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Quantifying improvements in water-stable aggregation caused by corn stover retention

Abimbola Ojekanmi | **Jane M. F. Johnson**

USDA–ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Avenue, Morris, MN 56267, USA

Correspondence
Jane M.F. Johnson, USDA–ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Avenue, Morris, MN 56267, USA.
Email: jane.m.johnson@usda.gov

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Abstract

Corn (*Zea mays* L.) stover harvest must be balanced against protecting soil properties, including water-stable aggregates (WSA). The formation and maintenance of WSA functions of multiple factors including management. Harvesting stover alters the mass of the residue retained, which might alter a soil's ability to form and maintain WSA. A study was conducted on two independently replicated fields under chisel plow (CP) and no-till (NT) management, both in a corn–soybean [*Glycine max*. (L.) Merr.] rotation with four corn residue retention treatments (RRT): [harvesting only grain, grain plus cobs, grain plus about half the stover, and grain plus as much stover as possible (Grain + Aggressive)], returning about 8, 5, 4 and 2 Mg ha^{-1} yr^{-1} dry stover, respectively. Water-stable aggregates, their distribution, and mean weight diameter (MWD) were determined on a clay loam or loam Mollisol collected at 0 to 5 and 5 to 10 cm. Treatments, crop phase, soil depth, and their interactions were analyzed via a mixed linear model. Linear regression was used to assay the relationships between WSA and the average mass of residue returned. In both fields, Grain + Aggressive had the lowest WSA and MWD, and fewer ≥2-mm aggregates than other RRTs and, in the NT field, fewer in the 1- to 2-mm class size as well. Overall, WSA increased by 0.85 and 2.25% per Mg stover returned under CP and NT, respectively. Harvesting stover reduced the formation and/or the maintenance of WSA, thereby reducing their ability to resist the erosive force of water.

1 | INTRODUCTION

The material remaining after harvesting corn (*Zea mays* L.) grain is referred to as material other than grain (Isaac, Quick, Birrell, Edwards, & Coers, 2006), residue, or stover (Wilhelm et al., 2010). As a material containing high-cellulose and because of the large quantity of corn produced annually, stover has long been targeted as a cellulosic feedstock for ethanol production (Perlack et al., 2005; US Department of Energy, 2016). The need to balance harvesting residue for bioenergy with returning it to the land to maintain soil organic carbon, conserve soil quality, prevent erosion, and sustain crop productivity has also been addressed by multiple researchers (Ibrahim, Chua-Ona, Liebman, & Thompson, 2018; Lal & Pimentel, 2007; Wilhelm et al., 2010; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004). Retaining enough residue for erosion control may not provide adequate mass residue to sustain soil organic carbon (Wilhelm, Johnson, Karlen, & Lightle, 2007). It has been demonstrated that the mass of crop residue retained is associated positively with the quantity of soil organic carbon stored in the soil and the level of water-stable aggregates (WSA) (Blanco-Canqui

Abbreviations: CP, chisel plow; MWD, mean weight diameter; NT, no-till; RRT, residue retention treatment; WSA, water-stable aggregate(s).

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& Lal, 2007) and shifted the distribution of dry aggregates toward larger aggregates and fewer in the wind-erodible size fractions (< 0.1 mm) (Jin et al., 2015; Johnson, Strock, Barbour, Tallaksen, & Reese, 2017; Johnson, Strock, Tallaksen, & Reese, 2016; Osborne et al., 2014). As the name implies, WSA is related to the ability of aggregates to remain intact when exposed to water. Previous studies have assessed the rate of residue return on WSA, such as Roldán, Caravaca, Hernández, Garcı, and Tiscareño (2003). They found that retaining corn residue coupled with no tillage increased water-stable aggregation on a sandy loam Andisol in Mexico, which is a very different soil and environment from those in the current study on clay loam in Corn Belt of the United States. A laboratory study with wheat (*Triticum aestivum* L.) residue found that the percentage of water-stable macroaggregation increased proportionally with the mass of residue added (De Gryze, Six, Brits, & Merckx, 2005). Increasing the percentage of WSA coincides with enhanced soil structure and pore configuration; enhanced infiltration, aeration, and soil moisture retention; and improved plant root growth (Chenu, Le Bissonnais, & Arrouays, 2000; Johnson et al., 2010). To summarize the literature, the formation of WSA is a function of clay content, organic matter, and adhesion to roots (Johnson et al., 2010). A recent meta-analysis concluded that wet aggregate stability was sensitive to tillage intensity; therefore, it was identified as a preferred physical indicator of soil quality (Nunes, Karlen, & Moorman, 2020).

As previously reported, parallel studies in Minnesota were established on a field managed with annual tillage with a chisel plow and a field that has been managed without tillage since 1995 (Johnson et al., 2016). The distribution of dry stable aggregates, and soil hydraulic, and soil physical properties in response to residue return rate differed between the two fields (Johnson et al., 2016). The fields used in this study had been managed in a corn–soybean [*Glycine max* (L.) Merr.] rotation for 12 yr. Each plot had been subjected to six stover harvest cycles at the time the soil was sampled. Long-term studies such as this are rare and present a unique opportunity to assess the collective impact of repeated stover harvest. Even though aggregate formation is a dynamic process (De Gryze et al., 2005), management-induced changes in soil organic carbon can take years to be detectable (Janzen et al., 1998) and because organic matter is important in the formation and stabilization of aggregates (Albalasmeh & Ghezzehei, 2014; Tiessen & Stewart, 1988; Yan et al., 2020); the full impact of changes in organic matter inputs on aggregation may only be apparent after repeatedly harvesting stover. The current study provides a unique opportunity to compare repeated stover harvest treatments on the distribution of WSA in side-by-side fields with contrasting tillage management. Furthermore, the variable rate of stover inputs allows us to conduct a relationship analysis between stover management and WSA.

Core Ideas

- Water-stable aggregates increased proportionally with the mass of stover returned
- Returning stover on a field without tillage increased the mean weight diameter
- Having fewer water-stable aggregates implies low resistance to erosive water forces
- Stover harvest should be limited to a moderate rate on fields without tillage

The work presented here is part of a multi-location effort designed to understand the long-term effects of harvesting residues like corn stover on soil properties (Karlen et al., 2014). The specific objectives of this work were (a) to quantify the impact of stover return rate on aggregate stability as a percentage of WSA, size distribution, and mean weight diameter (MWD); and (b) to use regression analyses to derive an empirical relationship between stover input rate and WSA.

