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# The Effect of Five Biomass Cropping Systems on Soil-Saturated Hydraulic Conductivity Across a Topographic Gradient

Lisa A. Schulte-Moore  
*Iowa State University*, [lschulte@iastate.edu](mailto:lschulte@iastate.edu)

Matthew J. Helmers  
*Iowa State University*, [mhelmers@iastate.edu](mailto:mhelmers@iastate.edu)

Randall K. Kolka  
*United States Department of Agriculture Forest Service*

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# The Effect of Five Biomass Cropping Systems on Soil-Saturated Hydraulic Conductivity Across a Topographic Gradient

## Abstract

Understanding the environmental impact of bioenergy crops is needed to inform bioenergy policy development. We determined the effects of five biomass cropping systems—continuous maize (*Zea mays*), soybean (*Glycine max*)-triticale (*Triticosecale* ×)/soybean-maize, maize-switchgrass (*Panicum virgatum*), triticale/sorghum (*Sorghum bicolor*), and triticale-aspen (*Populus alba* × *P. grandidentata*)—on soil-saturated hydraulic conductivity (K<sub>s</sub>) across a toposequence in central Iowa, USA. We compared data from the time of cropping system establishment in 2009 to 4 years post-establishment. Both our 2009 and 2013 data confirmed that cropping system impacts on K<sub>s</sub> vary by landscape position. We found that differences in cropping system impacts were more likely to occur at lower landscape positions, specifically, within footslope and floodplain positions. Previous research on cropping system impacts suggested that grass and woody systems were associated with a general increase in K<sub>s</sub> over time, with greater changes likely occurring at landscape positions with a higher erosive potential or lower SOC content. Our results confirmed that the triticale-aspen woody system was associated with a significant increase in K<sub>s</sub> across all landscape positions. In contrast, we did not observe an increase in K<sub>s</sub> under maize-switchgrass, which we attributed to the high density of switchgrass roots by the fourth year of study, but expect an increase in K<sub>s</sub> under switchgrass under longer measurement periods. We also found a significant increase in K<sub>s</sub> in the annual systems, likely due to the conversion to no-till soil management with cropping system establishment. We expect such differences to become more apparent over longer time scales as cropping systems continue to impact soil hydraulic properties.

## Keywords

Infiltration, Landscape biomass project, Maize, Soybean, Switchgrass, Woody biomass

## Disciplines

Agriculture | Agronomy and Crop Sciences | Bioresource and Agricultural Engineering | Forest Management | Sustainability | Water Resource Management

## Comments

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# The Effect of Five Biomass Cropping Systems on Soil-Saturated Hydraulic Conductivity Across a Topographic Gradient

Usman Anwar<sup>1</sup> · Lisa A. Schulte<sup>1</sup> · Matthew Helmers<sup>2</sup> · Randall K. Kolka<sup>3</sup>

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**Abstract** Understanding the environmental impact of bioenergy crops is needed to inform bioenergy policy development. We determined the effects of five biomass cropping systems—continuous maize (*Zea mays*), soybean (*Glycine max*)-triticale (*Triticosecale* ×)/soybean-maize, maize-switchgrass (*Panicum virgatum*), triticale/sorghum (*Sorghum bicolor*), and triticale-aspen (*Populus alba* × *P. grandidentata*)—on soil-saturated hydraulic conductivity ( $K_S$ ) across a toposequence in central Iowa, USA. We compared data from the time of cropping system establishment in 2009 to 4 years post-establishment. Both our 2009 and 2013 data confirmed that cropping system impacts on  $K_S$  vary by landscape position. We found that differences in cropping system impacts were more likely to occur at lower landscape positions, specifically, within footslope and floodplain positions. Previous research on cropping system impacts suggested that grass and woody systems were associated with a general increase in  $K_S$  over time, with greater changes likely occurring at landscape positions with a higher erosive potential or lower SOC content. Our results confirmed that the triticale-aspen woody system was associated with a significant increase in  $K_S$  across all landscape positions. In contrast, we did not observe an increase in  $K_S$  under maize-switchgrass, which we attributed to the high

density of switchgrass roots by the fourth year of study, but expect an increase in  $K_S$  under switchgrass under longer measurement periods. We also found a significant increase in  $K_S$  in the annual systems, likely due to the conversion to no-till soil management with cropping system establishment. We expect such differences to become more apparent over longer time scales as cropping systems continue to impact soil hydraulic properties.

