_4-N accumulated after a 7-day anaerobic incubation at 40°C[23]. Total soil C and N was determined by dry combustion using a Carlo Erba NA 1500 CN analyzer (Thermo Scientific, Waltham, MA, USA)[24]. Soil pH was <7.2 for the depths sampled, and so total soil C was considered equivalent to SOC. Gravimetric data were converted to a

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Table 3. Seasonal effects of winter grazing on soil properties at 0–7.5 cm within an integrated crop–livestock system near Mandan, ND. Sampling times corresponded to the time after crops had been swathed but not grazed (fall) and after the swathed crops had been grazed but not replanted (spring).

Sampling time	Soil bulk density ($Mg\,m^{-3}$)	Electrical conductivity ($dS\,m^{-1}$)	Soil pH ($-log[H^+]$)	Soil nitrate kg NO_3-N ha^{-1}	Soil ammonium (kg NH_4-N ha^{-1})	Available P (kg P ha^{-1})
Fall, 2001	1.08 (0.02)[1]	0.35 (0.01)	5.91 (0.05)	14.8 (2.6)	0.7 (0.4)	5.6 (0.6)
Spring, 2002	1.08 (0.04)	0.25 (0.02)	5.88 (0.10)	5.4 (1.3)	2.0 (0.4)	7.8 (0.5)
P-value	*0.93*	*< 0.01*	*0.55*	*< 0.01*	*< 0.01*	*< 0.01*
Fall, 2004	1.03 (0.03)	0.28 (0.02)	6.00 (0.06)	5.6 (0.9)	1.4 (0.1)	4.6 (0.8)
Spring, 2005	1.03 (0.07)	0.32 (0.02)	5.91 (0.16)	8.0 (0.9)	2.1 (0.2)	8.1 (1.9)
P-value	*0.98*	*0.27*	*0.14*	*0.21*	*< 0.01*	*< 0.01*
Fall, 2007	1.10 (0.05)	0.33 (0.04)	5.78 (0.07)	6.7 (2.8)	4.8 (1.8)	14.6 (1.5)
Spring, 2008	1.20 (0.06)	0.46 (0.04)	5.83 (0.16)	15.2 (1.7)	6.3 (1.4)	15.7 (1.8)
P-value	*0.04*	*< 0.01*	*0.48*	*0.01*	*0.40*	*0.45*

[1] Values in parentheses represent mean standard error.

volumetric basis for each sampling depth using field measured soil bulk density[25]. All data were expressed on an oven-dry basis prior to statistical analysis.

Data analyses

Analysis of variance was conducted with PROC mixed in SAS using a repeated measures analysis technique for testing effects of residue management, hoof traffic, season, year and production system on soil properties[26,27]. For each analysis, tested effects were considered fixed, while replicates were considered random. Treatment means were calculated across subplots and crop phases. A significance criterion of $P \leqslant 0.05$ was used to document differences between means.

Only data from the spring samplings were used for the residue management, hoof traffic and production system comparisons. Additionally, for frequency of hoof traffic, data from the CONTROL and HAYED treatments were combined to represent a no-traffic treatment (NT). Similarly, only data from the GRAZED treatment were used to compare seasonal effects on soil properties.

To assess production system effects on an integrative measure of soil quality, values for select soil properties were included in a soil quality index (SQI) using the Soil Management Assessment Framework (SMAF)[28]. The SMAF follows a three-step framework including (1) indicator selection, (2) indicator interpretation, and (3) integration into an SQI score. Briefly, data from six soil properties were used for step one: soil bulk density, electrical conductivity, soil pH, extractable P, potentially mineralizable N and total C. Non-linear scoring algorithms were used for step two to assign a score for each property (ranging from 0 to 1, with 1 representing highest potential soil function). To ensure that algorithms were appropriate for the edaphic, climatic and management attributes associated with the study site, appropriate factor class assignments were selected based on categories in the SMAF[28]. Individual property scores were summed and a mean value was calculated for step three to arrive at an aggregated SQI score. Individual property and SQI scores were subject to statistical analyses for production system comparisons as outlined above.

