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# Forage species and summer management impacts on soil carbon and nitrogen in winter stockpiled grazing systems

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**Abstract**

Soil organic matter (SOM) in managed grasslands have economic and environmental benefits. This experiment evaluated a stockpiled winter grazing system with two summer management treatments (grazing or hay harvest) and three forage species treatments: tall fescue (TF, *Schedonorus arundinaceus* Schreb.), switchgrass (SG, *Panicum virgatum* L.), and mixed big bluestem–Indiangrass [BBIG, *Andropogon gerardii* Vitman–*Sorghastrum nutans* (L.) Nash]. Soil was sampled on 18 dates (January 2016–July 2017) at two depths (0–5 and 5–15 cm) in 15 paddocks in central Tennessee. Total organic carbon and total nitrogen concentrations in 0–5-cm samples were greater in grazed paddocks relative to hay harvest, and greater in TF relative to BBIG and SG. Summer grazing also resulted in greater 0–5-cm permanganate-oxidizable carbon (POXC) and 5–15 cm hot-water extract ultraviolet absorbance at 254 nm ($A_{254}$). Hot-water extractable carbon, $A_{254}$, and POXC concentrations were reduced in SG soils compared with TF and BBIG. Summer hay harvests, compared with grazing, reduced hot-water extractable C/N in both soil horizons in TF. The interactions between management and plant species suggests contrasting nutrient cycling associated with TF and the morphologically different native grasses BBIG and SG. This study represents the first observations of soil impacts within stockpiled grazing systems and the first observations of grazed native grass species in the southeastern United States.

## 1 | INTRODUCTION

Managing ecosystems for C sequestration provides an opportunity to offset anthropogenic emissions of $CO_2$, while increasing fertility in agricultural lands (Lal, 2004). However, soil organic matter (SOM) concentrations change slowly and detecting management-induced effects can be challenging (Awale, Emeson, & Machado, 2017; Wuest, 2014). Labile C is a rapidly cycling fraction of SOM and is a potentially sensitive indicator of long-term SOM cycling and plant nutrient availability (Culman et al., 2012; Culman, Snapp, Green, & Gentry, 2013; Ghani, Sarathchandra, Ledgard, Dexter, & Lindsey, 2012). Various labile C pools have been proposed as indicators of improved soil health (Awale et al., 2017; Fine,

**Abbreviations:** $A_{254}$, hot-water extract ultraviolet absorbance at 254 nm; BB, big bluestem (*Andropogon gerardii* Vitman); HWEC, hot-water extractable carbon; HWEN, hot-water extractable nitrogen; IG, Indiangrass [*Sorghastrum nutans* (L.) Nash]; NWSG, native warm-season grasses; POXC, permanganate oxidizable carbon; SOM, soil organic matter; TN, total nitrogen; TOC, total organic carbon.

van Es, & Schindelbeck, 2017; Morrow, Huggins, Carpenter-Boggs, & Reganold, 2016).

Managed perennial grasslands such as pastures, rangelands, haylands or recently proposed bioenergy grasslands can potentially sequester SOM, but the impacts of different grassland species and management strategies are difficult to predict (Abdalla et al., 2018; Conant, Cerri, Osborne, & Paustian, 2017; McSherry & Ritchie, 2013). Two major management variables are the plant species and harvesting regime. In the southeastern United States, nearly 15 million ha are currently planted with tall fescue (TF, *Schedonorus arundinaceus* Schreb.; Fribourg, Hannaway, & West, 2009). Its prevalence is due to the combination of high digestibility as a $C_3$ grass and heat tolerance. Increased SOM has been reported in TF swards (Franzluebbers & Stuedemann, 2009; Franzluebbers, Endale, Buyer, & Stuedemann, 2012). Native warm-season grasses (NWSG) are an alternative forage base that are more drought and heat tolerant due to their $C_4$ photosynthetic pathway (Doxon, Keyser, Bates, Harper, & Waller, 2011). Further, NWSG pasture adoption restores endangered ecosystems and improves wildlife habitat (Chamberlain, Paine, Harrison, & Jackson, 2012; Harper et al., 2015; Noss, 2013). The commercially available and agronomically viable native grasses for the southeastern United States include switchgrass (SG, *Panicum virgatum* L.), Indiangrass [IG, *Sorgastrum nutans* (L.) Nash], and big bluestem (BB, *Andropogon gerardii* Vitman).

Rapid SOM sequestration under restored NWSG has been anticipated, due high historical SOM associated with grasslands (Crews & Rumsey, 2017). Biologically, NWSG allocate greater proportions of C belowground and have greater root recalcitrance relative to introduced $C_3$ grasses such as TF. However, prior studies have reported variable SOM results (Garten & Wullschleger, 2000; Kravchenko et al., 2019; Pryatel, 2015; Toliver et al., 2018). Soils of restored NWSG systems have exhibited greater SOM accumulation than annual cropping systems (Blanco-Canqui, Gilley, Eisenhauer, Jasa, & Boldt, 2014; Liebig, Johnson, Hanson, & Frank, 2005) but comparable or reduced SOM maintenance has been reported when restored NWSG are compared with other managed grassland systems. This outcome has been reported in both SG monocultures (Bransby, McLaughlin, & Parrish, 1998; Garten & Wullschleger, 2000; Sanderson, 2008) and NWSG-dominant prairie restorations (Ampleman, Crawford, & Fike, 2014; Fornara, Tilman, & Hobbie, 2009; Mahaney, Smemo, & Gross, 2008). Observations comparing the C and N pools of NWSG to widely adopted $C_3$ species, such as TF, may provide mechanisms for these descrepancies. In addition, no reports of grazed NWSG impacts have been published for the southeastern United States.

Two major management strategies for grasslands are livestock grazing or hay harvest. Previous literature evaluating the impact of grazing and hay harvests on SOM tend to support increased SOM accumulation with grazing management

**Core Ideas**

- Tall fescue pastures increased total organic C and total N concentrations.
- Soil organic matter accumulation is dependent on both management and species.
- Grazing management changed labile soil organic matter fractions compared with hay harvesting.

