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Short-Term Crop Residue Management in No-Tillage Cultivation Effects on Soil Quality Indicators in Virginia

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Abstract: The use of crop residues for biofuel production has the potential to provide environmental and economic benefits to modern societies. Because of the profound impacts that crop residues have on agricultural productivity and soil health, a sustainable utilization of these residues is required. Thus, we determined crop yield and quality response for a range of biomass retention rates in grain cropping systems. Combinations of corn (*Zea mays* L.) stover (0, 3.33, 6.66 and 10 Mgha^{-1}) and wheat (*Triticum aestivum* L.) straw (0, 1.0, 2.0, and 3.0 Mgha^{-1}) were soil applied in a corn-wheat/soybean (*Glycine max* L. Merr.) rotation in Virginia's Coastal Plain. Corn stover (0, 3.33, 6.66, 10 and 20 Mg ha^{-1}) was applied in a continuous corn cropping system in the Ridge/Valley province. For each system, residues were applied following grain harvest over two production cycles. Each experiment was conducted as a randomized complete block design with four replications. Two cycles of crop residue management, with retention rates of up to 20 Mg ha^{-1} of corn stover retention in Blacksburg, and up to 13 Mg ha^{-1} of corn stover and wheat straw in New Kent, had no effect on total nitrogen (TN) and carbon (TC) concentrations, CN ratios, bulk density (BD), soil pH, field capacity, permanent wilting point, plant available water and water aggregate stability across soil depths and aggregate sizes in Virginia. In one situation when residue management slightly affected BD (0–2.5 cm depth, NK1), differences across the sixteen total retained residues treatments were less than 5%, thus rendering them not biologically or environmentally meaningful. Overall, results of this study did not show any clear short-term impact, resulting from various rates of crop residue retention in Virginia cropping systems. These incipient negative impacts resulting from very low rates of residue return warrant further studies to corroborate whether these results are to be found following long-term scenarios of crop residue management.

Keywords: soil quality; residue removal; corn stover; soil organic carbon; total nitrogen

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1. Introduction

Over the last decade, economic and environmental concerns have spurred increased interest in the use of crop residues as sustainable, renewable sources for bioenergy and bio-products [1–4]. Among other advantages, biofuels from lignocellulosic feedstocks have a potential to reduce reliance on imported fossil fuels and the greenhouse gases emissions, while fostering the farm economy and the development of rural communities [5–11]. However, the balance between stover removed and carbon returned to the fields must be considered due to potential increased erosion [12], decreased soil organic matter content and detrimental impacts on other soil quality parameters with stover removal [6,13–17]. Moreover, crop residues can act as both sinks and sources of soil carbon that provide ecosystem services and contribute to agricultural productivity by enhancing soil structure and stability [18,19] through their positive effects on soil organic carbon (SOC) and nitrogen (SON) stocks, nutrient availability, bulk density, water holding capacity and water infiltration [20–28].

Based on the negative effects of corn stover removal on the physical and chemical indicators of soil health, such as soil organic matter (SOM) and SOC, particulate organic matter (POM), total soil carbon (TC) and nitrogen (TN), bulk density, water aggregate stability (WAS), among others, numerous studies suggested that no more than 30% of corn crop residues can sustainably be removed in the US Corn Belt area [24,29–31]. Other less conservative assessments indicate that 30 to 60% of stover removal could be sustainably harvested in the US [30,32–35]. Although the research data from the US Corn Belt provide guarded optimism about residue harvest systems in the Midwest, such practices may not be appropriate for other geophysical regions of the country due to differences in soils, climate and cropping systems. Recent interest from both farmers and bioenergy companies are growing the biomass industry in the Southeastern US with an expectation that cropping systems will supply biomass needed to sustain these new businesses. However, little information is available regarding sustainable crop residue harvest from the Southeast, and the effects of residue removal on soil health parameters remain to be defined [36,37]. Only one study has specifically studied the potential supply and the supply chain of residues in the Southeast [38], but this information provides no specific information to guide producers and industry about sustainable harvest levels for the region. The purpose of this research was to generate regionally relevant information on the short-term impacts of crop residue management on soil quality to help determine whether harvesting wheat straw and corn stover can be a sustainable practice for the region's cropping systems. The objectives of this experiment were to assess/evaluate the short-term impacts of various crop residue removal rates from common mid-Atlantic cropping systems in TC and TN, soil pH, bulk density, field moisture capacity (FC), permanent wilting point (WP) and WAS.

2. Materials and Methods

Three field experiments assessing the impact of crop residue removal were conducted over three years, from 2015 through 2017, in two physiographic regions in Virginia.

2.1. Experiment 1

The experiment was conducted in Blacksburg, Virginia (BB), in the physiographic province known as Valley and Ridge. The Valley and Ridge region is characterized by the presence of sedimentary rocks, including limestone, dolomite and shale [39]. Soils in the experimental site are very deep, well drained, moderately permeable and with high available water in the profile. Soils of this study area are classified as Unison and Braddock loams (fine, mixed semiactive, mesic hapludults), formed from granite, gneiss, schist, sandstone, quartzite and shale alluvium and colluvium parent materials [40]. The slopes range from 2 to 7%.

The experiment utilized a randomized complete block design (RCBD) with five levels of corn stover retention: 0, 3.33, 6.66, 10 and 20 Mg ha^{-1} corn stover retained in a continuous corn (CC) grain rotation (Table 1). Four replicates were established at BB, resulting in a total of 20 experimental units (EU), with 5 EU per replicate. Each EU was 4.6 m wide and 9.1 m long. Residue retention rates were calculated based on reported average grain yields of 8.7 Mg ha^{-1} in Virginia for the period 2011–2017 [41] and corn stover yields were calculated based on a harvest index (HI) of 0.45 [37]. The treatments retaining 0, 3.33, 6.66, 10 and 20 Mg dry matter ha^{-1} corresponded to 0, 33, 66, 100 and 200% of the total stover produced, respectively (Table 1). A detailed timeline chart with the information of each component for both crop rotations and the proposed soil sampling framework time for this location is shown in Figure 1.

Table 1. Residue sources and application rates for a residue management field-based experiment in a continuous corn rotation in Blacksburg, VA.

