Open Journal of Applied Sciences, 2025, 15(9), 2800-2819
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Poultry-Litter Effects on the Change in Water-Stable Aggregation in Loamy Soils in Eastern Arkansas

Kennedy Chapman, Eric Simon, Kristofor R. Brye*, Jace Clark, Hannah Nobles, Shelby Lebeau, Mike Daniels

Department of Crop, Soil, and Environmental Science, University of Arkansas, Fayetteville, AR, USA
Email: *kbrye@uark.edu

How to cite this paper: Chapman, K., Simon, E., Brye, K.R., Clark, J., Nobles, H., Lebeau, S. and Daniels, M. (2025) Poultry-litter Effects on the Change in Water-stable Aggregation in Loamy Soils in Eastern Arkansas. *Open Journal of Applied Sciences*, **15**, 2800-2819.
https://doi.org/10.4236/ojapps.2025.159187

Received: August 16, 2025
Accepted: September 21, 2025
Published: September 24, 2025

Abstract

A well-structured soil is paramount for a healthy, productive soil. Soil structure can be improved by applying organic amendments, such as poultry litter (PL) and can be quantified as water-stable aggregate (WSA) concentration. The objective of this field study was to evaluate the effects of PL rate on the change in WSA concentration across several loamy soils in eastern Arkansas. Soil core samples were collected in 2022 and 2024 at three locations (*i.e.*, Haigwood, Distretti, and Burris). Soil bulk density decreased over time ($P < 0.05$) at Haigwood in the two largest PL-rate treatments, but not the lowest, and increased over time ($P < 0.05$) at Distretti in at least one PL rate at each location. Averaged across soil depth (*i.e.*, 0 - 5 and 5 - 10 cm), WSA concentration at Distretti decreased over time ($P < 0.05$) in the >4 mm aggregate-size class and increased over time ($P < 0.05$) in the 0.25 - 0.5, 0.5 - 1, 1 - 2, and 2 - 4 mm size classes. At Haigwood, WSA concentrations increased over time ($P < 0.05$) in the 0.25 - 0.5 and 0.5 - 1 mm size classes in the 5 - 10 cm soil depth and increased over time ($P < 0.05$) in the > 4 mm size class in the 0 - 5 cm soil depth. At Haigwood, total WSA concentration increased over time ($P < 0.05$) in the smallest PL rate (4.49 $Mg \cdot ha^{-1}$). Differential PL application rates can affect WSA concentrations in as little as two years demonstrating WSA as a dynamic soil property.

Keywords

Soil Structure, Water-Stable Aggregates, Poultry Litter, Change over Time

1. Introduction

Soil erosion has become one of the, if not the most, concerning soil-degrading processes of modern times. As of the late 1990s and early 2000s, soil erosion was estimated to cost the United States (US) $30 to 44 billion annually [1]. Cultivated agriculture is a land use that often perpetuates soil erosion via excessive tillage, over-grazing, and/or mechanical soil disturbances. However, as the global human population continues to grow, large-scale production agriculture must respond to the necessary increased demand for food production, which means adjusting agricultural management practices for improved soil structure and resistance to destabilizing forces, such as raindrop impacts. Eroded soil can lead to both on- and off-site damages, including a decline in soil fertility and general soil quality, decreased crop yield, and reduction in soil microbial activity, as well as river sedimentation and increased water turbidity and eutrophication of local water bodies.

Many methods have been adopted to control soil erosion. Such methods include cover cropping, conservation tillage, increasing soil organic matter (SOM) and/or adding organic soil amendments. Cover cropping facilitates decreased soil erosion, as cover crops (CC) protect the soil from erosive water flow, add OM, and often increase plant-essential nutrients, such as nitrogen (N) and phosphorus (P), to help sustain plant growth. Bare soils are prone to erosion; thus, planting CC as off-season protection contributes to reducing the erosion potential.

Conventional tillage has been shown to mechanically degrade soil structure, increase carbon dioxide (CO_2) production and release into the atmosphere, reduce infiltration, and decrease microorganism populations in the soil [2]. Conservation tillage helps minimize erosion from agricultural lands, improves soil structure, increases soil water-holding capacity, and can sequester soil carbon (C) [3]. With decreased tillage disturbance, SOM can increase, which, in turn, can help stabilize the soil through improved soil structure and a greater proportion of water-stable aggregates (WSA). The ability of soil aggregates to maintain stability in wet-soil conditions is crucial to promote infiltration and reduce runoff [4].

Applying organic soil amendments, such as recycled animal wastes, can decrease soil bulk density, improve porosity, prevent crusting, and can improve overall soil tilth and productivity. Many of the realized benefits of organic soil amendments are the results of improved aggregate stability [5]. As the driver of aggregate stability improvement [5], OM is a key soil attribute to mitigating soil erosion through improved soil structure and increased soil aggregation.

Poultry litter (PL) is an animal waste material that is abundant in regions of intense poultry production, namely Arkansas. Poultry litter consists of a mixture of feathers, feeds, feces, and bedding material, typically saw dust or rice (*Oryza sativa*) hulls [6]. Poultry litter can be an exceptional source of water-soluble plant nutrients, such as N, P, calcium (Ca), and potassium (K) [7]. Arkansas is one of the top five poultry-producing states in the US, producing about 1.03 billion broilers in 2024 [8]. Consequently, in Arkansas, using poultry litter (PL) as an organic soil amendment is accessible for producers. However, minimal research has been conducted on PL effects on water-stable aggregation in Arkansas.

Though little has been done in Arkansas, many studies have been conducted on

PL effects on soil properties and organic-soil-amendment effects on WSA [6] [7] [9]-[11]. Li *et al.* [9] concluded that PL use generally benefited WSA in sandy loam collected from the top 15 cm depth in Mississippi. However, as Arkansas has almost double the poultry head count compared to Mississippi [8], evaluating the effects of PL in more intense poultry production regions is necessary. McMullen *et al.* [6] reported that PL additions increase plant productivity but also soil CO_2 production and release in a highly weathered, silt-loam-textured Ultisol in the Ozark Highland region of northwest Arkansas, thereby decreasing SOM and C contents that may decrease soil aggregation.

Other research in Arkansas has evaluated various effects on WSA. Motschenbacher *et al.* [12] concluded that adding large-residue-producing crops, when put into a rice-based rotation in Stuttgart, Arkansas on silt-loam soil, will increase the total WSA (TWSA)-sequestered C and N in the absence of tillage. However, Motschenbacher *et al.* [12] also reported that repeated soil saturation did affect the abundance of soil macroaggregates along with their C and N concentrations compared to a less routinely flooded crop rotation. In the Delta region of eastern Arkansas, on a Calloway silt-loam soil, Smith *et al.* [13] showed that TWSA concentrations were greater under dryland conditions. Additionally, Smith *et al.* [13] reported TWSA concentrations were reduced under a high-fertility/high-residue treatment, which was concluded to be due to added mineral-N that led to increased microbial decomposition rates from the greater amounts of OM. Anderson *et al.* [10] assessed the effects of different land management practices and reported that less managed land use, such as Conservation Reserve Program (CRP) practices, resulted in greater TWSA compared to row-cropped agroecosystems on fine-textured loessial and alluvial soils in the Delta region of eastern Arkansas. Anderson *et al.* [10] also reported that soil in the upper 5 cm had greater aggregate stability compared to soil in the 5- to 10-cm depth interval.

