Soil hydrological properties as influenced by long-term nitrogen application and landscape positions under switchgrass seeded to a marginal cropland

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Abstract
Switchgrass (*Panicum virgatum* L.) has the potential to recover the soil hydrological properties of marginal lands. Nitrogen (N) and landscape position are the key factors in impacting these soil properties under switchgrass. The specific objective of this study was to investigate the responses of N rate (low, 0 kg N/ha and high, 112 kg N/ha) and landscape positions (shoulder and footslope) on near-surface soil hydrological properties that included: infiltration rate (*q*), saturated hydraulic conductivity (*K*\textsubscript{sat}), bulk density (*ρ*\textsubscript{b}), penetration resistance (SPR), water retention (SWR), pore-size distribution (PSD), and carbon (C) and nitrogen (N) fractions under switchgrass production. Data showed that, in general, the N and landscape position significantly influenced soil hydrological properties. Higher N rate decreased *ρ*\textsubscript{b} (1.23 and 1.36 g/cm\textsuperscript{3} at 0–5 and 5–15 cm, respectively) and SPR (1.06 and 1.53 MPa at 0–5 and 5–15 cm, respectively) at both depths and increased the *q*, *K*\textsubscript{sat} and Green–Ampt estimated sorptivity (*S*) and hydraulic conductivity (*K*) parameters, and SWR (0–5 cm depth) at 0 and −0.4 kPa matric potentials (*ψ*\textsubscript{m}). Furthermore, footslope position significantly decreased *ρ*\textsubscript{b}, SPR at 0–5 and 5–15 cm depths, and increased the *q*, *K*\textsubscript{sat}, *S*, *K*, and SWR (0–5 cm depth) at every *ψ*\textsubscript{m} ranged from 0 to −30.0 kPa. The higher N rate increased the coarse mesopores (60–1,000 μm) and total pores, whereas, footslope position increased the coarse mesopores, micropores (<60 μm), and total pores. Data from this study showed that planting switchgrass with 112 kg N/ha under footslope position helped in improving the soil hydrological properties, those can be beneficial in enhancing the biomass yield under marginal lands.

**KEYWORDS**
landscape positions, N rates, saturated hydraulic conductivity, soil hydrological properties, soil water retention, switchgrass, water infiltration
In 1985, the United States Department of Energy identified switchgrass (Panicum Virgatum L.) as a renewable energy source that could be an alternative source for fuel instead of petroleum-based transportation fuels in the United States (Lee et al., 2012). Since 1987, the research interest in switchgrass for bioenergy production has exponentially been increased in the USA (Mitchell, Vogel, & Schmer, 2016). In 1991, switchgrass was selected as a “model” potential bioenergy crop for researchers (Wright & Turhollow, 2010). Switchgrass is a perennial warm-season C₄ grass species that is native to North America. It has a high tolerance to soil water deficits and low soil nutrients availability, thereby can successfully adapt to diverse environmental conditions over larger geographic regions and has high potential biomass production on marginal lands (Barney et al., 2009). The production of switchgrass has been increased over the past few decades due to the economic benefits, thus, there is strong need to assess the ecological impacts associated with its production in the United States (Hartman, Nippert, Orozco, & Springer, 2011). Studies have shown that switchgrass production can improve soils and environmental quality (e.g., Lai, Kumar, Osborne, & Owens, 2018) with low on-farm energy requirements and costs (Wright, Perlack, Turhollow, & Eaton, 2011). Switchgrass has prolific and deep root system that can add organic carbon to the soil, reduce soil bulk density ($\rho_b$), and improve water infiltration rate compared with the row crop annuals (Kahle, Hildebrand, Baum, & Boelcke, 2007).

Soil properties especially $\rho_b$ and infiltration rate are strongly related to soil water movement, porosity, and workability (Friedman, Hubbs, Tugal, Seybold, & Sucik, 2001). Infiltration rate reflects soil functions of regulating and partitioning water and solute flow and filtering, buffering, degrading, detoxifying organic or inorganic materials in crop-soil ecosystems (NRCS, 2015). Furthermore, physically based hydrologic models such as Green–Ampt (Green & Ampt, 1911) are generally used to fit measured infiltration data (Zaibon et al., 2017) to show soil water infiltration with respect to time via physical parameters like sorptivity ($S$, mm h$^{-1.5}$) and model estimated saturated hydraulic conductivity ($K_{sat}$, mm/hr). The estimated $K_s$ represents water-transmitting capability of soils under hydraulic head gradient and varies with the antecedent soil water content. As $S$ and $K_s$ are influenced by the management, therefore, quantification of these parameters is crucial in order to assess the soil hydrological conditions. Switchgrass plantation can enhance soil organic matter (Schmer, Liebig, Vogel, & Mitchell, 2011) and impact these soil hydrological properties including the soil water retention (SWR), the actual amount of water retained in the soil for crops (Smith & Kucera, 2018). Switchgrass, when managed with appropriate nitrogen fertilization and the landscape position can help in enhancing these soil hydrological properties.

Nitrogen fertilization rate (N rate) is a key factor in improving the switchgrass biomass production as it is considered a limiting nutrient for switchgrass (Hong et al., 2014). The N rate can improve soil fertility status and the yield (Bowman & Halvorson, 1998). The optimum N rate, however, depends on different soils and environmental conditions (Kering, Biermacher, Butler, Mosali, & Guretzky, 2012) because the impacts of N fertilizer on soil properties are different under various conditions. The N rate can significantly increase the soil organic carbon (SOC) in switchgrass fields (Jung & Lal, 2011). However, few studies reported no significant differences in SOC due to different fertilization rates, for example, Kibet, Blanco-Canqui, Mitchell, and Schacht (2016) and Lu et al. (2011). The increase in N rate significantly decreased the $\rho_b$ at the 0–5 cm depth in a barley (Hordeum vulgare L.)-maize (Zea mays L.) rotation system in Colorado (Halvorson, Reule, & Follett, 1999). However, no significant differences in $\rho_b$ values due to different fertilization rates were observed in other studies for example, Fabrizzi, Garcia, Costa, and Picone (2005) and Zhang, Yang, Wiss, Grip, and Lövdahl (2006). Similarly, infiltration rate was increased with the increase in N rate (Zuzel, Pikul, & Rasmussen, 1990) or unaffected (Walia, Walia, & Dhaliwal, 2010). Nitrogen fertilization can have positive effects on SWR and other hydrological properties because it increases biomass production and C input to soils (Zhang et al., 2006).