Treatment	Crop	Stover Retained	Crop	Straw Retained
		Mg ha^{-1}		Mg ha^{-1}
1	Grain Corn	0.00	none	-
2	Grain Corn	3.33	none	-
3	Grain Corn	6.66	none	-
4	Grain Corn	10.00	none	-
5	Grain Corn	20.00	none	-

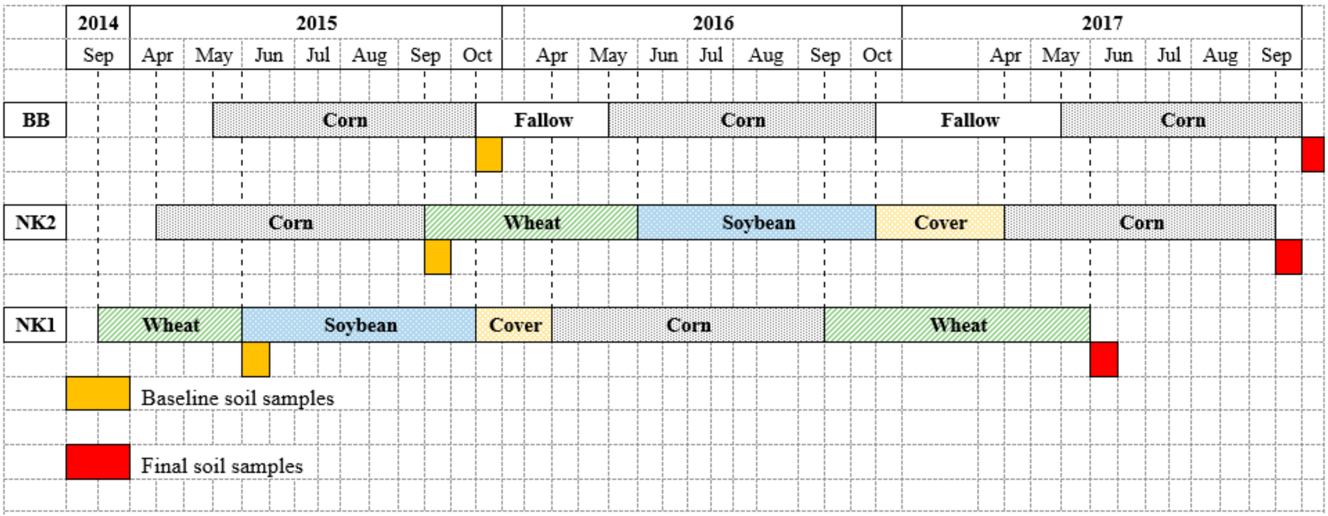

Figure 1. Chronological chart with details of the full crop rotations and soil sampling framework in Blacksburg (BB) and New Kent (NK1 and NK2), VA, USA.

2.2. Experiment 2 and 3

Two experiments were conducted in New Kent, Virginia (NK) in the Coastal Plain region. The Coastal Plain region is composed mostly of unconsolidated deposits such as sand, clay, gravel and shell strata. Experiments were initiated at different crop phases of the same corn—wheat/soybean (CWS) rotation (Figure 1), with one set of residue return treatments initiated in the wheat phase of the rotation in June 2015 (NK1), and another with identical treatments initiated after corn harvest in September 2015 (NK2). Soils in NK1 and NK2 are very deep, well drained, with high available water in profile and were both classified as Altavista sandy loam (fine-loamy, mixed, semiactive, thermic Aquic Hapludults) [40]. Each experiment at NK utilized a RCBD with a factorial arrangement of sixteen treatments, resulting from a combination of four residue retained rates, each for corn (0, 3.33, 6.66 and 10 Mg ha^{-1}) and wheat (0, 1, 2 and 3 Mg ha^{-1}), with soybean residues completely retained in the C-W/S rotation (Table 2). Total annual retained residues from both corn and wheat were also calculated. Four replications were established, resulting in 64 EU per experiment, with 16 EU per replication. Each EU of 4.6 m wide by 9.1 m long and residue retention rates, both for corn and wheat, were calculated as in Experiment 1 based on a HI of 0.45. Treatments retaining 0, 3.33, 6.66 and 10 Mg dry corn stover ha^{-1}, and 0, 1, 2 and 3 Mg dry wheat straw ha^{-1} (Table 2) corresponded to approximately 0, 33, 66 and 100% of the total stover and straw produced, respectively.

Table 2. Residue sources and application rates for residue management field-based experiments NK1 and NK2 in a corn-wheat/soybean rotation in New Kent, VA.

Treatment	Corn Stover †	Wheat Straw ‡	Total Residue ⁋
	Mg ha^{-1}		
1	0.00	0.00	0.00
2	0.00	1.00	1.00
3	0.00	2.00	2.00
4	0.00	3.00	3.00
5	3.33	0.00	3.33
6	3.33	1.00	4.33
7	3.33	2.00	5.33
8	3.33	3.00	6.33
9	6.66	0.00	6.66
10	6.66	1.00	7.66
11	6.66	2.00	8.66
12	6.66	3.00	9.66
13	10.00	0.00	10.00
14	10.00	1.00	11.00
15	10.00	2.00	12.00
16	10.00	3.00	13.00

† Corn stover retained rates either applied in NK2 in September 2015 or in NK1 in September 2016. ‡ Wheat straw retained rates either applied in NK1 in June 2015 or in NK2 in June 2016. ⁋ Total residue resulting from the summation of corn stover and wheat straw residues applied in a 2-year period. Soybean residues, even when part of the rotation, were not considered here.

Management applied to both Blacksburg and New Kent locations, including nutrient and pest control, fertility, plant density and planting and harvesting dates, followed best recommendation practices to optimize corn grain yields for Southwestern Virginia (CC rotation), and corn, wheat and soybean grain yields for Eastern Virginia (CWS rotation), according to Virginia Cooperative Extension Recommendations [42].

2.3. Soil Sampling and Soil Quality Parameters Determination

Baseline soil samples were taken in 2015 on a whole-plot basis at both locations, immediately after allocating the wheat straw treatments in NK1 (mid-June), and the corn stover treatments in NK2 (mid-September) and BB location (mid-October) (yellow boxes at the bottom of each timeline rotation in Figure 1). At this time, six and eleven intact soil cores were taken at three randomly chosen sites at the BB location (i.e., about half the size of each experiment in NK) and at each experiment in the NK location, respectively, from non-trafficked interrow, to a depth of 15-cm.