(Koncz et al., 2017; Oates & Jackson, 2014; Senapati et al., 2014). However, grazing alters multiple nutrient pathways through mechanisms such as trampling, manure distribution, and selective plant removal. It is unknown which of these pathways has the greatest influence on SOM. Winter stockpiled grazing of TF is an economically viable practice in the southeastern United States and provides novel conditions to study grassland management impacts (Fribourg & Bell, 1984; Poore & Drewnoski, 2010; Shireman, 2015). Stockpiling is the practice of allowing forage to accumulate in the field for grazing when other forage sources are unavailable. Stockpiling forage for winter grazing results in manure application and trampling, but without grazing during the growing season. Therefore, observations of winter stockpiling systems could both quantify the impacts of a common agronomic practice and also evaluate a novel land use strategy. Unlike TF, NWSG species are rarely used for winter stockpiled grazing in the southeastern United States and are considered nutritionally insufficient for most livestock at this senesced maturity stage (Hickman, 2013). However, stockpiled winter NWSG are used in rangeland grazing systems in the United States (Adams, Nelsen, Reynolds, & Knapp, 1986; Choat et al., 2003). Recent research has reported that winter stockpiled NWSG can be economically superior in the southeastern United States when low-input, high-biomass winter forage is required (McFarlane, Boyer, & Mulliniks, 2018).

Hot-water extraction and K permanganate oxidation are two methods for isolating labile soil C fractions. Both respond to agronomic management and correlate with microbial community size or microbially accessible nutrients (Culman et al., 2012; Ghani, Dexter, & Perrott, 2003; Sparling, Vojvodić-Vuković, & Schipper, 1998; Weil, Islam, Stine, Gruver, & Samson-Liebig, 2003). Hot-water extractable C and N include the microbial population, soluble soil proteins, and microbially accessible plant carbohydrates (Ghani et al., 2003; Sparling et al., 1998). Potassium permanganate oxidation reacts with C sources that are undecomposed or partially decomposed (Culman et al., 2012; Hurisso et al., 2016; Weil et al., 2003). The ultraviolet absorption (254 nm) of hot-water extractable C can also be recorded and correlates with solubilized aromatic C components (Bu et al., 2010; Weishaar et al., 2003).

The objective of this study is to evaluate bulk and labile soil C and N pools in a stockpiled winter grazing system with contrasting summer management and plant species in the southeastern United States.

# 2 | MATERIALS AND METHODS

## 2.1 | Site, history, and management

The study site is a field trial at the University of Tennessee's Middle Tennessee Research and Education Center in Spring Hill, TN (35.718576 N, −86.962832 W). Soil at the study location is a Maury silt loam, which is classified as a fine, mixed, active, mesic Typic Paleudalf. Routine agronomic soil analysis was carried through the University of Tennessee Extension Soil, Plant and Pest Center. Samples from the 0–15 cm profile indicated mean soil pH of 5.96, and extractable P, K, Ca, and Mg of 235, 96, 1,890, and 129 mg kg$^{-1}$, respectively (Mehlich-1 extraction). The elevated soil P content was due to the abundance of P-containing parent material at this location. No micronutrient deficiencies were observed within sampling units at the site.

The array of paddocks used in this experiment were established for a field trial evaluating red clover (*Trifolium pratense* L.) establishment, which assigned plant species to paddocks using a completely randomized design. In May 2008, swards were planted by no-till drilling 18 1.2-ha paddocks (Keyser et al., 2016). The plant species were tall fescue ('KY-31'), switchgrass ('Alamo'), or a 1:1 mixture of Indiangrass ('Rumsey') and big bluestem ('OZ-70'). Beginning in 2013, all paddocks were managed for stockpiled winter grazing (2–3 Angus heifers per paddock). Management was consistent for 3 yr prior to the initiation of soil sampling, and two winter grazing cycles occurred during sampling (McFarlane, 2018). Due to limited resources, this experiment sampled five of the eight replicates in the field study (15 out of 24 paddocks). Sampled replicates were chosen based on a common soil type. These paddocks were previously assigned, resulting in an unbalanced factorial experiment between management (summer grazing and summer hay harvest) and plant species. Notably, this experiment was not designed to quantify the impact of stockpiled winter grazing. Instead the treatment variables are three contrasting plant species [tall fescue; big bluestem–Indiangrass (BBIG), and switchgrass] and two summer management regimes (grazing and hay harvest).

The annual management cycle was the following: livestock grazing from January to April, regrowth from April to June, either haying or grazing during June to July, and clipping of the residual in late July to allow uniform regrowth for winter grazing beginning the following January (20-cm residual clipping height for NWSG; 10-cm for TF). Differences in residual height between these forages is in accordance with suggested management practices for NWSG and TF. Paddocks managed for hay were fertilized with 67 kg ha$^{-1}$ N (ammonium nitrate) in June of each year in accordance with conventional management practices. Grazed paddocks were not fertilized because manure inputs were expected to balance N availability.

## 2.2 | Soil sampling and analysis

Two 12-mm diameter soil cores (0–5 and 5–15 cm depth; litter layer removed) were taken from four random points in each paddock and composited for analysis (eight total per paddock). Soil samples were collected for extractions 11 times during 2016: 27 January, 9 March, 8 April, 10 May, 6 June, 27 June, 27 July, 24 August, 26 September, 26 October, and 30 November; and 7 times during 2017: 4 January, 3 February, 3 March, 31 March, 3 May, 14 June, and 11 July. Due to the lack of expected short-term variation in bulk nutrients, soil samples were analyzed for total organic carbon (TOC) and total nitrogen (TN) for only four sampling dates: 9 Mar. 2016, 24 Aug. 2016, 3 Mar. 2017, and 11 July 2017.