Results

From 1999 through 2008, weather patterns in most years followed trends typical of a semiarid continental climate, with cold and dry winters and warm to hot summers with erratic precipitation (Fig. 2). Mean annual precipitation over the 10-year period was 430 mm, slightly above the long-term (94-years) mean of 413 mm. Four years were marked by drought (2002–2004, 2006), where a lack of precipitation during the spring and summer months resulted in mean annual precipitation ranging from 228 to 335 mm. Mean monthly air temperatures followed expected seasonal patterns and rarely deviated by more than ±3°C from long-term means (Fig. 2)[29].

Residue management

Residue management did not affect near-surface soil properties in any year (Table 1). Across years, soil bulk density increased within the GRAZED treatment between 2005 and 2008, although increases were not sufficient to limit root growth[30]. Significant increases in electrical conductivity between 2005 and 2008 in all residue management treatments were driven by greater extractable N and P in 2008, the result of residual plant nutrients left in soil following the 2006 and 2007 growing seasons, early spring mineralization (N only, as discussed below) and/or manure accumulation (GRAZED only). Soil pH ranged from moderately to slightly acid and did not differ between years in any residue management treatment. Potentially mineralizable N increased significantly between 2002 and 2005 in the HAYED treatment ($\triangle = 18.1$ kg N ha^{-1}), the cause of which is unclear. Soil organic C (SOC) and TN increased between 2005 and 2008 in the GRAZED treatment

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($\triangle = 5.0$ Mg C ha^{-1} and 0.5 Mg N ha^{-1}, respectively). The increase in SOC and TN may have been driven by manure accumulation in the GRAZED treatment; although it is important to acknowledge the elevated soil bulk density in 2008, which would act to contribute to greater SOC when expressed volumetrically. Conversely, increased soil bulk density could not account for elevated TN in the HAYED treatment in 2008 as compared to 2005.

Frequency of hoof traffic; season

Frequency of hoof traffic within the integrated annual cropping system did not affect near-surface soil properties in any year (Table 2). Available P, SOC, and TN increased between 2005 and 2008 in the high-traffic zone (HT), possibly the result of greater manure accumulation from cattle due to the relatively close proximity of the zone to the winter shelter and water source (approximately 100 m). Similar to the residue management treatments, increased extractable N and P in 2008 within the no-traffic zone (NT) was likely the result of residual plant nutrients in soil following the previous growing season, early spring mineralization and/or manure accumulation.

Winter grazing of annual crops had minor effects on near-surface soil properties (Table 3). Of the three contrasted sampling times (i.e., 2001/2002, 2004/2005 and 2007/2008), changes in soil properties between fall and spring were most prevalent in 2001/2002 and least prevalent in 2004/2005. Soil bulk density increased following winter grazing between fall 2007 and spring 2008 by 0.1 Mg m^{-3}, possibly the result of hoof-induced compaction in December 2007. Trends in electrical conductivity and soil NO_3-N were similar between spring and fall in 2001/2002 and 2007/2008, with both parameters decreasing (2001/2002) or increasing (2007/2008) following grazing. The inconsistent trend between years was likely due to either NO_3-N loss following spring snowmelt (e.g., leaching, nitrification/denitrification) or NO_3-N release from mineralized organic material. Both soil NH_4-N and available P increased between spring and fall in 2001/2002 and 2004/2005; although increases were numerically small ($\triangle = 0.7$–1.3 kg NH_4-N ha^{-1}; 2.2–3.5 kg P ha^{-1}).

Production system

Comparisons between integrated annual cropping and perennial grass treatments exhibited few differences in near-surface soil properties in 2002, 2005 and 2008 (Table 4). The application of N and P fertilizers contributed to greater soil NO_3-N (2005, 2008) and available P (2008) under integrated annual cropping compared to perennial grass. Conversely, potentially mineralizable N was greater under perennial grass than integrated annual cropping, a finding that confirms previous comparisons of annual and perennial agroecosystems in temperate regions[31,32].