Soil samples were taken with a bulk density sampler with 5 cm diameter. Baseline soil samples were used to determine baseline routine soil analysis, soil bulk density, TC and TN. Two out of the six 0 to 15 cm depth cores were left intact, air-dried and submitted to the Virginia Tech Soil Testing Lab (https://www.soiltest.vt.edu/) for baseline routine soil analysis determination (Table 3). Briefly, nutrients available for plant uptake were extracted with Mehlich 1 solution (0.05N HCl in 0.025N H_2SO_4) [43] using a 1:5 vol:vol soil to extractant ratio and analyzed using ICP-AES analysis. Soil pH was determined in a 1:1 (vol/vol) ratio of deionized water:soil [44]. Cation exchange capacity (CEC) was estimated by summation of the Mehlich 1 extractable non-acid generating cations (Ca, Mg and K), plus the acidity estimated from the Mehlich soil-buffer pH after the conversion of all analytical results to meq/100 cm^3 or cmol(+)/kg. The remaining four cores were separated in place into 0 to 2.5, 2.5 to 7.5 and 7.5 to 15 cm depth increments as suggested in a prior study conducted in Virginia by Spargo et al. [45]. Samples were air-dried and later used for the determination of bulk density, TC and TN. Bulk density was determined for each soil depth increment as the weight of the intact air-dried soil over the corresponding depth volume. Small soils aliquots were oven dried (105 °C, 24 h) to obtain an air-to-oven dry mass correction factor in order to express values in an oven-dried basis [46]. Following this, air-dried samples were gently crushed and passed through a 2 mm sieve to determine, per each soil depth increment, the TC and TN contents. Total soil organic C and total N were determined in duplicate after the dry combustion of soil subsamples (between 1 to 1.5-g) that were first ground to a powder with an automatic mortar and pestle machine for 3 min and then analyzed through a dry combustion process using a VarioMax CNS macro elemental analyzer (Elementar, Mt. Laurel, NJ, USA).

Table 3. Values for selected soil routine analysis on baseline samples (0–15 cm depth) taken previously to residue treatment in the experiments conducted in Blacksburg (BB) and New Kent (NK1 and NK2), VA.

Location		Blacksburg	New Kent 1	New Kent 2
pH †		6	6.2	5.5
P		43	78.7	16.3
K		66.5	113.3	64.7
Ca		492.5	548	368
Mg	— mg/kg soil ‡ —	97	92.7	62.3
Zn		1.3	1.6	1
Mn		26.6	6.7	11.1
Cu		0.9	0.1	0.6
Fe		14.2	16.3	18.4
B		0.2	0.3	0.1
CEC	Cmol(+)/kg ¶	4.9	4.1	3.6
Acidity		28.8	9.1	30
Base Sat		71.2	90.9	70
Ca Sat	— % —	51.2	65.3	51
Mg Sat		16.6	18.5	14.4
K Sat		3.4	7.2	4.6
P		H	VH	M+
K	- Rating EUR -	M	H	M
Ca		M	M	M−
Mg		H+	H	M+

† Water pH was determined in a 1:1 (vol/vol) ratio of deionized water:soil [44]. ‡ Nutrients available for plant uptake were extracted with Mehlich 1 solution (0.05N HCl in 0.025N H_2SO_4) [43] using a 1:5 vol:vol soil to extractant ratio and analyzed using ICP-AES analysis. ¶ Cation exchange capacity (CEC) is estimated by summation of the Mehlich 1 extractable non-acid generating cations (Ca, Mg and K), plus the acidity estimated from the Mehlich soil-buffer pH after the conversion of all analytical results to meq/100 cm^3 or cmol(+)/kg. EUR rating levels were based on soil test recommendations for Virginia; Virginia Cooperative Extension (2017). Letters M, H and VH stand for medium, high and very high extractable levels of either P, K, Ca or Mg. Each category is subdivided into three subcategories to account for differences within a soil nutrient level availability (i.e., M−, M and M+ stand for medium low, medium average and medium high extractable levels).

Final soil samples were taken in mid-June at NK1 (post-wheat harvest), and between mid-September and the beginning of October in 2017 in NK2 and BB (post-corn grain harvest; red boxes in Figure 1). As per baseline soil samples, these samples were used for bulk density, TC and TN determination. Additionally, these samples were used for soil pH, C mineralization rates, water holding capacity and water aggregate stability determination. At sampling time, three intact soil cores were taken to a depth of 15 cm at each EU in the four replications, and each core was separated in place into 0 to 2.5, 2.5 to 7.5 and 7.5 to 15 cm depth increments, and each depth was stored in a paper bag. For water stable aggregate stability measurements, a fourth soil sample was taken at each EU to a depth of 5 cm and stored in a fourth paper bag. Soil cores were then air-dried until constant mass weight and bulk density was determined at each of the 0–2.5, 2.5–7.5 and 7.5–15 cm depths. Air-dried samples for each depth increment were then gently crushed to pass a 2 mm sieve for TC and TN determination, as previously described.

Soil pH was determined as previously described, for the soil depth increment 0 to 7.5 cm. Since this depth increment was not originally collected at the field level, samples were artificially created by compositing a proportional 1/3 and 2/3 portion from the 0 to 2.5 cm and 2.5 to 7.5 cm subsamples taken at each EU, respectively.

Water holding capacity (i.e., total amount of water a soil can hold at field moisture capacity (FC)) was determined for the 0 to 7.5 cm depth increment in pressure chambers set at a pressure of −0.033 MPa [47] in a 1500F2, 15 bar pressure plate extractor (Soil moisture equipment corp., Santa Barbara, CA, USA). The protocol for sample preparation followed the same procedure than that of soil pH samples. Following sampling preparation, soil samples were moistened and placed in chambers for 7 days. Recovered soil samples were then weighed and FC (%) calculated. With this information, permanent wilting point (WP; −1.5 MPa) [47] was calculated through chilled mirror technology from intact soil cores with a WP4 water potential meter (Decagon Devices, Inc., Pullman, WA, USA). Briefly, three soil subsamples were taken from each soil sample and placed into plastic cups. A known amount of water was added, and then plastic cups were closed with caps. One of the subsamples was kept dry in order to cover the FC-WP range. Following this, samples were left to equilibrate for a week and then run through the WP4C device for water potential determinations. With the water content and water potential information for different subsamples, WP at −15 bars was then interpolated. Finally, plant available water (PAW) was calculated as the difference between the FC and WP.