Landscape position across a field is also considered a key factor in influencing soil properties under a hillslope scale (Jackson-Gilbert et al., 2015). Elliott and Efetha (1999) reported that similar SOC levels were observed at the 0–10 cm depth at the shoulder and backslope positions, while higher SOC was found in the footslope position in a continuously cropped no-till system (pulse crops-oilseeds rotation). Sauer, Logsdon, Brahana, and Murdoch (2005) found that the upland and side slope soils had consistently lower infiltration rate compared to the soil in the valley bottom in a small forest/pasture watershed in Arkansas, USA. However, infiltration rate at different landscape positions has mixed results from other studies for example, Elliott and Efetha (1999) and Sandhu and Kumar (2017). Therefore, previous studies showed that the benefits of switchgrass plantation depend on different local conditions such as soil type, topography, harvest frequency, agronomic practices, and climate (Lai et al., 2018; Maughan, 2011). Yet, little is known about the information related to the long-term impacts of N rate and landscape position on soil physical and hydrological properties under switchgrass seeded to a marginal land. Therefore, the specific objective of this study was to evaluate the impacts of N rate and landscape position on soil physical and hydrological properties that include $\rho_b$, infiltration rate, SWR, saturated hydraulic conductivity under switchgrass seeded to a marginally yielding cropland.
MATERIALS AND METHODS

2.1 Study site, experimental design, and soil sampling

This study site was located at 45°16′24.55″N, 97°50′13.34″W, near Bristol, South Dakota, USA. Soils at the study location were classified as Nutley-Sinai (silty clay, mixed, Chromic Hapluderts) with 2%–20% slope. The experimental design at this site was a split-plot design comprised of two nitrogen (N) rates (low, 0 kg N/ha and high, 112 kg N/ha) as whole plots and the two landscape positions (shoulder and footslope) as subplots with four replications. Each plot size was 21.3 × 365.8 m to allow the use of conventional agricultural equipment. The site size was 9.7 ha. Urea was the source of N fertilizer and applied in late May or early June in each year. Switchgrass (cultivar: Sunburst; seeding rate: 10 kg pure live seed/ha) planting was done on May 17, 2008 and it was first harvested annually following a killing frost on October 28, 2009. This site was under maize (Z. mays L.)-soybean (Glycine max. L.) rotation prior to switchgrass establishment. The mean values of SOC under high and low N rates were 24.5 and 26.1 g/kg, at 0–5 cm depth, respectively, in 2009 (Lai et al., 2018).

Intact core samples (n = 2 from each plot) were collected from 0–5 and 5–15 cm soil depths using cores of 5 cm in diameter and height in July 2018 after the application of N fertilizer. Another set of soil cores of 7.6 cm in diameter and height were obtained from the same plots to determine the saturated hydraulic conductivity (Ksat). Soil cores were labeled, trimmed from each end, sealed in a plastic bag, and stored at 4°C pending analysis. Soil samples were also taken from both the depths to measure gravimetric moisture content and carbon and nitrogen fractions.

2.2 Carbon and nitrogen fractions

Water extractable organic carbon and nitrogen fractions were measured using the procedure given by Ghani, Dexter, and Perrott (2003). In brief, 3 g of soil was mixed with 30 ml of distilled water in 50 ml polypropylene centrifuge tubes and shook on vortex shaker for 10 s and then on rotatory shaker for 30 min at 40 revolutions per min (rpm). After shaking, the soil solution was centrifuged at 925.7 g for 25 min at 4°C. After centrifuging, suspensions were filtered by using 0.45 μm pore size syringe filters. The obtained filtrate is cold-water extractable organic carbon (CWC) and nitrogen (CWN). The soil left behind was further mixed with 30 ml of distilled water and shook on vortex shaker for 10 s. This soil solution was put in hot-water bath at 80°C for 12–15 hr, which was followed by shaking on vortex shaker for 10 s, and then centrifuged at 925.7 g for 25 min at 25°C. After centrifuging, suspensions were filtered by using 0.45 μm pore size syringe filters. The filtrate collected here is hot-water extractable organic carbon (HWC) and nitrogen (HWN). The concentration of cold and hot water C and N fractions were determined using the TOC-L analyzer (Shimadzu Corporation, model-TNM-L-ROHS).

2.3 Soil bulk density and soil penetration resistance

Soil bulk density was determined using the core method (Grossman & Reinsch, 2002) for the 0–5 and 5–15 cm depths under all the treatments and was calculated by dividing the oven-dry soil weight with the volume of the soil core. The soil penetration resistance (SPR) was measured for the 0–5 cm and 5–15 cm depths for each treatment using an Eijkelkamp-type hand penetrometer (Herrick & Jones, 2002). Ten readings of SPR were taken from each plot and the average value was used to represent the SPR of each plot at each depth. In order to confirm if the differences in SPR were in response to the soil moisture content or the treatment, soil samples were also taken from both the depths to determine the moisture content.

2.4 Infiltration rate (qs) and model fitted parameters

The qs was measured using a single-ring infiltrometer with 25.4 cm diameter and 20 cm in height using a constant-head method (Reynolds, Elrick, & Youngs, 2002). The qs measurements were conducted for all the four treatments, with two measurements per plot (total n = 32) until a steady state was achieved. Soil samples were also taken in the area surrounding the ring from each treatment in order to determine gravimetric soil water content.