Soil samples were oven dried at 60 °C and then passed through a 2-mm sieve to remove coarse material (Gasch, Mathews, Deschene, Butcher, & DeSutter, 2020). Hot-water extraction was carried out following the method described in Ghani et al. (2003), but using a shorter extraction time to extract primarily microbial, rather than plant, carbohydrates and minimize compositional alterations (Nkhili, Guyot, Vassal, & Richard, 2012). Briefly, 10 g of soil (oven dry wt.) were incubated for 4 h at 80 °C in 0.1 L water. The sample extracts were immediately filtered and refrigerated until analysis for total C (hot-water extractable carbon, HWEC) and total N (hot-water extractable nitrogen, HWEN) concentrations using Shimadzu TOC-5050 analyzer.

Hot-water extract UV-absorbance at 254 nm, measured in absorbance units per cm (a.u. cm$^{-1}$; $A_{254}$), was quantified using a Genesys 6 UV-VIS spectrophotometer (Thermo Scientific) with a 1-cm path-length cell to determine aromaticity of extracted C (Fernández-Romero, Clark, Collins, Parras-Alcántara, & Lozano-García, 2016; Weishaar et al., 2003). Although ultraviolet absorption at 254 nm ($A_{254}$) is frequently presented as the ratio of absorbance to the soluble carbon (HWEC), this experiment will report $A_{254}$ since short-term variability in the ratio of $A_{254}$ to HWEC is predominantly influenced by the more labile and volatile HWEC content (data not shown).

Determination of potassium permanganate ($KMnO_4$) oxidizable carbon (POXC) followed the method reported by Weil et al. (2003). Soil was reacted with $KMnO_4$ for 2 min on a shaker, immediately centrifuged (5 min at 3,000 rpm), and a diluted portion of the supernatant was analyzed for

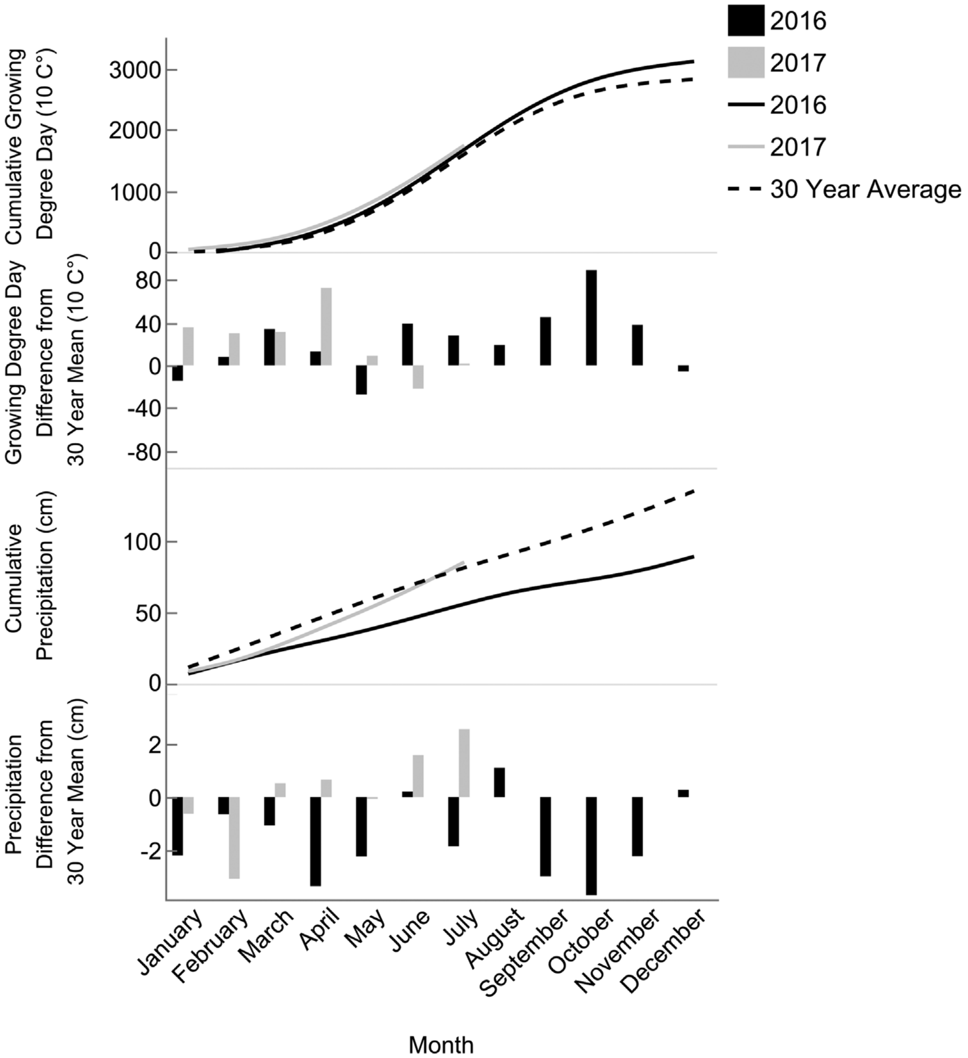


**FIGURE 1** Cumulative precipitation (cm), growing degree days (base 10 ˚), monthly difference from 30-yr mean growing degree days (base 10 ˚C), and monthly difference from 30-yr mean precipitation (cm)

absorbance at 550 nm (Powerwave XS, BioTek). The POXC was then calculated using the following equation:

$$\text{POXC} = (\text{Initial conc of KMnO}_4\ (\text{mol L}^{-1}) - b \times \text{Absorbance at 550 nm}) \times 9,000\ \text{mg C mol}^{-1} \times \text{Volume of reactant/weight of soil (kg)}$$

where $b$ is the slope of a standard curve.

Total organic C and total N of bulk soil were measured on pulverized soil samples by mass spectrometry using a ThermoFlash EA 1112 analyzer.