Water aggregate stability was measured in 0 to 5 cm soil samples, following a modified procedure from [48]. Briefly, air-dried soil samples were gently crushed to pass a 4 mm sieve, and the representative samples containing all sizes from ~4mm were collected. Small soil aliquots were weighed and oven-dried (105 °C, 24 h) for air-to-oven mass corrections (GWC, %). Following this, 50 g of soil samples were poured through two sieves (2000 µm on top of a 250 µm) on top of a solid pan and submerged in deionized water for 5 min. The entire stack of sieves was moved up and then down (approximate stroke length of 3-cm) about 50 times in 2 min. Aggregates remaining in the 2000 µm sieve were then washed with deionized water, separated from roots and small rocks and collected and weighed. Soil aggregates were oven-dried overnight at 55 °C and dry weights were recorded. The same procedure was applied to the other two fractions (i.e., >250 and <250 µm). Material contained in the soil slurry in the pan (i.e., <250 µm) was washed onto a 53 µm sieve. Then, five g of the oven-dried aggregates for the >2000-, 2000 to 250- and 250 to 53-µm aggregates were collected to determine the sand content (%) by hydrometer method. Finally, the weight of the sand-free aggregates was calculated. For example, for a sample with 12% sand, and 15.0 g of 250 to 2000 µm size, calculations were as follows:

Sand-free aggregate weight = 15.0 * (1 − 12/100)) = 15.0 × 0.88 = 13.2 g of sand-free soil in the size range 250 to 2000 µm.

2.4. Weather Data

Weather data for the BB and NK sites were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Kentland Farm and West Point, VA, USA, weather stations from the National Climate Data Center (https://www.ncdc.noaa.gov/cdo-web/search, accessed on 14 January 2023), respectively. Total accumulated rainfall (mm) and daily average air temperatures (°C) were collected from the beginning of May through the end of October at Blacksburg and New Kent, VA, USA. The 30-year average (1981–2010) rainfall and air temperature are also presented (Figure 2).

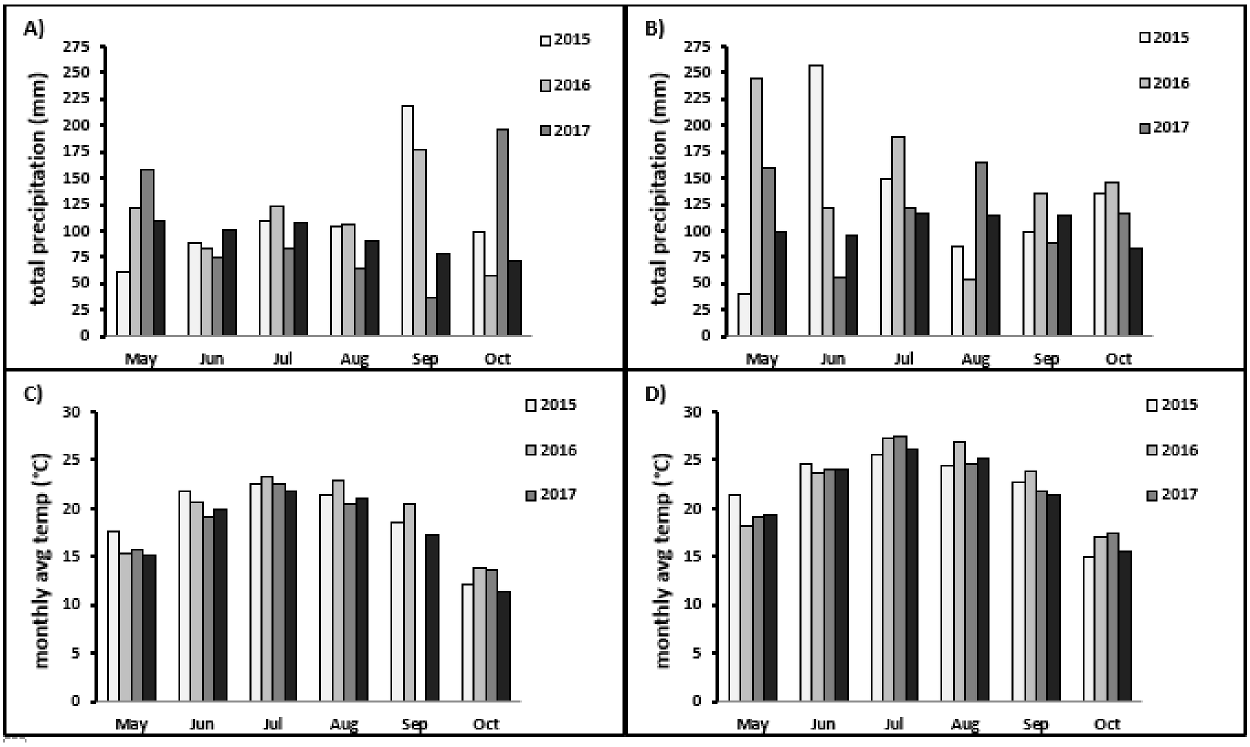

Figure 2. Total monthly and 30-year monthly averages rainfall (mm), and air temperatures (°C) from May through October during the period 2015–2017 in Blacksburg (**A**,**C**) and New Kent (**B**,**D**), VA, respectively. Source: National Oceanic and Atmospheric Administration, National Centers for Environmental Information (https://www.ncdc.noaa.gov/cdo-web/search, accessed on 14 January 2023).

2.5. Data Analysis

Linear regression analysis was conducted to examine the relationship between crop residue management on parameters of soil quality in 2017 using the PROC REG procedure in SAS version 9.4 [49]. Rates of crop residue return, years and locations were considered fixed effects, while blocks were considered random effects. The quadratic or linear models were selected based on R2 values and model *p*-values. Regression equations for each soil quality parameter as a function of either corn stover (BB), or total summation of corn and wheat residues applied in previous years in both NK experiments were developed. Minimum, maximum and mean for each comparison were also calculated (Tables 4–6). At Blacksburg, five corn stover retained rates (0, 3.33, 6.66, 10 and 20 Mg ha^{-1}) (Table 1) applied in the previous two years were considered as the treatment for the model effects in 2017. Total retained residues were considered in the model at both experiment in NK location (Table 2). In NK1, total retained residues in 2017 resulted from the factorial combination of four wheat straw treatments allocated in 2015 and four corn stover treatments allocated in 2016. In NK2, total retained residues in 2017 resulted from the combination of four corn stover treatments allocated in 2015 and four wheat straw treatments allocated in 2016. Normality of data was assessed with the univariate procedure. Prior to analysis, assumptions of equal variances for each group were visually checked by plotting the studentized residuals against predicted values. Across response variables and years, assumptions of homoscedasticity and approximation to normal distribution were met for all comparisons. The presence of outliers in Y was assessed with the influence procedure of SAS.

