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Research Article

Crop Diversity Effects on Near-Surface Soil Condition under Dryland Agriculture

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Unprecedented changes in agricultural land use throughout the northern Great Plains of North America have highlighted the need to better understand the role of crop diversity to affect ecosystem services derived from soil. This study sought to determine the effect of four no-till cropping systems differing in rotation length and crop diversity on near-surface (0 to 10 cm) soil properties. Cropping system treatments included small grain-fallow (SG-F) and three continuously cropped rotations (3 yr, 5 yr, and Dynamic) located in south-central North Dakota, USA. Soil pH was lower in the 3 yr rotation (5.17) compared to the Dynamic (5.51) and SG-F (5.55) rotations ($P \leq 0.05$). Among cropping system treatments, 5 yr and Dynamic rotations possessed significantly greater soil organic C (SOC) and total N (mean = 26.3 Mg C ha^{-1}, 2.5 Mg N ha^{-1}) compared to the 3 yr (22.7 Mg C ha^{-1}, 2.2 Mg N ha^{-1}) and SG-F (19.9 Mg C ha^{-1}, 2.0 Mg N ha^{-1}) rotations ($P \leq 0.05$). Comparison of SOC measured in this study to baseline values at the research site prior to the establishment of treatments revealed only the 5 yr and Dynamic rotations increased SOC over time. The results of this study suggest that a diverse portfolio of crops is necessary to minimize soil acidification and increase SOC.

1. Introduction

Producing a sufficient amount of food while protecting environmental quality and sustaining rural economies represents a significant agricultural challenge in the 21st century [1]. The immensity of this challenge is brought into focus when considering current trajectories in climate change and nonrenewable resource use [2]. Accordingly, increased emphasis has been placed on developing agricultural production systems that are inherently resilient to external stressors yet are highly productive, economically competitive, and environmentally benign. This nexus of *productivity, profitability,* and *ecosystem health* has underscored the critical role of soil, Earth's biogeochemical engine, to affect agricultural and environmental outcomes through impacts on ecosystem services [3].

Classification of soil ecosystem services is encompassed within supporting, regulating, provisioning, and cultural categories [4]. The retention and delivery of plant nutrients (supporting), regulation of element and hydrologic cycles (regulating), and physical support for plants (provisioning) can be inferred through the measurement of key soil physical, chemical, and biological properties and processes. Such assessments are needed to elucidate management effects on soil ecosystem services that directly affect agricultural sustainability.

Of the broad array of management decisions under direct producer control, crop rotation perhaps represents the most significant with regard to long-term economic and environmental outcomes [1, 5]. In the context of environmental outcomes related to soil ecosystem services, crop rotation effects can be manifested through alterations in soil structure, soil-water properties, and/or nutrient retention and availability.

Crop rotations including perennial legumes or grasses can increase the formation and stability of aggregates compared to two-year crop rotations or monocultures [6, 7]. Improvements in soil structure under extended crop rotations have corresponded with lower soil bulk density and higher infiltration rates [8, 9]. Crop residue inputs strongly affect soil nutrient stocks [10], thereby limiting generalizations regarding effects of extended crop rotations on soil C and N. Decreases in soil C and N have been observed with the inclusion of leguminous crops in rotation [11, 12]. Fixed N by leguminous crops, however, has been associated with greater net N mineralization in extended crop rotations compared to monocultures [9, 13]. Collectively, integrative assessments using the Soil Management Assessment Framework [14] found higher overall soil quality index values in longer and more diverse crop rotations compared to two-year crop rotations or monocultures, implying improved soil function in the former [7, 15].

This study sought to quantify effects of crop rotation on a suite of soil properties within four long-term cropping systems in south-central North Dakota, USA. The region represented by the study area has undergone an unprecedented transition in agricultural land use involving the conversion of grassland to annual crops [16]. Moreover, recent documentation of cropping patterns in the region suggests an increased prevalence of monoculture cropping [17]. These regional land use trends underscore the value of understanding crop rotation effects on soil properties that infer the status of critical soil functions.

2. Materials and Methods

2.1. Site and Treatment Description. The research site was located within the Missouri Plateau approximately 6 km south of Mandan, North Dakota, USA (46°46′12′′N, 100°54′57′′W) on the Area IV Soil Conservation Districts (SCD) Research Farm. The site is on gently rolling uplands (0–3% slope) with a silty loess mantle overlying Wisconsin-age till. Soils at the site are dominated by a mix of Temvik and Wilton silt loams (USDA: fine-silty, mixed, superactive, frigid Typic, and Pachic Haplustolls; FAO: Calcic Siltic Chernozems). Long-term (98 yr) mean annual precipitation is 412 mm, with 79% of the total received during the growing season (April–September). Long-term mean annual temperature is 4°C, though daily averages fluctuate from <−10°C in the winter to >20°C in the summer.

