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Land management effects on wet aggregate stability and carbon content

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Abstract

Land management affects soil structure and many other soil properties and processes. Our objectives were to evaluate soil organic C (SOC), aggregate size distribution, aggregate-associated C, and soil structure as affected by long-term land management and slope. A chronosequence of 38 on-farm sites with low to high (5–18%) slopes was selected to evaluate 5–40 yr of management. The sites were classified as business as usual (BAU) cropland (BAU-Crop), BAU pasture (BAU-Past), newly established conservation reserve program (CRP) areas (CRP-New), and established CRP (CRP-Old). Soil samples were collected from the 0-to-5- and 5-to-15-cm depth increments and processed for soil property measurements including fractionation by wet sieving into five aggregate size classes (>2,000, 1,000–2,000, 500–1,000, 250–500, and 53–250 μm). Within the surface 5 cm, mean weight diameter (MWD) and geometric mean diameter (GMD) were used to characterize soil structural stability. The BAU-Past and CRP-Old sites had 79% more macroaggregates (>2,000, 1,000–2,000, and 500–1,000 μm), 123% higher MWD, 38% higher GMD, and 47% higher SOC than BAU-Crop or CRP-New sites. The 5-to-15-cm depth increment showed a similar but lower magnitude response. Aggregate-associated C was quantified using a constant soil mass that reflected aggregate size distribution to prevent overestimating C content. Lower-slope locations had more SOC, more macroaggregates, more C associated with macroaggregates, and higher GMD and MWD compared with high-slope locations across all management classifications and soil depths. The results support our hypothesis that the high-slop soils may benefits from specific management decisions than the lower-sloping soils as a function of landscape property. We recommend reestablishing grassland on sloping land that is susceptible to excessive soil erosion, although those practices will likely take a long time to restore soil structural stability and SOC content to precultivation levels.

Abbreviation: BAU-Crop, business as usual cropland; BAU-Past, business as usual pasture; CRP, Conservation Reserve Program; CRP-New, newly established Conservation Reserve Program sites; CRP-Old, established Conservation Reserve Program sites; GMD, geometric mean diameter; MWD, mean weight diameter; SOC, soil organic carbon; SOM, soil organic matter; WSA, water stable aggregate.

1 | INTRODUCTION

Soil aggregation is an important indicator of soil structural stability (Kalhoro et al., 2017; Sekaran et al., 2021; Six et al., 2000; Tourn et al., 2019) that influences soil health factors, including (a) soil organic C (SOC) conservation and nutrient dynamics (Rodríguez et al., 2021; Somasundaram et al., 2017; Weidhuner et al., 2021; S. Xu et al., 2021), (b) porosity and water retention (Regelink et al., 2015; Sekaran et al., 2021), (c) water infiltration and surface runoff, and (d) soil erosion (Anderson et al., 2019). Soil organic matter (SOM) is one of the major binding agent responsible for formation and stabilization of soil micro- (<250 µm) or macroaggregates (>250 µm) (Jastrow & Miller, 1998; Six et al., 1999; Tisdall & Oades, 1982).

Microaggregates exhibit chemical bonding mechanisms that can withstand slaking and mechanical stress, enabling microaggregates to persist in soil for a long time (Totsche et al., 2018). They are the building blocks for macroaggregates (Totsche et al., 2018), being physically bound by SOM, plant root exudates, fungal hyphae (Angers, 1998; Jastrow et al., 1998; Miller & Jastrow, 1990), and microbial byproducts (Rillig et al., 2006). Soil aggregates thus protect SOM from microbial decomposition and enhance its storage because of both chemical binding and physical isolation (Golchin et al., 1994; Hernández et al., 2019; Sekaran et al., 2021; Tisdall & Oades, 1982). Microaggregates are continuously formed within macroaggregates, further contributing to aggregate size and SOC stabilization (Six et al., 2000, 2002).

The stability of soil aggregates reflects their ability to resist disintegration and withstand disruptive forces such as wet–dry cycles (J. Xu et al., 2017), freeze–thaw successions (Chen et al., 2019), and precipitation events (Fernández-Raga et al., 2017). Anthropogenic disruptions, such as frequent tillage, break soil macroaggregates into microaggregates and thus enhance SOM decomposition (Mikha & Rice, 2004; Mikha et al., 2015; Six et al., 1999).

Aggregate stability has been used as an indicator of soil structural stability (Six et al., 2000), erodibility, and overall soil health (Fernandez-Raga et al., 2017; J. Liu et al., 2021). Disintegration of soil aggregates, specifically macroaggregates, into microaggregates and fine particles causes a decrease in soil pore continuity (Tisdall & Oades, 1982) that reduces water infiltration and increases surface runoff and erosion (Anderson et al., 2019; Fernández-Raga et al., 2017). Soil macroaggregation is also crucial for root penetration, water retention and transport, gas exchange, and erosion resistance (Jastrow & Miller, 1998; Tisdall & Oades, 1982). Soil quality and health is improved by higher macroaggregate quantities relative to microaggregate quantities (Jastrow & Miller, 1998; Tisdall & Oades, 1982). Therefore, assessing soil aggregate stability can be an effective way to improve our knowledge of soil structural stability, water and nutrient transport, and soil erosion potential (Anderson et al., 2019; Fernández-Raga et al., 2017; J. Liu et al., 2021; M. Liu et al., 2019).

Core Ideas

- Land management significantly affected soil structural stability and C dynamics.
- Cropland was characterized more by microaggregates than macroaggregates.
- Higher slopes had lower soil structural stability and soil organic C (SOC) than lower slopes.
- SOC should be measured using a constant mass representing aggregate size distribution.
- Restoring soil stability to the prairie level will take 10–40 yr or more.

Soil aggregate stability can be evaluated by measuring the mean weight diameter (MWD) and the geometric mean diameter (GMD) of the soil (Kemper & Rosenau, 1986). The GMD describes the log-normal, rather than normal, of soil aggregate size distribution (Gardner, 1956). The GMD could be more accurate than normal aggregates distribution associated with the MWD approach (Kemper & Rosenau, 1986). The MWD and GMD are evaluated by measuring the quantity of various size of aggregates (Gelaw et al., 2015; Kalhoro, et al., 2017; Kemper & Rosenau, 1986). High MWD and GMD values represent improvement in soil macroaggregate stability (Kalhoro, et al., 2017; J. Liu et al., 2021), and they can be influenced by land management decisions (Anderson et al., 2019; Kalhoro et al., 2017; Six et al., 2002, 2004). Nevertheless, the MWD and GMD are not well documented in high-risk soils under different management practices.

Land management practices can alter soil structural stability and nutrient dynamics by influencing SOC, aggregate size distribution, and stability (Anderson et al., 2019; Guillaume et al., 2021; Singh, et al., 2020; S. Xu et al., 2021). Cropland management often includes tillage, which breaks down aggregates (Mikha et al., 2015; Six et al., 2000), reduces C protection within them, and thus promotes SOC loss (Blanco-Moure et al., 2012; Mikha et al., 2015; Sekaran et al., 2021; Six et al., 2000, 2002; Weidhuner et al., 2021). Tillage also negatively influences fungal hyphae (Jastrow et al., 1998) and decreases plant biomass inputs to the SOC pool through more rapid carbon mineralization (Rosenzweig et al., 2016). Conservation or no-tillage practices have been shown to increase aggregate stability, enhance SOC conservation, and increase SOC protection within aggregates (Conrad et al., 2018; Jin et al., 2021; Totsche et al., 2018).

No-tillage generally increases residue accumulation and slows decomposition, reduces direct rain impact on the soil surface, and thus decreases erosion (Fernández-Raga et al., 2017; Seitz et al., 2019; Sekaran et al., 2021; Somasundaram et al., 2017).

Prairie that has not been disturbed (i.e., tilled) tends to have higher SOM content, greater aggregate stability, increased root density, and more microbial diversity than cropland systems (Jastrow, 1996; Gelaw et al., 2015; Guillaume et al., 2021; Tourn et al., 2019). In pastures, high root–macroaggregate amounts are generally associated with fine roots absent within other management systems (Rodríguez et al., 2021). Labile C release by root exudates and microbial metabolic by-products also enhance aggregate stability (Kumar et al., 2017; Wang et al., 2017).