**Keywords** Infiltration · Landscape biomass project · Maize · Soybean · Switchgrass · Woody biomass

## Introduction

The development of sustainable bioenergy systems will require the expansion and use of alternative biomass feedstocks with varying environmental impacts. Globally, the conversion of native perennial vegetation to annual crops has led to declining water quality, freshwater habitat, and biodiversity [1]. Increased cultivation of annual crops such as maize (*Zea mays*) has led to an increase in runoff, erosion, and nutrient losses [2]. In contrast, perennial bioenergy crops are associated with reduced nutrient pollution, improved soil quality, lower nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) emissions, and lower runoff and subsequent soil erosion [3, 4].

To better understand the potential environmental impacts of alternative energy crops, we investigated steady-state infiltration rates associated with five different cropping systems across five different landscape positions.  $K_S$  can significantly influence hydrological processes such as infiltration, runoff generation, and soil moisture content [5–7]. An understanding of how  $K_S$  differs among biomass cropping systems and landscape positions will improve our understanding of their potential environmental and hydrologic impacts.

✉ Usman Anwar  
uanwar88@gmail.com

<sup>1</sup> Department of Natural Resource Ecology and Management, Iowa State University, 339 Science II, Ames, IA 50011, USA

<sup>2</sup> Department of Agricultural and Biosystems Engineering, Iowa State University, 1340 Elings Hall, Ames, IA 50011, USA

<sup>3</sup> Center for Research on Ecosystem Change, USDA Forest Service, 1831 Hwy 169 East, Grand Rapids, MN 55744, USA

$K_S$  is influenced to a large degree by processes that contribute to soil structure and macropore formation [8, 9]. Higher soil organic carbon (SOC) content impacts hydraulic conductivity by influencing the production of stable soil aggregates, which affects pore size distribution and soil structure [10]. Soil management practices affect soil organic carbon and therefore also  $K_S$  [4, 11]. Tillage results in the loss of SOC and can also prevent the formation of stable soil aggregates and inhibit the development of a soil structure conducive to high infiltration rates [10, 12, 13]. Conversion from conventional till to no till can increase the rate of SOC accumulation [14–16]. Logsdon et al. found that minimum tillage and no tillage had significantly higher  $K_S$  values than tillage systems [17]. Edwards et al. attributed reduced surface runoff in a no-till watershed to greater infiltration and number of macropores compared to conventional tillage [18].

Plant systems with a higher rate of root growth and decay may contribute to both higher soil macroporosity and greater organic matter accumulation [19, 20]. Several studies have shown differences in  $K_S$  among cropping and perennial treatments. Soil under dense perennial vegetation, as in a natural prairie, can have nearly double the organic matter content of crop fields, and the  $K_S$  of such fields can be nearly 10 times higher than in crop fields [21]. Udawatta et al. found significantly greater numbers of macropores and macroporosity in soils from tree and grass systems compared to row-crop areas, which was correlated with higher  $K_S$  in those treatments [22]. The number of macropores accounted for as much as 64% of the variation in  $K_S$ . Eldridge and Freudenberger found significantly higher  $K_S$  values under eucalyptus trees compared to pasture or cultivated cropland, though this effect was only observed on fine-textured soil [23]. Jung et al. observed significantly lower  $K_S$  in three annual cropping systems (two with a maize-soybean [*Glycine max*] rotation at different fertilization rates and one with a winter cover crop) compared to three perennial cropping systems (multi-species perennial systems), and no significant differences among individual annual cropping systems [24].

The case is not settled, however, on the impacts of perennial versus annual plants on  $K_S$ . Anderson et al. found no significant differences in  $K_S$  among annual crop, grass, and forest treatment plots [25]. Similarly, Schwartz et al. did not find a significant difference in  $K_S$  between cropland (wheat [*Triticum aestivum*]/sorghum [*Sorghum bicolor*]) converted to grassland, suggesting that even after 10 years, conversion of cropland to grasses did not ameliorate changes in soil structure related to previous land use history [26].

Differences in  $K_S$  among treatments may partially be attributed to landscape position effects. Jiang et al. found that  $K_S$  and bulk density were significantly related to landscape position, with the midslope having significantly lower  $K_S$  than summit or footslope positions [19]. They also observed  $K_S$

was significantly higher in Conservation Reserve Program (CRP) plots compared to a mulch-till maize-soybean system at the backslope position [19], suggesting that perennial systems are more likely to improve soil hydraulic properties at slope positions with greater vulnerability to soil degradation.