Four field-scale cropping system treatments were established at the site between 1984 and 2001 to evaluate long-term effects of rotation length and crop diversity on crop performance, precipitation-use efficiency, and soil quality [18]. Rotations and year of establishment included (1) small grain-fallow (SG-F, 1984), where the small grain included spring wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), or oat (*Avena sativa* L.); (2) spring wheat, winter wheat (*Triticum aestivum* L.), and sunflower (*Helianthus annuus* L.) (3 yr; 1984); (3) spring wheat, winter wheat, dry pea (*Pisum sativum* L.), corn (*Zea mays* L.), and soybean (*Glycine max* L.) (5-yr; 2001); and (4) a Dynamic rotation that included six of the following crops: corn, sunflower, spring wheat, winter wheat, soybean, and buckwheat (*Fagopyrum esculentum* Moench) (Dynamic; 2001). Crops in the Dynamic rotation were sequenced each year based on market opportunities, soil water and nutrient conditions at planting, and/or restrictions on herbicide use within the planted field [19]. Each phase of the SG-F, 3 yr, and 5 yr rotations was present every year. Crops in the Dynamic rotation were also present every year, though due to the availability of seven fields for the rotation some crops were present in duplicate. Field size for each crop phase varied, ranging from 2 to 14 ha. Crop rotations were not replicated. Prior to establishment in 2001, cropland areas allocated to the 5 yr and Dynamic rotations were cropped to the 3 yr rotation.

Corn, soybean, and sunflower were planted with a John Deere MaxEmerge II row crop planter in 76 cm rows (Deere & Company, Moline, IL), while all other crops were planted in 19 cm rows with a John Deere Model 750 no-till drill or a Bourgault air seeder (Bourgault Industries, St. Brieux, Saskatchewan, Canada). Nitrogen fertilizer (ammonium nitrate or urea) was applied to all crops prior to or concurrent with planting operations at recommended rates [20] while taking into consideration levels of residual soil N following years with below normal precipitation. Phosphorus fertilizer (triple superphosphate) was applied annually to all crops at 11 kg P ha^{-1} with the seed at planting. Burn-down and postemergent herbicides were applied to crops in all rotations to control weeds as needed, as were fungicides to control leaf spot disease. Scheduling of seeding, fertilizer and pesticide application, and harvest followed best management practices used by area producers.

2.2. Sampling Protocol and Laboratory Analyses. In May 2012, three 10 m^2 pseudoreplicates were established in each crop rotation phase prior to planting, resulting in 51 pseudoreplicates across all treatments (6, 9, 15, and 21 pseudoreplicates for SG-F, 3 yr, 5 yr, and Dynamic rotations, respectively). Selection of pseudoreplicates in each treatment was done carefully to ensure all sampling sites possessed the same soil type (Temvik silt loam) and landscape attributes (0-1% slope). Eight soil cores were collected in each pseudoreplicate from the 0 to 10 cm depth using a 3.13 cm (internal diameter) step-down probe and composited. To ensure composite samples were representative of each plot, three cores each were collected from the nonwheel- and wheel-tracked interrows, and two cores from the row. Each sample was stored in a double-lined plastic bag, placed in cold storage at 5°C, and analyzed for chemical and biological attributes within 3 weeks of collection.

Infiltration rate measurements (one pseudoreplicate^{-1}) were made at the time of sampling by inserting a piece of heavy-gauge aluminum irrigation pipe (15 cm internal diameter by 15 cm length) into the soil of a nonwheel-trafficked interrow to a 7.5 cm depth and applying two separate applications of water within the enclosed space of the ring [21]. The volume of water for each application was equivalent to a 2.54 cm depth in the ring. The time necessary for each application of water to infiltrate into the soil was recorded using a stopwatch. To eliminate effects associated with differences in antecedent water content among treatments, only data from the second water application were analyzed.

Soil processing was initiated by weighing the total tared soil mass at field moisture content. Gravimetric water content was determined for each sample by removing a 12–15 g subsample and measuring the difference in mass before and after drying at 105°C [22]. Samples were then split for chemical and biological analyses into two approximately equal portions. Samples for chemical analyses were dried at 32°C for 3 to 4 d 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 and discarded. Chemical analyses included assessments of electrical conductivity (EC), soil pH, particulate organic matter (POM), and total C and N. Soil pH and EC were estimated from a 1 : 1 soil-water mixture [23, 24]. Particulate organic matter (POM) was quantified by analyzing the C content of material retained on a 0.053 mm sieve [25]. Particulate organic matter C, along with total soil C and N, was determined by dry combustion. As pH was <7.2 for the depths sampled, total soil C was considered equivalent to soil organic C (SOC).