Green and Ampt (1911) model; a physically based infiltration model was used to fit the measured infiltration data. Philip (1957) modified the Green–Ampt infiltration model for time (t) vs cumulative infiltration (I), as follows:

\[
t = \frac{1}{K_s} - \frac{S^2 \ln \left(1 + \frac{2K_s}{S^2}\right)}{2K_s^2}
\]

where t is the time (h), I is the cumulative infiltration (mm), S is the sorptivity (mm/hr0.5), and Ks is the saturated hydraulic conductivity (mm/hr). We will be referring to Green and Ampt (1911) model as Green–Ampt model in this paper. For estimating the S and Ks parameters based on cumulative infiltration, procedures proposed by Clothier and Scotter (2002) were followed. For model fitting, the initial S parameter was estimated from initial infiltration divided by (time)0.5, and the initial Ks value was the final/steady state infiltration rate (mm/hr). The initial infiltration rate strongly depends upon the antecedent soil water content. Therefore, the sorptivity (S) parameter, which is
highly related to initial infiltration rate, is dependent on antecedent soil water content. Both parameters ($S$ and $K_s$) can be estimated to describe infiltration data. Green–Ampt model is generally used to assess the consistency in estimated physical parameters $S$ and $K_s$. Fitted parameters serve as an appropriate, compressed description of data and can be used for the predictive purposes (Hopmans, Clausnitzer, Kosugi, Nielsen, & Somma, 1997).

### 2.5 Saturated hydraulic conductivity

After fixing cheesecloth at the bottom of the soil cores (7.6 cm in diameter and height), these cores were saturated by capillarity prior to the $K_{sat}$ measurements. The $K_{sat}$ was measured with the constant-head method (Klute & Dirksen, 1986) by employing Darcy’s equation:

$$ K_{sat} = \left( \frac{Q}{A} \right) \left( \frac{L}{L + H} \right) $$

where $Q$ is the outflow volume (cm$^3$), $A$ is the cross-sectional area of soil column (cm$^2$), $t$ is the time (hr), $L$ is the length of soil column (cm), $H$ is the height of pounded water at the top of soil column (cm).

### 2.6 SWR and pore-size distribution

The SWR was measured using the intact soil cores for the 0–5 and 5–15 cm depths for each treatment. The cheesecloth was fixed at the bottom of each soil core, and then these cores were saturated with water by capillarity for 24 to 48 hr depending on the sampling depth. The SWR characteristics were then measured at eight (0, −0.4, −1.0, −2.5, −5.0, −10.0, −20.0, and −30.0 kPa) matric potentials ($\psi_m$) using a combination of tension table and pressure plate extractors (Soil moisture Equipment Corp.) (Klute & Dirksen, 1986). At each $\psi_m$ soil water content (g/g) was determined gravimetrically by oven-drying the soil samples at 105°C for 48 hr, and this moisture content was converted to volumetric water content (m$^3$/m$^3$) by multiplying with $\rho_w$ and dividing with the density of water.

Furthermore, pore-size distribution (PSD) of the soil was calculated using the measured SWR data by employing the capillary rise equation to estimate four classes of pore size (Jury, Gardner, & Gardner, 1991) that is, macropores (>1,000 μm equivalent cylindrical diameter, ecd), coarse mesopores (60–1,000 μm ecd), fine mesopores (10–60 μm ecd), and micropores (<10 μm ecd).

### 2.7 Statistical analysis

Statistical comparisons of differences in the soil physical and hydrological properties among different N rates and landscape positions for each depth were obtained using pairwise differences method to compare least-squares means estimated by a mixed model using the generalized linear mixed model (GLIMMIX) procedure in SAS 9.4 (SAS, 2013), where N rate, landscape position, and N rate × landscape position were considered as fixed effects and replication and replication × N rate as random effect. The ANOVA was used to test the fixed effects of the N rate and landscape position on the soil properties on the basis of mixed model. The P values were adjusted by Tukey method in the sas 9.4. Data were transformed when necessary and the transformation was determined using the Box–Cox method (Box & Cox, 1981). Significance was determined at $\alpha = 0.05$ level for all statistical analysis in this study. Pearson’s correlation coefficients between the soil physical, hydrological, and biological properties were determined using correlation (CORR) procedure in SAS 9.4. Microbial biomass carbon and soil organic carbon values used for correlation were extracted from previous published studies (Sekaran, Mc coy, Kumar, & Subramanian, 2018) and (Lai et al., 2018), respectively, from the same experiment. Furthermore, principal component analysis (PCA) was employed to define the most significant and important soil properties influenced by varying N rates and landscape positions. PCA is a mathematical technique that converts a number of correlated variables into a smaller number of uncorrelated or independent variables, based on eigenvector decomposition of the covariance (Vestin, Nambu, Hees, Bylund, & Lundström, 2006).

### 3 RESULTS

#### 3.1 Soil C and N fractions, bulk density, and SPR

The data on soil HWC, HWN, CWC, and CWN as affected by different N rates and landscape positions at 0–5 and 5–15 cm depths are depicted in Table 1. The HWC fraction was significantly higher (68.8 μg C/g soil) under high N rate as compared to that under low N rate (56.5 μg C/g soil) at 0–5 cm depth. Although, HWC and HWN were not affected by N rate at 5–15 cm depth, but these fractions showed an increasing trend with the increase in N rate application. Further, landscape positions significantly influenced HWC and HWN at both depths. HWC fraction was 12.6 and 12.4 μg C/g soil higher at footslope position than that at shoulder position at 0–5 and 5–15 cm depths, respectively. Likewise, HWN fraction was 24% and 16% higher at footslope as compared to that at shoulder position at 0–5 and 5–15 cm depths, respectively. The CWC and CWN were not affected by N rate at both depths; however, a numerical increase in these fractions with the increase in N rate was observed (Table 1). The landscape positions, in general, had a significant impact on these C fractions. The CWN was significantly higher (4.82 μg N/g soil) at footslope position as compared to that at shoulder (4.18 μg N/g soil) at 0–5 cm depth. Similarly, at 5–15 cm
depth, significantly higher CWC (1.24 times) and CWN (1.17 times) were recorded at footslope position than that at shoulder position, respectively.