Changes in near-surface soil properties between sampling times were common for both production systems (Table 4). Notable changes included significant increases in extractable N, available P and electrical conductivity in the integrated annual cropping system between 2005 and 2008; increases likely caused by residual plant nutrients from fertilizer not utilized by crops (in the case of P), early spring N mineralization, and/or manure accumulation. A similar trend was observed under perennial grass, but

Table 4. Soil properties at 0–7.5 cm in the spring of 2002, 2005 and 2008 for integrated annual cropping and perennial grass near Mandan, ND.

Year	Integrated annual cropping	Perennial grass	*P-value*
	-------Soil bulk density (Mg m^{-3})-------		
2002	1.07 (0.02)[1]	1.02 (0.02)	*0.49*
2005	1.07 (0.02)	1.11 (0.02)	*0.73*
2008	1.16 (0.07)	1.07 (0.02)	*0.29*
P-value	*< 0.01*	*< 0.01*	
	-----Electrical conductivity (dS m^{-1})-----		
2002	0.24 (0.02)	0.25 (0.02)	*0.70*
2005	0.30 (0.02)	0.29 (0.02)	*0.56*
2008	0.43 (0.01)	0.37 (0.02)	*0.25*
P-value	*< 0.01*	*< 0.01*	
	---------Soil pH (−log[H$^+$])---------		
2002	5.89 (0.06)	6.46 (0.10)	*0.08*
2005	6.00 (0.06)	6.58 (0.10)	*0.09*
2008	5.94 (0.18)	6.88 (0.08)	*0.06*
P-value	*0.18*	*< 0.01*	
	------SN (kg NO_3-N ha^{-1})------		
2002	5.6 (1.5)	0.7 (0.2)	*0.06*
2005	7.0 (1.5)	1.3 (0.2)	*0.02*
2008	12.7 (1.0)	0.9 (0.3)	*0.03*
P-value	*< 0.01*	*0.02*	
	-----Soil ammonium (kg NH_4-N ha^{-1})-----		
2002	1.8 (0.3)	1.9 (0.2)	*0.77*
2005	2.2 (0.1)	2.6 (0.2)	*0.13*
2008	5.5 (0.7)	4.0 (0.2)	*0.32*
P-value	*0.03*	*< 0.01*	
	--------Available P (kg P ha^{-1})--------		
2002	8.9 (1.0)	6.9 (1.0)	*0.18*
2005	7.6 (1.0)	2.2 (1.0)	*0.24*
2008	13.5 (1.6)	5.2 (0.7)	*0.02*
P-value	*< 0.01*	*< 0.01*	
	--Potentially mineralizable N (kg N ha^{-1})--		
2002	61.6 (5.1)	91.6 (6.4)	*0.03*
2005	69.7 (5.1)	109.3 (6.4)	*0.04*
2008	65.9 (5.4)	117.2 (4.6)	*0.02*
P-value	*0.28*	*< 0.01*	
	-------Soil organic C (Mg C ha^{-1})-------		
2002	23.6 (0.9)	23.8 (1.2)	*0.87*
2005	21.6 (0.9)	21.6 (1.2)	*0.99*
2008	24.3 (0.9)	25.6 (0.7)	*0.44*
P-value	*0.01*	*0.01*	
	--------TN (Mg N ha^{-1})--------		
2002	2.1 (0.1)	2.1 (0.1)	*0.72*
2005	1.9 (0.1)	1.8 (0.1)	*0.38*
2008	2.2 (0.1)	2.3 (0.1)	*0.81*
P-value	*< 0.01*	*0.04*	

[1] Values in parentheses represent mean standard error.