2 | MATERIALS AND METHODS

2.1 | Site description

The study site is located on the Swan Lake Research Farm, about 10 km north of Morris (45˚41′ N, 95˚48′ W) in Stevens County, MN. The site is located within the northern Corn Belt with a climate characterized as continental mid-latitude (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). The 1981–2010 normal winter temperature is −10.9 ˚C and the corresponding summer normal in 20.2 ˚C, with annual precipitation of 672.3 mm (NOAA–National Climatic Data Center, 2019). As previously reported by Johnson and Barbour (2019) and Johnson et al. (2016), soils in these fields are characterized as either Aastad clay loam (fine-loamy, mixed, superactive, frigid Pachic Argiudoll) or Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls), and are mostly well-drained and suitable for crop production. Corn and soybeans are the main crops grown within the region.

2.2 | Experimental designs and cropping history

In the fall of 2005, residue retention treatments (RRTs) were established in two adjacent fields with contrasting tillage management. Treatments in each field were independently assigned via a randomized complete block design with four replicates with both phases of the corn–soybean rotation present each year. Prior to 2005, the field under chisel plow (CP) management was moldboard plowed to ≥20 cm in the fall after harvest, with one or two disking operations at approximately 10- to 15-cm depths prior to planting. Subsequently, tillage was to ≤20 cm with a chisel plow and seedbed preparation was constrained to one-pass with a ≤15-cm disk. The no-till (NT) field (NT1995) had been managed without tillage since 1994 and continued to be managed without tillage and minimal disturbance. Both fields were planted to corn from 1996 to 2001 and soybean in 2002 and 2003. In 2004, plots were assigned randomly to a corn–soybean rotation, with both crop phases present each year throughout the study. More details on the pretreatment establishment or cropping history have previously been reported (Dalzell, Johnson, Tallaksen, Allan, & Barbour, 2013; Johnson & Barbour, 2019).

The baseline soil properties of these fields for the 0- to 5- and 5- to10-cm depth increments have also been measured and reported (Johnson, Acosta-Martinez, Cambardella, & Barbour, 2013). Total C measured was with a LECO TRU_SPEC CN analyzer (LECO Corporation, St. Joseph, MN). In the CP field, total C was 25.8 and 23.3 g kg^{-1}, and in the NT field, it was 27.9 and 20.9 g kg^{-1}, respectively for the two depths. Bulk density averaged 1.24 Mg m^{-3} at 0 to 5 cm and 1.29 Mg m^{-3} at the 5- to 10-cm depth in the CP field; in the NT1995 field, it averaged 1.37 and 1.41 Mg m^{-3} for the 0- to 5-and 5- to 10-cm depths, respectively (Johnson et al., 2016). The total C was at least 96% organic C in both depths and fields. At both depths, clay content averaged 280 g kg^{-1} in the CP field and 235 g kg^{-1} in the NT field.

2.3 | Residue treatment and crop rotation

During the corn phase, residue management consisted of harvesting only grain (Grain), harvesting grain plus removing cobs (Grain + Cob), harvesting grain plus a moderate amount of stover (Grain + Moderate), and harvesting grain plus an aggressive amount of stover (Grain + Aggressive). From 2005 to 2007, the amount of corn residue harvested or returned was a function of the percentage of rows harvested. For example, the Grain + Moderate treatment took stover from four of eight rows, and the Grain + Aggressive treatment took stover from eight of eight rows with a one-row flail chopper (Carter Manufacturing Company Inc.). The Grain + Cob treatment was originally (2005, 2006, and 2007) managed by removing stover from 75% of the plot rows (six of eight rows). In 2008, when a combine (model 9750 STS John Deere), was customized as a one-pass combine (Isaac et al., 2006), the 75% treatment was modified to harvest cobs at the same time the grain was combined. For the Grain + Cob treatment, the combine was operated as if combining for grain, but adjusted to capture cob while returning leaves and stems to the ground. The Grain + Moderate treatment was imposed by adjusting the combine head to cut just below the ear, whereas for the Grain + Aggressive treatment, the cutting height was set to about 10 cm above the ground, harvesting the residue. Dry corn grain yield in the fall of 2016 was similar among all residue treatments, averaging 11.9 ± 0.11 and 11.0 ± 0.36 Mg ha^{-1} for the CP and NT1995 fields, respectively. The residue mass remaining after combining was determined by collecting standing biomass and residue on the ground within one 0.762-m^{-2} area per plot. The biomass sample was dried to a constant mass at 60 ˚C. During the soybean phase, only the soybean grain was harvested, leaving about 4 Mg ha^{-1} yr^{-1} soybean residue in the field. In the fall prior to soil sampling, the dry soybean yield was similar among all residue treatments, averaging 3.7 ± 0.04 and 3.6 ± 0.07 Mg ha^{-1} for the CP and NT1995 fields, respectively. In 2017, when the soil was sampled for assessing aggregate stability, all plots were in the same phases as when the study was initiated and all plots been subjected to six cycles of the RRTs.

2.4 | Soil sampling and water-stable aggregation

In 2017, soil samples were collected on one randomly selected area between rows without wheel traffic from both fields at depths of 0 to 5 cm and 5 to 10 cm using a flat-headed shovel from each plot. The shovel was carefully slid horizontally to only acquire soil from the desired shallow depth. Soil samples were air-dried in a greenhouse and sieved through a 20-mm screen. Two 50-g subsamples per depth from each plot were used to determine WSA, according to Yoder (1936), using 4.75-, 2.0-, 1.0-, 0.5-, and 0.25-mm stacked sieves; a 5-min sieve time; a 3.5-cm travel distance; and 37 strokes per minute. Retained soil was dried at 110° C to a constant mass. The percentage of WSA was calculated via Equation (1).

$$\text{WSA} = \frac{\sum \text{DM}_{\text{sieve}}}{\text{DM}_{\text{soil}}} \times 100 \tag{1}$$

where $\underline{\text{DM}_{\text{sieve}}}$ is the dry mass of soil retained on sieves and DM_{soil} is the dry mass of soil sieved.