In the Lower Mississippi River Valley region of eastern Arkansas on loamy soils, Lebeau *et al.* [14] showed that TWSA concentrations were unaffected by a CC treatment. In a study to assess various fertilizer effects on near surface aggregate stability, Brye *et al.* [15] showed that the WSA concentrations under a non-struvite-P fertilizer treatment had similar WSA concentrations to struvite-fertilizer-P treatments. Similarly, Brye *et al.* [15] also reported that WSA concentrations among aggregate-size classes were unaffected by various fertilizer-P treatments, but that WSA concentrations differed by soil depth in raised beds of furrow-irrigated rice. Near Dumas, Arkansas on a Herbert silt-loam soil, Lebeau *et al.* [16] evaluated CC treatments and sample/measurement placement effects on near surface soil properties and reported that WSA concentrations for wheel-track and non-wheel-track combinations were lower than in the raised bed. Result also showed that CC-wheel-track and CC-no wheel-track combinations had greater WSA than the no-CC treatment in the same placements [16]. Most recently, Fanning *et al.* [17] reported that CC did not decrease soil bulk density and did not increase WSA compared to no CC. However, CC increased TWSA in the top 5 cm across various loamy soils in the Lower Mississippi River Valley [17].

As soil erosion continues to threaten areas of intensive, cultivated agriculture, particularly in the historically highly productive, row-crop region of eastern Arkansas, evaluating soil amendments that can potentially mitigate soil erosion through improved soil structure is essential. Furthermore, considering the lack of prior research on PL effects on WSA in Arkansas, investigating soil aggregation as affected by PL application is warranted. Therefore, the objective of this field study was to evaluate the effects of PL rate on the change in WSA concentration across several loamy soils in eastern Arkansas. It was hypothesized that annual application of PL will decrease soil bulk density and increase WSA concentration in some aggregate-size fractions and total WSA concentration over time and differ among soil depths.

2. Materials and Methods

2.1. Site Descriptions

Research was conducted at three private producers' farms in the Delta region of eastern Arkansas: Haigwood, Distrettri, and Burris (**Figure 1**). Each farm consisted of several PL-rate treatments. The Haigwood Farm, hereafter referred to as Haigwood, consisted of three separate fields, each with a different PL rate. One field had two series mapped with silt-loam surface textures, Amagon (fine-silty, mixed, active, thermic Typic Endoaqualfs) and Egam (fine, mixed, active, thermic Cumulic Hapludolls), and was managed as furrow-irrigated rice with minimum tillage from 2020 through 2024. While the other two fields were managed under flood-irrigated rice with minimum tillage from 2020 through 2024, where the second field was mapped with a combination of Amagon and Egam soil series and the third field was mapped with a combination of Amagon, Egam, Dexter (fine-silty, mixed, active, thermic Ultic Hapludalfs), and Dundee (fine-silty, mixed, active, thermic Typic Endoaqualfs) soils. Winter CC were not used in any of the three fields. After harvest, rice stubble was burned. Raised beds were reformed post-harvest, where necessary, in the furrow-irrigated rice field. All three fields were land leveled to a surface grade of 0.1% in 2021.

The Distretti Farm, hereafter referred to as Distretti, consisted of four separate fields, each with a different PL rate, generally cropped in a furrow-irrigated soybean (*Glycine max*)-corn (*Zea mays* L.) rotation. One field was mapped with a combination of Calloway (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) and Calhoun (fine-silty, mixed, active, thermic Typic Glossaqualfs) silt-loam soils) and was cropped to soybean in 2022 and 2024 and corn in 2021 and 2023. The second field was mapped with a combination of Calhoun, Calloway, and Hillemann (fine-silty, mixed, active, thermic Albic Glossic Natraqualfs) silt-loam soils and was cropped to soybean in 2021 and 2023 and corn in 2022 and 2024. The third field was mapped as Hillemann silt loam and was cropped to soybean in 2022 and 2024 and corn in 2021 and 2023. The fourth field was mapped as a combination of Calloway and Oaklimeter (coarse-silty, mixed, active, thermic

Fluvaquentic Dystrudepts) silt-loam soils and was cropped to soybean in 2021 and 2023 and corn in 2022 and 2024. No-tillage and winter CC were used on all four fields.

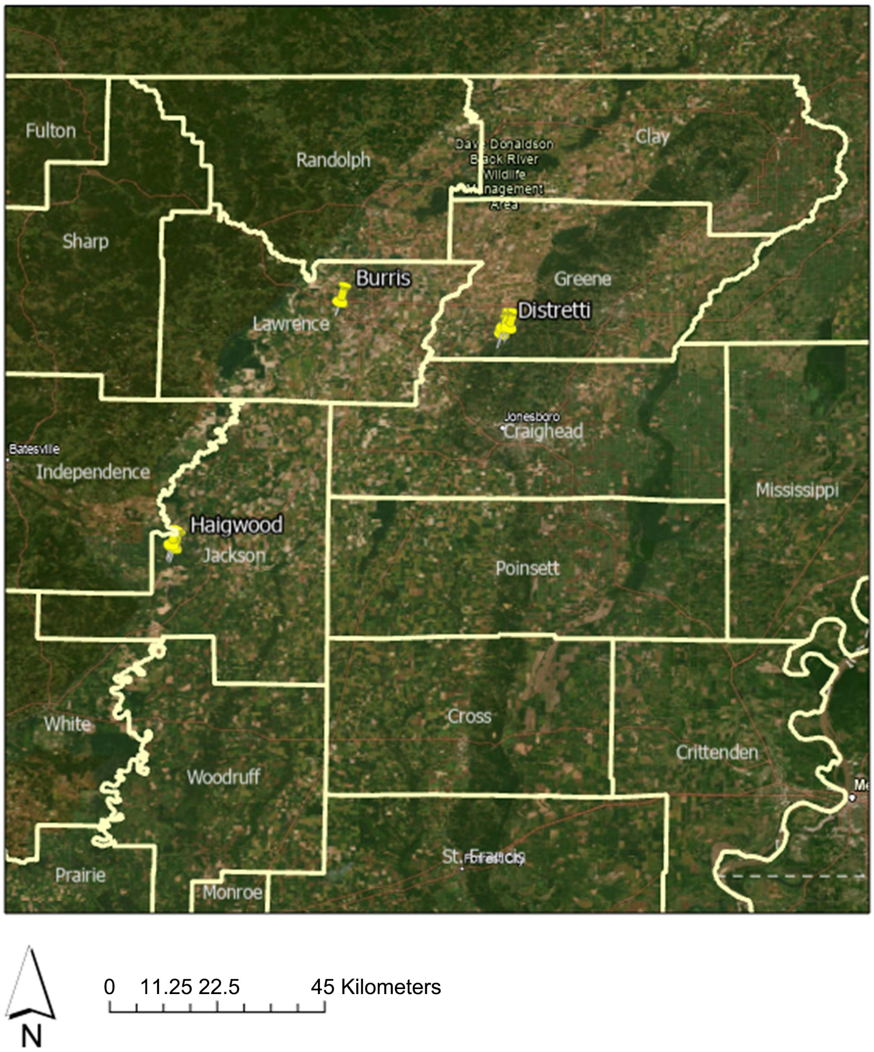

Figure 1. Geographic distribution of the three farm locations used in this study (*i.e.*, Haigwood, Distretti, and Burris) in northeast Arkansas.

The Burris Farm, hereafter referred to as Burris, consisted of four PL treatments as separate, large strips, with areas consisting of 19.4 (~230 m wide), 17.4 (~220 m wide), 7.7 (~215 m wide), and 5.3 (~110 m wide) ha, in a single field that used center-pivot irrigation. No-tillage soybean was grown in 2021 and 2022, but, in 2023, the field was transitioned to hay production, where Bermudagrass (*Cynodon dactylon* L.) was planted in the northern part and sorghum sudangrass (*Sorghum bicolor x S. bicolor* var. sudanese) was planted in the southern part of the field. The field was mapped with a combination of Beulah (coarse-loamy, mixed, active, thermic Typic Dystrudepts), Mcrory (fine-loamy, mixed, active, thermic Albic Glossic Natraqualfs), and Tuckerman (fine-loamy, mixed, active, thermic

Typic Endoaqualfs) soil series with sandy-loam surface textures.