Data on $\rho_b$, SPR, and $w$ as influenced by N rates and landscape positions are presented in Table 2. The N rates and landscape positions significantly affected $\rho_b$ at 0–5 and 5–15 cm depths. The $\rho_b$ was significantly reduced with high N rate at both depths. Similarly, the $\rho_b$ at footslope position was significantly lower (1.18 g/cm$^3$ for 0–5 cm and 1.32 g/cm$^3$ for 5–15 cm) than that at shoulder position (1.41 g/cm$^3$ for 0–5 cm and 1.50 g/cm$^3$ for 5–15 cm). The SPR was significantly impacted by treatments at each depth. Like $\rho_b$, the SPR was significantly higher with low N rate (1.78 MPa for 0–5 cm and 2.00 MPa for 5–15 cm) compared to that with high N rate (1.06 MPa for 0–5 cm and 1.53 MPa for 5–15 cm). At footslope position, SPR was also significantly lower than that at shoulder position at both depths. No significant difference was observed in the $w$ among the treatments at each depth (Table 2) and hence the differences in the SPR values were in response to the varying N rates and landscape positions.

## 3.2 Water infiltration rate and saturated hydraulic conductivity

The $q_s$ was significantly influenced by N rates and landscape positions (Table 3). It was 104% higher with high N rate compared to the low N rate. At shoulder position, $q_s$ was significantly lower (151.9 mm/hr) than that at footslope position (329.2 mm/hr). A similar trend was observed in the $K_{sat}$. The $K_{sat}$ was significantly higher with high N rate (344.8 mm/hr) compared to the low N rate (227.9 mm/hr). At footslope position, $K_{sat}$ was also significantly higher (394.4 mm/hr) as compared to that at shoulder position (178.3 mm/hr).
Green–Ampt model fitted the measured infiltration data considerately well with coefficients of determination ($r^2$) ranging from 0.98 to 0.99. The $S$ and $K_s$ parameters estimated with Green–Ampt model were significantly higher for the soils managed with high N rate (219.5 mm/hr$^{0.5}$ and 239.9 mm/hr, respectively) as compared to that of soils under low N rate (113.5 mm/hr$^{0.5}$ and 82.6 mm/hr, respectively) (Table 3). Further, Green–Ampt model estimated $K_s$ and $S$ parameters were significantly higher at footslope position than that at shoulder position ($p < 0.01$ for $S$ parameter and $p = 0.02$ for $K_s$ parameter; Table 3).

### 3.3 SWR and PSD

Data on average SWR at different $\Psi_m$ under different N rates and landscape positions for 0–5 cm depth are illustrated in Table 4. The SWR was significantly influenced at 0 kPa with higher SWR (0.52 m$^3$/m$^3$) for high N rate compared to the low N rate (0.46 m$^3$/m$^3$). The SWR was significantly affected by landscape positions for six of eight $\Psi_m$ (0, −0.4, −1.0, −2.5, −5.0, −10.0, −20.0, and −30.0 kPa). Footslope position retained significantly higher amount of water by 18%, 18%, 15%, 24%, 25%, and 26% compared to that under shoulder position at $\Psi_m$ of 0, −0.4, −1.0, −10.0, −20.0, and −30.0 kPa, respectively.

Data on SWR under different N rates and landscape positions for 5–15 cm depth are shown in Table 5. The N rate did not influence average SWR at different $\Psi_m$ (0, −0.4, −1.0, −2.5, −5.0, −10.0, and −30.0 kPa). However, the landscape position had a significant ($p < 0.01$) impact on SWR for three of eight $\Psi_m$ (0, −0.4 and −1.0 kPa). Average SWR at footslope position at 0, −0.4, and −1.0 kPa was significantly ($p < 0.01$) higher (0.50, 0.49, and 0.45 m$^3$/m$^3$, respectively) compared to that at shoulder position (0.42,
0.40, and 0.38 m$^3$/m$^3$, respectively) (Table 5). SWR was significantly higher at footslope with high N rate compared to the other three treatments at 0, −0.4 kPa $\Psi_m$ for 0–5 cm depth (Figure 1). Significantly higher SWR was observed under footslope with high N rate at −10.0, −20.0, and −30.0 kPa $\Psi_m$ compared to the shoulder managed with high N rate at 0–5 cm depth. Similar trend was observed at 5–15 cm depth, although the significance was observed only at 0, −0.4, and −1.0 kPa $\Psi_m$.

The PSD under different N rates and landscape positions for 0–5 cm depth are shown in Table 6. Among different categories of pores, that is, macropores, coarse mesopores, fine mesopores, and micropores; majority of the total pores were dominated by the micropores (<10 µm) at each depth. Coarse mesopores and total pores were significantly influenced by N rates at 0–5 cm depth. Soils under switchgrass managed with high N rate increased average coarse mesopores and total pores by 0.048 and 0.055 m$^3$/m$^3$, respectively, in the 0–5 cm depth relative to the low N rate (Table 6). Although other pore classes were not significantly affected by N rate ($p > 0.05$); however, a similar trend was observed, where macropores and fine mesopores were higher by 75% and 4%, respectively, under high N rate compared to the low N rate. Landscape position had a significant impact on coarse mesopores, micropores, and total pores at 0–5 cm depth with footslope position having 39%, 28%, and 18% higher respective pore class than that at shoulder position. A similar trend was noticed in case of macropores among different landscape positions although the differences were not significant (Table 6). The data on PSD as affected by varying N rates and landscape positions for 5–15 cm depth are presented in Table 7. The N rate did not influence PSD ($p > 0.05$), however, in general, all the pore classes, except fine mesopores, were numerically higher for soils treated with high N rate as compared to that of low N rate at 5–15 cm depth. Landscape position had