The U.S. Conservation Research Program (CRP) was initiated in 1985 by the Food Security Act to address soil erosion and land degradation (Lindstrom et al., 1994). Previous research has documented SOC increases by CRP (Knops & Tilman, 2000; De et al., 2020; Guillaume et al., 2021) and enhanced labile C as measured by microbial biomass C and potential mineralizable C (De et al., 2020; Rosenzweig et al., 2016; Scott et al., 2017). Several studies have documented nearly twice as much potential mineralizable C and 50% more microbial biomass C in CRP sites than in adjacent cropland (Baer et al., 2010; Karlen et al., 1999). The CRP land also exhibits higher root biomass, which improves several soil physical properties including lower soil bulk density and penetration resistance, and higher aggregate stability (Anderson et al., 2019; Culman et al., 2010; Idowu & Kircher, 2016; Kalhoro et al., 2017). Root exudates in grasslands increase aggregate stability against water disruptions (Czarnes et al., 2000).

Field slope is a factor that makes it difficult to assess management effects on soil properties (De et al., 2020; Quigley et al., 2018). Therefore, to accurately evaluate effects of new grassland (CRP) establishment on historical cropland, slope must be considered. We conducted an extensive literature investigation regarding land use and soil structure stability but found that interactions between slope and management history were generally not available. Our specific objectives were to quantify SOC quantities, aggregate size distribution, aggregate-associated C, and soil structural stability as affected by historical land management located on sloped area. We hypothesized that the relative benefits for those high-risk soils are expected to be greater than for the lower-sloping soils as a function of landscape property. Therefore, land management decisions and duration may significantly influence all four indicators. Recognizing that long periods of time are required for newly establish CRP will change these soil properties, we used a chronosequence of on-farm sites to evaluate the various land management practices.

2 | MATERIALS AND METHODS

2.1 | Sites description and sites management histories

The study sites were located ~80.5 km east (41.67˚ N, 93.02˚ W) and 80.5 km west (41.30˚ N, 94.46˚ W) of Des Moines, IA, at elevations of approximately 290 and 420 m asl, respectively. The areas have humid continental climates with mean annual temperatures of 10.0 and 11.2 ˚C and mean annual precipitation of 828 and 1,052 mm, respectively (Figure 1). Slope, soil series, and management histories for the 38 on-farm sites are briefly described in Table 1.

Based on management history, study sites were classified into four experimental treatments: business as usual cropland (BAU-Crop), business as usual pasture (BAU-Past), newly planted conservation reserve program land (CRP-New), and established CRP (CRP-Old). In 2018, soil samples were collected from the backslope positions at high-slope (13–25%) and along the summit at low-slope (7–13%) locations at each site. Composite samples were taken to represent the 0-to-5- and 5-to-15-cm depth increments. During field sampling, the composited soil samples were placed in sterile polypropylene bags, kept in coolers at 4 ˚C until processing. Field-moist soil samples were hand sieved through an 8-mm screen to remove stones and coarse organic matter, homogenize the samples, and define the initial soil aggregate dimensions. Sieved soil samples were air dried prior to determining aggregate size distribution and aggregate-associated C concentration.

2.2 | Aggregate size distributions

Water stable aggregate (WSA) size distribution was quantified using the modified apparatus reported by Mikha et al. (2005). Air-dried, sieved soil samples from each site were passed through nested sieves (12.7-cm diam.) to collect macroaggregate (>2,000, 1,000–2,000, 500–1,000, 250–500 µm) and microaggregate (53–250 µm) size classes. The aggregate fractions were normalized to a sand-free basis using 5 g L^{-1} sodium hexametaphosphate as reported in Mikha and Rice (2004).

The sand-free WSA data were used to compute MWD and GMD in millimeters as reported by Kemper and Rosenau (1986) and shown below:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i w_i \tag{1}$$

$$\mathrm{GMD} = \exp\left[\frac{\sum_{i=1}^{n} w_i \log\left(x_i\right)}{\sum_{i=1}^{n} w_i}\right] \tag{2}$$

TABLE 1 Land management practices (business as usual–cropland [BAU-Crop], business as usual-pasture [BAU-Past], Conservation Reserve Program–new [CRP-New], and Conservation Reserve Program–old [CRP-Old]), land topography (high and low slopes), and management history description

Management	Slope High	Slope Low	Series	Texture	Management history description
	%	%			
BAU-Crop	9–14	5–9	Lagoda	SiL[a]	No-till C-SB[b] rotation >10 yr (cereal rye cover crop since 2012)
	9–14	5–9	Sharpsburg	SiCL	Disk-till C-SB rotation >5 yr
	14–18	5–9	Shelby-Adair/Marshall	CL/SiCL	No-till C-SB rotation since 2012 (previous 40 yr in pasture).
	9–14	5–9	Sharpsburg	SiCL	No-till C-SB rotation >10 yr
	9–14	5–9	Sharpsburg	SiCL	No-till C-SB rotation >5 yr
	9–14	2–5	Downs/Tama	SiL/SiCL	Disk-till C-SB rotation >10 yr
	9–14	5–9	Tama	SiCL	C-C-SB rotation >10 yr; deep rip in corn phases only, no-till in soybean
	14–18	5–9	Gara/Sharpsburg	L/SiCL	No-till C-SB rotation >10 yr
	9–14	5–9	Fayette	SiL	No-till C-SB rotation >10 yr
	9–14	2–5	Shelby-Adair/Judson	CL/SiCL	No-till C-SB rotation >30 yr
	9–14	5–9	Tama	SiCL	No-till C-SB rotation >5-yr
BAU-Past	9–14	5–9	Lagoda	SiL	Historically grazed/hayed; <3 yr
	14–18	2–7	Gara/Olmitz-Colo	L/L-SiCL	Historically grazed; no grazing <5 yr
	9–14	5–9	Sharpsburg	SiCL	Historically grazed; active grazing apparent
	9–14	5–9	Downs	SiL	Planted to native prairie grass mixture >8 yr; burned every 2–3 yr (burned in spring 2018 prior to sampling)
	14–18	5–9	Gara/Sharpsburg	L/SiCL	Historically grazed (>50 yr)
	9–14	5–9	Tama	SiCL	Planted to Wildflower CRP in 2015; no-till corn/soybean for 4–5 yr prior; pasture for >10 yr
	9–14	5–9	Tama	SiCL	Historically grazed; no recent grazing
	14–18	9–14	Shelby/Sharpsburg	CL/SiCL	Historically grazed/hayed
	18–25	2–7	Gara/Olmitz-Colo	L/ SiCL	Historically grazed/hayed

(Continues)

TABLE 1 (Continued)

Management	Slope High	Slope Low	Series	Texture	Management history description
CRP-New	14-18	9–14	Gara/ Lagoda	L/SiL	Planted to CP-2[c] in fall 2016; previous no-till C-SB rotation >10 yr (cereal rye cover crop since 2012)
	9–14	5–9	Lagoda	SiL	Planted to CP-2 in fall 2016; previous no-till C-SB rotation >10 yr (cereal rye cover crop since 2012)
	9–14	5–9	Sharpsburg	SiCL	No-till C-SB rotation >5 yr
	9–14	2–5	Downs/Tama	SiL/SiCL	Planted to CP-38[d] in 2017; previous disk-till C-SB rotation >10 yr
	9–14	5–9	Tama	SiCL	Planted to CP-38 in 2018; previous no-till C-SB. rotation > 5-yr .
CRP-Old	9–14	5–9	Lagoda	SiL	Planted to CP-38 in 2018; previous 10 yr in CRP
	9–14	5–9	Sharpsburg	SiCL	Planted to CP-38 in 2018; previous >10 yr in CRP
	14–18	5–9	Shelby-Adair/Marshall	SiCL	Planted to CP-38 in 2018; previous 30 yr in CRP
	9–14	5–9	Sharpsburg	SiCL	Planted to CP-38 in 2018; previous 30 yr in CRP
	9–14	5–9	Sharpsburg	SiCL	Planted to CP-38 in 2018; previous 40 yr in CRP
	9–14	5–9	Tama	SiCL	Planted to CP-38 in 2018; previous 30 yr in CRP
	14–18	5–9	Shelby-Adair/Sharpsburg	CL/SiCL	Planted to CP-38 in 2018; previous 20 yr in CRP
	9–14	5–9	Fayette	SiL	Planted to CP-38 in 2018; previous 40 yr in CRP
	9–14	5–9	Tama	SiCL	Burned prior to CP-38 planting in 2018; previous 20 yr in CRP
	9–14	5–9	Tama	SiCL	Burned prior to CP-38 planting in 2018; previous 20 yr in CRP
	9–14	2–5	Shelby-Adair/Judson	CL/SiCL	Burned prior to CP-38 planting in 2018; previous >30 yr in CRP
	14–18	9–14	Shelby/Sharpsburg	CL/SiCL	Planted to CP-38 in 2018; previous 20 yr in CRP
	18–25	14–18	Gara	L	Planted to CP-38 in 2018; previous 30 yr in CRP

Note. The soil series were taken from the Natural Resources Conservation Service (NRCS) map. The soil texture was evaluated by the North Central Soil Conservation Research Laboratory, Morris, MN.