2.2. Treatments and Experimental Design

Poultry litter rates of 4.49, 6.73, and 8.97 $Mg \cdot ha^{-1}$ (*i.e.*, 2, 3, and 4 $T \cdot ac^{-1}$, respectively) were applied annually at Haigwood. Poultry litter rates of 2.24, 3.36, 4.49, and 5.61 $Mg \cdot ha^{-1}$ (1, 1.5, 2, and 2.5 $T \cdot ac^{-1}$, respectively) were applied annually at Distretti. Poultry litter rates of 2.24, 4.49, 6.73, and 8.97 $Mg \cdot ha^{-1}$ (1, 2, 3, and 4 $T \cdot ac^{-1}$, respectively) were applied annually at Burris. With inconsistent PL rates and cropping systems among the three farm locations, measured response variables were analyzed separately by farm assuming a completely random design for PL treatments at each farm location.

2.3. Soil Sampling and Processing

One set of soil samples was collected at the beginning of the project in each field to characterize initial soil properties. Multiple soil samples were collected manually with a 2-cm-diameter push probe from the top 10 cm of each 0.4-ha (1 acre) block in each field and combined for one composite sample per 0.4-ha block from each field. Locations were sampled on 27 October 2021 (Haigwood), 9 April 2021 (Burris), and 16 March 2022 (Distretti). Samples were oven-dried at 70˚C for 48 hr, ground, and sieved through a 2-mm mesh screen for soil property determinations.

Sand, silt, and clay percentages were determined with a modified 12-hour hydrometer procedure [18]. For soil pH, a 1:2 soil mass: water volume suspension was prepared and measured potentiometrically [19]. Soil organic matter was measured via loss-on-ignition. Mehlich-3-extractable soil nutrients [*i.e.*, Ca, magnesium (Mg), and iron (Fe)] were extracted in a 1:10 soil mass:extractant volume suspension, filtered [20], and analyzed by inductively coupled, argon-plasma spectrometry (Spectro Arcos ICP, Spectro Analytical Instruments, Inc. Wilmington, MA [15].

A second set of soil core samples was collected with a 4.8-cm-inside-diameter, stainless steel core chamber and slide hammer from the top 10 cm at five random locations within each PL treatment. Haigwood samples were collected in June 2022 and again in October 2024. Distretti samples were collected in June 2022 and again in July 2024. Burris samples were collected in July 2022 and again in October 2024. Samples were oven-dried at 70˚C for 48 hr and weighed for bulk density determination.

A third separate set of soil core samples was collected for aggregate stability from five random locations within each PL treatment. Following similar recent procedures [13] [15]-[17], a 7.4-cm-inside-diameter, stainless steel core chamber with no inner sleeve, and a slide hammer were used to collect an intact core from the top 10 cm. Each soil core was divided into 0- to 5- and 5- to 10-cm depths. Samples for the Haigwood fields were collected in June 2022 and again in November 2024. At Distretti, intact cores from all fields were collected in June 2022 and again in 2024, where two fields were sampled in July 2024, while the other two fields were sampled in October 2024. At Burris, all samples were collected initially in July 2022 and again in October 2024. All aggregate stability samples were manually moist-sieved through a 6-mm mesh screen, then air-dried at room temperature (*i.e.*, ~21˚C) for 7 days. All soil samples were collected at random locations throughout the PL-rate treatment area at each location.

Water-stable aggregates were determined according to original procedures of Yoder [21] and more recent procedures used by Brye *et al.* [15], Lebeau *et al.* [14], and Anderson *et al.* [10]. Approximately 150 (±0.1) g of air-dry soil were placed into a 5-sieve nest of decreasing mesh size (*i.e.*, >4, 2 - 4, 1 - 2, 0.5 - 1, and 0.25 - 0.5 mm) that was suspended in a wet-sieve apparatus. The wet-sieve apparatus mechanically oscillated at a rate of 15 oscillation per 30 sec, which was set to run for 5 min. At the end of the 5 min, the 5-sieve nest was removed from the wet-sieve apparatus, the sieves were separated, and the soil that remained on top of each sieve was transferred into a pre-weighed aluminum tray. The aluminum trays were left for at least 30 min to allow the suspended soil to settle. Excess water in each tray was decanted before being oven-dried at 70˚C for 24 hours. After 24 hr, each tray was weighed. Trays that held the soil from the 4- and 2-mm sieves were manually processed to pick out the >2-mm coarse fragments, which were weighed, and the mass was subtracted from the mass of the oven-dry soil aggregates. The WSA concentration ($g \cdot g^{-1}$) was determined for each aggregate-size class, on a sample-by-sample basis to retain replication, by dividing the oven-dry soil mass retained on each sieve by the initial soil mass. Total WSA concentration ($g \cdot g^{-1}$) was calculated as the sum of the WSA concentrations >0.25 mm on a sample-by-sample basis to retain replication.

2.4. Statistical Analyses

Based on a completely random design, using the PROC GLIMMIX procedure in SAS (version 9.4, SAS Institute, Inc.), a one-factor analysis of variance (ANOVA) was conducted to evaluate the effect of PL rate on initial soil properties (*i.e.*, sand, silt, clay, SOM, pH, and Mehlic-3-extractable soil Ca, Mg, and Fe) separately by farm location. A gamma distribution was used for all initial soil properties.

Similar to recent procedures by Fanning *et al.* [17], a one-factor ANOVA was also conducted in SAS to evaluate the effect of PL treatment on the change in soil bulk density over time, which was calculated as the 2024 measurement minus the 2022 measurement, such that a positive result represented an increase, while a negative result represented a decrease, over time. A three-factor ANOVA conducted to evaluate the effects of PL treatment, soil depth (*i.e.*, 0 - 5 and 5 - 10 cm), aggregate-size class (*i.e.*, 0.25 - 0.5, 0.5 - 1, 1 - 2, 2 - 4, and >4 mm), and their interactions on the change in WSA concentration over time [17]. In addition, a two-factor ANOVA was conducted to evaluate the effects of PL treatment, soil depth, and their interaction on TWSA concentration change over time [17]. All statistically evaluated response variables representing changes over time, for which the values could be positive or negative, were analyzed with a normal distribution. For all analyses, significance was judged at $P \leq 0.05$. When appropriate, means were separated by least significant difference at the 0.05 level.

3. Results and Discussion

3.1. Initial Soil Properties

Several soil properties at each of the three farms differed ($P < 0.05$) among pre-assigned PL rates before PL was applied (Table 1). At Haigwood, SOM concentration, pH, and Mehlich-3-extractable soil Ca and Fe in the top 10 cm differed among pre-assigned PL rates (Table 1). Soil organic matter concentration was greater in the pre-assigned 4.49 than in the pre-assigned 6.73 and 8.97 Mg PL ha^{-1} treatments, while SOM concentration was also greater in the 6.73 than in the 8.97 Mg PL ha^{-1} treatment (Table 1). Soil pH and Mehlich-3-extractable soil Ca were greater in the pre-assigned 8.97 than in the pre-assigned 4.49 and 6.73 Mg PL ha^{-1} treatments, which did not differ (Table 1). Mehlich-3-extractable soil Fe was greater in the pre-assigned 6.73 and 8.97, which did not differ, than in the pre-assigned 4.49 Mg PL ha^{-1} treatment (Table 1). In contrast, sand, silt, and clay and Mehlich-3-extractable soil Mg did not differ among pre-assigned PL rates at Haigwood (Table 1).