## Experimental Goals and Hypotheses

Improved understanding of the impacts of contrasting land uses on hydraulic properties of soils is critical for understanding the potential environmental and hydrological impacts of potential biomass cropping systems. Numerous factors may be involved in the development of hydraulic properties of soils under different cropping and management regimes. Specifically, the question of whether or not perennial systems alter the hydraulic properties of soils after conversion from annual cropping systems remains inconclusive.

To partially fill this knowledge gap, we compared  $K_S$  among five potential biomass cropping systems across a toposequence for a period of 4 years. Cropping systems included (1) continuous maize, (2) a modified rotation of soybean-triticale (*Triticosecale* ×)/soybean-maize, (3) maize-switchgrass, (4) triticale/sorghum, and (5) triticale-aspen (*Populus alba* × *P. grandidentata*), all under no-till soil management. We specifically sought to account for the influence of soil properties and landscape factors on hydraulic properties relative to crop or management effects. As reviewed above, previous research indicates that landscape position can interact with cropping and management treatments to influence soil hydraulic properties [15, 19]. Based on this research, we hypothesized the following:

- An increase in  $K_S$  over time with conversion from a maize-soybean system using conventional tillage to no-till biomass cropping systems;
- Greater increases in  $K_S$  over time in perennial than annual biomass systems;
- Higher  $K_S$  values in footslope and floodplain landscape positions than summit, shoulder, and backslope positions.

## Materials and Methods

### Site Description and Experiment Design

The Landscape Biomass experiment was established in fall 2008 at the Uthe Farm, an Iowa State University Research and Demonstration Farm located 20 km southwest of Ames, Iowa. The Uthe Farm provided the optimal landscape context and hill-slope properties for the experiment, which sought to understand soil-water-crop relationships over a topographic gradient. The experiment was established on an eastward facing hillslope in a

randomized, replicate block design. Two treatment factors (landscape position and cropping system) were applied to a total of 75 0.2-ha plots. Prior to establishment, the land use of the majority of the site was agriculture in a maize-soybean rotation with tillage, while approximately one half of the riparian floodplain plots were in mixed grasses. A full description of the experiment can be found in Wilson et al. [27].

### Landscape Positions

We considered the five landscape positions as a blocking factor in this experiment. Within each position, plots were randomly assigned to a cropping treatment. The point of highest elevation along the hillslope was designated the summit. The position at the lowest elevation was designated the floodplain. The shoulder, backslope, and footslope positions are intervening positions with progressively lower elevation between the summit and floodplain; their delineation was also based on slope angle. The average slope across the entire site is 6%, with an elevation difference of 20 m between the summit and floodplain.

Soils vary across the site by landscape position and replicate. Ontl et al. [28] provide a characterization of the soils at the Landscape Biomass experimental site. Briefly, they have been classified as Nicollet loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls), Coland clay loam (fine-loamy, mixed, superactive, mesic Cumulic Endoaqualls), Spillville loam (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls), and Zenor sandy loam (coarse-loamy, mixed, superactive, mesic Typic Hapludolls). Clarion loam is most predominant across the site. Summit plots are found on Clarion, Nicollet, and Zenor; shoulder plots are found on Clarion and Zenor; backslope plots are entirely found on Clarion; and footslope plots are found on Clarion and Spillville soils. The floodplain plots, however, are entirely located on Coland soil.

### Cropping Systems

All five biomass cropping systems investigated in this study were established in fall 2008 or spring 2009; cropping systems with triticale were established in fall 2008, while other crops were planted in spring 2009. Fertilization of treatments was based on soil nutrient tests; herbicide application was based on weed pressure. Detailed information on cropping system establishment and crop management can be found in Wilson et al. [27]. Within the maize-switchgrass system, maize was double cropped with switchgrass in 2009, while only switchgrass was grown in those plots between 2010 and 2013. The aspen trees in the triticale-aspen system were not harvested during the period of this study.

### Sampling Procedure

Measurements were taken using a constant-head permeameter (Precision Permeameter, Johnson Permeameter LLC, Fairfax, VA, USA), which maintains a hydraulic head of water and pressure difference within the borehole during measurement. We used a soil auger to create boreholes for sampling. The borehole dimension measured 4.5-cm radius and 19-cm depth. The constant height of water in this borehole measured 15 cm. Measurements of  $K_S$  were taken between May and July in each of 2009 and 2013. Three measurements were taken at random locations within each of the 75 treatment plots (5 replicates  $\times$  5 cropping systems  $\times$  5 landscape positions), for a total of 225 measurements for each year. As the samples were randomly taken within plots, the measurements and analysis did not account for any soil characteristics.