## 2.3 | Data analysis

Analysis was conducted in R. For each soil variable and soil depth, a mixed-effect model was created (package *lme*) including management, species, and their interaction as fixed effects. Sampling date was included as a random effect with first-order autocorrelation structure. Mean separation carried out using estimated marginal means with Tukey's adjustment (*emmeans* package; $P < .05$). Model residuals were tested for normal distribution using the Shapiro-Wilk test for normal distribution and where transformed accordingly.

# 3 | RESULTS

## 3.1 | Environmental conditions

During the 2016 season, mean temperature was greater than the 30-yr mean (Figure 1). A drought occurred from August to late November and prevented soil sampling from 5 to 15 cm depth on 26 Sept. 2016 due to excessively hard soil. The 2017 spring and summer had precipitation levels similar to the

**TABLE 1** Mixed model test statistics ($F$ values) of soil variables across 19 sampling dates, two management regimes, and three forage species treatments

| | Bulk (4 sampling dates; $n$ = 58) | | | Labile (18 sampling dates; $n$ = 250) | | | | |
|---|---|---|---|---|---|---|---|---|
| ***F* value** | **TOC** | **TN** | **TOC/TN** | **HWEC** | **HWEN** | **HWE** | $A_{254}$ | **POXC** |
| 0–5 cm | ——g kg$^{-1}$—— | | | ———mg kg$^{-1}$——— | | C/N | | mg kg$^{-1}$ |
| Forage species | 5.99* | 8.05* | 2.47 | 16.78* | 17.71* | 0.23 | 27.42* | 5.26* |
| Management | 10.27* | 9.49* | 2.13 | 0.25 | 13.65* | 25.68* | 0.92 | 9.29* |
| Forage species × Management | 0.19 | 0.08 | 2.03 | 0.47 | 3.36* | 3.77* | 4.33* | 0.57 |
| **5–15 cm** | | | | | | | | |
| Forage species | 0.65 | 2.49 | 1.72 | 2.27 | 5.78* | 1.45 | 1.3 | 3.05* |
| Management | 1.38 | 2.16 | 0.13 | 1.35 | 9.62* | 24.02* | 3.93* | 0.01 |
| Forage species × Management | 3.73* | 3.27* | 3.29* | 1.57 | 3.25* | 6.01* | 0.26 | 2.41 |

*Note*. TOC, total organic carbon; TN, total nitrogen; HWEC, hot-water extractable carbon; HWEN, hot-water extractable nitrogen; $A_{254}$, UV-absorbance at 254 nm; POXC, permanganate oxidizable carbon.
*Significants at $p < .05$.

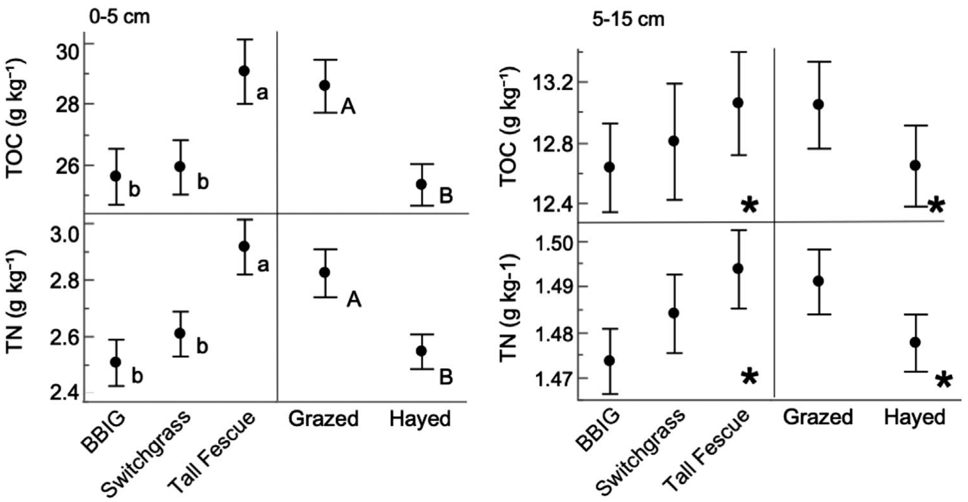


**FIGURE 2** Total organic carbon (TOC) and total nitrogen (TN) associated with different forage species and management treatments at two soil depths (0–5 and 5–15 cm). Error bars indicate 1 SE from the mean. Variables without a shared letter are significantly different according to Tukey's Honestly Significant Difference test ($P < .05$). Lower case indicates differences due to forage species. Upper case indicates differences due to management. Asterisk indicates a forage species × management treatment interaction (Figures 4 and 5). Note that the $y$ axes do not start at zero

30-yr mean but greater than average growing degree day (base 10 ˚C) accumulation (Figure 1).

## 3.2 | Soil properties

Residuals of models for HWEC, HWEN, $A_{254}$, and HWE C/N did not pass the Shapiro-Wilk test for normal distribution but passed the same test after log-normal variable transformation. Multiple significant relationships were detected between management, plant species and the sampled soil variables (Table 1; Supplemental Tables S1 and S2). Bulk soil C and N pools (TOC, TN) were influenced by forage species and management at the 0–5 cm sampling depth, whereas only interactive effects occurred at 5–15 cm (Table 1; Figure 2). Relative to hay harvest, paddocks that were grazed during summer contained 12.8% greater concentrations of TOC (25.3 and 28.5 g kg$^{-1}$, respectively) and 9.8% greater concentrations of TN (2.56 and 2.82 g kg$^{-1}$, respectively) in the 0–5 cm layer. At the same depth, TF had greater TOC (29.08 g kg$^{-1}$) and TN (2.919 g kg$^{-1}$) relative to BBIG (TOC 25.61 g kg$^{-1}$; TN 2.508 g kg$^{-1}$) and switchgrass (TOC 25.92 g kg$^{-1}$; TN 2.61 g kg$^{-1}$) (Figure 2).