### Table 5

Average soil water content (m$^3$/m$^3$) at different soil water pressures (−kPa) under varying nitrogen rates (low, 0 kg N/ha and high, 112 kg N/ha) applied to switchgrass grown at different landscape (shoulder and footslope) positions for 5–15 cm depth.

| Soil water pressure (kPa) | 0  | −0.4 | −1.0 | −2.5 | −5.0 | −10.0 | −20.0 | −30.0 |
|---------------------------|----|------|------|------|------|-------|-------|-------|
| N Rate                    |    |      |      |      |      |       |       |       |
| Low                       | 0.45<sup>a</sup> | 0.44<sup>a</sup> | 0.40<sup>a</sup> | 0.31<sup>a</sup> | 0.30<sup>a</sup> | 0.21<sup>a</sup> | 0.19<sup>a</sup> | 0.19<sup>a</sup> |
| High                      | 0.46<sup>a</sup> | 0.45<sup>a</sup> | 0.43<sup>a</sup> | 0.30<sup>a</sup> | 0.29<sup>a</sup> | 0.21<sup>a</sup> | 0.20<sup>a</sup> | 0.19<sup>a</sup> |
| Position                  |    |      |      |      |      |       |       |       |
| Shoulder                  | 0.42<sup>b</sup> | 0.40<sup>b</sup> | 0.38<sup>b</sup> | 0.29<sup>a</sup> | 0.28<sup>a</sup> | 0.19<sup>a</sup> | 0.18<sup>a</sup> | 0.17<sup>a</sup> |
| Footslope                 | 0.50<sup>a</sup> | 0.49<sup>a</sup> | 0.45<sup>a</sup> | 0.32<sup>a</sup> | 0.31<sup>a</sup> | 0.22<sup>a</sup> | 0.21<sup>a</sup> | 0.21<sup>a</sup> |

Note. Means with different letters within a column are significantly different at $p < 0.05$ within the nitrogen rate and landscape position.

#### Figure 1

Soil water retention curves for switchgrass managed with varying nitrogen rates (low, 0 kg N/ha and high, 112 kg N/ha) at different landscape (shoulder and footslope) positions for 0–5 and 5–15 cm depths. S-Low N: shoulder position with low nitrogen rate; S-High N: shoulder position with high nitrogen rate; F-Low N: footslope position with low nitrogen rate; F-High N: footslope position with high nitrogen rate.
a significant impact on coarse mesopores and total pores, where these were 0.054 and 0.082 m$^3$/m$^3$ higher, respectively, at footslope than at the shoulder.

Pearson’s correlation coefficient among different soil variables as influenced by varying nitrogen rates and landscape positions are depicted in Table 8. The $\rho_b$ was significantly and negatively correlated with $q_s$ ($r = -0.55^*$), $K_{sat}$ ($r = -0.68^{**}$), coarse mesopores ($r = -0.73^{***}$), total pores ($r = -0.75^{***}$), Green–Ampt estimated $S$ parameter ($r = -0.81^{***}$), CWC ($r = -0.51^*$), HWC ($r = -0.63^{**}$), and MBC ($r = -0.71^{**}$), while positively correlated with SPR ($r = 0.67^{**}$). The $q_s$ showed significant and positive correlation with water conducting variables such as $K_{sat}$ ($r = 0.53^*$), macropores ($r = 0.51^*$), coarse mesopores ($r = 0.63^{**}$), micropores ($r = 0.52^*$), total pores ($r = 0.79^{***}$), Green–Ampt estimated $S$ and $K_s$ parameter ($r = 0.76^{***}$, $r = 0.97^{***}$, respectively) and also with SOC ($r = 0.69^{**}$), CWC ($r = 0.60^*$), HWC ($r = 0.79^{***}$), and negatively correlated with SPR ($r = -0.56$). Similarly, significantly positive correlation was observed between $K_{sat}$ and other water conducting variables. The SPR showed significantly negative correlation with coarse mesopores ($r = -0.63^{**}$) and total pores ($r = -0.78^{***}$), however, it did not show any significant correlation with SOC and other carbon fractions. The SOC, CWC, HWC, and MBC showed significantly positive correlation with total pores ($r = 0.56^*$, $0.57^*$, $0.78^{***}$ and $0.72^{**}$, respectively). The principle component analysis showed that N rates and landscape positions had a significant impact on soil physical and hydrological properties (Figure 2) and placed shoulder and footslope positions opposite in the quadrant. The first principle component explained 78% of the total variation.

### Table 6

| Treatments | Macropores (>1,000 μm) | Coarse mesopores (60–1,000 μm) | Fine mesopores (10–60 μm) | Micropores (<10 μm) | Total pores |
|------------|------------------------|-------------------------------|------------------------|---------------------|-------------|
| N Rate     |                        |                               |                        |                     |             |
| Low        | 0.008$^a$              | 0.120$^b$                     | 0.115$^a$              | 0.217$^a$           | 0.460$^b$  |
| High       | 0.014$^b$              | 0.168$^a$                     | 0.120$^b$              | 0.213$^a$           | 0.515$^a$  |
| Position   |                        |                               |                        |                     |             |
| Shoulder   | 0.009$^a$              | 0.121$^b$                     | 0.128$^a$              | 0.189$^b$           | 0.446$^b$  |
| Footslope  | 0.012$^a$              | 0.168$^a$                     | 0.107$^a$              | 0.241$^a$           | 0.528$^a$  |

**ANOVA (p > F)**

| N Rate (N) | 0.11 | 0.01 | 0.68 | 0.76 | <0.01 | 0.01 |
| Position (P) | 0.34 | 0.01 | 0.09 | <0.01 | <0.01 |
| N × P        | 0.11 | 0.02 | 0.08 | 0.26 | 0.13 |

*Note.* Means with different letters within a column are significantly different at $p < 0.05$ within the nitrogen rate and landscape position.

