Long-Term Residue Management and Irrigation Practice Effects on Aggregate-Derived Particulate Organic Matter Fractions in a Wheat-Soybean, Double-Crop System

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Abstract

Conventional agricultural management practices, such as repeated annual tillage and crop residue burning, can lead to reductions in soil carbon (C) storage and degrade soil health. Through the use of conservation tillage and alternative residue management practices, the soil C pool can increase. The objective of this field study was to evaluate the effects of long-term agricultural management practices (i.e., residue level, residue burning, irrigation, and tillage) on soil particulate organic matter (POM) fractions and their associate C and nitrogen (N) concentrations in a wheat (*Triticum aestivum*)-soybean (*Glycine max* L. [Merr.]), double-crop production system on a silt-loam-textured, loess soil following 14 complete cropping cycles in eastern Arkansas. Averaged over irrigation and tillage, the fine POM C concentration in the burn-low- (2.59 g/kg) was 1.9 times greater (P = 0.04) than in the burn-high-residue treatment combination (1.35 g/kg), while the fine POM C concentration in the no-burn-high- and no-burn-low-residue combination were intermediate and did not differ (2.56 and 2.43 g/kg, respectively). The fine POM N concentration, averaged over irrigation and tillage treatments, was 1.9 times greater (P = 0.02) in the burn-low- (0.21 g/kg) than the burn-high-residue combination (0.11 g/kg), while the fine POM N concentration in the no-burn-high- and no-burn-low-residue combinations did not differ (0.21 and 0.23 g/kg; respectively). Sustainable management practices in a wheat-soybean, double-crop production system in eastern Arkansas, such as no-tillage (NT) and non-burning of crop residues, compared to the traditional practices of conventional tillage (CT) following residue burning, provide alternative management practices that can potentially reduce the dependency on external inputs, including irrigation and nutrient inputs.

Introduction

In the Lower Mississippi River Delta (LMRD) region of eastern Arkansas, groundwater aquifer levels continue to decline from extensive agricultural irrigation (Scott et al., 1998). Agricultural withdrawals, coupled with increased volatility and unpredictability of weather patterns due to climate change result in a need for increasing resiliency of agricultural soils in addition to the soil's use as a potential carbon (C) sink (IPCC, 2013). Soil organic matter (SOM), some of which is at least partially microbially processed organic residues within soils that is resistant to further microbial degradation, contains the largest terrestrial C reserve in the form of soil organic carbon (SOC), (Follet, 2001; Lal, 2000).

Conventional agricultural management practices, such as repeated annual tillage and crop residue burning, can lead to reductions in soil C storage and degrade soil health, which is the capacity of a soil to sustain or promote plant and animal health and productivity, while maintaining or enhancing water and air quality (Doran, 2001; Franzluebbers and Doraiswamy, 2007). Approximately half of the SOC pool can be depleted compared to undisturbed ecosystems (i.e., forest and grasslands) following conversion to cultivated agriculture within 10 years, largely due to conventional tillage (Lal and Bruce, 1999). Implementing sustainable agricultural management practices and technologies that increase food production, while improving environmental conditions, can provide a semi-permanent C sink by increasing SOC storage (Pretty, 2008). Through the use of conservation tillage and alternative residue management practices, the SOC pool can increase substantially. Practices that reduce microbial activity and SOM decomposition, decrease soil disturbances, and increase plant productivity, such as fertilization, cover cropping, and irrigation, are attributed to increases in SOM and subsequent SOC fractions.

In a process described by Six et al. (1999), upon entry into the soil, fresh residues partially decompose forming particulate organic matter (POM), thus forming nucleation centers for aggregation and microbial activity (Puget et al., 1995). This microbial activity results in the binding of fresh residues and induces macro-aggregate (>250 µm or >0.01 in.) formation, which subsequently break down to form micro-aggregates (53–250 µm or 0.002–0.01 in.; Six et al., 2004). The non-aggregated mineral fraction consists of silt- and clay-free primary particles (<53 µm or <0.002 in.). Macro- and micro-aggregates reduce the degradation of labile C by physically protecting the coarse- and fine-POM, respectively. The aggregate protective capacity (PC; the protection of SOC against biodegradation) generally increases with increases in SOM and clay and reductions in tillage or other soil disturbances (Balesdent et al., 2000). Several mechanisms are responsible for macro-aggregate PC, including sorption of SOM to solid surfaces, sequestration into small pores, control of microbial turnover by predators, and O_2 limitation (Balesdent et al., 2000). Quantifying C derived from within and between aggregate fractions can further support the understanding of POM-associated C accumulation by increasing PC.