Table 4. Quadratic regression parameters, R square coefficient of determination, *p*-value, minimum, maximum and mean response values for total carbon (TC) and nitrogen (TN) (%), CN ratio and bulk density (g cm^{-3}) measured at the 0–2.5, 2.5–7.5 and 7.5–20 cm soil depths in 2017 in Blacksburg and New Kent (NK1 and NK2), Virginia.

Blacksburg									
		Parameter			**R-sq**	**Pr > t**	**Min**	**Max**	**Mean**
Soil Indicator	**Depth, cm**	**a**	**b**	**c**					
TN, %	0–2.5	-3.2×10^{-6}	0.0002	0.129	0.035	0.894	0.12	0.15	0.13
	2.5–7.5	1.9×10^{-5}	−0.0002	0.094	0.031	0.765	0.08	0.11	0.09
	7.5–20.0	-1.2×10^{-7}	-4.0×10^{-5}	0.074	0.003	0.998	0.07	0.09	0.07
TC, %	0–2.5	−0.0005	0.0210	1.320	0.400	0.444	1.22	1.67	1.43
	2.5–7.5	0.0001	0.0002	0.943	0.162	0.698	0.87	1.05	0.96
	7.5–20.0	−0.0002	0.0052	0.775	0.024	0.718	0.70	0.95	0.79
CN Ratio	0–2.5	−0.0047	0.1599	10.170	0.389	0.262	9.47	12.82	10.92
	2.5–7.5	−0.0010	0.0264	10.079	0.005	0.866	8.74	11.28	10.18
	7.5–20.0	−0.0026	0.0750	10.530	0.138	0.408	9.76	11.93	10.84
Bulk density (g cm^{-3})	0–2.5	0.0004	−0.0079	1.571	0.143	0.191	1.48	1.64	1.55
	2.5–7.5	0.0001	−0.0018	1.650	0.061	0.549	1.59	1.70	1.65
	7.5–20.0	0.0001	−0.0016	1.603	0.088	0.425	1.57	1.64	1.60
New Kent 1									
		Parameter			**R-sq**	**Pr > t**	**Min**	**Max**	**Mean**
Soil Indicator	**Depth, cm**	**a**	**b**	**c**					
TN, %	0–2.5	-3.8×10^{-5}	0.0018	0.111	0.069	0.843	0.08	0.16	0.12
	2.5–7.5	-2.9×10^{-5}	0.0009	0.081	0.042	0.799	0.06	0.11	0.09
	7.5–20.0	-6.0×10^{-5}	0.0010	0.046	0.023	0.511	0.03	0.07	0.05
TC, %	0–2.5	−0.0003	0.0163	1.230	0.051	0.915	0.88	1.80	1.32
	2.5–7.5	0.0005	0.0001	0.872	0.042	0.713	0.67	1.22	0.90
	7.5–20.0	−0.0006	0.0113	0.542	0.021	0.608	0.34	0.93	0.58
CN Ratio	0–2.5	0.0017	−0.0274	11.060	0.007	0.650	9.94	11.62	10.98
	2.5–7.5	0.0073	−0.0898	10.730	0.036	0.212	8.52	11.70	10.57
	7.5–20.0	0.0038	−0.0523	12.070	0.003	0.705	10.40	15.27	11.95
Bulk density (g cm^{-3})	0–2.5	0.0012	−0.0187	1.590	0.077	0.097	1.16	1.62	1.54
	2.5–7.5	0.0001	−0.0010	1.580	0.003	0.796	1.44	1.66	1.58
	7.5–20.0	0.0004	−0.0091	1.660	0.064	0.611	1.47	1.81	1.62
New Kent 2									
		Parameter			**R-sq**	**Pr > t**	**Min**	**Max**	**Mean**
Soil Indicator	**Depth, cm**	**a**	**b**	**c**					
TN, %	0–2.5	−0.0001	0.0034	0.150	0.084	0.507	0.08	0.21	0.16
	2.5–7.5	-5.8×10^{-5}	0.0015	0.100	0.045	0.683	0.07	0.13	0.10
	7.5–20.0	2.1×10^{-5}	0.0003	0.054	0.093	0.778	0.04	0.07	0.06
TC, %	0–2.5	−0.0015	0.0409	1.620	0.131	0.517	0.95	2.37	1.80
	2.5–7.5	−0.0003	0.0117	1.010	0.054	0.816	0.79	1.31	1.06
	7.5–20.0	0.0002	0.0024	0.581	0.110	0.730	0.50	0.74	0.61
CN Ratio	0–2.5	0.0001	0.0258	10.810	0.060	0.976	10.15	11.94	10.98
	2.5–7.5	0.0023	−0.0266	10.360	0.010	0.544	9.76	11.29	10.32
	7.5–20.0	1.8×10^{-5}	−0.0081	10.860	0.004	0.998	9.52	11.98	10.81
Bulk density (g cm^{-3})	0–2.5	−0.0005	0.0061	1.470	0.012	0.513	1.33	1.59	1.48
	2.5–7.5	−0.0003	0.0053	1.510	0.018	0.554	1.29	1.59	1.52
	7.5–20.0	0.0004	−0.0033	1.600	0.024	0.524	1.47	1.70	1.60

Table 5. Quadratic regression parameters, R square coefficient of determination, *p*-value, minimum (min), maximum (max) and mean response values for field capacity, wilting point and plant available water (kg kg^{-1}) and soil pH measured at the 0 to 7.5 cm soil depth in 2017 in Blacksburg and New Kent (NK1 and NK2), Virginia.