Labile fractions responded to both management and forage species (Table 1). At 0–5 cm, switchgrass soils had reduced HWEC and HWEN concentrations (639.6 and 77.35 g kg$^{-1}$, respectively) relative to TF (775.9 and 96.38 g kg$^{-1}$, respectively) and BBIG (731.1 and 88.33 g kg$^{-1}$, respectively)

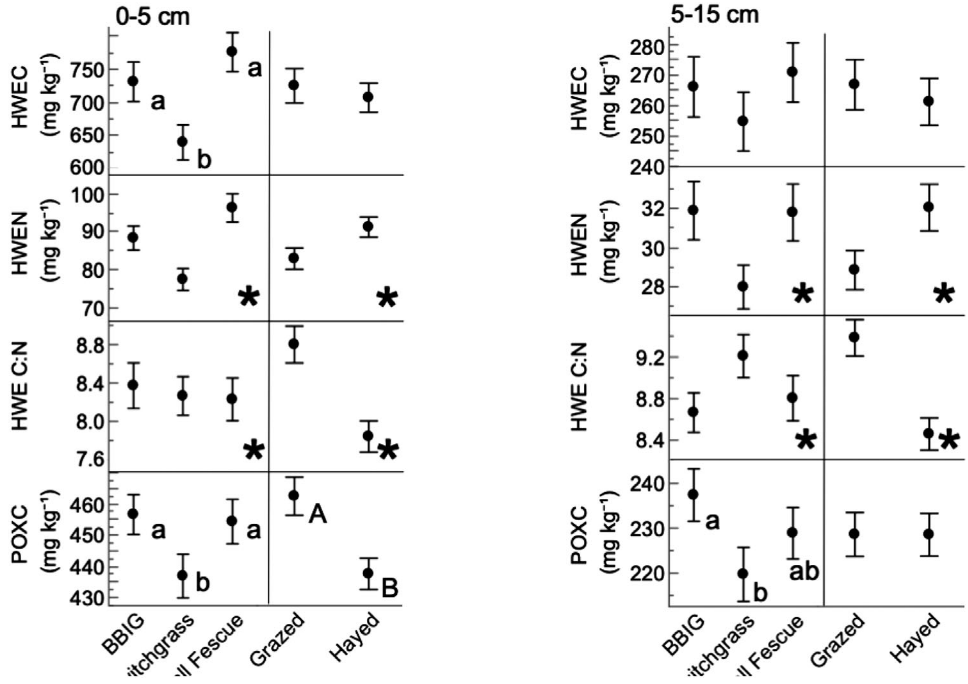


**FIGURE 3** Values of hot-water extractable carbon (HWEC), hot-water extractable nitrogen (HWEN), the ratio of HWEC and HWEN (HWE C/N), and potassium permanganate oxidizable carbon (POXC) of different forage species and management treatments at two soil depths (0–5 and 5–15 cm). Error bars indicate 1 SE from the mean. Variables without a shared letter are significantly different according to Tukey's Honestly Significant Difference test ($P < .05$). Lower case indicates differences due to forage species. Upper case indicates differences due to management. Asterisk indicates a forage species × management treatment interaction (Figures 4 and 5). Note that the *y* axes do not start at zero

(Figure 3). An interaction occurred for HWEN at both soil depths (Figures 4 and 5). Interestingly post-hoc tests did not indicate significant differences due to the interactions in the 5–15 cm TOC, TN, and TOC/TN variables (Figure 5). The strongest management × species interactions in these tests were for SG TOC ($p = .11$), SG TN ($p = .08$), and TF TOC/TC ($p = .11$; Figure 5).

Post-hoc tests provide evidence that this interaction is due to a greater HWEN concentration in hayed TF relative to grazed and a lack of management variation in SG (Figure 4). A strong management effect (grazed > hayed) was found in HWE C/N (12.2% at 0–5 cm and 10.9% at 5–15 cm), with an additional interactive effect for HWEN (Table 1; Figures 4 and 5). The HWE × C/N interaction can be attributed to a strong response in TF due to management (Figures 4 and 5). The POXC pool varied due to both species and management at 0–5 cm and only varied due to species at 5–15 cm (Table 1; Figure 3). Specifically at 0–5 cm, BBIG and TF had greater POXC concentration relative to SG and grazed paddocks had greater POXC concentration compared with paddocks managed for hay in summer (Figure 3). At 5–15 cm, BBIG had a greater POXC concentration relative to SG (Figure 3). An interactive effect occurred in A254 at 0–5 cm depth due a greater A254 concentration in grazed BBIG and a lack of significant management responses in SG and TF (Figure 4). At 5–15 cm, grazed paddocks contained greater A254 relative to hayed paddocks (0.287 and 0.276 a.u. $cm^{-1}$, respectively; Table 1).

## 4 | DISCUSSION

### 4.1 | Bulk organic matter variation

In agreement with prior reports, TF soils contained greater TOC and TN concentrations relative to the NWSG and grazing summer management resulted in greater TOC and TN concentrations relative to hay harvest (Bransby et al., 1998; McSherry & Ritchie, 2013; Abdalla et al., 2018; Kravchenko et al., 2019; Figure 2). Franzluebbers and Stuedemann (2009) reported comparable effects for grazed and hayed TF at a cumulative 0–15 cm depth, with TOC of 20.8 g $kg^{-1}$ in grazed treatments (18.2 g $kg^{-1}$ in current study) and 14.8 g $kg^{-1}$ in hayed treatments (16.8 g $kg^{-1}$ in current study). The narrower deviation due to management is due either to the longer length the Franzluebbers and Stuedemann experiment (12 yr) or the mixed grazing and haying management in the stockpiled grazing schedule of the current experiment.