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The objective of this field study was to assess and compare the effects of long-term agricultural management practices (i.e., residue level, residue burning, irrigation, and tillage) on soil aggregate and POM aggregate-derived C and N concentrations (i.e., macro-aggregate, micro-aggregate, coarse- and fine-POM C and N concentrations) in a wheat *(Triticum aestivum)*-soybean (*Glycine max* L. [Merr.]), double-crop production system on a silt-loam-textured, loess soil following 14 complete cropping cycles in eastern Arkansas. Compared to the currently common practices of residue burning and conventional tillage (CT), the effects of non-residue burning and NT are hypothesized to increase soil micro-aggregate POM C and N concentrations.

Procedures

A wheat-soybean, double-crop system consisting of 48, 10-ft wide by 20-ft long plots including three replications of 16 differing residue and water management combinations at the University of Arkansas System Division of Agriculture's Lon Mann Cotton Branch Experiment Station near Marianna, Ark. has been established since 2002. The differing management practices include wheat residue burn and no burn, CT and no-tillage (NT), high- and low-wheat residue level, and irrigated and dryland soybean production. Further details of annual plot management are provided in Desrochers (2017). On 15 Sept. 2015, 12 to 15, 0.8-in.-diameter soil cores were collected at random from the top 4 in. (10 cm) and combined for one sample per plot to assess long-term management practice effects on POM fractions and their associated C and N concentrations according to procedures described by Six et al. (1999; Fig. 1).

After air-drying for several weeks, soil samples were hand-crushed to pass through a 0.3-in. (8-mm) sieve, then two sub-samples of approximately 3.35 oz (95 g) per plot of air-dried soil were separately wet-sieved using a soil-slaking procedure to derive macro- (>250 µm or >0.01 in.), micro-aggregate (>53 to <250 µm or >0.002 to <0.01 in.), and silt-clay (<53 µm or <0.002 in.) fractions (Elliott, 1986; Cambardella and Elliott, 1993; Six et al., 1998; Fig. 1). The fractionation procedure is further explained in Desrochers (2017).

To obtain total POM (i.e., POM within and around aggregate fractions), two, approximately 0.18-oz (5-g) sub-samples of the macro- (>250 µm or >0.01 in.) and micro-aggregate (>53 µm or >0.002 in.) fractions were placed in 1.8-oz (50-mL), glass beakers and oven-dried overnight at 221 ˚F (105 ˚C) in a forced-air oven to obtain the coarse and fine total POM, respectively. The next morning, both respective sub-samples were removed from the oven, cooled in a desiccator, weighed, and added to 3.5-oz (100-mL) cylindrical glass tubes filled with 1.1 oz (30 mL) of sodium hexametaphosphate solution [5 g/L $(NaPO_3)_6$] and shaken on a reciprocal shaker for 18 hours or overnight to accomplish full dispersion. Dispersed samples were then poured over a 0.002-in. (53-µm) sieve in a plastic basin, rinsed thoroughly until th.e water coming through the sieve was clear, then the sand and total POM was lightly washed into a pre-weighed, 1.8-oz (50-mL) glass beaker and oven-dried overnight at 221 ˚F (105 ˚C). After 24 hours, the intra-aggregate sub-samples within the 1.8-oz (50-mL) beakers were cooled in a desiccator, weighed, and stored in 0.7-oz (20-mL) glass scintillation vials for subsequent chemical analyses. The difference in the initial 0.18-oz (5-g) sub-sample mass and total POM mass constituted the silt and clay fraction. The sand fraction was assumed to equal the mass of the total POM, and C or N concentrations per aggregate were adjusted to a sand-free basis using the following formula (Six et al., 1998):

$$\text{Sand-free (C or N)}_{\text{fraction}} = \frac{\text{(C or N)}_{\text{fraction}}}{1 - \text{(sand proportion)}_{\text{fraction}}}$$

Bulk soil, macro- and micro-aggregate and coarse- and fine-POM sub-samples were homogenized by grinding/ mixing for 20 seconds with a metal ball using a Wig-L Bug® (Model MSD, DENTSPLY, York, Pa.). Soil-fraction sub-samples were weighed in small tin capsules for C and N concentration analyses using an elemental analyzer (Model NC2500, Carlo Erba, Milan, Italy).