Table 1. Analysis of variance summary of the initial (2021 or 2022) soil properties in the top 10 cm at three locations in eastern Arkansas in pre-assigned poultry-litter (PL)-rate treatment areas.

Location	PL rate (Mg·ha^{-1})	Sand (g·g^{-1})	Silt (g·g^{-1})	Clay (g·g^{-1})	SOM† (%)	pH	M3 Ca† (mg·kg^{-1})	M3 Mg† (mg·kg^{-1})	M3 Fe† (mg·kg^{-1})
Haigwood	4.49	11.8a††	61.1a	27.2a	2.4a	5.86a	1620a	276.9a	157.7b
	6.73	11.5a	59.5a	29.0a	2.2b	5.89a	1611a	265.3a	183.4a
	8.97	14.5a	58.0a	27.5a	1.8c	5.43b	1245b	267.1a	188.1a
	P-value	0.40	0.20	0.70	<0.01	<0.01	<0.01	0.37	<0.01
Distretti	2.24	35.1a	61.8c	3.1a	2.0b	7.13a	1267a	102.8c	216.5a
	3.36	27.4b	68.6b	4.0a	1.8c	6.94a	1049a	72.8d	207.2a
	4.49	22.4c	74.3a	3.3a	2.3a	5.95b	789.5b	155.0a	248.0a
	5.61	25.7bc	69.9ab	4.4a	1.7c	6.15b	615.2c	126.2b	186.4a
	P-value	<0.01	<0.01	0.19	<0.01	<0.01	<0.01	<0.01	0.17
Burris	2.24	88.1a	8.6c	3.3a	-	5.89a	383.6b	67.6b	127.6b
	4.49	85.7a	12.1ab	2.2a	-	6.01a	509.8a	81.0a	119.4b
	6.73	86.1a	11.7b	2.2a	-	5.69b	374.8b	58.1b	118.1b
	8.97	81.1b	14.9a	3.8a	-	5.58b	379.5b	64.0b	169.1a
	P-value	<0.01	<0.01	0.22	-	<0.01	<0.01	<0.01	<0.01

†SOM, soil organic matter; M3 Ca, Mehlich-3 calcium; M3 Mg, Mehlich-3 magnesium; M3-Fe, Mehlich-3 iron, ††Means in a column within a location with different lower-case letters are different at $P < 0.05$.

Similar to Haigwood, at Distretti, SOM concentration, pH, and Mehlich-3-extractable soil Ca in the top 10 cm differed among pre-assigned PL rates, while, in contrast to Haigwood, sand, silt, and Mehlich-3-extractable soil Mg also differed among pre-assigned PL rates (Table 1). Soil organic matter concentration was greater in the pre-assigned 4.49 than in the other three pre-assigned PL treatments, while SOM concentration was also greater in the 2.24 than in the 3.36 and 5.61 Mg PL ha^{-1} treatments, which did not differ (Table 1). Soil pH was greater in the pre-assigned 2.24 and 3.36, which did not differ, than in the pre-assigned 4.49 and 5.61 Mg PL ha^{-1} treatments, which did not differ (Table 1). Mehlich-3-extractable soil Ca was greater in the pre-assigned 2.24 and 3.36, which did not differ, than in the other two pre-assigned PL treatments, while Mehlich-3-extractable soil Ca was also greater in the 4.49 than in the 5.61Mg PL ha^{-1} treatments (Table 1). Mehlich-3-extractable soil Mg differed among all four pre-assigned PL treatments, with: 4.49 > 5.61 > 2.24 > 3.36 Mg·ha^{-1} (Table 1). Sand concentration was greater in the pre-assigned 2.24 than in the other three pre-assigned PL treatments, while sand concentration was also greater in the pre-assigned 3.36 than in the 4.49 Mg·ha^{-1}, where sand in the 5.61 was intermediate and was similar to both the pre-assigned 3.36 and 4.49 Mg·ha^{-1} PL treatments (Table 1). Silt concentration was greater in the pre-assigned 4.49 and 5.61, which did not differ, than in the pre-assigned 2.24 Mg·ha^{-1} treatment, while silt in the 3.36 was also greater than in the 2.24, but was similar to that in the 5.61 Mg·ha^{-1} PL treatment (Table 1). In contrast, clay and Mehlich-3-extractable soil Fe did not differ among pre-assigned PL rates at Distretti (Table 1).

Similar to Distretti, at Burris, sand, silt, pH, and Mehlich-3-extractable soil Ca and Mg in the top 10 cm differed among pre-assigned PL rates, while, in contrast to Distretti, Mehlich-3-extractable soil Fe also differed among pre-assigned PL rates (Table 1). At Burris, sand concentration was greater in the pre-assigned 2.24, 4.49, 6.73, which did not differ, than in the pre-assigned 8.97 Mg PL ha^{-1} treatments (Table 1). Silt concentration was greater in the pre-assigned 4.49 and 8.97, which did not differ, than in the pre-assigned 2.24 Mg PL ha^{-1} treatment, while silt concentration was also greater in the 6.73 than in the 2.24 Mg PL ha^{-1} treatment, but was similar to that in the 4.49 Mg PL ha^{-1} treatment (Table 1). Soil pH was greater in the pre-assigned 2.24 and 4.49, which did not differ, than in the pre-assigned 6.73 and 8.97 Mg PL ha^{-1} treatments, which did not differ (Table 1). Mehlich-3-extractable soil Ca and Mg were both greater in the pre-assigned 4.49 than in the pre-assigned 2.24, 6.73, and 8.97 Mg PL ha^{-1} treatments, which did not differ (Table 1). Mehlich-3-extractable soil Fe was greater in the pre-assigned 8.97 than in the pre-assigned 2.24, 4.49, and 6.73 Mg PL ha^{-1} treatments, which did not differ (Table 1).

Since there were some differences in initial soil properties among fields/treatment areas, the change over time was calculated and statistically analyzed for soil bulk density, WSA, and TWSA. Analyzing and presenting change-over-time results allows any identified treatments differences to be attributable to actual PL treatments rather than being confounded by the various differences in initial soil properties.

3.2. Change in Bulk Density over Time

The change in bulk density over time in the top 10 cm differed ($P < 0.02$) among PL rates at Haigwood and Distretti, but the change in bulk density over time was unaffected ($P = 0.76$) by PL rate at Burris (Table 2). At Haigwood, soil bulk density in the two largest PL rates (*i.e.*, 6.73 and 8.97 Mg·ha^{-1}) decreased over time and did not differ between one another, while bulk density did not change over time in the lowest PL rate (*i.e.*, 4.94 Mg·ha^{-1}; Table 2).

Table 2. Analysis of variance summary of the effect of poultry litter (PL) rate on the change in soil bulk density (ΔBD) in the top 10 cm over time (2022 to 2024) at three locations in eastern Arkansas.

Location	PL Rate (Mg·ha^{-1})	ΔBD† (g·cm^{-3})
Haigwood	4.49	0.02 a
	6.73	−0.25 b*
	8.97	−0.38 b*
	P-value	<0.01
Distretti	2.24	−0.09 b
	3.36	0.12 a
	4.49	−0.10 b
	5.61	0.13 a*
	P-value	0.02
Burris	2.24	−0.08 a
	4.49	−0.13 a
	6.73	0.40 a
	8.97	−0.11 a
	P-value	0.76

†Means within a location with different lower-case letters are different at $P < 0.05$. * Asterisks (*) indicate a significant change over time (*i.e.*, a positive value indicates an increase and a negative value indicates a decrease over time).