Bulk soil responses were weaker at the 5–15 cm depth, which resulted in significant interactive responses in all bulk soil concentrations, but no significant differences in post-hoc tests (Figure 5). Responses to land use changes are expected

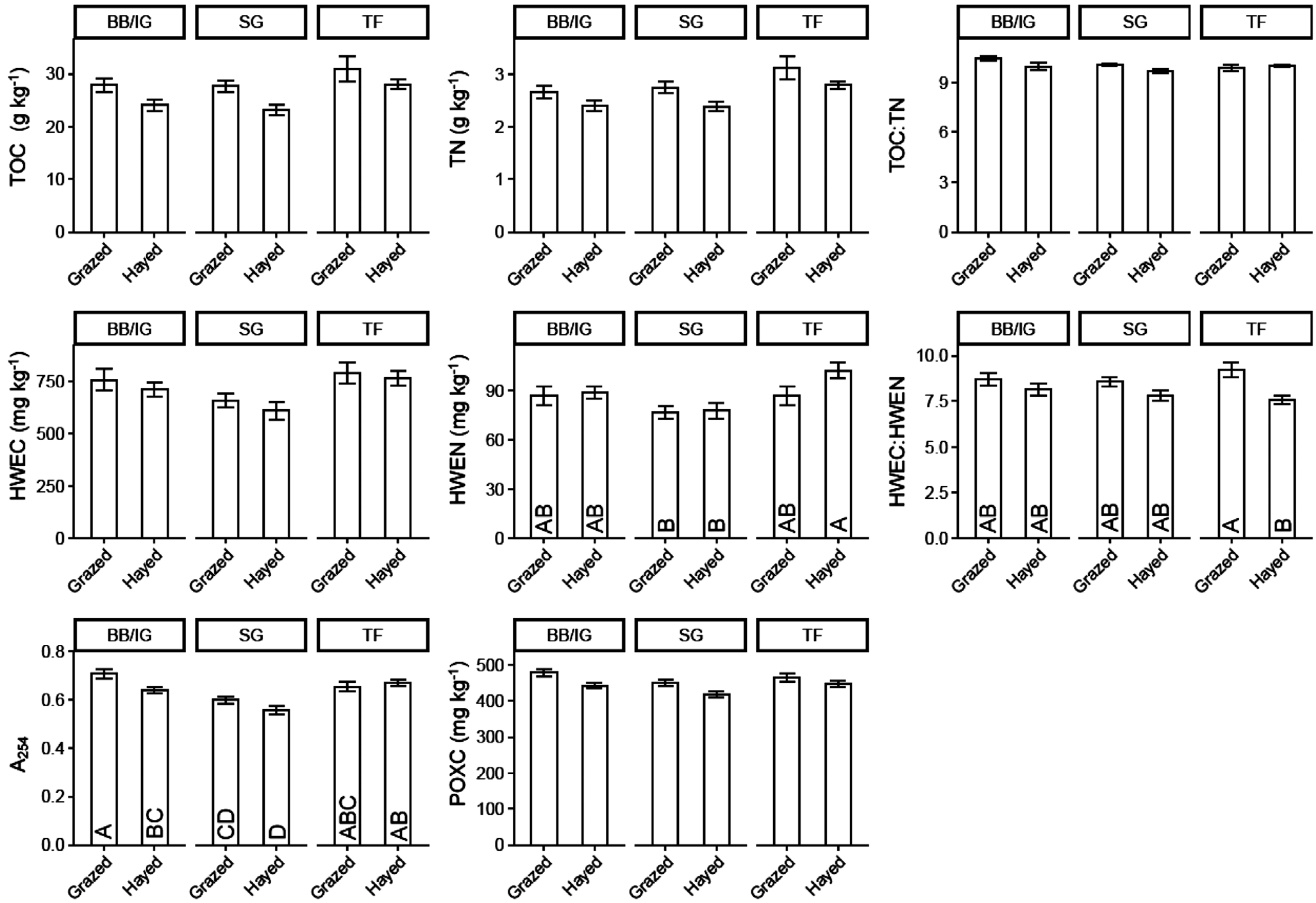


**FIGURE 4** Values of total organic carbon (TOC), total nitrogen (TN), the ratio of TOC/TN, hot-water extractable carbon (HWEC), hot-water extractable nitrogen (HWEN), the ratio of HWEC and HWEN (HWE C/N), UV-absorbance at 254 nm ($A_{254}$; a.u. $cm^{-1}$) and potassium permanganate oxidizable carbon (POXC; mg $kg^{-1}$) measured at 0–5 cm soil depth. Variables without a shared letter are significantly different according to Tukey's Honestly Significant Difference test ($P < .05$). Bars without letters indicate no significant interaction between management and forage species. Main effects depicted in Figures 2 and 3

to be slower in deeper soil horizons. A trend toward increased accumulation of TOC ($p = .11$) and TN ($p = .08$) in grazed SG is a potentially valuable area for further study since organic matter accumulates slowly at depth and has slower turnover. The interactive response of TOC/TN is likely due to minor increases in the NWSG TOC/TN (BBIG: 4.6%; SG: 3.6%) and a minor TOC/TN reduction in TF (−1.1%; Figure 5). It is difficult to speculate on the mechanisms for this change, but the most probable mechanism would be due to differing root morphologies or nutrient uptake strategies between the species (discussed below).

## 4.2 | Variation in labile carbon and nitrogen fractions

Labile fractions in the current study indicate multiple potential pathways for the bulk soil organic matter variability described above. However, the limited number of previous soil studies involving stockpiled grazing systems and grazed NWSG in non-rangeland systems limits the conclusions that can be drawn regarding mechanisms and causality.