### Table 7

| Treatments | Macropores (>1,000 μm) | Coarse mesopores (60–1,000 μm) | Fine mesopores (10–60 μm) | Micropores (<10 μm) | Total pores |
|------------|------------------------|-------------------------------|------------------------|---------------------|-------------|
| N Rate     |                        |                               |                        |                     |             |
| Low        | 0.012$^a$              | 0.140$^a$                     | 0.111$^a$              | 0.186$^a$           | 0.450$^a$  |
| High       | 0.015$^a$              | 0.157$^a$                     | 0.099$^a$              | 0.192$^a$           | 0.463$^a$  |
| Position   |                        |                               |                        |                     |             |
| Shoulder   | 0.014$^a$              | 0.122$^b$                     | 0.107$^a$              | 0.173$^a$           | 0.415$^a$  |
| Footslope  | 0.013$^a$              | 0.176$^a$                     | 0.104$^a$              | 0.205$^a$           | 0.497$^a$  |

**ANOVA (p > F)**

| N Rate (N) | 0.74 | 0.22 | 0.53 | 0.83 | 0.44 |
| Position (P) | 0.83 | <0.01 | 0.88 | 0.21 | <0.01 |
| N × P        | 0.19 | 0.83 | 0.68 | 0.25 | 0.07 |

*Note.* Means with different letters within a column are significantly different at $p < 0.05$ within the nitrogen rate and landscape position.
|       | $\rho_b$ | $q_s$ | $K_{sat}$ | SPR     | Macro | CM   | FM    | Micro | Total pores | S     | $K_s$ | SOC   | CWC   | HWC   | MBC   |
|-------|----------|-------|----------|---------|-------|------|-------|-------|-------------|-------|-------|-------|-------|-------|-------|
| $\rho_b$ |          | –     |          | –0.55*  | –0.68**| 0.67**| 0.00  | –0.73* | –0.38       | –0.75**| –0.81***| –0.46 | –0.45 | –0.27 | –0.62**| –0.71**|
| $q_s$   | –        | 0.53* | –        | –0.56*  | 0.51*  | 0.63**| –0.19 | 0.52*  | 0.79***     | 0.76***| 0.97***| 0.69**| –0.12 | 0.53* | 0.47   |
| $K_{sat}$ | –       | –0.58*| 0.27     | 0.57*   | –0.11 | 0.25  | 0.58* | 0.64** | 0.41        | 0.19   | 0.47   | 0.84***| 0.72**|
| SPR    | –       | –0.37 | –0.63**  | –0.24   | –0.22 | –0.78***| –0.58*| –0.49  | –0.23       | –0.30  | –0.46  | –0.48  |
| Macro  | –       | –0.08 | 0.13     | 0.24    | 0.28  | 0.22  | 0.49  | 0.47   | 0.16        | 0.19   | 0.11   |        |
| CM     | –       | –0.26 | 0.30     | 0.84*** | 0.74***| 0.57* | 0.40  | 0.18   | 0.57*       | 0.72** |
| FM     | –       | –0.63**| –0.11    | –0.33   | –0.17 | –0.47 | 0.31  | 0.03   | –0.33       |        |
| Micro  | –       | 0.59* | 0.52*    | 0.42    | 0.65**| –0.46 | 0.24  | 0.49   |            |
| Total pores | –     |       |          | 0.78*** | 0.69** | 0.56* | 0.02  | 0.60*  | 0.72**       |        |
| S      | –       |       |          | 0.66**  | 0.72** | 0.11  | 0.54* | 0.65** |
| $K_s$  | –       |       |          | –       | 0.65**| –0.17 | 0.42  | 0.35   |
| SOC    | –       |       |          | –       | –0.11 | 0.18  | 0.49  |
| CWC    | –       |       |          | –       | 0.25  |       | 0.32  |
| HWC    | –       |       |          | –       |       |       |       |        |
| MBC    | –       |       |          | –       |       |       |       |        |

Note: CM: coarse mesopores; CWC: cold-water soluble organic carbon; FM: fine mesopores; HWC: hot-water soluble organic carbon; $K_s$: estimated saturated hydraulic conductivity parameter from Green–Ampt model; $K_{sat}$: measured saturated hydraulic conductivity; Macro, macropores; MBC: microbial biomass carbon; Micro: micropores; $\rho_b$: soil bulk density; $q_s$: steady state infiltration rate; $S$: sorptivity; SOC: soil organic carbon; SPR: soil penetration resistance.

*Correlation is significant at the 0.05 level. **Correlation is significant at the 0.01 level. ***Correlation is significant at the 0.001 level.
and the second explained 19%, a two component model thus accounted for 97% of the total variance. The PCA results showed that low and high N rates under footslope position had a significant influence on soil physical and hydrological properties, viz. Green–Ampt estimated $K_s$ parameter, SOC, $q_s$, $K_{sat}$, Green–Ampt estimated $S$ parameter, total pores, HWC, coarse mesopores, MBC, and micropores.

## DISCUSSION

In the current study, we examined the impacts of varying N rates and different landscape positions on soil physical and hydrological properties under switchgrass production managed for 10 years. Significant changes in the soil hydrological properties in response to the treatments were observed. Soil organic carbon was not impacted by the N rates but impacted by the landscape position (higher value observed at footslope compared to the shoulder) in 2009 (Lai et al., 2018), however, it was higher with the high N rate, and footslope position compared to that under low N rate, in 2016 (data not shown). The impacts of N rates and landscape position on soil C fractions and hydrological properties have been discussed below as:

### 4.1 Impacts of N rate on soil properties

Significant increase in HWC under high N rate at 0–5 cm depth was observed in this study which could be due to the increase in microbial activity which further accelerates the decomposition rate of plant residues. This can increase the hot-water soluble carbon as it gets easily fragmentized by the soil microorganisms (Mikanová, Šimon, Kopecký, & Ságová-Marečková, 2015). We did not find any significant differences in other labile pools as affected by the N rates.