Blacksburg								
	Parameter			R-sq	Pr > t	Min	Max	Mean
Soil Indicator	**a**	**b**	**c**					
Field capacity, kg kg^{-1}	2.2×10^{-5}	-1.3×10^{-5}	0.198	0.095	0.749	0.19	0.22	0.20
Wilting point, kg kg^{-1}	4.2×10^{-5}	−0.0008	0.049	0.175	0.147	0.04	0.05	0.05
Plant available water, kg kg^{-1}	-1.9×10^{-7}	0.0008	0.150	0.081	0.754	0.14	0.17	0.15
Soil pH	0.0012	−0.0072	4.920	0.100	0.664	4.24	5.95	4.99
New Kent 1								
	Parameter			R-sq	Pr > t	Min	Max	Mean
Soil indicator	**a**	**b**	**c**					
Field capacity, kg kg^{-1}	0.0002	−0.0007	0.124	0.059	0.510	0.10	0.18	0.13
Wilting point, kg kg^{-1}	0.0002	−0.0013	0.045	0.119	0.148	0.02	0.07	0.05
Plant available water, kg kg^{-1}	0.0000	0.0006	0.079	0.006	0.984	0.03	0.13	0.08
Soil pH	−0.0014	0.0165	5.270	0.018	0.733	4.72	7.02	5.30
New Kent 2								
	Parameter			R-sq	Pr > t	Min	Max	Mean
Soil indicator	**a**	**b**	**c**					
Field capacity, kg kg^{-1}	−0.0001	0.0018	0.141	0.006	0.620	0.09	0.19	0.14
Wilting point, kg kg^{-1}	0.0001	0.0009	0.029	0.023	0.379	0.02	0.04	0.03
Plant available water, kg kg^{-1}	−0.0001	0.0008	0.112	0.002	0.804	0.05	0.17	0.11
Soil pH	−0.0040	0.0560	5.560	0.014	0.451	4.55	6.72	5.69

Table 6. Quadratic regression parameters, R square coefficient of determination, *p*-value, minimum (min), maximum (max) and mean response values for water aggregate stability measured as the free-sand dry weight (DW, in g) per each aggregate size (in μm) for the 0 to 5 cm depth in 2017 in Blacksburg and New Kent (NK1 and NK2), Virginia.

Blacksburg									
		Parameter			R-sq	Pr > t	Min	Max	Mean
Soil Indicator	**Aggregate Size, μm**	**a**	**b**	**c**					
Free sand DW, g	>2000	−0.0040	0.0768	1.200	0.111	0.264	0.53	2.41	1.36
	<2000 to >250	−0.0082	0.1424	12.180	0.100	0.329	10.17	15.12	12.41
	<250 to >53	0.0077	−0.1195	8.030	0.116	0.359	5.33	9.89	7.93
New Kent 1									
		Parameter			R-sq	Pr > t	Min	Max	Mean
Soil indicator	**Aggregate size, μm**	**a**	**b**	**c**					
Free sand DW, g	>2000	0.0085	−0.0997	2.700	0.006	0.643	0.18	7.08	2.55
	<2000 to > 250	−0.0107	0.1454	10.470	0.023	0.318	8.25	12.45	10.80
	<250 to >53	−0.0003	−0.0180	5.380	0.003	0.984	1.64	8.34	5.24
New Kent 2									
		Parameter			R-sq	Pr > t	Min	Max	Mean
Soil indicator	**Aggregate size, μm**	**a**	**b**	**c**					
Free sand DW, g	>2000	−0.0183	0.2905	1.470	0.069	0.262	0.54	5.59	2.31
	<2000 to > 250	−0.0165	0.2077	6.880	0.042	0.275	5.43	9.75	7.29
	<250 to >53	0.0281	−0.4202	7.570	0.108	0.110	4.23	8.93	6.45

3. Results and Discussion

3.1. Weather Data

Blacksburg and New Kent locations are located in a region classified as humid subtropical, according to the Köppen climate classification [50]. Annual long-term average (30-year period, 1981–2010) precipitations and average air temperatures are typically higher in New Kent (1153 mm and 15.6 °C) compared with Blacksburg (1039 mm and 12.2 °C). The three years under study were wetter and slightly hotter in most comparisons than an average year at both locations. In New Kent, accumulated rains were 23, 43 and 13% greater than average for the period May–October in 2015, 2016 and 2017, respectively (Figure 2B,D). As a result of this, the remarkable rates of biomass decomposition that occur in this region of the US leave negligible amounts of undecomposed biomass from previous crops after one year in the field (Thomason, personal communication), resulting in a robust estimation of the total corn and wheat residues produced in the previous season. Over the same subperiod, accumulated precipitations across years in BB (range: 615–679 mm) were 10% to 21% greater (Figure 2A) and air temperatures up to 1.6 °C higher (Figure 2C) than the 30-year average. The rapid and near complete decomposition mean that there are negligible residues from before the experiment began. Although rates of decomposition in Blacksburg are expected to be lower compared to those occurring in New Kent, these conditions over the length of the study resulted in a negligible amount of undecomposed material following one year in the field.

3.2. Effect of Corn Stover and Wheat Straw Retention on Total Soil Nitrogen and Carbon Concentrations, CN Ratio and Bulk Density