Biological analyses included assessment of soil microbial biomass, which was estimated using the microwave irradiation method [26]. Prior to analysis, each split sample was sieved through a 2.0 mm sieve at field moisture content. Fifty grams of sieved soil was incubated 10 d at 55% water-filled pore space in the presence of 10 mL of 2.0 M NaOH. Carbon dioxide content was determined by single end-point titration with 0.1 M HCl [27], and the flush of CO_2-C following irradiation was calculated without subtracting a 10 d control [28]. Gravimetric data were converted to a volumetric basis using field measured soil bulk density [29]. All data were expressed on an oven-dry basis.

For purposes of comparison, near-surface soil samples (0 to 10 cm) from a grazed pasture were collected and analyzed following sampling guidelines and laboratory analyses outlined above. The pasture, located approximately 2.5 km east of the crop rotation treatments, possessing the same soil type and landscape attributes, has never been tilled and has been grazed by cattle at a low stocking rate (2.6 ha steer^{-1}) as part of a long-term experiment established in 1916 [30].

2.3. Data Analyses. Crop rotation effects on soil properties were evaluated by ANOVA using PROC mixed in SAS [31]. The PDIFF option of the LSMEANS statement was used to document differences between treatment means using a significance criterion of $P \leq 0.05$. Means were calculated across phases for each crop rotation. Means of soil properties within the grazed pasture were not included in data analyses but presented for general comparison only.

3. Results and Discussion

Crop rotation diversity had a pronounced effect on soil physical condition, soil solution chemistry, and soil organic matter attributes. Soil bulk density was significantly lower in the 5 yr rotation compared to the SG-F and Dynamic rotations (Table 1), though observed values for all treatments were not indicative of physical conditions restrictive of root growth [32]. Soil bulk density among cropped treatments ranged from 0.30 to 0.37 Mg m^{-3} greater than grazed pasture, the result of abundant near-surface root biomass in the latter [33]. Despite observed differences in soil bulk density, crop rotation effects on infiltration rate were not significant ($P = 0.16$). Treatment assessments of infiltration rate are often challenging at large spatial scales, with coefficients of variation >100% for many water transport properties [34, 35]. Despite this fact, there was a notable numerical trend among treatments (SG-F < 3 yr < 5 yr < Dynamic), with infiltration rate increasing 6.1 to 7.1 cm hr^{-1} with increasing rotational diversity (Table 1).

Measurements of soil solution chemistry suggested near-surface soil conditions among crop rotation treatments were nonsaline and moderately to strongly acidic [36] (Table 2). While crop rotation did not affect EC ($P = 0.15$), soil pH was significantly higher in the SG-F and Dynamic rotations compared to the 3 yr rotation. Use of urea and ammonium nitrate fertilizers, coupled with differences in N fertilization frequency, likely contributed to observed treatment effects on soil pH. Nitrification of ammonium-based fertilizers causes soil acidification, particularly if nitrate is not taken up by plant roots [37]. Such acidification is expected to be greater where N is applied each year compared to crop-fallow, where N is applied biannually. Accordingly, soil pH has been found to be higher in dryland cropping systems including fallow [38]. Decreased acidification in the Dynamic versus the 3 yr rotation was likely the result of differences in applied N over time. Compared to grazed pasture, crop rotation treatments were 0.67 to 1.05 pH units more acidic (Table 2). Moreover, soil samples collected in 1983 prior to the establishment of rotation treatments on one of the fields included in this study possessed a pH of 6.4 for the 0 to 7.6 cm depth [39], suggesting substantial surface acidification during the intervening 29 years.