Our results are in accord with Benbi, Brar, Toor, and Sharma (2015), who also reported nonsignificant influence of N fertilizers on labile carbon pools. The findings from this study showed that the N rate had a significant impact on soil $\rho_b$ in switchgrass plots at each depth. Significant reduction in $\rho_b$ with the high N rate at each depth may probably be due to higher biomass yield (Lee et al., 2018). Further, higher switchgrass root biomass production and residue retention on the soil under high N fertilization can also decrease soil $\rho_b$ (Banashree, Satya, Sreyashi, & Bhaswatee, 2015). As an evidence, significantly negative correlation of $\rho_b$ with HWC and MBC (Table 8) was also found in the present study. These results corroborate the findings of Halvorson, Wienhold, and Black (2002), who also found a decrease in $\rho_b$ with the increasing N rate within the annual crop rotation in North Dakota, USA. Furthermore, reduction in $\rho_b$ could also be due to the application of higher dose of inorganic N fertilizer which increased the SOC of this site (data not shown). Similar findings were also reported by Alvarez (2005). High N rate can enhance microbial and biological activity which can lead to improved soil physical conditions. In another study conducted by Halvorson et al. (1999) showed that $\rho_b$ significantly decreased with increasing N rate at the 0–5 cm depth in a barley ($H. vulgare$)–maize ($Z. mays$) rotation system in Colorado, USA. Similar results have also been reported by Hati, Swarup, Dwivedi, Misra, and Bandyopadhyay (2007). Deep root systems of switchgrass can increase the soil organic matter and hence reduce the soil compaction (Thomas, Haszler, & Blevins, 1996). Furthermore, switchgrass roots penetrate the soil matrix layers to change soil pores structure and hence reduce the soil $\rho_b$ (Blanco-Canqui, 2010). After the 10-year switchgrass establishment in Iowa, Rachman, Anderson, Gantzer, and Alberts (2004) found that the $\rho_b$ was reduced in the switchgrass buffer strips.

The SPR, a measure of soil compaction (Hamza & Anderson, 2003) is dependent on various factors such as water content of the soil, soil texture, soil matric potential (Lipiec, Ferrero, Giovanetti, Nosalewicz, & Turski, 2002), and other soil physical properties that vary among locations or soil horizons. The SPR under different nitrogen rates and landscape
position followed a similar trend as that of $\rho_b$. The reduction in SPR for high N rate at both depths can be related to lower $\rho_b$ as a result of enhanced microbial community and SOC, which loosens the soil by improving the soil structure. A 13-year experiment conducted by Celik, Gunal, Budak, and Akpinar (2010) also showed that SPR was significantly decreased by N fertilizer at 11–20, 21–30, and 31–50 cm depths in Turkey.

The high N rate was effective in enhancing the $q_s$ due to less compaction (lower $\rho_b$ and SPR, as reported above) and improved pore stability and continuity that can enhance the $q_s$. A significantly positive correlation of $q_s$ with HWC and SOC (Table 8) also supports these results. In an experiment conducted by Dunjana, Nyamugafata, Nyamangara, and Mango (2014), a significant increase in $q_s$ was observed due to 100 kg N/ha on clayey soil as compared to the control. The $q_s$ significantly increased with the increase in N rate under a long-term experiment in Oregon, USA (Zuzel et al., 1990). The Green–Ampt model estimated $S$ and $K_s$ parameters were also higher for the soils managed with high N rate as compared to those managed with low N rate due to the improved PSD. Further, switchgrass root growth can create channels after decay which can lead to the increased $q_s$ and hence the $S$ and $K_s$ parameters. Wu et al. (2016) also reported improved $q_s$ due to higher root biomass in a grassland. The production of perennial biomass feedstock had significant effects on $q_s$ as it often changes soil physical and biological properties (Bharati, Lee, Isenhart, & Schultz, 2002). This land management system affects soil properties due to differences in litter quantity and quality, root biomass, root penetration, and soil architecture due to activities of microorganisms (de Graaff, Six, Jastrow, Schadt, & Wullschleger, 2013). Switchgrass enriches above and belowground organic carbon through aboveground biomass returned (Blanco-Canqui, 2010) as well as decay and decomposition of older roots, which increase the soil aggregation (Blanco-Canqui, 2016) and $q_s$. The gradual changes in biopore shape, orientation, and size distribution due to the extensive root system of switchgrass influence the $q_s$ and water flow as well as SWR in the soil (Rasiah & Aylmore, 1998). The relatively compacted soil horizon such as a plow pan and hardpan can be penetrated and alleviated by perennial grass deep roots which increase $q_s$, nutrient uptake, and groundwater recharge (Blanco-Canqui, 2016). This study indicated that planting switchgrass on degraded soil increased the $q_s$ which can reduce the soil erosion and runoff. When switchgrass is planted on the eroded soil (shallow topsoil thickness treatment) which has poor soil characteristics, the extensive and deeper root systems of switchgrass can improve soil structure that promotes water infiltration (Zaabon et al., 2017).

The $K_{sat}$ was also found to be significantly affected by varying N rates and followed similar trend as that of $q_s$ as well as Green–Ampt model estimated $S$ and $K_s$ parameters in the current study. The $K_{sat}$ is mainly dependent on PSD and pore continuity of the soils. Higher $K_{sat}$ values in the high N rate treatment was likely due to lower $\rho_b$ ($r = -0.68^{**}$, Table 8) and higher macroporosity as well as coarse mesoporosity ($r = 0.57^{*}$, Table 8). Shi, Zhao, Gao, Zhang, and Wu (2016) also reported an increase in $K_{sat}$ with soil amendments including inorganic fertilizers at 0–5 cm depth compared to the control.

Significantly higher SWR was observed in the soils receiving high N rate at saturation (0 kPa) as compared to the low N rate at 0–5 cm depth. However, N fertilizers did not significantly influence SWR characteristics at other $\Psi_m$ at both the depths. Results are in agreement with Walia et al. (2010) who also reported a nonsignificant increase in SWR in response to N fertilization. The results from a long-term (71-year) study indicated that N fertilizer simply maintained SWR capacity (Blanco-Canqui, Hergert, & Nielsen, 2015). Higher categories of pore sizes were observed in the soils treated with higher N rate as compared to that of low N rate, which can partially attribute to lower $\rho_b$ and SPR recorded in the same treatment.