$K_S$  is a measure of the ability of a soil to transmit water and is a measure of hydraulic conductivity under saturated conditions, or when the hydraulic gradient is at unity [29].  $K_S$  is typically reported as a rate. Under steady-state conditions, the infiltration rate is equivalent to  $K_S$  near the surface. The saturated hydraulic conductivity is estimated by an analytical solution that incorporates the steady-state flow rate of water into the soil, height of water in the borehole, and borehole geometry, known as the Glover solution [30].

$$K_S = Q_S \left[ \sinh^{-1}(H/r) - (r^2/H^2 + 1)^{0.5} + r/H \right] / (2\pi H^2) \quad (\text{Glover solution})$$

where  $K_S$  is the saturated hydraulic conductivity,  $Q_S$  is the steady-state flow rate of water into the soil,  $H$  is the constant height of water in the borehole, and  $r$  is the radius of the borehole.

The steady-state flow rate,  $Q$ , was determined by visually observing the changing volume of water in a graduated cylinder at an interval of 1 min, until steady-state flow was achieved. Steady-state flow was considered the point at which the rate of volume change within the cylinder achieved a

constant value. Using this procedure,  $K_S$  can be considered the average  $K_S$  of the entire wetted region [31].

### Data Analyses

The observed measurements were analyzed using analysis of variance. Landscape position, cropping system, and year were treated as fixed effects. Interaction effects

included landscape by cropping system, year by cropping system, and year by landscape position. A random effect was included to account for repeated measures within a plot. Comparison of individual treatments was achieved using the Holm-Tukey adjustment for multiple comparisons. Due to the difference in land use history for about one half of the floodplain, in preliminary investigations, we analyzed the data with and without floodplain measurements; because exclusion of the floodplain did not change our overall results or other pairwise comparisons [32], only analyses including data from the floodplain position are presented here. Significance of model parameters was determined at  $P < 0.05$ .

## Results

### Initial Conditions Following the Establishment of Treatments (2009)

In 2009, we observed a significant landscape position effect, but no significant effect of cropping system or interaction between landscape position and cropping system (Table 1). Differences by landscape position were driven by higher  $K_S$  in the backslope and floodplain positions (Table 2 and Fig. 1a).

### Conditions 4 Years After the Establishment of Treatments (2013)

The landscape position effect, cropping system effect, and interaction between landscape position and cropping system were all significant in 2013 (Table 1). The landscape position effect and landscape position by cropping system interaction were affected by differences associated with the footslope and

floodplain positions; average  $K_S$  values are higher in these positions (Fig. 1b and Table 2).

All cropping systems except maize-switchgrass were significantly affected by landscape position, although there were no significant differences among the upper four landscape positions for any cropping system (Table 2). Continuous maize, triticale/sorghum, and triticale-aspen all had significantly lower  $K_S$  values at the summit, shoulder, backslope, and footslope compared to the floodplain (Table 2 and Fig. 1b). The soybean-triticale/soybean-maize system showed significant differences amount the summit, footslope, and floodplain positions (Table 2).

Within landscape position, differences in cropping systems were only found in the footslope and floodplain positions (Table 2). Specifically, the continuous maize, soybean-triticale/soybean-maize, triticale/sorghum, and triticale-aspen systems each had significantly higher  $K_S$  values than the maize-switchgrass system at the footslope position. In total, seven significant differences were found within nine pairwise comparisons at the floodplain position; continuous maize, maize-switchgrass, and triticale/sorghum all had lower  $K_S$  values than triticale-aspen (Table 2). Continuous maize and the modified rotation had significantly higher  $K_S$  values than maize-switchgrass (Table 2).

### Change in $K_S$ Between 2009 and 2013

We found significant effects for year, year by landscape position, and year by cropping system (Table 2). This indicates that  $K_S$  changed significantly over time by both landscape position and cropping system (Fig. 2). Multiple comparisons showed that the footslope and floodplain landscape positions had significantly higher  $K_S$  in 2013 (Fig. 2a). All cropping system treatments, except switchgrass, had significantly higher  $K_S$  in 2013 than in 2009 (Fig. 2b).