[a]Si, silt; L, loam; C, clay.

[b]C-SB represents corn–soybean rotation.

[c]CP-2 is a mixture of native grass, shrub, and forbs species of the study region.

[d]CP-38 refers to the Gaining Ground for Wildlife initiative makes available new CRP practices. It is designed to restore native grasslands and wetlands where they will be the most beneficial for grassland songbirds where their preferred habitats have been eliminated. Theses grassland will help sustain bird populations (https://www.iowadnr.gov/portals/idnr/uploads/Wildlife%20Stewardship/gaining_ground_wildlife.pdf).

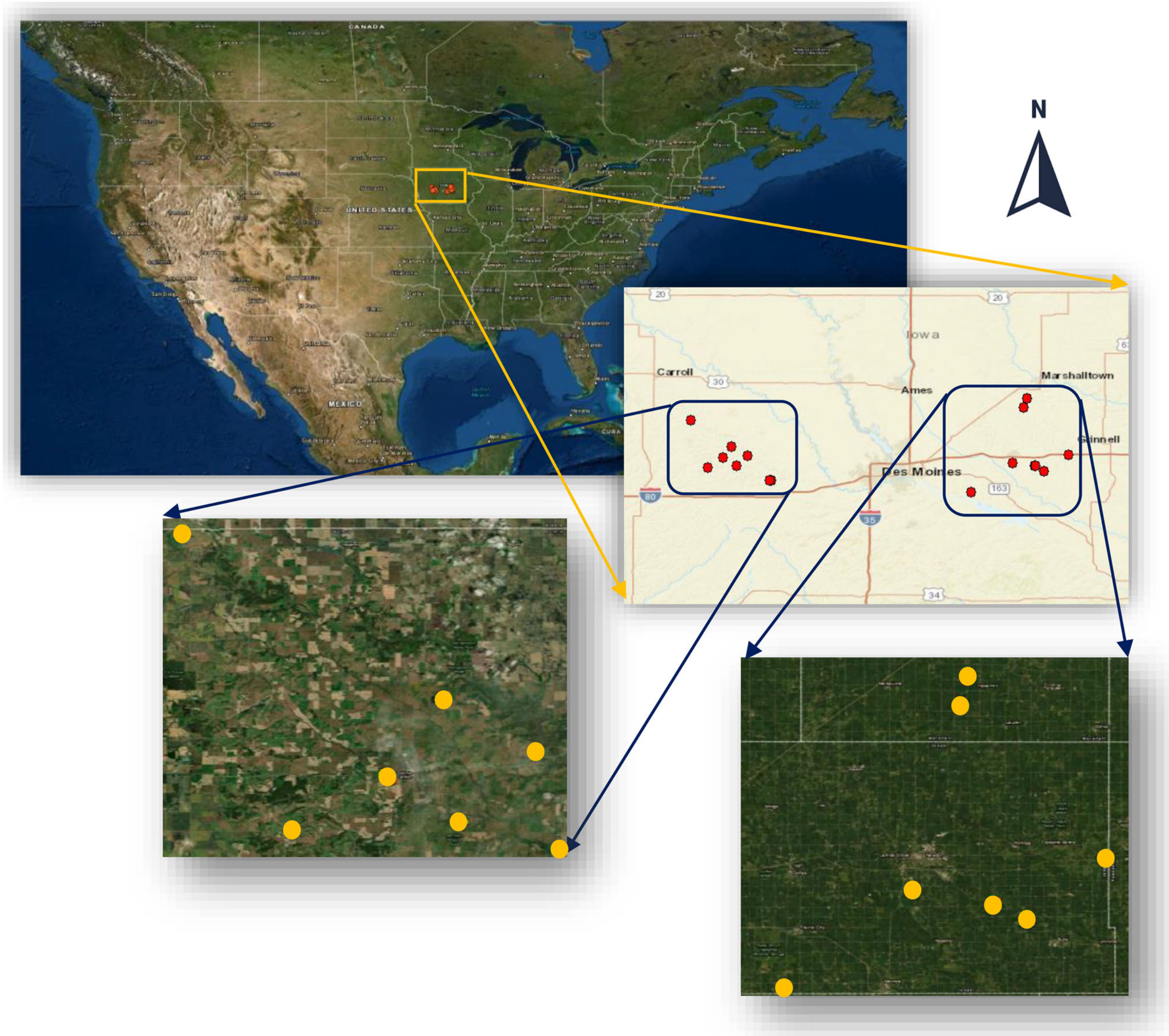

FIGURE 1 Maps illustrate the sampling locations near Des Moines, IA, USA. Map was produced by Tim Kettler at USDA-ARS, Lincoln, NE, USA. The red dots represent the sampling locations on the road map picture, and the orange dots represent the same sampling location on the setline image

where n represents the number of aggregate size fractions, x_i represents the mean diameter of the ith size fraction measured in millimeters, and w_i represents the proportion of the total sample weight associated with the ith size fraction. The GMD describes the soil aggregate size distribution as log-normal rather than normal (Gardner, 1956) and may be accurate compared with the normal distribution associated with the MWD calculation Kemper and Rosenau (1986). Overall, MWD and GMD represent the sum of all products that carried over n size fractions including the microaggregate (53–250 μm) size class Kemper and Rosenau (1986).

2.3 | Total SOC, N, and aggregate-associated organic C

Soil organic C and total N were measured by direct combustion (950 ˚C) using a LECO CHN-2000 (LECO Corporation) with ∼0.2 g air-dried soil that was ground to a fine powder using a roller mill. Soil pH at the 0-to-15-cm depth ranged between 5.0 and 7.7, and generally there were no carbonates in the samples (data not shown). However, before measuring SOC in samples with pH of 7.0 or greater, a 6% (60 ml L^{-1}) sulfuric acid solution was added to a finely ground, air-dried soil subsample (approximately 0.1–1.0 g) to

TABLE 2 Soil organic C (SOC) as influenced by land management practices (business as usual–cropland [BAU-Crop], business as usual-pasture [BAU-Past], Conservation Reserve Program–new [CRP-New], and Conservation Reserve Program–old [CRP-Old]) and land topography (high and low slopes) at 0-to-5- and 5-to-15-cm depths

Source of variation	0-to-5-cm depth High slope	0-to-5-cm depth Low slope	5-to-15-cm depth High slope	5-to-15-cm depth Low slope
	SOC (g C kg^{-1} soil)			
Management × slope				
BAU-Crop	21.41	22.26	14.42	15.80
BAU-Past	30.17	34.23	17.99	18.90
CRP-New	20.96	22.60	14.60	15.76
CRP-Old	32.43	31.52	17.58	18.71
Pr > *F*	.1203		.9902	
Management				
BAU-Crop	21.84b[a]		15.11	
BAU-Past	32.20a		18.44	
CRP-New	21.78b		15.18	
CRP-Old	31.98a		18.14	
Pr > *F*	<.0001		.1684	
Slope	26.24	27.66	16.15b	17.29a
Pr > *F*	.0834		.0445	

[a]Means with different lowercase letters represent significant differences among the land managements and slope within each depth)0–5 and 5–15 cm) for SOC or total N (ANOVA); $P < .05$ based on Tukey–Kramer adjusted *P* values.

remove the carbonates as outlined by Skjemstad and Baldock (2007). Aggregate-associated C concentrations are presented as grams of C per kilogram of sand-free WSAs.

2.4 | Statistical analyses

The experiment was analyzed using a completely randomized, split-plot design with three factors: management (BAU-Crop, BAU-Pasture, CRP-new, and CRP-old), slope (high and low), and depth (0–5 and 5–15 cm). Each management combination had a different numbers of replicates (sites), so the statistical analysis was considered to be an unbalanced design. The statistical analysis was repeated for each depth increment with no comparisons between depths because of uneven sampling increments.