At Distretti, soil bulk density in the largest PL rate (*i.e.*, 5.61 Mg·ha^{-1}) increased over time and was similar to the change from the second smallest PL rate (*i.e.*, 3.36 Mg·ha^{-1}), which did not change over time (Table 2). Soil bulk density did not change over time in the other two PL rates (*i.e.*, 2.24 and 4.49 Mg·ha^{-1}), which was similar to one another and was lower than from the 3.36 and 5.61 Mg·ha^{-1} PL rates (Table 2). At Burris, soil bulk density did not change over time and did not differ among any of the four PL rates (Table 2).

Soil bulk density decreased over time in the two largest PL rates at Haigwood, which aligned with the hypothesis that the addition of PL will decrease bulk density and increase soil porosity. Soil bulk density in the lowest PL rate treatment (4.49 $Mg \cdot ha^{-1}$) at Haigwood likely did not change over time due to having the largest initial SOM concentration among the three fields (**Table 1**), suggesting that not enough PL was applied to significantly affect soil bulk density with an already-large SOM concentration. Results of the current study were similar to that of Brye *et al.* [7], who concluded that greater PL rate applications (*i.e.*, >4 $Mg \cdot ha^{-1}$) are needed to reduce bulk density in silt-loam soils in the Lower Mississippi River Valley region of eastern Arkansas. Similarly, Tisdall and Oades [5] concluded that, in soils with initially large SOM concentrations, adding polysaccharides to soil, such as PL, would be ineffective.

Contrary to that hypothesized, soil bulk density increased over time at Distretti in the largest PL treatment (**Table 2**), but the low initial soil Ca concentration was likely a contributing factor. Lime (*i.e.*, calcium carbonate) additions are generally known to promote flocculation and aggregation [22]. However, low soil Ca levels can potentially lead to deflocculation and dis-aggregation [22] [23], also potentially leading to decreased porosity and increased bulk density, as was measured in the current study. In contrast, soil bulk density decreased more in the 2.24 and 4.49 than in the 3.36 $Mg \cdot ha^{-1}$ PL rate (**Table 2**), likely due to the larger initial Mg and Fe concentrations in the 2.24 and 4.49 Mg PL ha^{-1} treatment areas (**Table 1**). Results of the current study reflect results from Chaudhari *et al.* [24], where the increase in secondary macronutrients, such as Ca, Mg and Fe, contributed to decreased soil bulk density from improved soil structure. However, the lack of change in bulk density over time in the 2.24, 3.36 and 4.49 Mg PL ha^{-1} treatments were similar to Brye *et al.* [25], who reported that bulk density was unaffected even with increased Mg and Fe concentrations in loamy soils of northeastern Arkansas.

The lack of PL treatment effects on bulk density at Burris was likely due to the sandy soil-surface texture (*i.e.*, >80%) in the top 10 cm among all four PL-treatment areas (**Table 1**). A sandy texture is generally not conducive to flocculation or aggregation, as sand particles do not possess charged surfaces, thus do not possess requisite Van der Waal forces that could otherwise contribute to binding other soil particles together [26].

3.3. Change in Water-Stable Aggregates over Time

The change in WSA concentration over time was affected ($P < 0.02$) by one or more of the treatment factors evaluated (*i.e.*, PL rate, soil depth, and/or aggregate-size class; **Table 3**). At Haigwood, the change in WSA concentration was unaffected by PL rate but differed among soil depth-size-class combinations (**Table 3**). Averaged across PL rates, WSA concentration increased over time in the 0.25 - 0.5 mm/5 - 10 cm, 0.5 - 1 mm/5 - 10 cm, and >4 mm/0 - 5 cm combinations, which did not differ among one another and did not differ from the change in WSA in the 1 - 2 mm size class in both soil depths (**Figure 2**). Water-stable aggregate concentration did not change over time in all other soil depth-size-class combinations

(Figure 2). The change in WSA was greater in the 5 - 10 than in the 0 - 5 cm depth in the 0.25 - 0.5- and 0.5 - 1-mm size classes, while the change in WSA was unaffected by soil depth in the other three size classes (Figure 2).

Table 3. Analysis of variance summary of the effects of poultry litter (PL) rate, soil depth (Depth), aggregate size class (Class), and their interactions on the change in water-stable-aggregate concentration over time (2022 to 2024) at three locations in eastern Arkansas.

Source of Variation	Location		
	Haigwood	Distretti	Burris
		P	
PL rate	0.19	<0.01	0.76
Depth	0.05	0.4	0.33
Size class	0.96	<0.01	<0.01
PL rate × depth	0.60	0.45	0.09
PL rate × size class	0.72	<0.01	0.63
Depth × size class	<0.01	0.02	0.43
PL rate × depth × size class	0.74	0.48	0.79

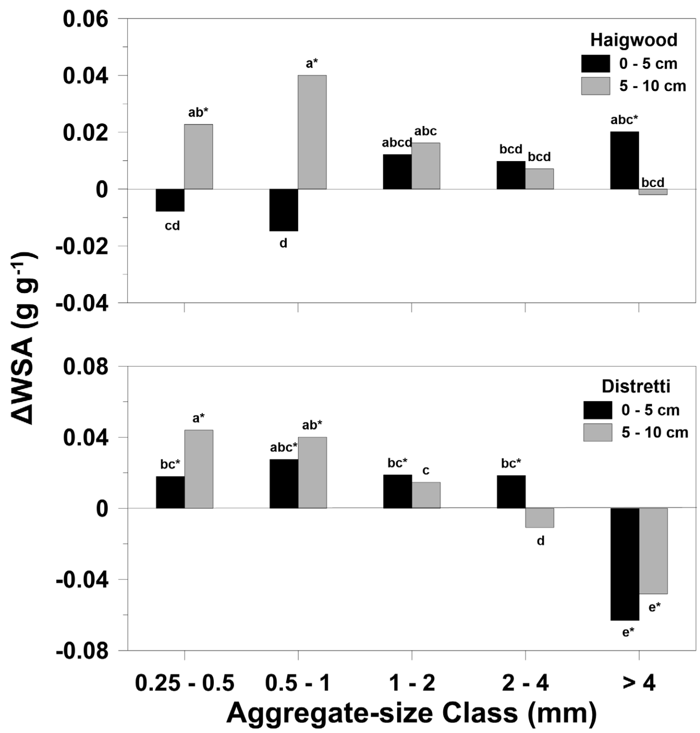

Figure 2. Change in water-stable aggregate (ΔWSA) concentration over time as affected by soil depth and aggregate-size class for the Haigwood and Distretti Farms in northeast Arkansas. Different letters associated with bars within a panel are different at $P \leq 0.05$. An asterisk (*) indicates that the change was significantly different ($P \leq 0.05$) from a change of 0.

Similar to Haigwood, averaged across PL rates, at Distretti, WSA concentration increased the most over time in the 0.25 - 0.5 mm/5 - 10 cm and 0.5 - 1 mm/0 - 5 and 5 - 10 cm depths, which did not differ, while WSA concentration did not change over time in the 1 - 2 mm/5 - 10 and 2 - 4 mm/5 - 10 cm combinations (**Figure 2**). Water-stable aggregate concentration also increased over time in the 0.25 - 0.5 mm/0 - 5, 1 - 2 mm/0 - 5, and 2 - 4 mm/0 - 5 cm combinations, which did not differ, and were similar to that in the 0.5 - 1 mm/0 - 5 and 5 - 10 cm combinations (**Figure 2**). The change in WSA was greater in the 5 - 10 than in the 0 - 5 cm depth only in the 0.25 - 0.5 mm size classes, while the change in WSA was greater in the 0 - 5 than in the 5-10 cm depth only in the 2 - 4 mm size classes and was unaffected by soil depth in the other three size classes (**Figure 2**). In contrast to the other four size classes, WSA concentration decreased over time only in the > 4 mm/0 - 5 and 5 - 10 cm, which did not differ (**Figure 2**).