The HWEC and HWEN concentrations of TF and BBIG were approximately 20% greater than switchgrass, albeit with an additional interactive response in TF HWEN (Figure 3). Similarly, POXC had reduced concentrations in the SG associated soil (Figure 3). These labile pools have rapid turnover rates; however, the sustained difference across this experiment suggests large cumulative differences in labile inputs (Bu et al., 2010, 2011; Culman et al., 2013; Ghani et al., 2012). Greater labile nutrient availability within TF paddocks may explain the greater TOC and TN maintenance relative to SG since these fractions stimulate greater microbial activity (Figure 2; Castellano, Mueller, Olk, Sawyer, & Six, 2015; Cotrufo, Wallenstein, Boot, Denef, & Paul, 2013). This explanation, however, does not hold for BBIG, which has elevated labile concentrations relative to SG, but equivalent TOC and TN contents (Figure 2). The comparable labile soil pools between TF and BBIG contrasts with their TOC and TN contents (Figure 2). The elevated labile soil concentrations are

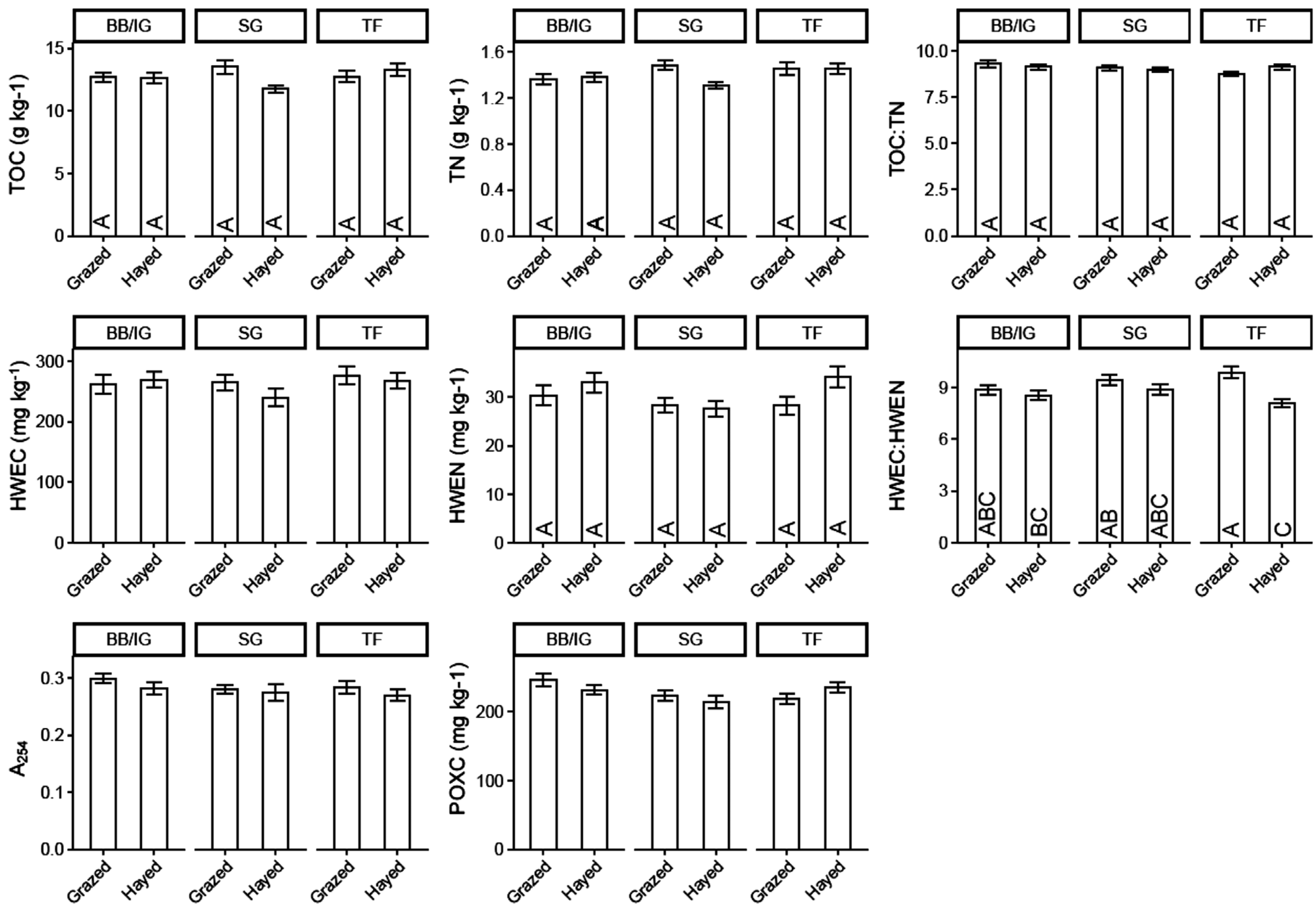


**FIGURE 5** Values of total organic carbon (TOC), total nitrogen (TN), the ratio of TOC/TN, hot-water extractable carbon (HWEC), hot-water extractable nitrogen (HWEN), the ratio of HWEC and HWEN (HWE C/N), UV-absorbance at 254 nm ($A_{254}$; a.u. $cm^{-1}$) and potassium permanganate oxidizable carbon (POXC; mg $kg^{-1}$) measured at 5–15 cm soil depth. Variables without a shared letter are significantly different according to Tukey's Honestly Significant Difference test ($P < .05$). Bars without letters indicate no significant interaction between management and forage species. Main effects depicted in Figures 2 and 3

also unexpected as BBIG is more similar morphologically with SG and both are $C_4$ grasses. The lack of TOC accumulation in BBIG could be due to the mixed species composition of the treatment or be the result of plant traits specific to BBIG (Craine, 2006; Craine, Froehle, Tilman, Wedin, & Chapin, 2001). Alternatively, switchgrass may be an outlier among warm-season bunchgrasses due to adaptations for deep rooting and highly recalcitrant root material (Craine et al., 2002). Both of these traits could contribute to the observed decrease in SG labile soil concentrations.

The NWSG did have a shared response in shallow soil soluble aromatic concentrations ($A_{254}$), which increased with summer grazing (Figure 4). This was significant in BBIG, with a parallel trend in SG (Figure 4). Increased soluble aromatic compounds could be due to an increased litter layer in grazed NWSG. Specifically, NWSG maintain greater aboveground biomass with greater proportions of stem material, particularly in mid-summer (Gelley, Nave, & Bates, 2016). This standing biomass resulted in large quantities of trampled aboveground material during grazing.