Due to confounding logistical constraints, the irrigation treatment block added in 2005 directly corresponds to the residue-burn treatment block, making both treatments unable to be simultaneously statistically analyzed. As a result, two separate three-factor analyses of variance (ANOVAs) were conducted using the MIXED type-three, least-squared procedure in SAS v. 9.4 (SAS Institute, Inc., Cary, N.C.) to evaluate the effects of tillage, burning, residue level, and their interactions as well as tillage, irrigation, residue level, and their interactions on bulk-soil C and N concentrations, aggregate-separated C and N concentrations (i.e., silt-clay, macro- and micro-aggregate), coarse- and fine-POM C and N concentrations, and coarse- and fine-POM C:N ratio. Means were separated by least significant difference at the 0.05 level.

Results and Discussion

Several main effects and treatment interactions occurred for the aggregate- and POM-separated soil fractions; however bulk-soil C was only affected by irrigation, while bulk-soil N did not differ among treatments and averaged 1.15 g/ kg. Averaged over tillage, residue-level, and burn, bulk-soil C concentration in the irrigated treatment was 1.21 times greater ($P = 0.02$) than in the non-irrigated treatment (13.2 and 10.9 g/kg, respectively).

Within the sand-free, macro-aggregate fraction, averaged over irrigation, burn, and residue-level treatments, C concentration was 9.9% greater ($P = 0.05$; Table 1) under NT (17.1 g/kg) than under CT (15.6 g/kg), likely due to a reduction in annual soil disturbance from tillage disrupting macro-aggregates. Additionally, Andruschkewitsch et al.

(2013) observed greater macro-aggregate C concentration differences in NT (178 lb/ac) compared to CT (116 lb/ac) in the top 2 in. (5 cm) of a silt-loam soil. Comparatively, Six et al. (1998) did not observe macro-aggregate C concentration differences between NT and CT in the top 2 in. (5 cm) of a Duroc silt loam (Pachic Haplustoll) in Sidney, Nebraska following 26 years of consistent management. In contrast, the C concentration of the sand-free micro-aggregate fraction was unaffected by any field treatment in this study, though Six et al. (1998) observed greater NT micro-aggregate C concentration compared to CT.

In both the macro- and micro-aggregate fractions, several field treatments significantly affected coarse-and fine-POM C and N concentrations in the top 4 in. (10 cm). Averaged over irrigation and tillage, the fine-POM C concentration in the burn-low- (2.59 g/kg) was 1.9 times greater ($P = 0.04$; Table 1) than in the burn-high-residue treatment combination (1.35 g/kg), while the fine-POM C concentration in the no-burn-high- and no-burn-low-residue combination were intermediate and did not differ (2.56 and 2.43 g/kg, respectively; Fig. 2). The burn-high-residue combination likely had a lower fine-POM C concentration from the cumulative effect of nearly 14 years of consistent management achieving a more thorough burn due to greater aboveground biomass and ultimately reducing the amount of potential crop residue and organic material returned to the soil. Additionally, the fine-POM N concentration, averaged over irrigation and tillage treatments, was 1.9 times greater ($P = 0.02$; Table 1) in the burn-low- (0.21 g/kg) than the burn-high-residue combination (0.11 g/kg), while the fine-POM N concentration in the no-burn-high- and no-burn-low-residue combinations did not differ (0.21 and 0.23 g/kg; respectively; Fig. 2). The burn-high-residue combination likely increased fine POM N concentration by stimulating greater SOM turnover and N mineralization after burning removed nearly all aboveground plant material on an annual basis. In comparison, coarse-POM C and N concentrations within the burn-residue-level combination did not differ and averaged 6.94 and 0.51 g/kg, respectively (Fig. 2).

When calculated using C and N concentrations, fine-POM C:N ratios in the top 4 in. (10 cm) differed among field treatments, while the bulk soil, macro- and micro-aggregate, and coarse-POM fraction C:N ratios were unaffected by field treatments. Andruschkewitsch et al. (2013) also did not observe a macro- and micro-aggregate difference in C:N ratio in the top 2 in. (5 cm). Averaged over tillage, burn, and residue-level treatments, the fine-POM C:N ratio was 16% ($P < 0.01$; Table 1) greater under non-irrigated (C:N ratio = 13.7) than irrigated soybean production (C:N ratio = 11.9), likely the result of greater soil moisture increasing microbial decomposition of SOM and loss of C through respiration.