The mass of soil passing through the 0.25-mm sieve was calculated as dry mass of soil sieved minus the sum of soil retained on sieves. Mean weight diameter, as defined by Kemper and Rosenau (1986), is the size-weighted average of the stable aggregates (Equation 2):

$$\text{MWD} = \sum_{i=1}^{n} \left(X_i W_i \right), \tag{2}$$

where n is the number of sieves and X_i is the mean diameter and W_i is the fraction of the total mass retained (g g^{-1}) within that size-class fraction. As the fraction of soil retained on the

TABLE 1 Descriptive statistics (minimum, mean ± SE, and maximum) of corn stover residue returned between 2005 and 2016 during the corn phase in each residue retention treatment: aggressive stover harvest plus grain (Grain + Aggressive), moderate stover harvest plus grain (Grain + Moderate), grain and cob harvest (Grain + Cob), and a grain only harvest (Grain) of each of the two study fields; $n = 48$

Residue treatments	Stover return rates		
	Min.	Mean ± SE	Max.
	Mg ha^{-1} yr^{-1}		
Chisel Plow			
Grain + Aggressive	0.31	1.80 ± 0.22	6.77
Grain + Moderate	0.88	4.06 ± 0.27	9.04
Grain + Cob	1.74	5.29 ± 0.28	8.58
Grain	6.21	8.59 ± 0.21	13.3
No-till			
Grain + Aggressive	0.18	1.46 ± 0.15	5.27
Grain + Moderate	0.96	3.55 ± 0.22	7.33
Grain + Cob	1.02	4.82 ± 0.29	8.25
Grain	4.72	7.86 ± 0.25	13.6

sieves increases, the MWD increases, corresponding to more and larger aggregates.

2.5 | Statistical analysis

The CP and NT fields were analyzed independently. The RRT, soil depth, and crop phase were treated as fixed discrete treatment effects and replicates as a random treatment effect. The effect of these variables on WSA, the fraction of WSA within a given class size, and MWD were tested via the PROC MIXED model in SAS 9.4 software (SAS Institute, 2012). When the model indicated significant treatment effects at $P \leq .05$, mean comparison tests were completed using Tukey's honest significant difference. For $P > .5$ and $< .1$, the P value is reported as a trend. Linear regression was used to model the relationship between the average mass of corn stover retained and measured WSA in JMP Pro 14 software (Statistical Discovery From SAS, Cary, NC). Chi-square analysis was used to test if the intercepts and the slopes of the regression models were equal to zero ($P < .05$) in JMP Pro 14. Graphical data visualization was done using SigmaPlot 14.0 software (Systat Software Inc., San Jose, CA).

3 | RESULTS

3.1 | Mass of corn stover residue returned

The different harvest treatments successfully provided a wide range of corn stover returned annually (Table 1). On average, in the CP field, the Grain + Aggressive, Grain + Moderate, and Grain + Cob treatments returned stover at 21, 47, and 62% relative to the Grain treatment, respectively. In the NT fields, on average, the Grain + Aggressive, Grain + Moderate, and Grain + Cob treatments represent returned stover at 19, 45, and 61% of the Grain treatment, respectively. The minimum and maximum mass returned during the corn phase reflects both the aggressiveness of the harvest, the biomass growth, and sampling variability. The minimum mass returned in the Grain + Cob treatment also reflected that in 2005–2007, these plots had a more aggressive stover harvest that was intended to remove about 75% of the residue.

TABLE 2 Statistical probability of the effects of residue rates of return (RRT), soil depth (Depth), and crop phase (Phase) on water-stable aggregates in two fields, one managed under tillage with a chisel plow and the other managed with no tillage, determined via Proc mixed studies (bold P values indicate significant probabilities)

Factors	DF	Probability
Chisel plow		
RRT	3	**.0101**
Phase	1	**.0003**
Depth	1	**.0001**
RRT × Phase	3	.0593
RRT × Depth	3	.3723
Phase × Depth	1	.6915
RRT × Phase × Depth	3	.6016
No-till		
RRT	3	**<.0001**
Phase	1	**.0058**
Depth	1	**<.0001**
RRT × Phase	3	**.0003**
RRT × Depth	3	.9135
Phase × Depth	1	.3598
RRT × Phase × Depth	3	.2793

3.2 | Effect of RRT, crop phase, and soil depth on WSA under CP

The effects of RRT, soil sampling depth, and crop rotation phase were significant (Table 2). The mean WSA measured in the Grain + Aggressive treatment was about 15 to 18% lower than in the Grain and Grain + Cob treatments, respectively (Table 3). The Grain + Moderate treatment did not differ significantly from any of the other residue treatments. The surface 0- to 5-cm depth had fewer WSA than the 5- to 10-cm depth. The plots in the soybean phase had more WSA than those in the corn rotation phase at the time of sampling. A trend ($P = .06$) for the RRT × phase interaction may be because WSA measured during the corn phase increased as

TABLE 3 Effect of four rates of corn residue return (RRT) [aggressive stover harvest plus grain (Grain + Aggressive), moderate stover harvest plus grain (Grain + Moderate), grain and cob harvest (Grain + Cob), and a grain-only harvest (Grain)]; two crop rotation phases (corn and soybeans); and soil depth on water-stable aggregates (WSA, %) in a field under with tillage with a chisel plow, and in a field under no-till management (bold *P* values indicate significant probabilities)