Table 4. Summary of the combined effects of poultry litter rate and aggregate-size class on the change in water-stable aggregate (ΔWSA) concentration over time (2022 to 2024) at one location (Distretti) in eastern Arkansas.

Poultry Litter Rate ($Mg \cdot ha^{-1}$)	Aggregate-size Class (mm)	ΔWSA† ($g \cdot g^{-1}$)
2.24	0.25 - 0.5	0.005 def
	0.5 - 1	0.041 bc*
	1 - 2	0.033 bcd*
	2 - 4	0.035 bcd*
	>4	−0.062 g*
3.36	0.25 - 0.5	0.008 cdef
	0.5 - 1	0.004 def
	1 - 2	−0.012 ef
	2 - 4	−0.014 ef
	> 4	−0.063 g*
4.49	0.25 - 0.5	0.015 bcde
	0.5 - 1	0.049 b*
	1 - 2	0.043 b*
	2 - 4	0.017 bcde
	> 4	−0.024 f
5.61	0.25 - 0.5	0.096 a*
	0.5 - 1	0.041 bc*
	1 - 2	0.004 def
	2 - 4	−0.022 f
	> 4	−0.074 g*

† Means in the column with different lower-case letters are different at $P < 0.05$, * Asterisks (*) indicate a significant change over time (*i.e.*, a positive value indicates an increase and a negative value indicates a decrease over time).

In addition, and in contrast to Haigwood and Burris, the change in WSA over time at Distretti differed among PL rate-size-class combinations (Table 4). Averaged across soil depths, the change in WSA concentration was most positive in the smallest aggregate-size class (*i.e.*, 0.25 - 0.5 mm) with the largest PL rate (*i.e.*, 5.61 Mg·ha^{-1}). The most negative change in WSA concentration occurred in the >4 mm size class with the largest PL rate, which did not differ from the change in WSA concentration in the >4 mm size class with the two lowest PL rates (Table 4).

The WSA concentrations increased over time in the 0.5 - 1, 1 - 2 mm, and 2 - 4 mm size classes with the 2.24 Mg·ha^{-1} PL rate, increased over time in the 0.5 - 1- and 1 - 2-mm size classes with the 4.49 Mg·ha^{-1} PL rate, and increased over time in the 0.25 - 0.5 and 0.5 - 1 mm size classes with the 5.61 Mg·ha^{-1} PL rate (Table 4). In contrast, WSA concentration decreased over time in the >4 mm size class with the 2.24, 3.36, and 5.61 Mg·ha^{-1} PL rates (Table 4). The WSA concentration did not change over time for all other PL-rate/size-class combinations (Table 4).

In contrast to Haigwood and Distretti, at Burris, the change in WSA differed among aggregate-size classes only but was unaffected by PL rate and soil depth (Figure 3). Averaged across PL rate and soil depth, WSA concentrations decreased over time in the >4 mm size class and was similar to that in the 0.5 - 1 mm size class, while, in all other size classes, WSA concentration did not change over time and was similar to one another (Figure 3).

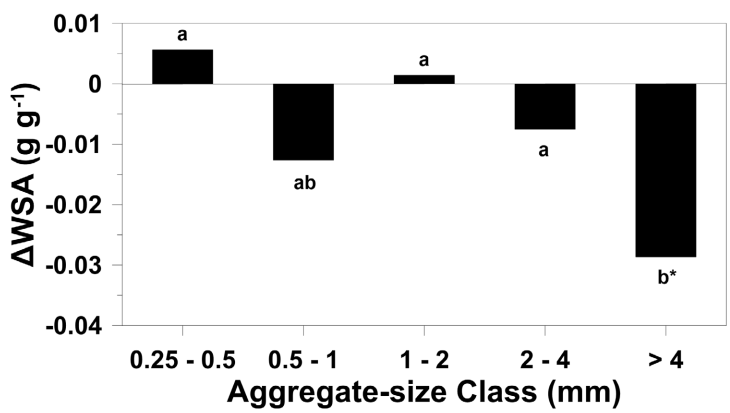

Figure 3. Change in water-stable aggregate (ΔWSA) concentration over time as affected by aggregate-size class for the Burris Farm in northeast Arkansas. Different letters associated with bars are different at $P \leq 0.05$. An asterisk (*) indicates that the change was significantly different ($P \leq 0.05$) from a change of 0.

In contrast to that hypothesized, WSA concentrations were unaffected by PL rate at Haigwood, likely due to the initially large SOM and clay concentrations at Haigwood (Table 1) that impacted greater effects on WSA than the three consecutive years of PL addition. Similar to Tisdall and Oades [5], the application of polysaccharides in organic materials, like those in PL, to soils with already-large SOM concentrations tend to be less effective than when applied to low-SOM soils. Water-stable aggregate concentrations also increased over time in the two smallest aggregate size-classes in the 5 - 10 cm depth at Haigwood, likely as at least a partial result of slaking due to the flood- and furrow-irrigation management [23]. In contrast, flood- and furrow-irrigation management likely contributed to the increase in WSA concentration over time in the largest aggregate-size class in the 0 - 5 cm depth at Haigwood, as Igwe and Stahr [27] and Watanabe and Furusaka [28] both concluded that microbial activity increases after flooding or water-logged conditions cease. After consistent wetted conditions, microbial activity tends to thrive and increase aggregate stability [27]. Naylor *et al.* [29] and Anders *et al.* [30] also reported that microbial activity is more prominent near the soil surface. At Distretti, WSA concentrations increased over time the most in the smaller aggregate-size classes as a result of the largest aggregate size class breaking down and creating the smaller aggregate-size classes [31].

At Burris, WSA concentrations were unaffected by PL rates, likely due to the sandy surface texture (*i.e.*, >80%) in the top 10 cm among all four PL-treatment areas. As Amezketa [23] explained, for aggregation to occur, clay particles are needed to facilitate flocculation and aggregation. Aggregation is also promoted with SOM and soil Ca, Mg, and/or Fe, depending on the soil pH [23]. Though SOM was not measured and formal comparison of initial soil properties among the three research locations was not conducted, the four strips in one field at Burris generally had numerically lower initial extractable soil Ca, Mg, and Fe in the top 10 cm compared to the other two locations (**Table 1**). The extractable soil nutrients act as binding agents for particles within the soil to promote flocculation, but with little to no physical and/or chemical binding agents in the soil, soil aggregation tends to be low [5]. The large proportion of sand particles in the top 10 cm at the

Burris sites lacked the ability to form coherent and stable soil aggregates due to sand particles' inability to bind with each other without the sufficient presence of other binding agents, such as clay particles, OM, and Fe, Ca, and/or Mg. Consequently, sandy soils tend to be inherently less responsive to aggregate-promoting soil amendments, such as PL, compared to other loamy soils.

3.4. Change in Total Water-Stable Aggregates over Time

The change in TWSA concentration was unaffected by soil depth ($P > 0.05$) at all three locations, but, at Distretti, the change in TWSA concentration differed ($P = 0.02$) among PL rates (**Table 5**; **Figure 4**). At Burris, the change in TWSA concentration did not differ among PL rates and did not change over time (**Figure 4**). Similar to Burris, at Haigwood, the change in TWSA concentration did not differ among PL rates, but, in contrast to Burris, TWSA increased over time in the 4.49 $Mg \cdot ha^{-1}$ PL rate (**Figure 4**). In contrast to Burris and Haigwood, at Distretti, the change in TWSA concentration was largest among the 2.24, 4.49, and 5.61 $Mg \cdot ha^{-1}$ PL rates, which did not differ, but TWSA increased over time only in the 4.49 $Mg \cdot ha^{-1}$ PL rate, while TWSA decreased over time in the 3.36 $Mg \cdot ha^{-1}$ PL rate (**Figure 4**).