Quantifying the status and trajectory of soil organic matter attributes is critically important for understanding management impacts on the productivity and stability of agroecosystems [40]. Soil organic C and total N followed a similar trend among cropped treatments, with 5 yr > Dynamic > 3 yr > SG-F (Table 3). Statistically, SOC and total N were greater in 5 yr and Dynamic rotations compared to 3 yr and SG-F rotations, while the 3 yr rotation possessed significantly greater total N than SG-F ($P \leq 0.01$). Soil C : N ratio for cropped treatments ranged between 10.20 and 10.73, with values greatest for the 5 yr and Dynamic rotations (10.67 to 10.73) and least for the 3 yr and SG-F rotations (10.20 to 10.23). Statistical differences in C : N ratio among cropped treatments were limited to 5 yr > 3 yr and SG-F and 3 yr < 5 yr and Dynamic ($P = 0.02$). Particulate organic matter C, a moderately labile fraction composed mostly of plant residue, exhibited the widest range in observed values among C and N parameters (1172 to 3078 kg C ha^{-1}). Among cropped treatments, POM-C was the greatest in the 5 yr rotation, intermediate in the Dynamic rotation, and the least in SG-F ($P \leq 0.01$). Particulate organic matter in the 3 yr rotation was not different from the 5 yr and Dynamic rotations. Microbial biomass C was not different among cropped treatments ($P = 0.17$).

All soil C and N parameters were numerically greater in grazed pasture than cropped treatments. Soil organic C, total N, C : N ratio, POM-C, and MBC were 15, 4, 12, 52, and 33% greater, respectively, in grazed pasture compared to the cropped treatment with the highest value for each parameter (5 yr rotation for four of five parameters). In contrast, the same five parameters were 56, 30, 17, 300, and 81% greater in grazed pasture compared to SW-F.

Table 1: Crop diversity effects on soil bulk density at 0–10 cm and infiltration rate for long-term crop and pasture treatments near Mandan, ND.

Soil property	Small grain-fallow	3 yr fixed rotation	5 yr fixed rotation	Dynamic rotation	Grazed pasture[†]
Bulk density ($Mg\,m^{-3}$)	1.20 (0.02) a[‡]	1.18 (0.04) ab	1.13 (0.01) b	1.18 (0.01) a	*0.83 (0.02)*
Infiltration rate ($cm\,hr^{-1}$)	7.9 (4.8)	15.0 (6.9)	22.1 (4.6)	28.2 (5.7)	—

[†]Soil property values for grazed pasture with the same soil type are shown for comparison but were not included in statistical analyses. Infiltration rate not measured in grazed pasture due to excessive soil wetness at time of sampling.
[‡]Values in parentheses represent mean standard error. Mean values in a row followed by a different letter are significantly different at $P \leq 0.05$.

Table 2: Crop diversity effects on electrical conductivity and soil pH at 0–10 cm for long-term crop and pasture treatments near Mandan, ND.

Soil property	Small grain-fallow	3 yr fixed rotation	5 yr fixed rotation	Dynamic rotation	Grazed pasture[†]
Electrical conductivity ($dS\,m^{-1}$)	0.59 (0.14)	0.58 (0.03)	0.66 (0.06)	0.74 (0.04)	*0.39 (0.01)*
Soil pH ($-\log[H^+]$)	5.55 (0.16) a[‡]	5.17 (0.06) b	5.37 (0.04) ab	5.51 (0.09) a	*6.22 (0.03)*

[†]Soil property values for grazed native vegetation with the same soil type are shown for comparison but were not included in statistical analyses.
[‡] Values in parentheses represent mean standard error. Mean values in a row followed by a different letter are significantly different at $P \leq 0.05$.

Table 3: Crop diversity effects on soil carbon, nitrogen, C : N ratio, particulate organic matter (POM) C, and microbial biomass C at 0–10 cm for long-term crop and pasture treatments near Mandan, ND.

Soil property	Small grain-fallow	3 yr fixed rotation	5 yr fixed rotation	Dynamic rotation	Grazed pasture[†]
Soil organic C ($Mg\,C\,ha^{-1}$)	19.9 (1.0) b[‡]	22.7 (0.9) b	26.9 (0.4) a	25.7 (0.7) a	*31.0 (0.7)*
Total N ($Mg\,N\,ha^{-1}$)	2.0 (0.1) c	2.2 (0.1) b	2.5 (0.1) a	2.4 (0.1) a	*2.6 (0.1)*
C : N ratio	10.23 (0.26) bc	10.20 (0.11) c	10.73 (0.10) a	10.67 (0.12) ab	*12.02 (0.11)*
POM-C ($kg\,C\,ha^{-1}$)	1172 (144) c	2834 (151) ab	3078 (162) a	2486 (144) b	*4690 (262)*
Microbial biomass C ($kg\,C\,ha^{-1}$)	549 (48)	748 (89)	657 (42)	671 (32)	*992 (116)*

[†]Soil property values for grazed native vegetation with the same soil type are shown for comparison but were not included in statistical analyses.
[‡]Values in parentheses represent mean standard error. Mean values in a row followed by a different letter are significantly different at $P \leq 0.05$.