Treatments		WSA			
		Chisel plow		No-till	
		Mean	CV[a]	Mean	CV
		%			
RRT					
Grain + Aggressive		31.8 b[b]	33.4	49.9 c	26.4
Grain + Moderate		37.0 ab	29.8	57.4 b	15.9
Grain + Cob		38.7 a	25.8	60.0ab	17.4
Grain		37.6 a	18.1	64.9 a	20.3
Crop phase	Corn	33.4 b	24.7	55.8b	18.4
	Soybean	39.2 a	27.6	60.2a	24.0
Depth	0–5 cm	33.2 b	26.7	62.6 a	19.9
	5–10 cm	39.4 a	25.8	53.5 b	21.1
Treatment interactions					
Crop phase	RRT				
Corn	Grain + Aggressive.	28.8 b	28.3	53.0 bc	23.0
	Grain + Moderate.	31.1 b	17.8	56.1 b	16.1
	Grain + Cob	35.8 ab	26.5	55.9 b	11.5
	Grain	37.7 ab	17.6	58.3 b	21.5
Soybean	Grain + Aggressive	34.7 ab	34.9	46.9 c	29.4
	Grain + Moderate	42.0 a	28.4	58.7 b	15.9
	Grain + Cob	41.7 a	23.7	64.1 ab	19.0
	Grain	37.4 ab	19.2	71.4 a	14.6

[a]Coefficient of variability.
[b]Values followed by different letter in a column differed at $P \leq .05$.

the RRT returned more residue. However, during the soybean phase, the Grain + Aggressive treatment had the lowest WSA, and Grain + Moderate had the highest WSA.

3.3 | Effect of RRT, soil depth, and crop phase on WSA under NT

The main effects of RRT, soil sampling depth, and crop phase were significant in the NT field (Table 2). The only significant interaction observed was between RRT and crop phase. Overall, this field managed without tillage had 50% or more WSA. In general, WSA increased as the RRT returned more residue, such that the Grain + Aggressive treatment had 13, 17, and 23% fewer WSA than the Grain + Moderate, Grain + Cob, and Grain treatments, respectively (Table 3). The Grain + Moderate treatment had similar WSA to the Grain + Cob but fewer than the Grain treatment. The Grain + Cob treatment had arithmetically fewer than the Grain treatment, but the difference did not meet the $P < .05$ criteria.

The WSA was larger at 0- to 5-cm depth than at the 5- to 10-cm depth by a difference of 9.1, which corresponds to a 15% reduction in the percentage of WSA between the depths (Table 3). During the soybean phase, higher WSA than in the corn phase was observed. The interaction effects of crop phase with RRT demonstrated a difference of 5.3% between the corn × Grain + Aggressive treatments and the corn × Grain treatment. The difference between the soybean × Grain + Aggressive and the soybean × Grain treatments was 24.5%, which corresponds to a 45% increase. Since this is a corn–soybean rotation, the soybean phase reflects the most recent stover treatment.

3.4 | Distribution and MWD of WSA

3.4.1 | Chisel plowing field

In all the RRT treatments, since the WSA was less than 50%, most of the soil passed through the 0.25-mm sieve. Among the five class sizes, the ≥0.25-mm size fraction represented 15 to 17% of the aggregates in all the treatments (Figure 1a). Aggregate sizes ranging from 0.25 to 0.50 mm accounted for 6 to 7% of the aggregates. The lowest proportion of aggregates were within the 0.50- to 1.0-mm size range ranging from 2.5 to 3%, whereas 4.5 to 6.5% were in the 1.00- to 2.00-mm size range and 2 to 6% were in the 2.00- to 4.75-mm size range.

The RRT significantly impacted the proportion of aggregates in two of the size classes, 1- to 2-mm and 2- to 4.75-mm, and nearly significant ($P = .06$) for the ≥0.25-mm sieve (Figure 1a, Table 4). The Grain + Aggressive treatment had the lowest percentage of soil retained on the 2-mm sieve compared with the remaining three RRTs. The percentage of soil retained on the 4.75-mm sieve was lowest for the Grain + Aggressive treatment, which did not differ significantly from the Grain treatment but did differ from the other two treatments. The lowest percentage of soil retained on the 0.25-mm sieve was observed for the Grain + Aggressive treatment, which differed from the Grain treatment and was intermediate to the other two RRTs.

The distribution of WSA was impacted by crop phase and soil sampling depth (Table 4). In general, there were more WSA in each class size when sampled during the soybean phase than during the corn phase (data not shown). Likewise, the proportion of WSA was greater at 5 to 10 than at 0 to 5 cm (data not shown). Interactions between the RRT and crop phase and between the RRT and depth were significant for WSA in the 2.0- to 4.75-mm class size. The change in distribution of WSA was reflected in the MWD.

TABLE 4 Probability that main effects of residue retention treatment (RRT), soil depth (Depth), and crop phase (Phase) affected the distribution of water-stable aggregates and mean weight diameter (MWD) as determined by a mixed linear model from two independent field studies, one under chisel plow management and the other under no-till (NT) management (bold *P* values indicate significant probabilities)

Treatments	df	Water-stable aggregate class sizes 0.25–0.50 mm	0.5–1.00 mm	1.0–2.00 mm	2.0–4.75 mm	≥4.75 mm	MWD
		P value					
Chisel Plow							
RRT	3	.0620	.7663	.1540	**.0006**	**<.0001**	**.0002**
Phase	1	**.0247**	**.0037**	**.0001**	**<.0001**	**.0101**	**<.0001**
Depth	1	.4148	.2481	**.0034**	**<.0001**	**<.0001**	**.0029**
RRT × Phase	3	.1708	.3573	.0881	.1239	**.0309**	**.0259**
RRT × Depth	3	.5886	.7150	.4563	.9385	**.0112**	**.0213**
Phase × Depth	1	.6753	.9580	.6332	.9816	.4737	.4848
RRT × Phase × Depth	3	.6579	.8218	.4198	.1278	.9052	.8451
No-till							
RRT	3	**<.0001**	.2055	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Phase	3	**.0033**	.5849	.0703	**.0010**	**<.0001**	**<.0001**
Depth	1	.5184	**<.0001**	**<.0001**	**.0010**	**<.0001**	**<.0001**
RRT × Phase	1	.3441	**.0079**	**.0036**	**.0048**	**.0015**	**.0006**
RRT × Depth	3	.0671	.3909	.3167	.3104	.3281	.4403
Phase × Depth	3	.3873	.5446	.1230	.4043	.4297	.3684
RRT × Phase × Depth	1	.1616	.9373	.9122	.1399	**.0215**	**.0315**

The MWD differed among RRTs, between crop phase, and between soil sampling depths (Table 4). The Grain + Aggressive treatment had the lowest MWD, which did not differ from the Grain treatment but was less than both the other two RRTs (Figure 2a). Although the difference was small, MWD was greater when soil was sampled during the soybean phase than during the corn phase (Figure. 2b). Tillage buries residue and, as a result, the MWD at 5- to 10-cm depth was greater than at the 0- to 5-cm depth (Figure 2c). Both two-way interactions were significant (Table 4). In the Grain treatment, only the MWD based on soil samples collected during the corn phase was greater than or equal to when soil was sampled from plots in the soybean phase (data not shown). Even though the RRT × soil depth interaction was significant, the same general pattern of MWD being larger at 5 to 10 cm than at 0 to 5 cm was observed. However, the response was muted in the Grain and Grain + Aggressive treatments (data not shown). This might be because the Grain treatment retained enough residue to support aggregate formation at both depths, whereas the Grain + Aggressive treatment did not have enough residue buried to support WSA at either depth.