Table 5. Analysis of variance summary of the effects of poultry litter (PL) rate, soil depth (Depth), and their interactions on the change in total-water-stable-aggregate concentration over time (2022 to 2024) at three locations in eastern Arkansas.

Source of Variation	Location		
	Haigwood	Distretti	Burris
		P	
PL rate	0.36	0.02	0.90
Depth	0.12	0.60	0.89
PL rate × depth	0.72	0.69	0.38

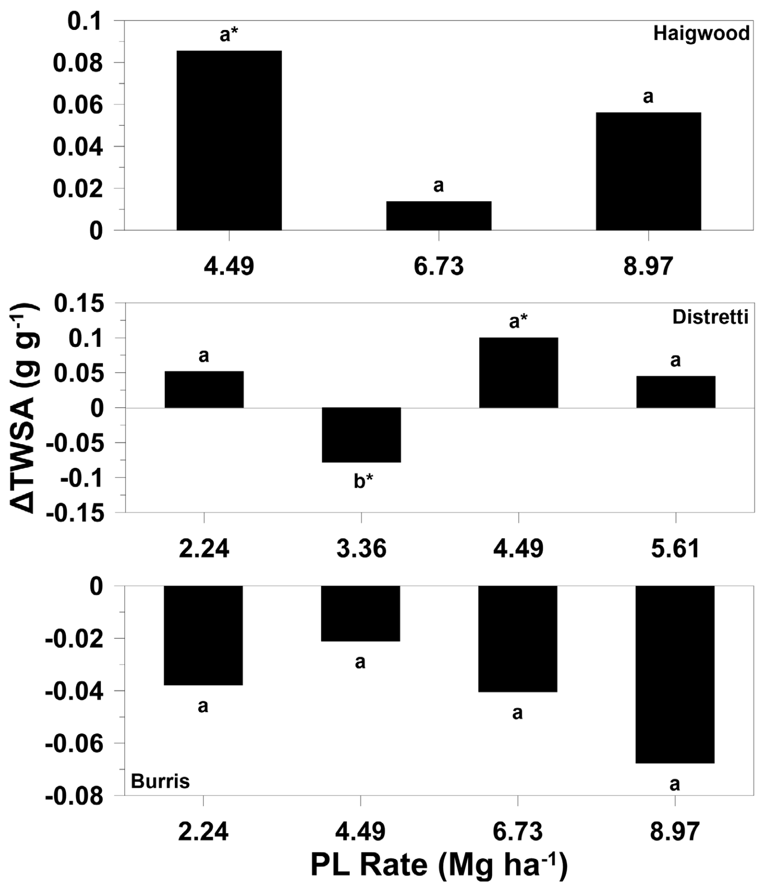

Figure 4. Change in total water-stable aggregate (ΔTWSA) concentration over time as affected by poultry litter (PL) rate for the Haigwood, Distretti, and Burris Farms in northeast Arkansas. Different letters associated with bars within a panel are different at $P \leq 0.05$. An asterisk (*) indicates that the change was significantly different ($P \leq 0.05$) from a change of 0.

The increase in TWSA over time in the 4.49 Mg·ha^{-1} PL rate at Haigwood can likely be explained by the summation of the individual WSA concentrations among the five aggregate-size classes. Even though the WSA concentration in the individual size classes did not change over time, the accumulation of WSA among the individual size classes was enough to change the TWSA concentration [10].

At Distretti, TWSA concentration decreasing over time in the 3.36 Mg·ha^{-1} PL rate, while increasing over time in the 4.49 Mg·ha^{-1} PL rate, reflects WSA concentrations among individual aggregate-size classes. Within the 3.36 Mg·ha^{-1} PL treatment, when significant, WSA concentrations only decreased over time, while, within the 4.49 Mg·ha^{-1} PL treatment, when significant, WSA concentrations only increased over time at Distretti (**Table 4**). In silt-loam soils across several ecosystems in eastern Arkansas, Anderson *et al.* [10] showed that TWSA reflected the trends in individual WSA concentrations among individual aggregate-size classes. Similar to bulk density and WSA concentrations, at Burris, TWSA did not differ among PL treatments or change over time due to the sandy soil-surface texture (**Table 1**), where sandy soils generally have few colloidal surfaces for binding silt and clay particles and SOM [26].

4. Conclusions

This study evaluated the effects of various PL rates on the change in soil bulk density and WSA concentration over time at three different locations with loamy soils in eastern Arkansas. Similar to that hypothesized, soil bulk density in the top 10 cm decreased over time in the two largest PL-rate treatments at one location (Haigwood). However, in contrast to that hypothesized, soil bulk density increased over time in the largest PL-rate treatment at a second location (Distretti), while at the third location (Burris), soil bulk density did not change over time and was unaffected by PL rate.

Contrary to that hypothesized, WSA concentrations only differed among soil depth-size-class combinations at one location (Haigwood) and were unaffected by PL rate at two locations (Haigwood and Burris). However, similar to that hypothesized, at a second location (Distretti), WSA concentration decreased over time in the largest aggregate-size classes, while increased over time in the smaller aggregate-size classes. Similar to that hypothesized, TWSA concentration increased over time in select aggregate-size classes at two locations (Haigwood and Distretti), but, in contrast to that hypothesized, was unaffected by PL rate at the third location (Burris). Poultry litter application affected TWSA concentrations more than WSA concentrations among aggregate-size classes, partially supporting the original hypothesis, thus demonstrating the benefit of PL as an organic soil amendment on soil structure. Furthermore, differential PL application rates can affect WSA concentrations in a little as two years demonstrating WSA as a dynamic soil property.

Acknowledgements

The authors gratefully acknowledge the specific producers who were willing to allow this research to occur on their farms.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Morgan, R.P.C. (2005) Soil Erosion and Conservation. 3rd Edition, National Soil Resources Institute and Cranfield University.

[2] Bhattacharyya, S.S., Leite, F.F.G.D., France, C.L., Adekoya, A.O., Ros, G.H., de Vries, W., *et al*. (2022) Soil Carbon Sequestration, Greenhouse Gas Emissions, and Water Pollution under Different Tillage Practices. *Science of the Total Environment*, **826**, Article 154161. https://doi.org/10.1016/j.scitotenv.2022.154161

[3] Lv, L., Gao, Z., Liao, K., Zhu, Q. and Zhu, J. (2023) Impact of Conservation Tillage on the Distribution of Soil Nutrients with Depth. *Soil and Tillage Research*, **225**, Article 105527. https://doi.org/10.1016/j.still.2022.105527

[4] Udom, B.E., Nuga, B.O. and Adesodun, J.K. (2016) Water-Stable Aggregates and Aggregate-Associated Organic Carbon and Nitrogen after Three Annual Applications of Poultry Manure and Spent Mushroom Wastes. *Applied Soil Ecology*, **101**, 5-10. https://doi.org/10.1016/j.apsoil.2016.01.007

[5] Tisdall, J.M. and Oades, J.M. (1982) Organic Matter and Water-Stable Aggregates in Soils. *Journal of Soil Science*, **33**, 141-163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