Crop rotations contributing greater above- and below-ground biomass generally increase soil C and N under conditions of equivalent tillage and nutrient management [5]. Accordingly, inclusion of fallow in semiarid cropping systems is associated with decreased C and N in near-surface soil depths compared to continuous cropping due to lower biomass contributions in the former [41, 42]. Under continuous cropping, effects of crop rotation length and/or crop diversity on soil C and N have been mixed depending on residue quantity and quality, as well as water availability for growth of subsequent crops [43]. In this study, crops included in the 5 yr and Dynamic rotations were sequenced to favor snow capture and efficient precipitation use, which would serve to enhance production over a rotation cycle [44]. While the inclusion of wheat was a consistent feature in the continuously cropped rotations, it is possible that the addition of corn, a high residue-producing crop with a moderately high C : N stover ratio, may have contributed to increased SOC and TN in the 5 yr and Dynamic rotations. Sequencing corn after dry pea (as done in the 5 yr rotation) has been found to increase corn residue production by 33 to 55% compared to corn after corn [45], thereby providing increased aboveground biomass in the former, which serves as an important precursor to SOC accrual [41]. Sherrod et al. [46, 47] observed greater SOC and POM-C under continuous corn compared to wheat-corn-fallow and wheat-fallow in a long-term study in eastern Colorado. Conversely, sunflower, a crop well-known for high water use and limited residue production relative to other crops common to the northern Plains [44, 48], can severely restrict crop production in subsequent years when precipitation is below the long-term mean [49]. Given its inclusion in the 3 yr rotation coupled with the consistency of periodic drought in the region, constraints to spring wheat production would be expected during drought years following sunflower [50].

Comparison of soil C and N pools between grazed pasture and cropped treatments indirectly reflected effects of cropping system diversity relative to a “native” baseline. Previous comparisons of cropland and virgin grassland in southwest North Dakota documented differences in SOC ranging from 33 to 36% in the 0 to 15.2 cm depth [51, 52]. Accordingly, results from this study suggesting modern cropping systems utilizing diverse rotations under no-till management have narrowed the gap in near-surface SOC between cropland and un-tilled native grassland. This inference is predicated on the assumption that SOC in native grassland has not decreased, which recent assessments suggest is not the case [53]. This inference is further supported by a previous evaluation of soil conditions at the research site. Black and Tanaka [39] reported a SOC content of 21.4 $g\,C\,kg^{-1}$ at 0 to 7.6 cm and 20.5 $g\,C\,kg^{-1}$ at 7.6 to 15.2 cm in 1983 prior to the establishment of rotation treatments. When these values were weighted to a 0 to 10 cm depth and compared to SOC measured in this study, the 5 yr and Dynamic rotations were found to have increased by 2.6 and 0.6 $g\,C\,kg^{-1}$, respectively. Conversely, SOC in the SW-F and 3 yr rotations decreased by 4.6 and 2.0 $g\,C\,kg^{-1}$ compared to baseline measurements in 1983. Such findings suggest accrual of near-surface SOC in northern Plains no-till cropping systems requires not just continuous cropping, but a diverse mixture of crops sequenced in a manner to enhance biomass production over the long-term.

4. Conclusion

Increased crop diversity has been found to foster greater and more stable crop yields, improved nutrient- and water-use efficiencies, and increased profit compared to less diverse cropping systems [1, 45, 54]. Less attention, however, has been directed to understanding crop diversity effects on soil properties, particularly in the northern Great Plains of North America.

Under conditions of this study, decreased soil acidification in the Dynamic and SW-F rotations compared to the 3 yr rotation implied greater resistance to pH change in the former, though mechanisms for resistance likely differ between rotations. In SW-F, N fertilizer was applied biannually, thereby decreasing the rate of acidification from N loss compared to continuously cropped rotations where fertilizer N was applied annually. In contrast, crops in the Dynamic rotation were sequenced to optimize nutrient and precipitation use which, over the long-term, would serve to reduce N loss. A detailed characterization of N use efficiency among cropped treatments is needed to ascertain the suitability of this inferred mechanism in the Dynamic rotation.

Among continuously cropped treatments, soil organic matter attributes were generally the greatest in the 5 yr rotation, intermediate in the Dynamic rotation, and the least in the 3 yr rotation. Moreover, comparison of SOC values measured in this study to baseline values measured prior to the establishment of rotation treatments indicated only the 5 yr and Dynamic rotations increased SOC in the near-surface depth over time. These findings suggest rotating a diverse portfolio of annual crops under no-till management is necessary to maintain or accrue SOC in this region.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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