A two-way ANOVA was conducted using SAS 9.4 (SAS Institute) using the generalized linear mixed models (Proc GLIMMIX). Management and slope were defined as fixed factors and replicates as being a random factor. Management x aggregate-associated C, evaluated as grams of C per kilogram of aggregates and grams of C per kilogram of soil, were analyzed using the two-way ANOVA. A three-way interaction (management × aggregates × slope) was also evaluated using the ANOVA. A post-hoc least squares mean analysis was conducted using Fisher's LSD at $P < .05$. Multiple comparisons between treatments were evaluated using Tukey-Kramer adjusted *P* values ($P < .05$) to be conservative on significance. The univariate procedure was used to confirm normality, and the means procedure was used for evaluating equal variance. Linear regression and correlation analyses between percentage sand-free WSAs, MWD, and GMD were also conducted for the two depth increments at each site.

3 | RESULTS AND DISCUSSIONS

3.1 | SOC

Soil organic C showed no significant interactions between land management and slope at either depth (Table 2). Land management affected SOC ($P < .0001$) at the 0-to-5-cm depth. The BAU-Past and CRP-Old had significantly higher SOC (~47% or 10.3 g C kg^{-1} soil) compared with BAU-Crop or CRP-New. Land management had no significant effect on SOC within the 5-to-15-cm depth increment ($P = .1684$), with BAU-Past and CRP-Old having numerically higher SOC content (~21% or 3.2 g C kg^{-1} soil) compared with BAU-Crop and CRP-New sites. Eliminating or minimizing land disturbance (i.e., tillage) and continuous perennial plant cover used with BAU-Past or BAU-Old for at least 10–40 yr (Table 1) presumably contributed to higher SOC within the 0-to-5-cm depth increment. In other studies, eliminating and/or minimizing soil disturbance in pasture or CRP sites enhanced root density (Ampleman et al., 2014), increased plant biomass and root exudate accumulations (García-Orenes et al., 2010;

Poeplau & Don, 2015; Soussana et al., 2010), increased root C and SOC stocks (Poeplau & Don, 2015), and decreased SOC turnover and loss (Baer et al., 2010; Karlen et al., 1999; Poeplau & Don, 2015; Soussana et al., 2010). Those factors contribute to greater surface layer SOC (Guillaume et al., 2021; Stumpf et al., 2018) compared with deeper soil layers, as was observed in this study.

The lower SOC concentration associated with BAU-Crop observed in this study was consistent with previous research documenting a depletion in SOC due to cultivation (Guillaume et al., 2021; Stumpf et al., 2018). Cropping often reduces SOC due to the short growing season and tillage frequency and intensity that enhances crop residue decomposition compared with grassland. Inclusion of fallow periods within the cropping system or excessive crop residue removal (Rosenzweig et al., 2016; Schmer et al., 2014) can also increase SOC loss. No SOC differences were observed between BAU-Crop and CRP-New because the CRP-New lands had been converted to CRP between 2016 and 2018 (i.e., shortly before sampling in 2018). Therefore, soil health benefits of changing from cropland to CRP were neither expected nor evident during this timeframe, as it may take several years before significant changes can be detected. These observations agree with previous research conducted at 19 sites within north-central Iowa and southern Minnesota which showed a mean annual SOC increase equivalent to 0.18 g SOC kg^{-1} soil with land management change (De et al., 2020). They also reported that the conversion period, from cropland to CRP land, may take more than 50 yr before the cropland attains the SOC level of pasture (De et al., 2020).

Although slope had only a marginal effect on SOC at the 0-to-5-cm depth ($P < .0834$), it influenced SOC ($P = .0445$) within the 5-to-15-cm depth (Table 2). The SOC values tended to be higher at lower slope compared to steeper slopes locations, likely due to downslope transport of SOM and nutrients via surface and subsurface water movement, especially in cropland fields (Olson et al., 2016a, 2016b; Tang et al., 2010). Pasture and grassland sites tended to have higher SOC at low slope locations, which agrees with previous grassland research in Saskatchewan, Canada (Mensah et al., 2003). They reported an increase in SOC of 88 to 169% in low-slope vs. high-slope locations, attributing the differences to enhanced soil moisture, greater plant biomass production, and decreased plant residue decomposition.

There were no statistical comparisons between depth increments because of the different sizes of the depth intervals, although the 0-to-5-cm depth tended to have higher SOC (41–84.5%) values than the 5-to-15-cm depth (Table 2). A dilution effect of the greater soil volume and residue stratification associated with pasture, CRP, and no-tillage practices likely contributed to the differences. These data agree with previous research showing a SOC reduction with depth (Amanuel et al., 2018; Gelaw et al., 2015), which was attributed to reduced residue input below the surface 5-cm depth.

3.2 | Aggregate size distribution

Land management, slope, and their interaction influenced aggregate size distribution at both depths (Figure 2, Table 3). Averaged across slope for the 0-to-5-cm depth, the quantity of macroaggregates (>2,000, 1,000–2,000, and 500–1,000 μm) associated with BAU-Past and CRP-old was significantly greater ($P < .0001$) than the quantities of either 250-to-500-μm macroaggregates or 53-to-250-μm microaggregates (Figure 2A). Macroaggregates >2,000 μm associated with CRP-Old (417 g kg^{-1} soil) were 92% greater in quantity among all management treatments than the 1,000-to-2,000-μm size (217 g kg^{-1} soil), and 263% greater than the 500-to-1,000-μm group (115 vs. 417 g kg^{-1} soil). Macroaggregates that were 250–500 μm in size (72.5 g kg^{-1} soil) and microaggregates (53–250 μm or 58 g kg^{-1} soil) were the lowest in quantity within CRP-Old sites (Figure 2A). Macroaggregates ranging from 1,000 to 2,000 μm in BAU-Past sites were 8% greater in quantity (260 g kg^{-1} soil) than those >2,000 μm (239 g kg^{-1} soil), and 24% greater than those in the 500-to-1,000-μm group (209 g kg^{-1} soil). Macroaggregates ranging from 250 to 500 μm (97 g kg^{-1} soil) and microaggregates from 53 to 250 μm (82 g kg^{-1} soil) were lowest with BAU-Past management (Figure 2A). Higher amounts of macroaggregates associated with BAU-Past and CRP-old presumably reflected the long period of undisturbed soils planted with perennial grasses (i.e., 10–40 yr for CRP-old). Eliminating soil disturbance enhanced SOM and likely increased microbial activity (Archer et. al., 2015; Cambardella & Elliott, 1993; Jastrow, 1996; Jastrow et al., 1998), factors that maintain soil macroaggregate integrity and stability (Jastrow et al., 1998; Six et al., 1999, 2000). The extensive root systems that grasslands develop promote formation and stabilization of macroaggregates (Celik, 2005; Oades & Waters, 1991; Six et al., 1999, 2000; Tisdall & Oades, 1982).

The smaller macroaggregates ranging from 250 to 500 μm and microaggregates (53–250 μm) at BAU-Crop and CRP-New sites accounted for the highest amount of aggregates among size classes (Figure 2A). The aggregate size distributions observed with BAU-Crop and CRP-New were consistent with expectations for cropland agriculture management practices. Our results also agree with prior studies that reported reduced quantities of soil macroaggregates and increased amounts of microaggregates in cropland compared with pasture or CRP land (Anderson et al., 2019; Idowu & Kircher, 2016; Jastrow, 1996). Once again, macroaggregate reduction in cropland is highly influenced by anthropogenic

TABLE 3 Analysis of variance (ANOVA) of the effects of different management practices and land slope normalized on sand-free water stable aggregates averaged across management, slope, and their interaction with soil aggregates at 0-to-5- and 5-to-15-cm depth

Source of variation	Sand-free water stable aggregates									
	0-to-5-cm depth					5-to-15-cm depth				
	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm
	g aggregates kg^{-1} soil									
Aggregates (Agg)	226.06a	187.43b	154.75c	140.71d	148.13c	145.75cd	152.02c	164.89b	144.06d	179.38a
(Pr > *F*)			<.0001					<.0001		
Slope (S)										
High			166.14b					152.35b		
Low			176.69a					162.09a		
(Pr > *F*)			<.0001					<.0001		
S × Agg										
High	202.79b	164.28cd	137.30e	159.23d	167.11cd	124.90f	121.28f	120.18f	188.28b	207.08a
Low	249.33a	210.58b	172.20c	122.20f	129.15ef	179.13bc	170.21cd	167.93d	141.49e	151.67e
(Pr > *F*)			<.0001					<.0001		
Management (M)										
BAU-Crop[a]			160.16b[b]					152.28b		
BAU-Past			177.48a					156.08ab		
CRP-New			172.01a					159.36ab		
CRP-Old			176.02a					161.15a		
(Pr > *F*)			<.0001					.0048		
M × S (Pr > *F*)			.6542					.5729		
M × Agg[c] (Pr > *F*)			<.0001					<.0001		
M × S × Agg (Pr > *F*)			.0755					.938		

[a]Represents land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old).
[b]Means with different lowercase letters represent significant differences among the land managements, slope, and their interaction with aggregates within each depth (0–5 and 5–15 cm) (ANOVA); $P < .05$ based on Tukey–Kramer adjusted P values.
[c]Data presented in Figures 2A and 2B.