Practical Applications

Greater overall POM C and N concentrations, and subsequent macro- and micro-aggregate C and N concentrations, can lead to improved soil fertility and soil C storage capacity, thus likely benefitting crop production and providing a C sink to mitigate climate change. Additionally, an increase in POM C and N concentration will increase soil health and, therefore, increase the natural resiliency of soils to sustain crop yields in the LMRD region of eastern Arkansas. Sustainable management practices in a wheat-soybean, double-crop production system in eastern Arkansas, such as NT and non-burning of crop residues, compared to the traditional practices of CT following residue burning, provide alternative management practices that can potentially reduce the dependency on external inputs, including irrigation and nutrient inputs.

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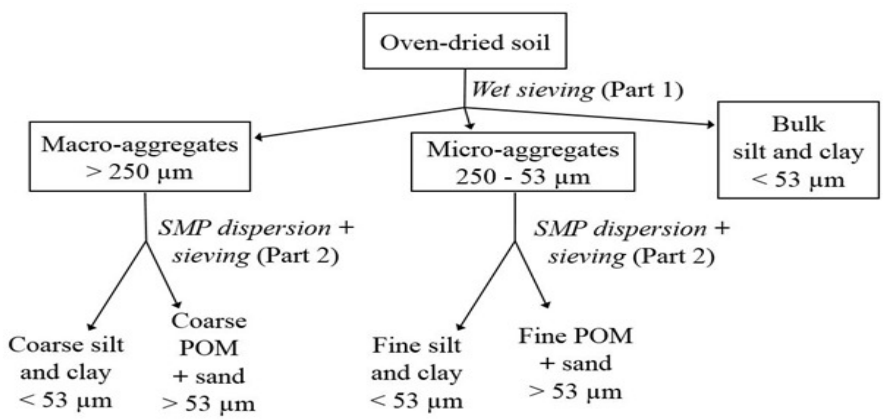

Fig. 1. Flow chart of the aggregate fractionation (Part 1) procedure to obtain macro-aggregates (> 0.01 in. or > 250 µm), micro-aggregates (> 0.002 to < 0.01 in. or > 53 to < 250 µm), and silt and clay fractions (< 0.002 in. or < 53 µm) and particulate organic matter (POM) separation (Part 2) procedure to obtain coarse- and fine-POM.

Table 1. Analysis of variance (ANOVA) summary of the effects of tillage, residue level, burning, irrigation, and their interactions on macro- and micro-aggregate, coarse- and fine-particulate organic matter (POM) carbon (C) and nitrogen (N) concentrations (g/kg sand-free aggregate) and their C:N ratios in the top 4 in. (10 cm) following more than 13 years of consistent management in a wheat-soybean, double-crop production system at the University of Arkansas System Division of Agriculture's Lon Mann Cotton Research Station near Marianna, Ark. on a silt-loam soil. Significant ($P < 0.05$) effects are bolded.

Source of variation	Macro- C	Macro- N	Macro- C:N	Micro- C	Micro-N	Micro-C:N	Coarse-POM C	Coarse-POM N	Coarse-POM C:N	Fine-POM C	Fine-POM N	Fine-POM C:N
		P										
Tillage (T)[a]	**0.05**	0.13	0.92	0.12	0.48	0.12	0.19	0.12	0.77	0.35	0.34	0.62
Residue level (RL)	0.57	0.59	0.72	0.38	0.64	0.07	0.94	0.61	0.22	0.03	0.07	0.37
Burn (B)	0.31	0.36	0.72	0.68	0.47	0.22	0.83	0.63	0.29	0.63	0.60	0.43
T × RL	0.75	0.27	0.88	0.71	0.29	0.34	0.58	0.95	0.56	0.91	0.76	0.33
T × B	0.49	0.65	0.13	0.92	0.73	0.55	0.14	0.30	0.16	0.96	0.45	0.09
B × RL	0.06	0.42	0.06	0.68	0.28	0.74	0.35	0.75	0.14	**0.04**	**0.02**	0.75
T × B × RL	0.40	0.47	0.89	0.86	0.92	0.56	0.79	0.42	0.22	0.52	0.31	0.34
Tillage[†]	0.13	0.13	0.75	0.12	0.48	0.12	0.32	0.23	0.75	0.35	0.34	0.63
Residue level	0.63	0.45	0.24	0.26	0.50	0.21	0.98	0.67	0.24	0.02	0.01	0.30
Irrigation (I)	0.44	0.43	0.60	0.22	0.41	0.59	0.09	0.19	0.60	0.31	0.28	**< 0.01**
T × RL	0.85	0.63	0.50	0.76	0.40	0.18	0.75	0.98	0.50	0.87	0.72	0.30
T × I	0.91	0.62	0.37	0.87	0.39	0.37	0.85	0.65	0.37	0.20	0.19	0.32
I × RL	0.09	0.19	0.19	0.08	0.10	0.32	0.13	**< 0.01**	0.19	0.72	0.82	0.74
T × I × RL	0.51	0.82	0.64	0.72	0.61	0.21	0.66	0.69	0.64	0.55	0.77	0.26