3.4.2 | No-till field

In the NT field, more than half the soil was in aggregates greater than 0.25 mm. The greatest fraction, 16 to 19% of WSA, were within the 0.25- to 0.5-mm size range (Figure 1b). Aggregate sizes ranging from 0.5 to 1 mm accounted for 9.5 to 10.5% of the WSA. The lowest proportion (6–9%) of aggregates were in the 1.0- to 2-mm range. The 2- to 4.75- and ≥4.75-mm ranges contained 9 to 16 and 5 to 14% of the WSA, respectively.

The RRT was significant for the proportion of aggregates observed in all aggregate sizes, except those ranging from 0.25 to 1 mm (Figure. 1b, Table 4). The Grain + Aggressive and the Grain + Moderate treatments had more aggregates in the 0.25- to 0.5-mm range than the Grain treatment, whereas the percentage of aggregates measured in the Grain + Cob treatment was between the amounts of the other treatments. Conversely, the Grain treatment had the greatest percentage of the aggregates in the three class sizes ≥1.0 mm compared with the Grain + Aggressive treatment and the Grain + Moderate treatment. This pattern was also observed when we compared the Grain with the Grain + Cob treatment for the 1.0- to 2.0- and the 2- to 4.75-mm size ranges.

Crop phase was significant for the aggregate sizes, except those within the 0.5- to 1.0- and the 1- to 2-mm size ranges (Table 4). In general, during the soybean phase, there was less soil in the 0- to 0.25-mm class size but more in the 1- to 2- and 2- to 4.75-mm size ranges than during the corn phase (data not shown). The proportion of WSA was greater at 0 to 5 than at 5 to 10 cm. This difference was significant for all aggregates ≥1 mm. (Table 4). Since this field is managed without tillage, the

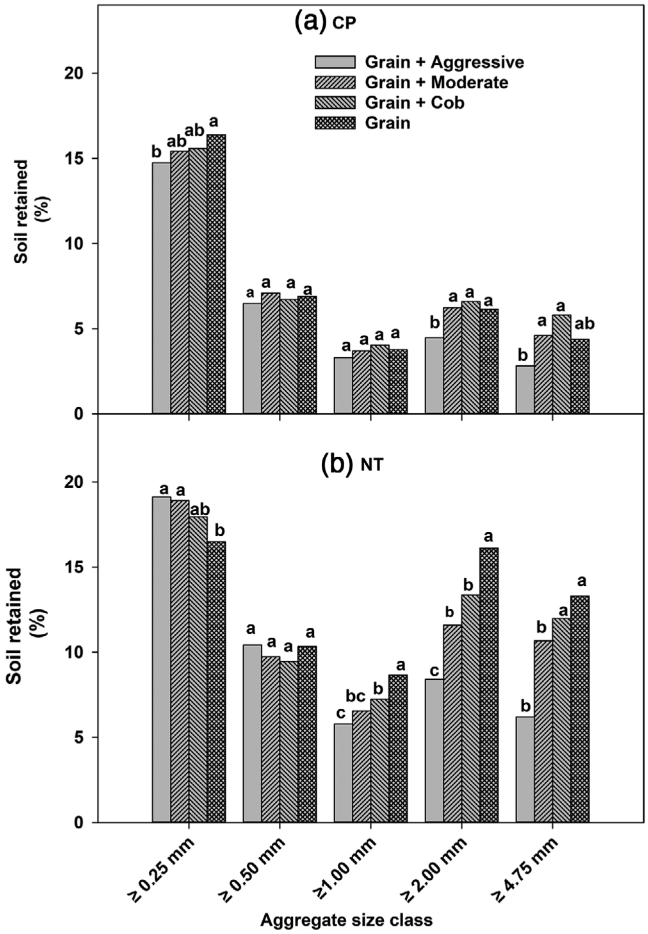

FIGURE 1 Distribution of water-stable aggregates among five fractions of water-stable aggregate in response to residue retention treatment fields managed with chisel plowing (CP) and no-till (NT). Bars within an aggregate size class with different letters differ at $P \leq .05$

residue remained at the soil surface, contributing to surface aggregate formation.

The RRT × crop phase interaction was significant for all class sizes except 0.25 to 0.5 mm (Table 4). The interaction was attributed primarily to the Grain + Aggressive treatment having a greater proportion of aggregates measured during the corn phase than during the soybean phase, whereas the reverse (soybean > corn) was the more common response. This observation was attributed to the lack of residue returned to the soil when the previous year's corn stover was aggressively harvested (data not shown).

In the NT field, MWD significantly responded to the main effects of RRT, crop phase, and soil depth, and to the two-way interaction between RRT and crop phase, and the three-way interaction of RRT × crop phase × soil depth (Table 4). The Grain + Aggressive treatment had a lower MWD than all three other RRTs (Figure. 2d). A greater MWD was observed during the soybean phase than during the corn phase (Figure 2e). The MWD was greater at the 0- to 5-cm soil depth than at the 5- to 10-cm depth (Figure 2f). The interaction between RRT and crop phase on MWD integrated the shifts in the distribution of aggregates among class sizes, such that the Grain + Aggressive treatment had an MWD of 0.5 mm when sampled in the corn phase and 0.40 mm in the soybean phase. For all other RRTs, the MWD in the soybean phase was greater than that measured during the corn phase. As mentioned above, the Grain + Aggressive treatment returned <2 Mg ha^{-1} yr^{-1} when in the corn phase (Table 1). Typically, during the soybean phase, 4.3 to 4.8 Mg ha^{-1} yr^{-1} of residue was returned (Johnson & Barbour, 2019).