The retention of 0, 3.33, 6.66, 10.00 and 20.00 Mg ha^{-1} of corn stover over a two-year period did not affect total soil nitrogen (TN) ($p > 0.76$) or carbon (TC) ($p > 0.44$), or the CN ratio ($p > 0.26$) at any soil depth in the continuous corn rotation in Blacksburg (Table 4). Similarly, total retained residues resulting from the application of wheat straw and corn stover rates in NK1, and corn stover and wheat straw rates in NK2 in the period 2015/2016, respectively, did not affect TN ($p > 0.50$) or TC ($p > 0.51$) or the CN ratio ($p > 0.21$) at any soil depth in the corn-wheat/soybean rotations in New Kent (Table 4). Maskina et al. [51] measured the residual effects of previous no-till residue rates over an eight-year period in a silty clay loam soil in Nebraska. During the first three years (1978–1980), residue rates of 0, 50, 100 and 150% were retained for each crop in the rotation corn, sorghum and soybean. In the second five years (1980–1984), sorghum treatment was omitted, and continuous corn and soybean were grown in two separate blocks in the same experimental area. Same annual retention rates were applied for each crop in this period. The residues applied ranged between 0 to 15 and 8 Mg ha^{-1} yr^{-1} for corn and soybean, respectively [52], and the average quantity of both crop residues varied from 0 to about 6 Mg ha^{-1} yr^{-1} (150% rate) [51]. Two and three years after residue treatment were discontinued, soil samples were taken at the 0–30 cm and 0–7.5 cm depths, respectively, and composed each year across corn and soybean blocks. Similar to our short-term results in New Kent, the addition of 100% crop residue rates or less over an eight-year period did not affect TN and soil organic carbon (SOC; TC was not measured in this experiment) in the study conducted by [51]. However, retaining more than 100% residue had a different long-term effect in TN and SOC, a situation that we did not observe in the short-term with corn retention rates of up to 200% in Blacksburg. In a study [51], an eight-year residual effect of 150% retention rates increased TN by 16% at the 0–30, and TN and SOC by 12% and 14% at the 0–7.5 cm depth, respectively, compared with 0 and 50% rates ($p < 0.10$). Moreover, long-term organic matter levels only decreased by about 10% at the 0–7.5 cm depth when no residue was applied over the eight years period compared with 150%, but not with 50% and 100% retention rates [51]. Although the impact of crop residue management on these parameters has not been previously studied in Virginia, the impact of time under no-till in soil organic C and N in sandy loam soils in the Coastal Plain region of Virginia have been studied [45]. Similar to results from the long-term studies conducted [51], total soil organic C and N increased linearly with time under continuous no-till in the 0–2.5 and 2.5–7.5, but not in the 7.5–15 cm depths in Virginia [45].

Bulk density (BD) was not affected by corn stover ($p > 0.19$) or total residue retention rates ($p > 0.51$) at any soil depth in Blacksburg or NK2, respectively. In NK1, total residues retained affected BD in the 0–2.5 ($p = 0.097$) (Table 4; Figure 3) but not in the 2.5–7.5 ($p = 0.796$) or the 7.5–20 cm ($p = 0.611$) depths (Table 4). When differences were significant at the 0–2.5 cm depth in NK1, the calculated minimum point in the regression curve corresponded to a total residue retained rate (x-axis) of 7.79 Mg ha^{-1} (approximately 60% retention rate). Predicted BD response (y-axis) at this minimum total retained rate in 2017 was 1.52 g cm^{-3}. As a result, BD at the 0–2.5 cm depth gradually decreased with increasing residue retention of up to total retention rates around 60% to further increase when more than 60% of the total residue was retained (Figure 3). However, significant differences in BD do not seem to be biologically or environmentally meaningful in the top 2.5 cm soil in NK1. The best fitting line for the quadratic model had a seemingly flat shape across the range of predicted values for the total retained treatments (Figure 3). In fact, the range between the minimum and maximum predicted values across the sixteen treatments was less than 5% (Figure 3). Similar to our results in loams (BB) and sandy loam (NK) soils, retention of up to 150% residue over an eight-year period did not affect BD in the upper 7.5 cm of silty clay loam soils in measurements taken two [51] and nine years [53] after residue-treatment completion in studies conducted in Nebraska. In other studies, 100% of corn stover retention did not affect BD in the first 20 cm in Québec [54] or 50 cm of soil in Iowa [13], but reduced BD in the first 15-cm, compared with 0% retention, in other short [26] and long-term studies [55,56].

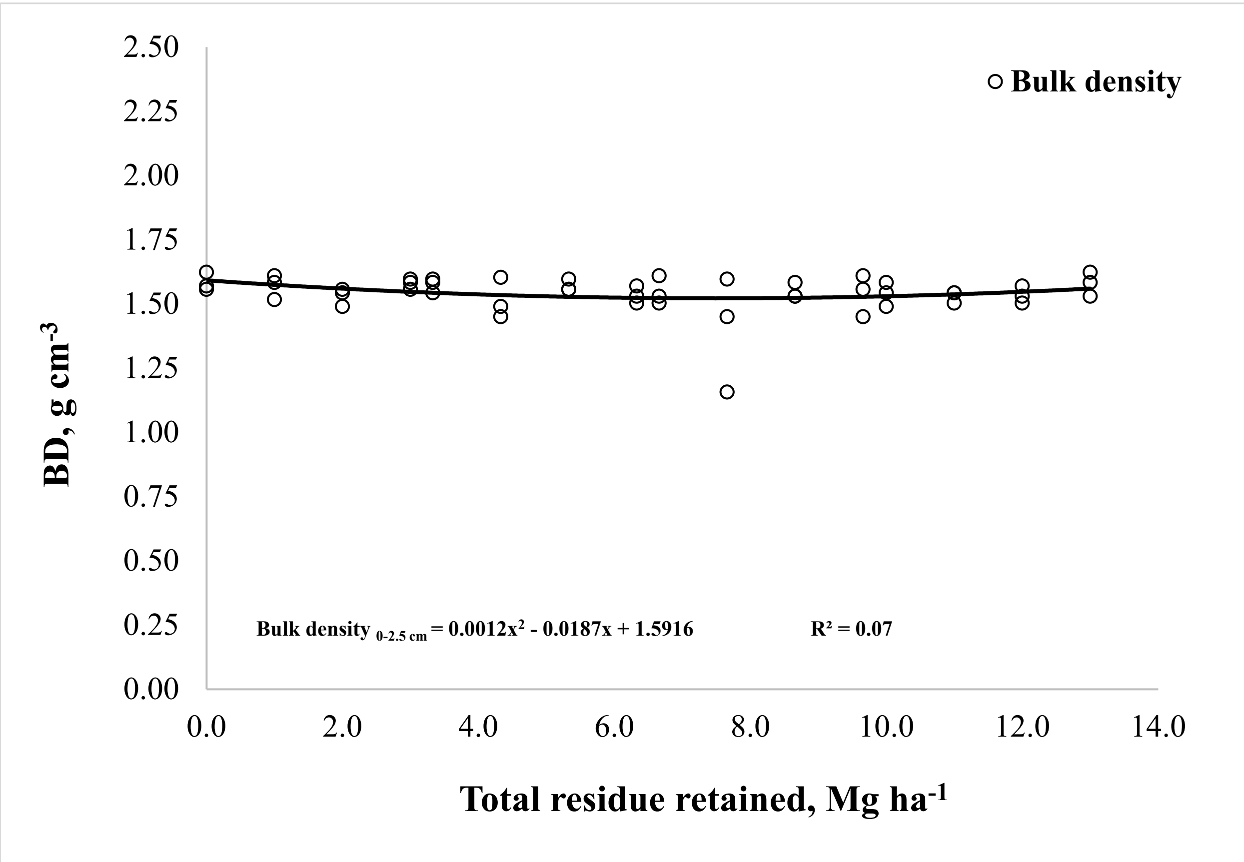

Figure 3. Bulk density (g cm^{-3}) at the 0–2.5 cm soil depth in a factorial design of sixteen total residue retained rates (in Mg dry matter ha^{-1}) from corn and wheat in a corn-wheat/soybean rotation in 2017 in New Kent, experiment 1 (NK1), Virginia. Polynomial best fit line, quadratic equation and R-square value are presented in the figure.