**Table 1** ANOVA results from 2009 and 2013 testing for differences in hydraulic conductivity by year, landscape position, and cropping system

Year	Source of Variation	Num <i>df</i>	Den <i>df</i>	<i>F</i>	<i>P</i>
2009	Landscape position	4	195	6.08	0.0001
	Cropping system	4	195	2.06	0.0873
	Landscape position × cropping system	16	195	1.47	0.1152
2013	Landscape position	4	198	31.12	<0.0001
	Cropping system	4	198	6.34	0.0002
	Landscape position × cropping system	16	198	2.4	0.0125
2009 and 2013	Year	1	409	404.33	<0.0001
	Year × landscape position	4	409	60.61	<0.0001
	Year × cropping system	4	409	1.44	0.0006
	Landscape position	4	409	31.12	<0.0001
	Cropping system	4	409	6.34	<0.0001
	Landscape position × cropping system	16	409	2.4	0.0019

**Table 2** Mean saturated hydraulic conductivity ( $K_S$ ; cm/d) of cropping systems and landscape positions in 2009 and 2013

Landscape position	Cropping system	2009 <sup>a</sup>			2013 <sup>a</sup>		
		$K_S$	Upper	Lower	$K_S$	Upper	Lower
Summit	Continuous maize	48.3	A	a	51.3	A	a
	Soybean-triticale/soybean-maize	38.1	A	a	54.0	A	a
	Maize-switchgrass	32.0	AB	a	50.1	A	a
	Triticale/sorghum	29.5	A	a	43.0	A	a
	Triticale-aspen	26.9	A	a	80.0	AB	a
Shoulder	Continuous maize	25.9	A	a	42.9	A	a
	Soybean-triticale/soybean-maize	33.3	A	a	68.7	AB	a
	Maize-switchgrass	56.6	A	a	46.3	A	a
	Triticale/sorghum	35.3	A	a	34.4	A	a
	Triticale-aspen	42.1	A	a	66.9	AB	a
Backslope	Continuous maize	27.4	A	a	43.1	A	a
	Soybean-triticale/soybean-maize	26.3	A	a	65.9	AB	a
	Maize-switchgrass	23.0	B	a	31.7	A	a
	Triticale/sorghum	18.9	A	a	54.9	AB	a
	Triticale-aspen*	15.3	A	a	81.2	AB	a
Footslope	Continuous maize*	21.7	A	a	117.0	B	a
	Soybean-triticale/soybean-maize *	23.9	A	a	121.4	B	a
	Maize-switchgrass	30.5	AB	a	23.3	A	b
	Triticale/sorghum*	17.5	A	a	105.0	B	a
	Triticale-aspen*	37.8	A	a	162.2	C	a
Floodplain	Continuous maize*	48.3	A	a	312.9	C	a
	Soybean-triticale/soybean-maize *	41.7	A	a	400.0	C	ad
	Maize-switchgrass	48.3	A	a	111.9	A	be
	Triticale/sorghum*	22.7	A	a	220.9	C	ae
	Triticale-aspen*	79.1	B	a	533.2	D	cd

\*Significant difference between years.  $P < 0.05$

<sup>a</sup>Uppercase letters indicate significant differences between landscape positions within a cropping system. Lowercase letters indicate cropping system differences within a landscape position.  $P < 0.05$