3.5 | Relationship between rate of residue input and WSA

3.5.1 | Chisel plow field

The intercepts ranged from 22 to 37% WSA, which reflects the ability of this soil and management to form and maintain aggregates as a function of edaphic properties, including clay and organic matter content. Overall, WSA was a function of the average residue returned during the corn phase, which had a low R^2. However, the slope was significant and positive (Table 5; Figure 3a,b). Parsing the data by crop phase, the R^2 was very low for both phases, with the slope significant when measured during the corn phase but not the soybean phase. The greatest slope and R^2 were observed for WSA measured during the corn phase at the 0- to 5-cm depth. The slopes of the other linear models were not significant.

3.5.2 | No-till field

In the NT field, the intercepts were 39 to 59%, reflecting a lack of disturbance degrading the aggregates, which was independent of residue retained (Table 5). The linear regression models of WSA were a function of residue returned as stover, as visualized in Figure 3c,d. The R^2 of the regression model based on all data implied that the rate of stover return accounted for 18% of the variation observed in the WSA. The slope for all data indicated that WSA increased by 2.2% per Mg stover returned on average. When parsing the data by crop cycle, during the soybean phase, nearly 40% of the variation in WSA was accounted for by the RRT, with WSA increasing by 4% per Mg stover returned. In contrast, when sampled during the corn phase, WSA was not sensitive to the previous stover management cycle. The response was similar between the two sampling depths, although there was an interaction between crop phase and sampling depth. During the corn phase, the R^2 and slope did not provide any evidence that WSA responded to how the corn was managed during the previous corn phase. In contrast, during the soybean phase, WSA was responsive

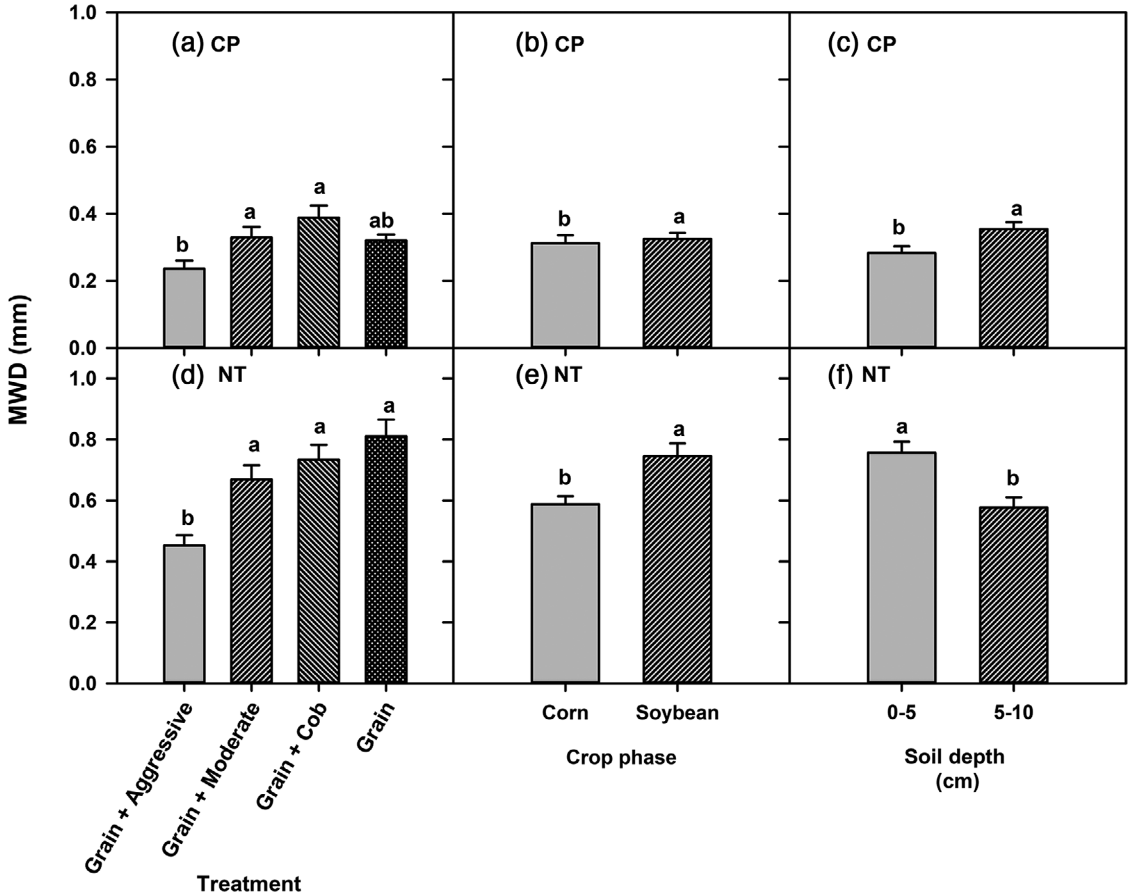

FIGURE 2 Effects of residue retention treatment (RRT), crop rotation phase and soil depth on mean weight diameter (MWD) in fields under chisel plow (CP) management (a, b, and c) or no-till (NT) (d, e, and f) management. Bars with different letters differ within an effect ($P \leq .05$)

to RRT management during the preceding corn phase. During the soybean phase, soil in the 0- the 5-cm depth had R^2 values showing that 62% of the variation was from stover return, increasing 4.7% per Mg corn residue returned.