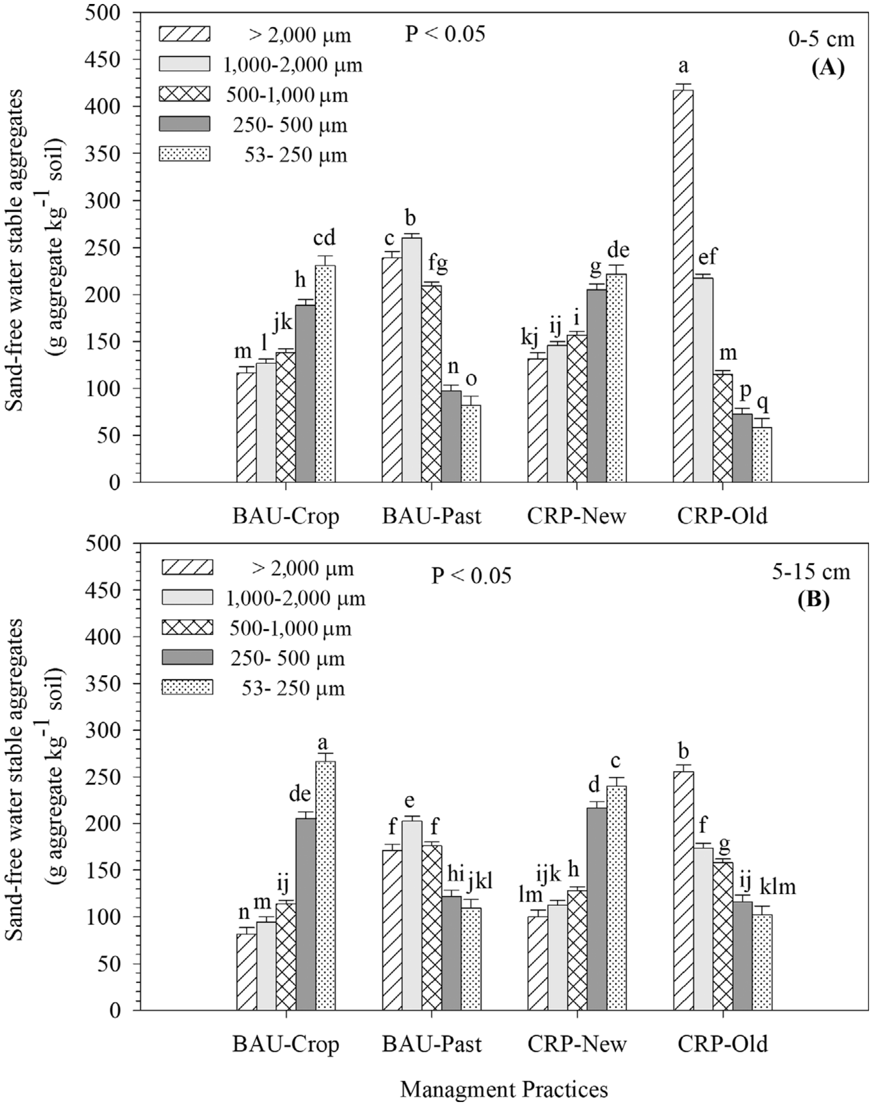

FIGURE 2 Sand-free water stable aggregates (g aggregates kg^{-1} soil) average across land slope at (A) 0-to-5-cm and (B) 5-to-15-cm depths as influenced by different land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old). Lowercase letters represent significant differences ($P \leq .05$) among management × aggregates interactions using Tukey–Kramer adjusted P values. The error bars represent standard errors of the mean

disturbance (i.e., tillage), which decreases aggregate stability and shifts size distribution towards smaller aggregate classes (Blanco-Canqui et al., 2009; Blanco-Moure et al., 2012). The CRP-New management exhibited similar aggregate mass distribution to BAU-Crop because the benefits of management changes from cropland to CRP land may take more than 1–2 yr to be detected.

Macroaggregates and microaggregates within the 5-to-15-cm depth increment had the same distribution pattern as in the surface 5 cm for all land management treatments (Figure 1B). There were no statistical comparisons between the depths studied because of the different sampling increments, 0-to-5- and 5-to-15-cm depth. Averaged across management, land slope significantly ($P < .0001$) influenced aggregate size distribution at both depths studied (Table 3). Macroaggregates (>2,000, 1,000–2,000, and 500–1,000 µm) associated with lower slopes were greater by about 26% for 0–5 cm and by 41% for 5–15 cm compared with the higher slopes at both depths studied. In contrast, macroaggregates (250–500 µm) and microaggregates (53–250 µm) were significantly greater with higher slopes by about 30% for 0–5 cm and by 35% for 5–15 cm compared with the lower slope locations. Greater macroaggregates associated with low slopes were related to the trend of higher SOC that we observed at both depths studied compared with higher slopes (Table 2). Our current data agree with previous research documenting that SOC contributed to the formation and stabilization of soil macroaggregates, whereas microaggregates stabilized by persistent binding agents that are not sensitive to SOC content (Jastrow, 1996; Oades & Waters, 1991; Six et al., 1999, 2000, 2002; Tisdall & Oades, 1982). Data generated from this study supported our hypothesis that land management decisions can substantially influence soil structure stability and long-term CRP (CRP-Old) could enhance macroaggregates formation and stabilization to the degree of long-term pastures (BAU-Past).