## Discussion

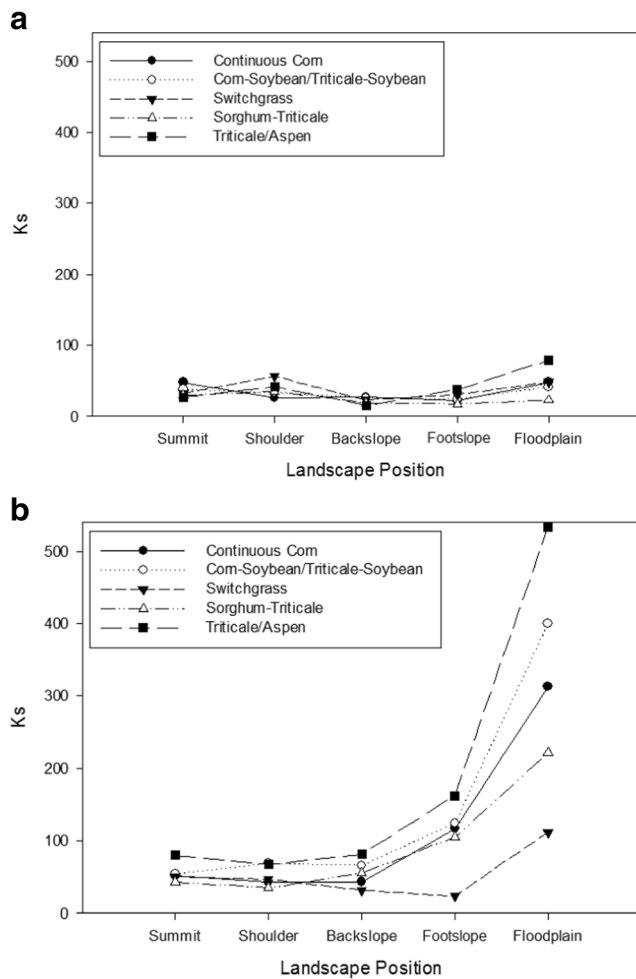
Saturated hydraulic conductivity primarily describes saturated water flow through macropores; in previous studies, as much as 64% of the variability in  $K_S$  measurements can be explained by the number of macropores [22, 33]. Macropore formation is significantly influenced by cropping effects and tillage [26, 34]. Tillage can form large, unstable fractures and macropores, while lowering macropore connectivity, but may initially lead to significantly higher saturated hydraulic conductivity. The general trend for no-till is an increase in macropore connectivity and saturated hydraulic conductivity over time [35].

The broad, site-wide increase in  $K_S$  across four of five cropping systems and four of five landscape positions over a 4-year period (2009–2013) is consistent with the adoption of site-wide no-till management during the establishment phase of the experiment in 2008 [35]. This was consistent with our first hypothesis, which tested for an increase in  $K_S$  over time across all systems. Elliott and Efetha also observed significantly higher  $K_S$  in no-till plots compared to conventionally

tilled plots at all landscape positions and sampling dates [15]. In their study, for the conventionally tilled plots, the backslope and shoulder positions had lower  $K_S$  than other positions, suggesting that lower  $K_S$  is correlated with landscape positions that have greater slopes and erosion potential.

We observed that footslope and floodplain landscape positions had significantly higher  $K_S$  values in 2013, which confirms our third hypothesis, which tested whether the footslope and floodplain positions had higher  $K_S$  values than the summit, shoulder, and backslope positions. Higher  $K_S$  values at the footslope may be caused by SOC accumulation [36]. The summit and backslope are more likely to suffer erosion and losses of SOC, which can accumulate at lower elevations at the footslope and floodplain positions [37]. All cropping systems, except switchgrass, had showed a significantly higher  $K_S$  at the footslope and floodplain positions in 2013 compared to 2009; the  $K_S$  of triticale-aspen was also significantly higher in 2013 at the backslope position.

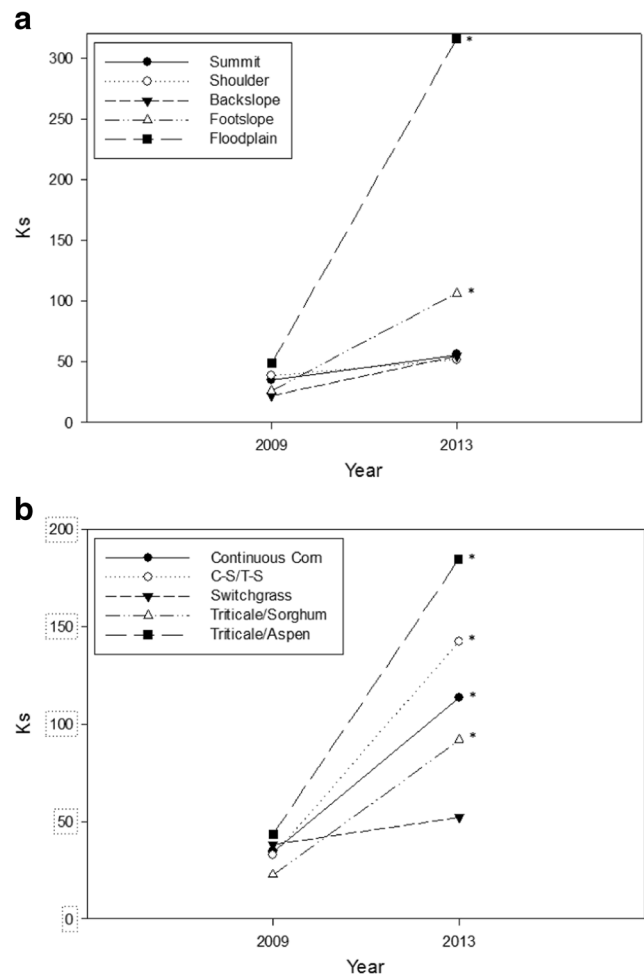
Results surrounding our second hypothesis regarding  $K_S$  rates in annual versus perennial systems were more equivocal.