4 | DISCUSSION

The purpose of this work was to assess the impact of variable rates of corn residue returned from two fields on fine-textured Mollisol soil, both under corn–soybean rotations, on WSA size distribution. Novel aspects of the study included the repeated cycles of four RRTs from corn–soybean rotations in two adjacent fields over the same timeframe with similar soils but different tillage management. The study described by Jin et al. (2015), though from a long-term study, focused on dry aggregates in continuous corn, only measuring the water stability of select aggregate class sizes. Although the works by Hammerbeck, Stetson, Osborne, Schumacher, and Pikul (2012) and by Johnson et al. (2016) were on corn–soybean rotations, both these studies focused on dry aggregate distribution rather than wet aggregate distribution. Moreover, Yan et al. (2020) focused only on tillage effects on WSA without residue treatments. Thus, the present study provides insights and data into the response of WSA in a agronomically important Mollisol of the highly productive Corn Belt, thereby adding to the body of knowledge and understanding necessary to balance soil sustainability and residue harvest decisions.

Measuring wet aggregate stability across four residue management rates allowed us to relate WSA as a function of stover mass returned. The incubation study by De Gryze et al. (2005) found that aggregate formation increased linearly with wheat residue. Furthermore, they found that respiration rate was proportional to the mass of residue added. Their subsequent empirical model predicted that 65% of aggregation changes were explained by the mass of residue added. They estimated that macroaggregate turnover rate in the laboratory was 40 to 60 d. If the dynamic nature of aggregate association or dissociation holds in the field setting, then the aggregation level measured in this long-term study reflects the cumulative impact of repeated residue harvest on a dynamic process. Throughout the 12-yr study, the Grain + Aggressive treatment kept about 36 Mg residue (stover plus soybean residue in the field) compared with 72 Mg residue (stover plus soybean residue) in the Grain treatment. The impact of the residue returned

TABLE 5 Linear models of water-stable aggregates (WSA) as a function of average residue return during the corn phase (WSA = $m \times$ RRT + b)

			Intercept (b)	$P < .05$	Slope (m)	$P < .05$	R^2
			%		% Mg^{-1}		
Chisel plow							
	All data		32.102	**<.0001**[a]	0.846	**.015**	0.045
Crop phase[b]	Corn		27.539	**<.0001**	1.207	**<.0001**	0.135
	Soybean		37.170	**.0108**	0.398	.3971	0.009
Depth	0–5 cm		28.336	**<.0001**	0.982	**<.0001**	0.008
	5–10 cm		35.869	**.0365**	0.709	.1311	0.031
Interaction							
	Corn	0–5 cm	22.063	**<.0001**	1.764	**<.0001**	0.594
		5–10 cm	33.015	**.0005**	0.651	.2013	0.035
	Soybean	0–5 cm	35.119	**<.0001**	0.131	.8594	0.001
		5–10 cm	39.221	**<.0001**	0.666	.3661	0.029
No-till							
	All data		48.114	**<.0001**	2.247	**<.0001**	0.182
Crop phase	Corn		53.033	**<.0001**	0.676	.209	0.028
	Soybean		41.360	**<.0001**	4.014	**<.0001**	0.397
Depth	0–5 cm		52.583	**<.0001**	2.265	**<.0001**	0.193
	5–10 cm		43.645	**<.0001**	2.230	**<.0001**	0.229
Interaction							
	Corn	0–5 cm	59.173	**<.0001**	0.114	.865	0.001
		5–10 cm	46.893	**<.0001**	1.238	.065	0.136
	Soybean	0–5 cm	43.559	**<.0001**	4.666	**<.0001**	0.621
		5–10 cm	39.160	**<.0001**	3.361	**<.0001**	0.361

[a]Bold P values indicate significant probabilities.

[b]Crop phase is the crop phase at the time of soil sampling in two independent field studies.

partly reflects the fact that organic matter was available to support aggregate formation. Decomposition rate is a function of temperature, moisture, pH, particle size, and biochemical composition (Johnson, Barbour, & Weyers, 2007). The macroclimate would be the same across the field; however, the mass and/or placement of residue may influence decomposition kinetics by altering the microclimate, as reviewed by Johnson et al. (2010). For example, if returning all the residue subsequently kept soil cooler, then the decomposition rate may be slowed. Conversely, aggressive harvest leaving the soil surface exposed and dark might change the surface albedo, such that the soil could become too hot and/or dry for optimum decomposition kinetics. The dynamic nature of aggregate turnover might explain why the strongest correlations between RRT and WSA were observed in the soybean phase, as this would reflect the previous fall's differential stover harvest having the most direct impact on the soil microclimate and biomass inputs.

Our rate studies were independently conducted on these fields managed with and without tillage. The studies were not designed to compare the two fields directly; however, the similarities and contrasting responses are discussed. In both fields, RRT, soil sampling depth, and phase caused significant differences in WSA, the distribution among aggregate sizes, and MWD. In general, WSA was adversely impacted by the most aggressive stover harvest in both fields, with the fraction of aggregates shifted toward those that are smaller and more readily eroded. Response in the fields differed in that overall CP field was poorly aggregated (38%), even when all stover was returned and only grain was harvested. However, the NT field still had 50% WSA when stover was aggressively harvested. This suggests that chisel plowing disrupted aggregates more than could be compensated for by returning all the stover. Conversely, the absence of tillage allowed about half the aggregates to remain stable, even with minimal stover returned. If erosion is the primary constraint to mass of stover harvested, as was assumed in the early stover supply estimates (Graham, Nelson, Sheehan, Perlack, & Wright, 2007; Perlack et al., 2005), then, clearly, more stover can be removed when a field is managed without tillage compared with a tilled field. Although many authors (Blanco-Canqui, 2013; Johnson, 2019; Karlen et al., 2009; Lal, 2008; Wilhelm