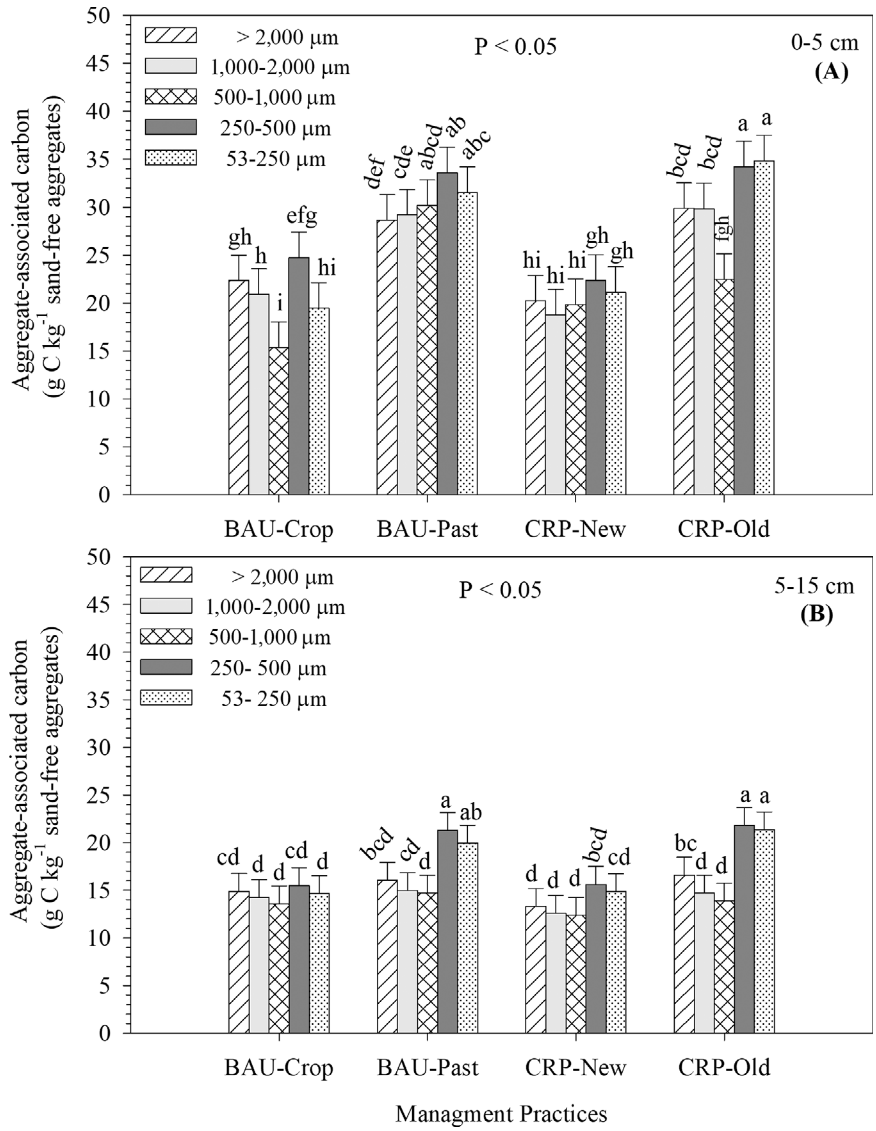

FIGURE 3 Aggregate-associated C concentration (g C kg^{-1} sand-free aggregate) average across land slope at (A) 0-to-5-cm and (B) 5-to-15-cm depths as influenced by different land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old). Lowercase letters represent significant differences ($P \leq .05$) among management × aggregates interactions using Tukey–Kramer adjusted P values. The error bars represent standard errors of the mean

3.3 | Aggregate-associated C

Aggregate-associated C (g aggregate-associated C kg^{-1} aggregates) was significantly influenced by management ($P < .0001$), slope ($P < .0024$), aggregate size ($P < .0001$), and two-way interactions ($P < .0001$) for management × aggregates within the 0-to-5-cm depth (Figure 3A) and slope × aggregate size (Table 4). Aggregate-associated C was not influenced by management ($P < .1422$) within the 5-to-15-cm depth but was influenced by slope ($P < .0026$), aggregate size ($P < .0001$), and the two-way interactions ($P < .0001$) between management × aggregate size (Figure 3B) and slope × aggregate size (Table 4). Substantially greater amounts (by ~49%, ~10.5 g C kg^{-1} aggregates) of aggregate-associated C at 0-to-5-cm depth were within aggregates sized 250–500 µm and 53–250 µm in the high-slope fields compared with macroaggregates sized >2,000, 100–2,000, and 500–1000 µm). In contrast, a greater amount (by ~21%, ~5 g C kg^{-1} aggregates) of aggregate-associated C was within macroaggregate sized >2,000, 100–2,000, and 500–1,000 µm in low-slope fields compared with macroaggregates sized 250–500 µm and microaggregates sized 53–250 µm (Table 4). Similar pattern for aggregate-associated C was observed at 5-to-15-cm depth with different magnitude (Table 4). The aggregate-associated C dynamics associated with land slope well corresponded with aggregate size distribution influenced by slope (Table 3). The three-way interaction (management × aggregates × slope) within the 0-to-5-cm depth ($P = .496$) was not significant, but it was significant ($P < .0001$) at the 5-to-15-cm depth (Table 4).

Aggregate-associated C within the 0-to-5- and 5-to-15-cm depth increments was equally distributed among size classes at BAU-Crop and CRP-New sites (Figure 3). Continuous land disturbance with BAU-Crop and the short duration of CRP-New contributed to the differences in aggregate-associated C compared with BAU-Past and CRP-Old management. Soil

TABLE 4 Analysis of variance (ANOVA) of the effects of different management practices and land topography (slope) on aggregate-associated C (normalized to sand-free basis) averaged across management, slope, and their interaction with soil aggregates-associated C at 0-to-5- and 5-to-15-cm depth

	Aggregate-associated C									
	0-to-5-cm depth					5-to-15-cm depth				
Source of variation	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm
	g C kg $^{-1}$ aggregate									
Aggregates (Agg)	24.68c	25.27bc	28.73a	21.96d	26.73ab	15.22b	14.12bc	13.63c	18.56a	17.71a
(Pr > F)			<.0001					<.0001		
Slope (S)										
High			24.66b1					15.07b		
Low			26.29a					16.62a		
(Pr > F)			.0024					.0026		
S × Agg										
High	21.79ef	21.07f	16.57g	32.97a	30.89ab	12.57f	11.02fg	10.38g	21.24a	20.17ab
Low	28.75bc	28.28bc	27.36cd	24.49de	22.58ef	17.87bc	17.22cd	16.88cde	15.88de	15.26e
(Pr > F)			<.0001					<.0001		
Management (M)										
BAU-Crop[a]			20.56b[b]					14.57		
BAU-Past			30.63a					17.39		
CRP-New			20.46b					13.75		
CRP-Old			30.24a					17.67		
(Pr > F)			<.0001					.1422		
M × S (Pr > F)			.1023					.8057		
M × Agg[c] (Pr > F)			<.0001					<.0001		
M × S × Agg (Pr > F)			.496					<.0001		

[a]Represents land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old).
[b]Means with different lowercase letters represent significant differences among the land managements, slope, and their interaction with aggregates within each depth (0–5 and 5–15 cm) (ANOVA); $P < .05$ based on Tukey–Kramer adjusted P values.
[c]Data presented in Figures 3A and 3B.

disturbance is one of the main reasons for soil aggregates-associated C depletion due to disruption of soil macroaggregates and exposure of protected SOC to microbial decomposition (Sekaran et al., 2021; Six et al., 2000; Song et al., 2019; Tisdall, 1996; Weidhuner et al., 2021).

Evaluating aggregate-associated C in specific size classes, we found that macroaggregates (250–500 μm) and microaggregates (53–250 μm) contained 16% greater aggregate-associated C (4.7 g C kg^{-1} aggregates) for CRP-Old and 13% greater aggregate-associated C (3.6 g C kg^{-1} aggregates) for BAU-Past than macroaggregates (>2,000 μm and 1,000–2,000 μm) at 0-to-5-cm depth. Similarly, with macroaggregates sized 250–500 μm and microaggregates sized 53–250 μm, 38% (6.0 g C kg^{-1} aggregates) and 33% (5.1 g C kg^{-1} aggregates) greater aggregate-associated C was observed for CRP-Old and BAU-Past, respectively, than with macroaggregates sized >2,000 μm and 1,000–2,000 μm at 5-to-15-cm depth. S. Xu et al. (2021) similarly observed more microaggregate-associated C than macroaggregate-associated C from different pasture management practices. They hypothesized that this observation was related to microaggregate C protection due to reduced soil disturbance, conserved macroaggregate integrity, persistent binding agents associated with microaggregates, and small pore size distributions. All those factors help protect SOC from microbial decomposition and enhance SOC conservation (Conrad et al., 2018; Totsche et al., 2018).

Macroaggregates at low-slope locations contained more ($P < .0001$) aggregate-associated C than the same size aggregates at high-slope locations at both depths (0-to-5- and 5-to-15-cm depth, Table 4). The aggregate-associated C dynamics corresponded well with SOC content (Table 2) and aggregate size distribution (Table 3), and all were influenced by land slope. This type of aggregate-associated C calculation (g C kg^{-1} aggregates) may overestimate soil aggregate C content because it is based on a fixed aggregate mass that could have varied due to management practices.