The increased POXC in grazed paddocks, relative to hay, aligns with expected greater belowground investment in roots and exudates in response to grazing (Abdalla et al., 2018; Piñeiro, Paruelo, Oesterheld, & Jobbágy, 2010; Sun et al., 2017). However, the lack of management response in HWEC does not support this conclusion. Prior reports have found associations between HWEC, soil organic matter accumulation, and grazing (Ghani et al., 2003; Lambie, Ghani, Mudge, & Stevenson, 2019; Stevenson, Sarmah, Smernik, Hunter, & Fraser, 2016). The aromatic C component of HWEC ($A_{254}$) was also elevated in grazing, relative to hay paddocks at 5–15 cm (0.287 and 0.276 a.u. $cm^{-1}$, respectively; Table 1). Similar to the lack of management responses in HWEC overall, it is difficult to account of which mechanisms could be causing these observations.

A strong, parallel species × management interactive response occurred at both depths in HWE C/N and HWEN (Table 1; Figures 4 and 5). The decrease in TF HWE C/N relative to NWSG is likely a reflection of contrasting plant nutrient acquisition traits. Relative to the NWSG species, TF is morphologically adapted for rapid growth and rapid turnover of above- and belowground material (Craine et al., 2001, 2002). This can be seen in the low C/N of TF, which may directly or indirectly elevate labile N contents.

One possible explanation is that TF swards poorly buffer the N input provided by the fertilization in the hay treatment. The N fertilization rate of the current study was expected to be below the expected N removal from harvests. Boyer et al. (2015) reported mean yields of 5–8 and 10–15 Mg ha$^{-1}$ and crude protein contents (N% × 6.25) between 9–12 and 9–11% for BBIG and SG hay harvests, respectively. This accounts for average removal rates around 70–150 kg N ha$^{-1}$ per harvest, relative to the 67 kg ha$^{-1}$ applied in this experiment. Similarly, TF, with crude protein contents between 11 and 20%, would require 3–4 Mg ha$^{-1}$ yr$^{-1}$ in summer hay removal to balance the N inputs in the current experiment (Burns, Fisher, & Pond, 2011; Kallenbach, Bishop-Hurley, Massie, Rottinghaus, & West, 2003). It is therefore possible that this labile N response is due to fertilization of TF when managed for summer hay harvest.

Although fertilization is a potential explanation, there was no evidence of bulk soil N accumulation in TF (Figures 4 and 5). To the contrary, a weak increase in hayed TOC/TN occurred at 5–15 cm in TF ($p$ = .11), which contrasted with slight decreases in NWSG and resulted in a significant interactive effect (Table 1; Figure 5). Therefore, it is unlikely that the TF swards are accumulating N overall. Instead, the more extensive, high C/N NWSG root systems may rely on a different N uptake strategy relative to TF and this results in the observed contrasting labile N availability. These strategies could include more efficient scavenging, greater N mineralization, or even diffuse associative N-fixation (Roley et al., 2018). Earlier research has found that high C/N plants tend to rely less on exudation and instead rely on scavenging N over a larger area compared with low C/N plants (Kaštovská, Edwards, Picek, & Šantrůčková, 2015; Personeni & Loiseau, 2005). These contrasting strategies could alter the proportion of soluble N observed in soil when the plant species have longer duration of stress (grazing) compared with single recovery periods (haying). In addition, increased N mineralization in grazed SG could result in the observed decrease in TN and increase in TOC/TN (Figure 4 and 5). Differences in rooting strategies have potentially large impacts on long-term SOM accumulation, N efficiency in grasslands, and agronomic utility. Further evaluations of NWSG and TF grazing systems could provide further evidence of mechanisms causing these observations.

There are important caveats that should be acknowledged in interpreting this experiment. First, soils samples prior to establishment or management were unavailable, which would have improved the certainty of the observed soil changes and accuracy of treatment effect sizes. Second, the unmeasured impact of management on soil bulk density may act as a confounding variable. Specifically, grazing compaction or differential root growth could alter bulk density due to the experimental treatments. Previous experiments in the region have indicated an inverse relationship between bulk density and SOM in the southeastern United States (Franzluebbers & Stuedemann, 2010). In addition, previous reviews have found increases in bulk density with increased grazing (Abdalla et al., 2018; Piñeiro et al., 2010). Also, the scale of bulk density variability due to management is smaller than many of the observed effects in the current experiment (Franzluebbers & Stuedemann, 2010; Franzluebbers, Stuedemann, Schomberg, & Wilkinson, 2000). More research is necessary to evaluate the impact of alternative management systems on soil bulk density and C. Lastly, the management and plant species unbalanced factorial design resulted in either two or three replicates for a given treatment combination. This limited replication resulted in insignificant post-hoc interactive effects despite significant experiment wide interactive effects. Therefore, further research should be carried out to confirm the management interactions observed in this experiment.

## 5 | CONCLUSIONS

This study observed that summer grazing increased TOC and TN concentrations and altered multiple labile SOM fractions (HWE C/N, POXC) compared with hay harvesting. Also, TF increased TOC and TN concentrations compared with the NWSG species (BBIG and SG), but TF was not different from BBIG in the labile soil fractions (HWEC, HWEN, POXC). Tall fescue responded to hay management, relative to grazing, with a strong increase in HWE C/N. It is difficult to determine a mechanism for the above observations, but they suggest contrasting N uptake strategies between TF and the NWSG. These results provide novel preliminary evidence about soil organic matter cycling associated with these contrasting agricultural managements and forage species.

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### AUTHOR CONTRIBUTIONS

Neal Wepking Tilhou: Data curation; Formal analysis; Writing-original draft; Writing-review & editing. Renata Nave: Conceptualization; Funding acquisition; Investigation; Project administration; Resources; Writing-review & editing. Sindhu Jagadamma: Data curation; Formal analysis; Validation; Visualization; Writing-review & editing. Neal Eash: Conceptualization; Funding acquisition; Resources. J. Travis

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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