Table 5. SMAF index scores in the spring of 2002, 2005 and 2008 for integrated annual cropping and perennial grass near Mandan, ND. Values reflect scores for six soil properties included in SMAF, as well as an aggregated score (SQI) for each year.

Variable[1]	Integrated annual cropping	Perennial grass	*P-value*[2]	Integrated annual cropping	Perennial grass	*P-value*	Integrated annual cropping	Perennial grass	*P-value*
	2002			2005			2008		
SBD	0.99	0.99	*0.47*	0.99	0.99	*0.53*	0.95	0.99	*0.45*
EC	1.00	1.00	*1.00*	1.00	1.00	*1.00*	0.99	1.00	*0.50*
PH	0.98	0.98	*0.67*	0.98	0.98	*0.98*	0.97	0.95	*0.43*
P	0.97	0.91	*0.03*	0.95	0.34	*0.10*	0.99	0.92	*0.07*
PMN	1.00	1.00	*1.00*	1.00	1.00	*1.00*	0.99	1.00	*0.50*
SOC	0.64	0.68	*0.73*	0.56	0.52	*0.75*	0.59	0.71	*0.25*
SQI	0.93	0.93	*0.91*	0.91	0.80	*0.10*	0.91	0.93	*0.57*

[1] SBD, soil bulk density index score; EC, electrical conductivity index score; PH, soil pH index score; P, available phosphorus index score; PMN, potentially mineralizable N index score; SOC, soil organic C index score; SQI, aggregated soil quality index score.
[2] *P*-values reflect comparison between scores within year.

without the increase in soil NO_3-N. Small, but significant increases in soil bulk density were observed in each production system, with soil bulk density greater in 2008 than 2005 for integrated annual cropping and greater in 2005 than 2002 for perennial grass (both increasing by 0.09 $Mg\,m^{-3}$). Large numerical increases in SOC and TN in 2008 contributed to significantly greater values in both production systems when compared with 2005 ($\triangle =$ 2.7–4.0 $Mg\ C\,ha^{-1}$; 0.3–0.5 $Mg\ N\,ha^{-1}$). However, SOC and TN were not different between 2002 and 2008 for either production system.

Among individual soil properties, SMAF index scores differed between production systems only for available P in 2002, being greater under integrated annual cropping than perennial grass (0.97 versus 0.91, respectively; $P = 0.03$) (Table 5). Although not statistically different in 2005, a numerical difference in the available P score between integrated annual cropping and perennial grass ($\triangle = 0.61$) contributed to the largest difference in the aggregated SMAF scores (SQI) between production systems in any year. This difference notwithstanding, SQI scores did not differ between production systems at $P \leqslant 0.05$, implying a similar capacity of each system to perform critical soil functions.

Discussion

Soil resistance has been defined as the capacity of a soil to continue to function without change throughout a disturbance[33,34]. Small changes in soil function resulting from disturbance imply high resistance, whereas large changes in soil function suggest low resistance. The capacity of soil to maintain functional integrity under disturbance reflects a key component of agroecosystem stability[35]. Such an attribute is increasingly important given the context of 21st century agriculture, where concurrent trends of increased demand for agricultural products, increasingly scarce non-renewable resources and accelerating climate change will favor agroecosystems that are resistant to change yet highly productive[36].

We sought to quantify the effects of disturbance (residue management, frequency of hoof traffic, season and production system) on near-surface soil quality for an integrated crop–livestock system in central North Dakota. Overall, results from the study suggest disturbances had minimal effects on soil properties during the timeframe of measurement, with no differences in soil function between integrated annual cropping and perennial grass at 3, 6 and 9 years after study establishment. While the lack of significant treatment effects may be disconcerting to some readers, our data demonstrate that sustainable agroecosystem management mitigates significant alterations to the soil environment. While management-related factors certainly contributed in conferring resistance to soil disturbance over time, inherent features related to weather and soil may also have played a role.