Aggregate-associated C was also evaluated for the aggregate mass recovered from a constant soil mass (g aggregate-associated C kg^{-1} soil). This approach provides the actual representation of aggregate-associated C that exists within each aggregate mass associated with fixed soil mass (kg soil) influenced by management practices (Mikha et al., 2015; S. Xu et al., 2021). The ANOVA for land management, aggregate size, slope, and their interaction (three-way interaction: management × aggregate-associated C × slope) effects on aggregate-associated C calculated with this approach is presented in Table 5. The data generated using this approach (Figure 4) reflected aggregate size distribution (Figure 2) at both depths studied. The amounts of aggregate-associated C increased with increasing aggregate size classes (Figures 2 and 4). Variations in aggregate-associated C were related to the aggregate size distribution pattern (Mikha et al., 2015; S. Xu et al., 2021). High amounts ($P < .0001$) of macroaggregate-associated C were observed with BAU-Past and CRP-Old compared with microaggregate-associated C (Figure 4) at 0-to-5-cm depth. This observation reinforces the important role of macroaggregates formation and stabilization in conserving SOC in these management practices as previously reported by Chevallier et al. (2004), Conrad et al. (2018), and S. Xu et al. (2021). Macroaggregate-associated C (250–500 μm) and microaggregate-associated C (53–250 μm) contents with BAU-Crop and CRP-New were greater ($P < .0001$) than the macroaggregate-associate C (>2,000, 1,000–2,000, and 500–1,000 μm) at both depths (Figure 3). The reduction in the amount, stability, and life span of macroaggregates due to different practices causes macroaggregates to breakdown into microaggregates, reduces SOC protection within macroaggregates, and exposes SOC to microbial decomposition (Blanco-Moure et al., 2012; Mikha et al., 2015; Six et al., 1999, 2002; Totsche et al., 2018). Consequently, substantial amounts of microaggregate-associated C were observed with BAU-Crop and CRP-New management compared with BAU-Past and CRP-Old. The CRP-New had a similar pattern to BAU-Crop regarding microaggregate-associated C because the benefits of CRP management may take more than 1–2 yr to be detected. A greater amount of soil microaggregates and their associated C could be lost from these study sites (Blanco-Moure et al., 2012; Zhang et al., 2007), through wind, water erosion, or through tillage practices, especially in the area that exhibits land slope. Our data supported our hypothesis that CRP-Old will enhance aggregate-associated C to the degree of BAU-Past, whereas CRP-New will require longer than 1–2 yr to enhance aggregate-associated C to surpass the BAU-Crop management. In general, this type of aggregate-associated C calculation approach prevents overestimation of aggregate C content because it is based on fixed soil mass.

3.4 | MWD and GMD

The MWD and GMD were significantly influenced by land management and slope ($P < .0001$) at both depths. Both indicators were not significantly affected by the management × slope interaction in the surface soil layer of 5 cm; however, they were significantly affected at the 5-to-15-cm depth (Table 6). CRP-Old had the highest MWD and GMD values followed by BAU-Past for both depths. The MWD and GMD were lowest with CRP-New followed by BAU-Crop (Table 6). When averaged, CRP-Old and BAU-Past had 123% (1.1 mm) greater MWD and 38% (0.31 mm) greater GMD than CRP-New and BAU-Crop in the top 5 cm. Anderson et al. (2019) also reported a 68% increase in MWD associated with native prairie and grasslands compared with agriculture land, presumably due to the perennial root systems

TABLE 5 Analysis of variance (ANOVA) of the effects of different management practices and land topography (slope) on aggregate-associated C recovered from soil averaged across management, slope, and their interaction with soil aggregates-associated carbon at 0-to-5- and 5-to-15-cm depth

	Aggregate-associated C									
	0-to-5-cm depth					5-to-15-cm depth				
Source of variation	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm	>2,000 µm	1,000–2,000 µm	500–1,000 µm	250–500 µm	53–250 µm
	g C kg $^{-1}$ soil									
Aggregates (Agg)	6.22a	4.94b	3.62cd	3.79c	3.46d	2.47b	2.17c	2.06c	2.95a	2.99a
(Pr > *F*)			<.0001					<.0001		
Slope (S)										
High			4.07b					2.38b		
Low			4.74a					2.68a		
(Pr > *F*)			<.0001					<.0001		
S × Agg										
High	4.93c	3.70e	2.42f	4.85c	4.47d	1.36f	1.65e	3.77a	1.26f	3.83a
Low	7.51a	6.18b	4.81cd	2.73f	2.45f	2.99c	3.28b	2.12d	2.86c	2.15d
(Pr > *F*)			<.0001					<.0001		
Management (M)										
BAU-Crop[a]			3.36b[b]					2.27		
BAU-Past			5.37a					2.70		
CRP-New			3.62b					2.31		
CRP-Old			5.26a					2.83		
(Pr > *F*)			<.0001					<.0001		
M × S (Pr > *F*)			.0002					.089		
M × Agg[c] (Pr > *F*)			<.0001					<.0001		
M × S × Agg (Pr > *F*)			.9116					<.0001		

[a]Represents land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old).
[b]Means with different lowercase letters represent significant differences among the land managements, slope, and their interaction with aggregates within each depth (0–5 and 5–15 cm) (ANOVA); $P < .05$ based on Tukey–Kramer adjusted P values.
[c]Data presented in Figures 4A and 4B.

TABLE 6 Analysis of variance (ANOVA) of the effects of different management practices and land slope on soil aggregate stability evaluated as mean weight diameter (MWD) and geometric mean diameter (GMD) averaged across management, slope, and their interactions at 0-to-5- and 5-to-15-cm depth

	MWD				GMD			
	0-to-5-cm depth		5-to-15-cm depth		0-to-5-cm depth		5-to-15-cm depth	
Source of variation	**High slope**	**Low slope**	**High slope**	**Low slope**	**High slope**	**Low slope**	**High slope**	**Low slope**
	mm							
Management[a]								
BAU-Crop	0.87d[b]		0.67d		0.82c		0.78c	
BAU-Past	1.55b		1.18b		1.06b		0.98b	
CRP-New	0.97c		0.78c		0.83c		0.80c	
CRP-Old	2.12a		1.46a		1.22a		1.03a	
Pr > F	<.0001		<.0001		<.0001		<.0001	
Slope								
High (mean)	1.25b		0.87b		0.95b		0.85b	
Low (mean)	1.51a		1.17a		1.02a		0.94a	
Pr > F	<.0001		<.0001		<.0001		<.0001	
Management × slope								
BAU-Crop	0.73	1.00	0.53e	0.81d	0.79	0.86	0.74f	0.82e
BAU-Past	1.42	1.68	1.02c	1.34b	0.02	1.09	0.93d	1.02b
CRP-New	0.84	1.10	0.65e	0.92cd	0.80	0.87	0.76f	0.84e
CRP-Old	1.99	2.23	1.23b	1.63a	1.18	1.23	0.98c	1.09a
Pr > F	.9582		.0069		.6415		<.0001	

[a]Represents land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old).
[b]Means with different lowercase letters represent significant differences among the land managements, slope, and their interaction with aggregates at 0-to-5- and 5-to-15-cm depth (ANOVA); $P < .05$ based on Tukey–Kramer adjusted P values.