**Fig. 1** Saturated hydraulic conductivity ( $K_S$ ) among five landscape positions in 2009 and 2013

We did not observe any cropping system differences at the summit, shoulder, and backslope positions. However, we did find that the triticale-aspen treatment had significantly higher  $K_S$  than the continuous maize, switchgrass, and sorghum/triticale treatments when considered across all landscape positions. This partially confirms our second hypothesis, as we did not observe an increase over time in  $K_S$  for the switchgrass system. Eldridge and Freudenberger also observed significantly higher  $K_S$  under woodland trees compared to pasture or cultivated areas, and attributed this result to a greater proportion of soil macropores under trees [23]. In a meta-analysis of  $K_S$  studies in the tropics, Ilstedt et al. concluded that afforestation of agricultural fields led to an average threefold increase in  $K_S$  [38].

Our results also indicate that maize-switchgrass had the lowest associated  $K_S$  compared to other cropping treatments. Maize-switchgrass measurements were conducted in late May and early June. The low saturated hydraulic conductivity below maize-switchgrass may partly be explained by the high density of living roots of the switchgrass by 2013. Living roots may initially reduce hydraulic conductivity by



**Fig. 2** Change in saturated hydraulic conductivity ( $K_S$ ) from 2009 to 2013 for five landscape positions (a) and five biomass cropping systems (b). Asterisk indicates significant difference between years at the  $P < 0.05$  level

compacting soil and filling macropore channels. Gish and Jury observed that infiltration was highest following crop removal due to the presence of root channels left behind by decomposed roots [39]. Preferential flow paths or macropores were observed after root decay. Active switchgrass rhizomes can essentially be sod forming, and 68.2–90.4% of switchgrass root weight density occur in the upper 15 cm of soil [40, 41]. Although density of living switchgrass roots reaches a peak in August [42], we noted a high density of living roots in the boreholes when conducting field measurements during the spring, when switchgrass infiltration is typically thought to be at its peak [43]. This was confirmed by root biomass measurements, which indicate that switchgrass had significantly higher root productivity than the annual cropping systems, with nearly double the root biomass compared to continuous maize [28]. The high root productivity of switchgrass may explain the relatively low observed  $K_S$  during this period.

While we observed a broad, site-wide increase in  $K_S$  across all cropping systems when considering all



landscape positions over a period of 4 years, it is likely that more time may be required to observe additional individual treatment effects. We observed significant increases in  $K_S$  over time at the footslope and floodplain positions, and for all cropping systems except switchgrass. Rachman et al. observed significantly greater hydraulic conductivities under stiff-stemmed grass hedge systems as compared to maize and soybean systems 10 years after establishment [44]. However, Schwartz and Unger suggest that conversion of cropland to perennial grasses had little impact on soil hydraulic properties even after a period of 10 years [26].

## Conclusion

The widespread adoption of perennial biomass crops and associated land use changes may have beneficial or adverse impacts on the environment. Our research fulfills a key knowledge gap by revealing how alternative biomass cropping systems impact saturated hydraulic conductivity across landscape positions. Our results demonstrate that, over a 4-year period, alternative cropping systems can have significant though variable impacts on soil hydraulic properties. We observed a significant increase in  $K_S$  over a period of 4 years at the footslope and floodplain positions and for all cropping systems except switchgrass. Differences among cropping system treatments were only observed at the floodplain position. We also observed a broad site-wide increase in  $K_S$ , consistent with the adoption of no-till management.

We expect that cropping system treatment effects will become more apparent over longer timescales, as the ecological processes that contribute to changes in soil hydraulic properties, such as SOC accumulation and macropore development, evolve over extended periods. While we observed significant changes in soil hydraulic conductivity over a short period, some systems did not complete a harvest cycle (triticale-aspen). Due to the establishment time associated with perennial systems, some longer-term impacts may not be apparent at this time.

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