Inherent weather- and soil-related features may have contributed to soil resistance through annual freeze–thaw and wet–dry cycles characteristic of soils in the northern Great Plains. Such cycles would act to expand/contract soil minerals and water in soil pores, thereby ameliorating compaction caused by cattle and/or vehicular traffic by fracturing compacted soil zones[37,38]. Accordingly, these cycles would act to mitigate changes in near-surface soil bulk density over time.

In addition to weather-related features, the inherent fertility of the soils evaluated in the study may have made the soil more resistant to disturbance. As Pachic and Typic Haplustolls, the soils possessed high inherent fertility (82 $Mg\ SOC\,ha^{-1}$), large buffering capacity (18 $cmol\,kg^{-1}$ cation exchange capacity), and a favorable particle-size distribution (280 $g\,kg^{-1}$ sand, 190 $g\,kg^{-1}$ clay) for supporting critical soil functions (data pertains to 0–30 cm)[39]. Accordingly, deterioration or improvement of this soil under different management would be expected to occur slowly, and most likely on a decadal timescale[16].

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Management-related factors governing soil resistance in the integrated annual cropping system may have been associated with the use of no-till seeding operations, as well as the fertility and grazing regimes employed throughout the study. No-till conversion of the crested wheatgrass pastures to annual cropping in 1999 likely conferred an inherent resistance against changes in near-surface soil properties caused by subsequent disturbances from cropping and grazing. A lack of tillage during conversion to annual cropping allowed for the maintenance of soil structure (e.g., pore continuity and pore-size distribution) developed under perennial grass[40]. Maintenance of a favorable soil structure during the transition to annual cropping may have been critical in buffering potential changes in soil condition caused by differences in plant type (annual crops versus perennial grass) and the implementation of field activities (e.g., spraying, planting and swathing). Moreover, the use of no-till operations negated tillage-induced 'flushes' of mineralized nutrients typically observed in tilled agroecosystems[41,42]. Tillage is well documented to contribute to seasonal fluctuations in available nutrients and decreased SOC in temperate agroecosystems[16,43].

Modest application rates of N and P fertilizer, coupled with relatively high production of aboveground biomass, likely contributed to low levels of residual nutrients in soil throughout the study. The application of N to soil was lower than recommended for traditional no-till cropping systems in North Dakota[44], but was deemed adequate in order to take advantage of N-fixing legumes in the crop sequence. Production of total aboveground biomass in the integrated annual cropping system was impressive early in the study, ranging from 1.7 to 9.2 $Mg\,ha^{-1}$ for oat/pea, from 3.2 to 13.8 $Mg\,ha^{-1}$ for triticale/sweet clover and from 12.8 to 26.9 $Mg\,ha^{-1}$ for corn from 1999 to 2002[18]. Biomass production at these levels would act to draw down residual nutrient levels, leaving limited soil N and P for subsequent crop production.

Because near-surface soil depths were typically frozen from November through March, soil in the GRAZED treatment was less susceptible to compaction by hoof traffic than if grazing had occurred in the fall or spring, when excessive soil moisture can increase the potential for hoof-induced compaction[45]. Mid-winter warming periods during the grazing time would act to thaw near-surface soil, thereby increasing the likelihood of surface compaction. Relatively warm air temperatures at the study site in December 2007 (8 days $>0°C$ from December 1 to December 31)[46] created the potential for this to occur, which may explain the significant increase in soil bulk density between fall 2007 and spring 2008 in the GRAZED treatment.

Conclusions

Results from this study suggest that winter grazing by cattle in an integrated annual cropping system will not adversely affect near-surface soil properties associated with key soil functions. These results underscore the value of designing and implementing management systems that minimize significant changes to the soil environment. However, caution should be exercised in applying these results outside of the northern Great Plains or to other management systems. The consistent freeze/thaw and wet/dry cycles characteristic of the region, coupled with the use of no-till management, modest fertilizer application rates and winter grazing likely played an important role in the outcome of the results.

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