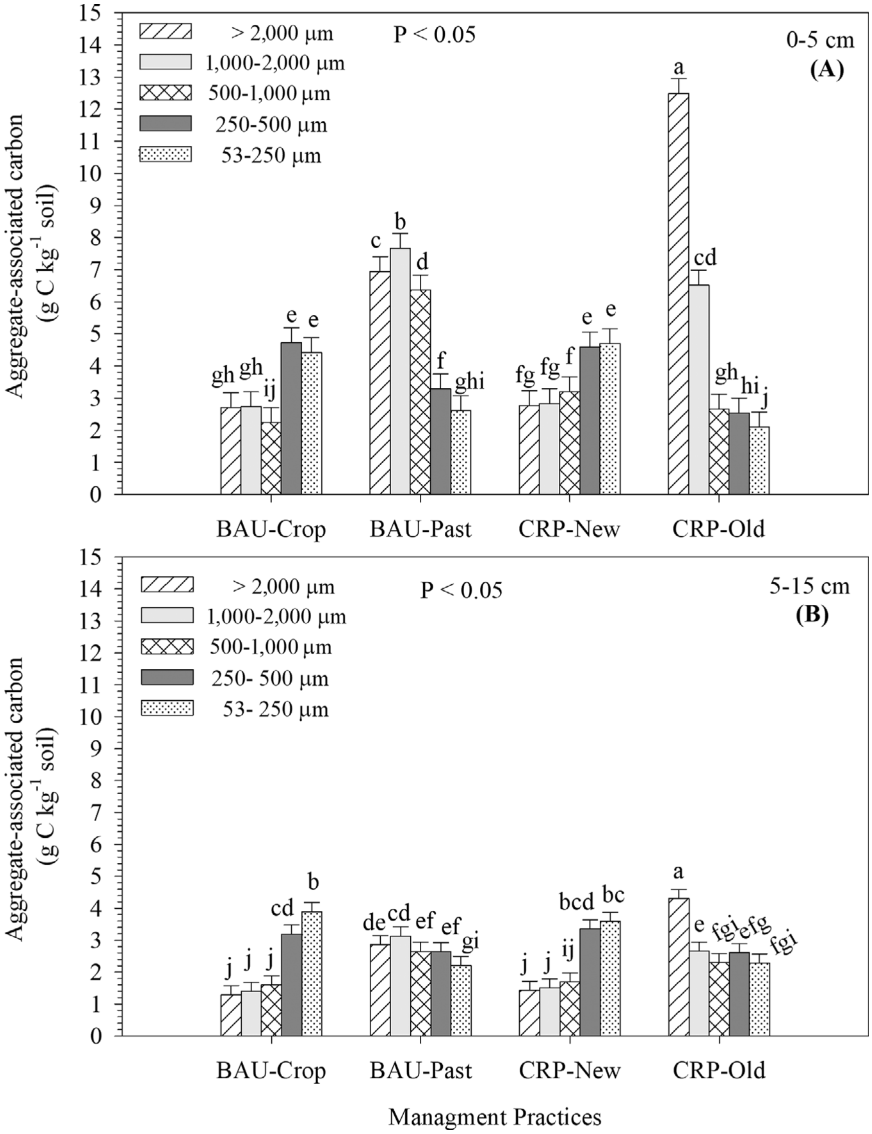

FIGURE 4 Aggregate-associated carbon recovered from kg soil (g C kg^{-1} soil) average across land slope at (A) 0-to-5-cm and (B) 5-to-15-cm depths as influenced by different land management practices: business as usual–cropland (BAU-Crop), business as usual–pasture (BAU-Past), Conservation Reserve Program–new (CRP-New), and Conservation Reserve Program–old (CRP-Old). Lowercase letters represent significant differences ($P \leq .05$) among management × aggregates interactions using Tukey–Kramer adjusted P values. The error bars represent standard errors of the mean

associated with grasslands (Anderson et al., 2019; Celik, 2005; Gelaw et al., 2015; Kalhoro, et al., 2017; Tisdall & Oades, 1982). Soil structure was stabilized with greater amount of macroaggregates (Figure 2) and higher amount of SOC (Table 1) associated with CRP-Old and BAU-Past compared with CRP-New and BAU-Crop managements (Kalhoro, et al., 2017; Sekaran et al., 2021). Aggregate stability, represented by MWD and GMD, were greater at lower-slope compared with higher-slope locations (Table 6). This observation was probably due to less erosion under lower slopes that enhanced SOC, soil aggregate formation, and aggregate stabilization. Soil structural stability was evaluated by MWD and showed significant differences between CRP-New and BAU-Crop at both depths studied. However, these differences were eliminated when aggregate stability was evaluated using the GMD (Table 6). The different outcome between the two managements (CRP-New and BAU-Crop) could be related to the different calculation approach, GMD as log-normal distribution and MWD as normal distribution (Gardner, 1956; Kemper & Rosenau, 1986). Previously, Kemper and Rosenau (1986) reported that the GMD could better describe aggregate size distribution than MWD approach. Soil structural stability may need to be evaluated using both indices (MWD and GMD), specifically when the calculation approach influenced the differences among land management. A positive linear relationship was observed between MWD and GMD withing the surface 5-cm (r^2 = .9886) and 5-to-15-cm (r^2 = .9657) depths (Figure 5). Management practice, slope, and depth did not affect relationships between MWD and GMD indices, indicating that either can be used to characterized soil structural stability as influenced by management practices.

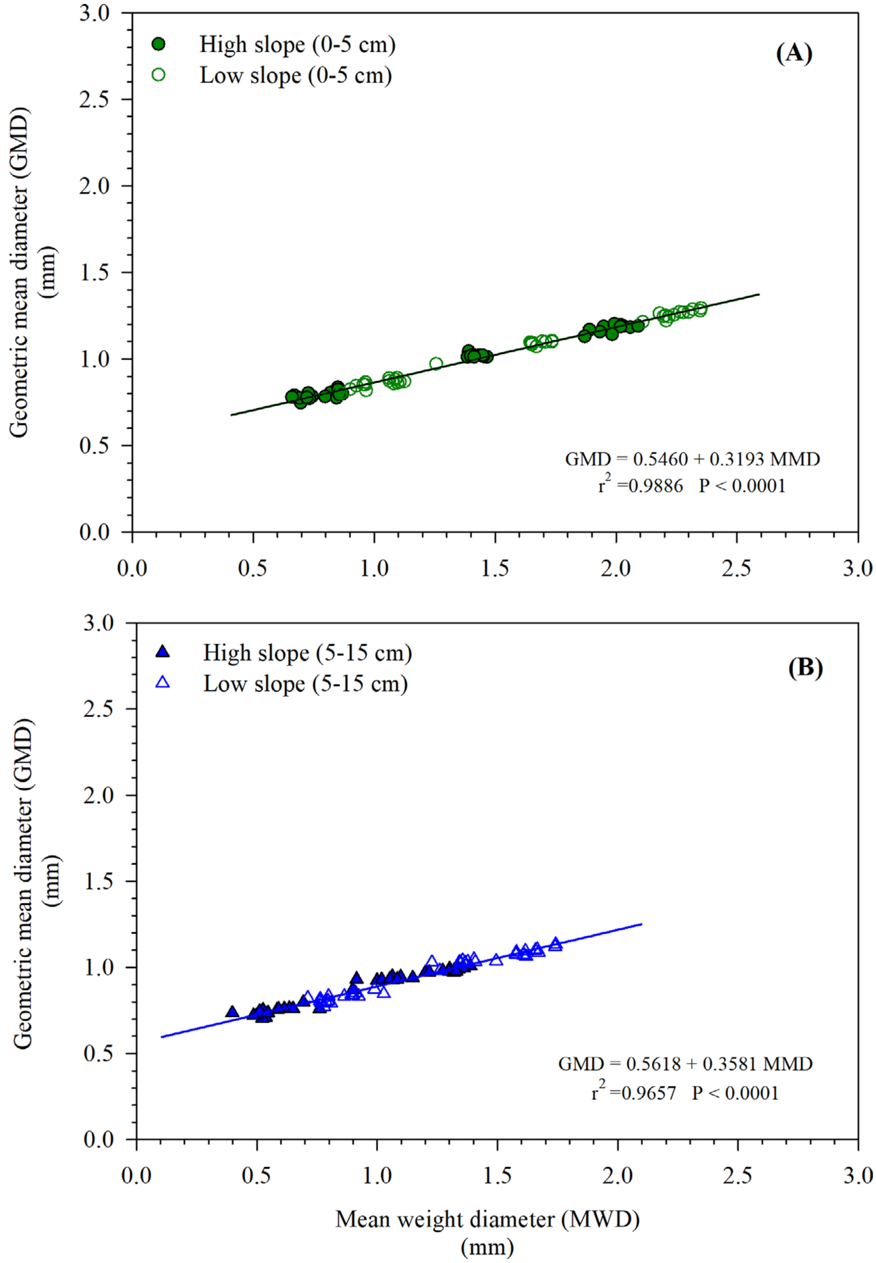

FIGURE 5 Relationship between mean weight diameter (MWD) and geometric mean diameter (GMD) across all sites with low slope as the open symbol and high slope as the solid symbol: (A) 0-to-5-cm depth interval, and (B) 5-to-15-cm depth interval

4 | CONCLUSIONS

Land management can significantly affect soil properties affecting soil structural stability as well as SOC conservation and dynamics. Eliminating soil disturbance greatly improved SOC, aggregate-associated C, macroaggregate size, and soil structural stability. This study documented increased macroaggregate size associated with BAU-Past and CRP-Old, which led to increased MWD and GMD values and greater SOC storage within soil aggregates. High microaggregate quantities associated with BAU-Crop and CRP-New led to poor soil structure, low MWD and GMD values, and minimum SOC storage within soil aggregates. SOC quantity, macroaggregate size, and structural stability were all greater at lower slope locations than at higher slope locations.

Aggregate-associated C based on a known mass of soil provided a better assessment of SOC content than simply estimating the effect of land management using measurements of grams C per kilogram. Overall, our data confirm that land management decisions can influence soil structural stability and SOC dynamics and that it may take 10–40 yr of CRP management to return SOC content and soil structure to precultivation prairie levels. We recommend that to conserve land resources, enhance soil stability, and potentially provide cellulosic feedstocks for bioenergy or other bioproducts, establishing grassland on sloping highly erosive areas is a good land management practice.

AUTHOR CONTRIBUTIONS

Maysoon M. Mikha: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing-original draft. Virginia L. Jin: Project administration; Writing-review & editing. Jane M.F. Johnson: Project administration; Writing-review & editing. R. Michael Lehman: Writing-review & editing. Douglas L. Karlen: Project administration; Writing-review & editing. Jalal D. Jabro: Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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