3.3. Effect of Corn Stover and Wheat Straw Retention on Field Moisture Capacity, Permanent Wilting Point, Plant Available Water and Soil pH

Field moisture capacity (FC) and permanent wilting point (PW) were not affected ($p > 0.14$) by corn stover or total residue retention rates at the 0–7.5 cm soil depth at any location (Table 5). As a result, the plant available water (PAW) between matric potentials of -1.5 and -0.033 MPa (WP and FC, respectively), was not affected ($p > 0.75$) by different residue managements at any location (Table 5). The residual effect of different crop retention rates over an eight-year period did not affect ($p > 0.10$) FC values measured at the 0–7.5 cm depth two years following residue treatment completion [51]. Karlen et al. [13] did not find differences in PAW between 0 and 100% corn stover retention rates over a ten-year period in a silt loam soil in Wisconsin. In this study, retaining 150% of the stover increased PAW by 11% compared with the 0% retention rate, but was not different than 100% retention rate. Different to our results, Wilhelm et al. [57] found that returning 100 and 150% of the corn stover over a four-year period increased PAW at planting in a silty clay loam by 28% and 15% when compared with 0% and 50% return rates. However, different techniques used to determine PAW may likely explain, at least in part, some of the differences seen in each case. Measurements in the Wilhelm et al. [57] study were determined for the 0 to 1.8 m depth increment and by means of the use of a neutron-scatter technique, compared to our determinations through soil sampling and lab techniques for the 0–7.5 cm soil depth. Moreover, differences in PAW are highly influenced by soil texture [58], which may in turn explain the differences between the moderate coarse and medium texture soils in our experiments, and the moderately fine silty clay loam soil [57]. Regardless of these differences in PAW, several authors reported on the positive impacts that corn stover returned had on soil available water (i.e., total available water at a given time minus WP) [31,52,59].

Retaining up to 20.00 Mg ha^{-1} of corn stover for two consecutive years in Blacksburg or up to 13 Mg ha^{-1} of corn stover and wheat straw over a two years period at both experiments in New Kent, did not impact the soil pH at the 0 to 7.5 cm depth ($p > 0.45$) (Table 5). Power et al. [53] did not measure changes in soil pH ($p < 0.10$), resulting from retention of up to 150% residue over an eight-year period at neither the 0–7.5, 7.5–15, or 15–30 cm soil depths nine years after residue treatment completion in Nebraska. In short-term studies with three or less cycles of residue management, soil pH did not change ($p > 0.05$) in most comparisons in sandy loam soil in South Carolina [60] and in silt loams soils with 2 and 10% slopes, and clay loam soils with less than 1% slope in Ohio [24].

3.4. Effect of Corn Stover and Wheat Straw Retention on Water Aggregate Stability

Water aggregate stability (WAS) measured as the free-sand dry weight for the 0 to 5 cm depth was not affected by corn stover (BB; $p > 0.26$) or total residue retention rates (NK; $p > 0.11$) at any aggregate size (Table 6). In the Karlen et al. [13] study, residue management also had no effect in the WAS when $\leq$ 100% of the corn stover was retained over a ten-year period. In this study, WAS only increased by 43 and 31% when 200% of the corn stover was returned over ten years, compared with 0 and 100% retention rates, respectively. Working in a corn-soybean rotation in a silty clay loam soil in South Dakota, Hammerbeck et.al. [61] reported a 40% increase in the WAS only for aggregate sizes between 0.84 and 2.0 mm, when 100% of the stover was left on surface, compared with retention rates $\leq$ 50%. However, stover management did not affect WAS for other aggregate sizes (i.e., 2.0–6.4, 6.4–19.2 and >19.2 mm) in this study. In other cases, soil texture and climatic conditions may result in WAS being more susceptible to changes in residue management. In the long-term study conducted by Bordovsky et al. [62] in coarse sandy soils in Texas, micro aggregation values were 15% and 19% higher when residue was retained, both in non-irrigated (27.1 vs. 23.5 g kg^{-1}) and under-irrigated conditions (32.3 vs. 27.1 g kg^{-1}).

4. Conclusions

Weather conditions at the Blacksburg and New Kent locations were characterized by equally distributed and abundant precipitations, and average air temperatures were above average over the three years when studies were conducted. These conditions were conducive to optimum plant growth and resulted in high rates of crop residue decomposition applied in previous years. In our studies, systems were most likely at a state of equilibrium following several years of continuous crop residue incorporation and best management practices, including no-till systems to prevent wind and water erosion, adequate fertilization and maintenance of soil organic matter and soil structure. Under these conditions, a portion of the crop residue produced in current cropping systems could be sustainably harvested for extended uses [63] without negative impacts in parameters on soil quality parameters. Two cycles of crop residue management in Virginia, with retention rates of up to 20 Mg ha^{-1} of corn stover in Blacksburg and up to 13 Mg ha^{-1} of corn stover and wheat straw in New Kent, had no effect on parameters of soil quality like TN, TC, CN ratios, bulk density, soil pH, field capacity, permanent wilting point, plant available water and water aggregate stability across different soil depths and aggregate sizes. In the single situation when residue management affected bulk density at the 0–2.5 cm depth in NK1, differences in BD were not biologically or environmentally meaningful. These differences across the sixteen total retained residues treatments were less than 5%. In all cases, retaining none of the residues produced in Virginia cropping systems did not result in negative short-term effects in this experiment. These incipient negative impacts resulting from very low rates of residue return warrant further studies to corroborate whether these results are to be found in the long-term.

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