[6] McMullen, R.L., Brye, K.R. and Gbur, E.E. (2015) Soil Respiration as Affected by Long-Term Broiler Litter Application to Adult in the Ozark Highlands. *Journal of Environmental Quality*, **44**, 115-126. https://doi.org/10.2134/jeq2014.05.0223

[7] Brye, K.R., Slaton, N.A., Norman, R.J. and Savin, M.C. (2004) Short-Term Effects of Poultry Litter Form and Rate on Soil Bulk Density and Water Content. *Communications in Soil Science and Plant Analysis*, **35**, 2311-2325. https://doi.org/10.1081/lcss-200030655

[8] United States Department of Agriculture (USDA) (2024) Broiler Production by State Million Head, 2024, National Agricultural Statistics Service. https://www.nass.usda.gov/Charts_and_Maps/Poultry/brlmap.php

[9] Li, Y., Feng, G., Tewolde, H., Zhang, F., Yan, C. and Yang, M. (2020) Soil Aggregation and Water Holding Capacity of Soil Amended with Agro-Industrial Byproducts and Poultry Litter. *Journal of Soils and Sediments*, **21**, 1127-1135. https://doi.org/10.1007/s11368-020-02837-3

[10] Anderson, R., Brye, K.R. and Wood, L.S. (2019) Soil Aggregate Stability as Affected by Landuse and Soil Properties in the Lower Mississippi River Valley. *Soil Science Society of America Journal*, **83**, 1512-1524. https://doi.org/10.2136/sssaj2019.05.0139

[11] Brye, K.R., Golden, B. and Slaton, N.A. (2006) Poultry Litter Decomposition as Affected by Litter Form and Rate before Flooding for Rice Production. *Soil Science Society of America Journal*, **70**, 1155-1167. https://doi.org/10.2136/sssaj2005.0201

[12] Motschenbacher, J.M., Brye, K.R., Anders, M.M., Gbur, E.E., Slaton, N.A. and Evans-White, M.A. (2013) Rice Rotation and Tillage Effects on Water-Stable Soil Macroaggregates and Their Associated Carbon and Nitrogen Contents in a Silt-Loam Soil. *Soil Science*, **178**, 596-611. https://doi.org/10.1097/ss.0000000000000028

[13] Smith, S.F., Brye, K.R., Gbur, E.E., Chen, P. and Korth, K. (2014) Residue and Water Management Effects on Aggregate Stability and Aggregate-Associated Carbon and Nitrogen in a Wheat-Soybean, Double-Crop System. *Soil Science Society of America Journal*, **78**, 1378-1391. https://doi.org/10.2136/sssaj2013.12.0534

[14] Lebeau, S., Brye, K.R., Daniels, M.B. and Wood, L.S. (2023) Cover Crop Effects on Infiltration, Aggregate Stability, and Water Retention in the Lower Mississippi River Valley. *Agrosystems, Geosciences & Environment*, **6**, e20341.

https://doi.org/10.1002/agg2.20341

[15] Brye, J.B., Lunga, D.D., Brye, K.R., Arel, C. and Ylagan, S. (2023) Phosphorus Fertilizer Effects on Near-Surface Soil Aggregation in Furrow-Irrigated Rice on a Silt-Loam Soil. *Agricultural Sciences*, **14**, 819-842. https://doi.org/10.4236/as.2023.146055

[16] Lebeau, S.G., Brye, K.R., Daniels, M. and Wood, L.S. (2024) Cover Crop and Wheel-Track Effects on Soil Properties under Cotton Production in Eastern Arkansas. *Agrosystems, Geosciences & Environment*, **7**, e20549. https://doi.org/10.1002/agg2.20549

[17] Fanning, C., Brye, K.R., Daniels, M., Roberts, T.L., Fernandes, S. and Wood, L. (2025) Cover-Crop Effects on Near-Surface Soil Physical Properties, Infiltration, and Nematodes over Time in the Lower Mississippi River Valley. *Agrosystems, Geosciences & Environment*, **8**, e70119. https://doi.org/10.1002/agg2.70119

[18] Gee, G.W. and Or, D. (2002) Particle Size Analysis. In: Dane, J.H. and Topp, G.C., Eds., *Methods of Soil Analysis, Part* 4, *Physical Methods*, Soil Science Society of America, 255-293.

[19] Harper, T.W., Brye, K.R., Daniel, T.C., Slaton, N.A. and Haggard, B.E. (2008) Land Use Effects on Runoff and Water Quality on an Eastern Arkansas Soil under Simulated Rainfall. *Journal of Sustainable Agriculture*, **32**, 231-253. https://doi.org/10.1080/10440040802170806

[20] Zhang, H., Hardy, D.H., Mylavarapu, R. and Wang, J. (2014) Mehlich-3. In: Sikora, F.J. and Moore, K.P., Eds., *Soil Test Methods from the Southeastern United States, Southern Cooperative Series Bulletin*, University of Georgia, 101-110. https://aesl.ces.uga.edu/sera6/MethodsManualFinalSERA6.pdf

[21] Yoder, R.E. (1936) A Direct Method of Aggregate Analysis of Soils and a Study of the Physical Nature of Erosion Losses. *Agronomy Journal*, **28**, 337-351. https://doi.org/10.2134/agronj1936.00021962002800050001x

[22] Stratford, M. (1989) Yeast Flocculation: Calcium Specificity. *Yeast*, **5**, 487-496. https://doi.org/10.1002/yea.320050608

[23] Amézketa, E. (1999) Soil Aggregate Stability: A Review. *Journal of Sustainable Agriculture*, **14**, 83-151. https://doi.org/10.1300/j064v14n02_08

[24] Chaudhari, P.R., Ahire, D.V., Ahire, V.D., Chkravarty, M. and Maity, S. (2013) Soil Bulk Density as Related to Soil Texture, Organic Matter Content and Available Total Nutrients of Coimbatore Soil. *Journal of Scientific and Research Publication*, **3**, 1-8.

[25] Brye, K.R., Cordes, F. and McKee, M. (2020) Near-Surface Soil Nutrient Changes over Time under Native Prairie and Managed Agriculture in Arkansas. *Natural Resources*, **11**, 243-256. https://doi.org/10.4236/nr.2020.116015

[26] Weil, R.R. and Brady, N.C. (2016) The Nature and Properties of Soils. 15th Edition, Pearson Education Inc.

[27] Igwe, C.A. and Stahr, K. (2004) Water-Stable Aggregates of Flooded Inceptisols from South-Eastern Nigeria in Relation to Mineralogy and Chemical Properties. *Australian Journal of Soil Research*, **42**, 171-179.

[28] Watanabe, I. and Furusaka, C. (1980) Microbial Ecology of Flooded Rice Soils. In: *Advances in Microbial Ecology*, Springer, 125-168. https://doi.org/10.1007/978-1-4615-8291-5_4

[29] Naylor, D., McClure, R. and Jansson, J. (2022) Trends in Microbial Community Composition and Function by Soil Depth. *Microorganisms*, **10**, Article 540. https://doi.org/10.3390/microorganisms10030540

[30] Anders, M.M., Beck, P.A., Watkins, B.K., Gunter, S.A., Lusby, K.S. and Hubbell, D.S. (2010) Soil Aggregates and Their Associated Carbon and Nitrogen Content in Winter Annual Pastures. *Soil Science Society of America Journal*, **74**, 1339-1347. https://doi.org/10.2136/sssaj2009.0280

[31] Puget, P., Chenu, C. and Balesdent, J. (2000) Dynamics of Soil Organic Matter Associated with Particle-Size Fractions of Water-Stable Aggregates. *European Journal of Soil Science*, **51**, 595-605. https://doi.org/10.1111/j.1365-2389.2000.00353.x