[a] Two sets of three-factor ANOVAs were conducted due to the similar blocking structure for the burn and irrigation treatments.

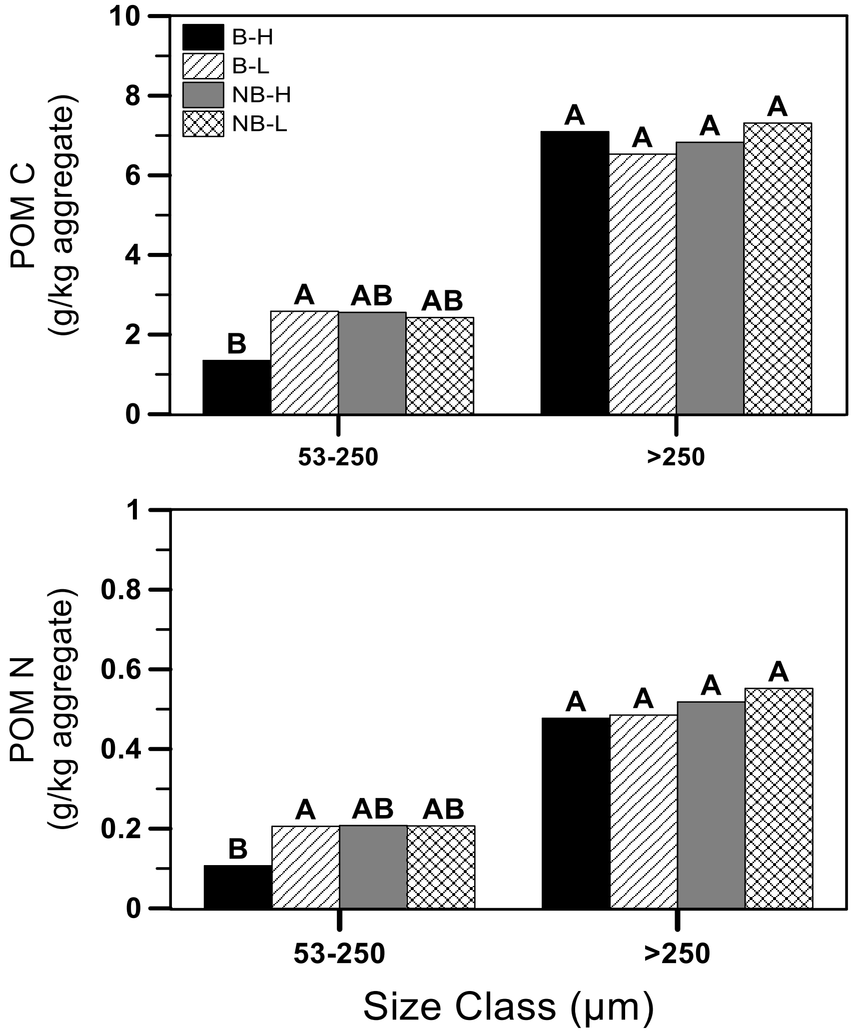

Fig. 2. Burn [burn (B) and no burn (NB)]-residue-level [high (H) and low (L)] treatment effects on particulate organic matter (POM) C and N concentration among aggregate-size classes (0.002-0.01 in. or 53-250 µm and > 0.01 in. or > 250 µm) in the top 4 in. (10 cm) of soil in September 2015 following more than 13 years of consistent management in a wheat-soybean, double-crop system near Marianna, Ark. Different letters atop bars within a size class within a panel denote significant differences (*P* < 0.05) between treatment combinations.