### 4.2 Landscape position effects on soil properties

Nutrient cycling is greatly controlled by labile fractions of C (e.g., CWC and HWC) (Chan, Bowman, & Oates, 2001), thus an important measure to describe C balance as affected by the management. Soil C and N fractions were significantly higher at footslope compared to the shoulder position probably due to the reason that erosion from shoulder position may have deposited the organic matter at the footslope position. Soil $\rho_b$ and SPR at the footslope position were significantly lower than that at shoulder position at either depths. Topography can result in soil erosion (Guzman & Al-Kaisi, 2011), which can re-distribute SOC (Martinez-Mena et al., 2012). Soil erosion generally occurs at the shoulder and backslope positions and leads to soil deposition at the footslope position (Papiernik et al., 2007), where soil nutrients are accumulated. Therefore, the SOC and other soil parameters are improved at the footslope compared with those at the shoulder position. This can result in increased root biomass and soil aggregation at footslope, and soil degradation at shoulder position. The increase in SOM, soil structure, and root biomass at the footslope can primarily contribute to decreased soil $\rho_b$ (Guzman & Al-Kaisi, 2011) and SPR (Table 2). It is also evident from the significant positive correlation between SPR and $\rho_b$ found in this study (Table 8). The SPR at eroded landscape position was higher than that for the depositional position in a soybean field in South Dakota, USA (Sandhu & Kumar, 2017). Another study also showed that cone index, a measure of soil compaction was significantly lower at the backslope and footslope position than that at summit in Missouri, USA (Jung, Kitchen, Sudduth, Lee, & Chung, 2010).

The $q_s$ was also higher at the footslope than the shoulder position due to higher water conducting macropores and
coarse mesopores observed at the footslope position. A significant positive correlation between $q_s$, macropores, and coarse mesopores further corroborates this finding. Another reason for enhanced $q_s$ at the footslope may be due to the improved soil structure due to high contents of C and N fractions found at this position compared to the shoulder (Table 1). Guzman and Al-Kaisi (2011) also reported that toeslope position recorded higher $q_s$ as compared to that of summit and midslope positions. Similar findings were reported by Sauer et al. (2005), who found that the upland and side slope soils had consistently lower $q_s$ compared to the soil in the valley bottom in a small forest/pasture watershed in Arkansas, USA. Green–Ampt model estimated $S$ and $K_s$ parameters followed the same trend as that of $q_s$. This is also evident from highly significant correlation coefficient between $q_s$ and model estimated $S$ and $K_s$ parameters. Higher value of model estimated $S$ and $K_s$ parameters can be attributed to the existence of better soil physical conditions at footslope in terms of lower $\rho_b$, SPR, and higher porosity.

Similar to $q_s$ and model estimated $S$ and $K_s$ parameters, the $K_{sat}$ was also significantly higher at the footslope than the shoulder position. An isotopic study conducted by Chen, Hu, Nie, and Wang (2017) has also shown that vertical flow velocity was higher at footslope position demonstrating faster hydrological process in this landscape position. A significant positive correlation between $K_{sat}$, $q_s$, model estimated $S$ and $K_s$, and coarse mesoporosity further showed that these hydraulic parameters are strongly influenced by the extent of coarse mesopores present in the soils, which were also found to be significantly higher at footslope than that at shoulder position.

At footslope position, higher SWR at measured matric potentials (0 kPa, −4.0 kPa, −10.0, −20.0, and −30.0 kPa) for 0–5 cm depth (Table 4) could be attributed to greater volume fraction of micropores (Table 6) those are responsible for higher SWR. Furthermore, high content of C and N fractions, those are labile forms of SOC may have aided in enhancing the SWR at footslope position compared to that at shoulder position (Table 1). Significantly higher volume fraction of total pores at surface and subsurface depths at footslope could be attributed to the better soil structure as evident from lower $\rho_b$, SPR, higher SWR, and C and N fractions (as reported above). High positive correlation of total pores with HWC, SOC, and MBC ($r = 0.60^*, 0.56^* and 0.72^{**}$, Table 8) further corroborate our findings. Landscape positions have strong effect on SOM distribution due to erosion (Guzman & Al-Kaisi, 2011). Erosion might cause the accumulation of organic carbon at footslope position by detaching the soil particles along with organic matter from the shoulder position. Results are in accord with Oguike, Chukwu, and Njoku (2006) who reported an increase in total porosity with the increase in organic carbon. The principle component analysis showed that N rates and landscape positions had a significant impact on soil physical and hydrological properties and placed shoulder and footslope positions opposite in the quadrant and showed that low and high N rates under footslope position significantly improved soil physical and hydrological properties.

Soil physical and hydrological properties play a key role in soil functioning and the restoration of marginal lands. The current study examined the response of physical and hydrological properties of soil to varying N rates and landscape positions under switchgrass. The N rate and landscape positions significantly influenced the soil hydrological properties. The results indicated that higher N rate decreased $\rho_b$ and SPR. A general increasing trend on hot and cold-water soluble carbon and nitrogen fractions with increase in N rate was also observed. Nitrogen applied at higher rate also increased the soil water infiltration rate, saturated hydraulic conductivity; Green–Ampt estimated sorptivity, and hydraulic conductivity and also retained more water at the surface depth. Total porosity was also enhanced with the application of N at higher rate. Among the landscape positions, footslope position recorded higher content of C and N fractions, lower $\rho_b$ and SPR, higher soil water infiltration rate, saturated hydraulic conductivity, Green–Ampt estimated sorptivity and hydraulic conductivity, SWR and an increase in coarse mesoporosity, microporosity, and total porosity. Thus, this study showed that nitrogen fertilization of 112 kg N/ha to switchgrass planted at footslope on a marginally yielding cropland improved the soil physical and hydrological properties, those can be beneficial in enhancing the biomass yield.

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