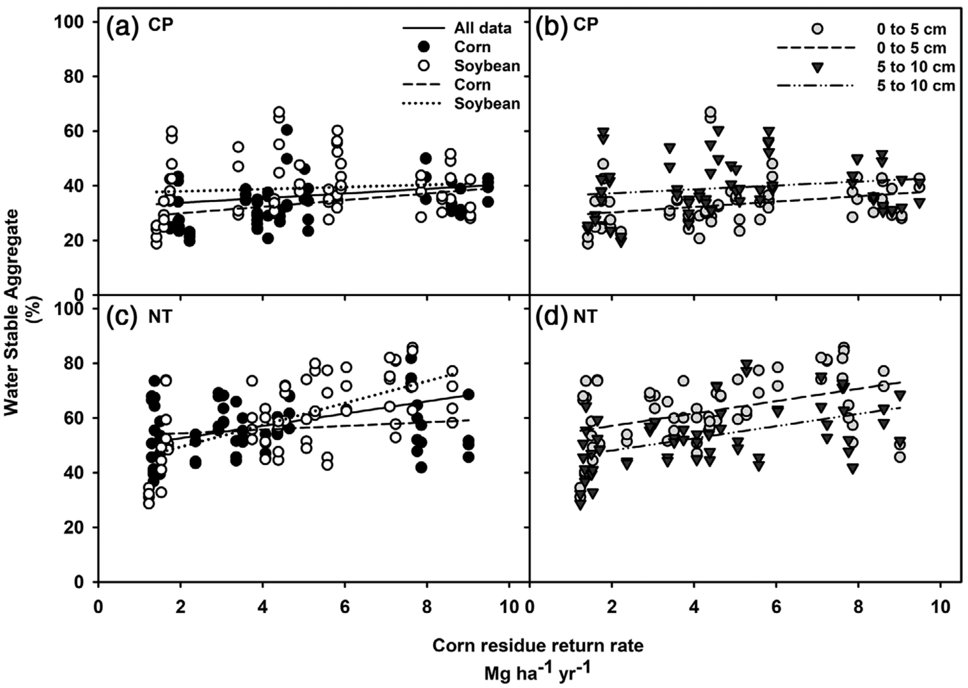

FIGURE 3 Linear regression between water-aggregate stability (WSA) as function of the average annual mass of residue during corn phase (Mg ha^{-1} yr^{-1}) in two independent fields managed with chisel plowing (CP) (panels a and b) or no tillage (NT), (panels c and d)., The regression using all data, and the main phase effect shown in (a) and (c), and the main effect of sampling depth is in (b) and (d) for the CP and NT fields, respectively. Equation coefficients are reported in Table 5

et al., 2007) have contended that despite erosion control being important, other soil indices like soil organic matter and nutrient management must also be considered when determining a sustainable rate of stover removal.

The observed changes in aggregate stability related to tillage are consistent with the results reported by others. For example, Roldán et al. (2003) reported that WSA was >50% under NT compared with 45% with conventional tillage on an Andisol with 10% clay. Van Eerd, DeBruyn, Ouellette, Hooker, and Robinson (2018) found that a clay loam soil managed without tillage had greater WSA (54%) than when that soil was managed with annual tillage(47%). Nevertheless, in our study, under NT, the WSA was 50% or more compared with the CP field, where the WSA was <40% WSA. This difference in WSA observed between these two studies might be because of the slightly different range of aggregate sizes that were included by Van Eerd et al. (2018) compared with our study. In China, managing a silty clay loam Mollisol without tillage had more macroaggregates and greater MWD of WSA than this soil managed with tillage (Yan et al., 2020). Thomas et al. (2019) reported that WSA measured with a rainfall simulator nearly doubled under NT compared with conventional tillage (moldboard plow) on silt loam soil.

The pattern of reducing tillage as means to improve soil structure was also reported for an erodible silt loam by shifting away from smaller, more erodible aggregates (Williams, Reardon, Wuest, & Long, 2018). Greater WSA is expected to occur with more clay content (Eynard, Schumacher, Malo, & Lindstrom, 2004), but the CP and NT fields had similar clay contents, so the difference in WSA between the fields cannot be attributed to soil texture. Likewise, differences between the fields are unlikely to be attributable to differences in carbonate content, which is another edaphic property associated with WSA (Dimoyiannis, 2012). Earthworms (Marashi & Scullion, 2003) and fungi (Helfrich, Ludwig, Thoms, Gleixner, & Flessa, 2015) have been shown to play a role in aggregate formation, but tillage has been demonstrated to reduce the presence of these organisms (Liebig, Carpenter-Boggs, Johnson, Wright, & Barbour, 2006; Nuutinen, 1992); therefore, we suspect that differences between the two fields in addition to the direct physical disruption caused by the tillage might be caused by the soil's biological characteristics. Early soil biology measurements in our fields indicated that the CP field had less fungal fatty acids than the NT field (Johnson et al., 2013).

Soil sampling at two depths in these two fields generally reflects the effect of tillage and residue placement on the availability of organic matter for the formation of stable aggregates. Residue placement explains why the WSA and MWD increased with depth in the CP field but decreased with depth in the NT field. The greater WSA and MWD imply that soil in the NT field has a greater capacity to withstand erosive water forces than the CP field. As others have noted, stover harvest on a field without tillage still leaves the field susceptible to erosion by leaving it exposed to erosive forces (Johnson et al., 2016), which is exacerbated by reducing WSA and MWD (Blanco-Canqui, Mitchell, Jin, Schmer, & Eskridge, 2017).

In both fields, the regression intercept was greater than zero. This was expected, since organic matter input only partially explains aggregate formation, which is also a function of clay content (Johnson et al., 2010). In the CP field, although slope was significant, the R^2 was very low, implying that any effect of stover return was overshadowed by the highly disruptive effect of tillage, which was also observed for hydrological properties and dry aggregate distribution in this field (Johnson et al., 2016). The strongest relationship ($R^2 = 0.621$) between the WSA and RRT was for the surface 0 to 5 cm during the soybean phase in the NT field. This relationship most directly reflected how the most recent stover harvest in the previous fall impacted WSA during the subsequent soybean phase.

5 | CONCLUSION

Water-stable aggregates were sensitive to the rate of RRT. A unique finding of the field study was that the percentage of WSA increased proportionally with the mass of stover returned. Returning stover without tillage increased the MWD of WSA. Fewer WSA in these plots imply less resistance to water erosive sources. Therefore, harvesting stover can leave a field vulnerable to soil erosion and is more likely to cause undesirable downstream negative impacts on quality. If stover harvest is considered, the field should be managed without tillage but with a moderate harvest rate. This information is valuable to producers considering harvesting stover for bioenergy or other uses such as animal bedding.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

Abimbola Ojekanmi: formal analysis, visualization, writing—original draft, writing—review and editing. Jane M.F. Johnson:Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing—original draft, writing—review and editing.

ORCID

Jane M. F. Johnson https://orcid.org/0000-0002-1687-4007

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