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Cover crops and landscape positions mediate corn–soybean production

Gurbir Singh[1] | Madhav Dhakal[1] | Gurpreet Kaur[1] | Jon E. Schoonover[2] | Karl W. J. Williard[2]

[1]National Center for Alluvial Aquifer Research, Delta Research and Extension Center, Mississippi State Univ., Stoneville, MS 38776, USA (Email: gk340@msstate.edu)

[2]Dep. of Forestry, College of Agricultural Sciences, Southern Illinois Univ., Carbondale, IL 62901, USA (Email: jschoon@siu.edu; williard@siu.edu)

Correspondence
Gurbir Singh, National Center for Alluvial Aquifer Research, Delta Research and Extension Center, Mississippi State Univ., Stoneville, MS, 38776, USA
Email: gurbir.singh@msstate.edu

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Abstract

Ecosystem services and cash crop benefits provided by cover crops (CCs) can be affected by temporal and spatial variability of CC performances as influenced by topographic position of the field. A watershed-scale study was initiated in 2015 to assess the influence of crop rotations [cereal rye (*Secale cereale* L.)–soybean [*Glycine max* (L.) Merr.]–hairy vetch (*Vicia villosa* Roth.)–corn (*Zea mays* L.) (CC) and winter-fallow soybean–winter-fallow corn (NoCC)] and topography (i.e., shoulder, backslope, and footslope) on corn and soybean productivity in southern Illinois. Cereal rye increased soybean yield by 0.29 Mg ha^{-1} at the shoulder position, but it reduced yield by 0.44 Mg ha^{-1} at the footslope position when compared with the NoCC treatments. At the footslope position, every 1 Mg ha^{-1} increase in cereal rye biomass increased soybean yield by 0.87 Mg ha^{-1}. Soybean yield was negatively related to the cereal rye biomass at the shoulder and backslope positions. Within the CC rotation, corn yield was greater at the shoulder and backslope positions than at the footslope. Hairy vetch biomass affected corn yield positively within each landscape position. Cover cropping did not improve soybean and corn yield at the footslope position. Site-specific CC management is critical if the landscape has significant variability in soil characteristics.

1 | INTRODUCTION

Cover crops have been reported to improve the sustainability and resilience of corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] production systems (Blanco-Canqui et al., 2015). Cover crops can improve soil organic carbon (C), reduce nutrient loss via leaching and runoff, scavenge residual nitrogen (N), suppress winter weed population, and improve grain yields (Adler et al., 2020; Blanco-Canqui et al., 2015; Reddy, 2003; Ruis & Blanco-Canqui, 2017; Singh et al., 2018; Singh et al., 2019; Singh et al., 2020a; Tonitto et al., 2006). Cereal rye (*Secale cereale* L.) has an extensive rooting system that can explore deep soil horizons and recycle residual N in its biomass (Dean & Weil, 2009; Kaspar et al., 2012), thereby increasing aboveground cover and reducing weed pressure (Cherr et al., 2006). Overwintering legume CCs such as hairy vetch (*Vicia villosa* Roth.) and clover (*Trifolium* spp.) can suppress weed populations (Fisk et al., 2001) in addition to fixing atmospheric N in the soil. Faster mineralization of N from hairy vetch biomass (Sievers & Cook, 2018; Singh et al.,

Abbreviations: CC, cover crop.

2020b) can increase N availability to cash crops and boosts cash crop yields (Fageria et al., 2005). In a meta-analysis conducted by Miguez and Bollero (2005) on the response of corn yield to CCs, legume CCs increased corn yield by 37%, compared with the no CC control (NoCC). In the same study, grass CCs showed a net neutral effect on corn yields. Davis (2010) reported a significant increase in soybean yield following cereal rye compared with no CC, whereas yield reduction in soybean that followed hairy vetch was observed only in one out of three years, compared with no CC.

Although there are benefits of using CCs, the adoption rates of CCs in the United States is relatively low because of the increased cost of planting, challenges associated with establishing CCs, soil water depletion during dry periods, variability in CC biomass production, lack of data on atmospheric N fixed by CCs, and chances of reduction of cash crop yield by temporarily immobilizing N (Hauggaard-Nielsen et al., 2010; Kaspar & Bakker, 2015; Kaspar et al., 2008; Nykänen et al., 2008). Poor establishment of CCs before the first frost in the fall can result in lower biomass accumulation and thereby minimize benefits provided by CCs (Mirsky et al., 2017a; Mirsky et al., 2017b). Additionally, the field-scale complexity of managing CCs increases due to the variability caused by landscape positions.

The effect of spatial and temporal variability has been studied previously where the distribution of plant biomass, C accumulation, N uptake, and yield have been correlated with topographic positions (Dymond et al., 2017; Green et al., 2007; Jiang & Thelen, 2004; Kaspar et al., 2004; Kravchenko & Bullock, 2000; Singh et al., 2018). Bennett et al. (1972) reported the influence of slope orientation on the rate of growth, total yield, N recovery, and seasonal distribution of biomass of Kentucky bluegrass (*Poa pratensis* L.) in West Virginia where the production on the south-facing slope was less than half of the north-facing slope due to high soil temperature and low soil moisture levels. Jiang & Thelen (2004) studied the influence of soil properties and landscape positions on crop yield at a field scale where 28 to 85% variability in crop yield was explained by soil and topography together. In Illinois and Indiana, topography alone explained 20% of yield variability of corn and soybean with greater yields at lower landscape positions (Kravchenko & Bullock, 2000). In an 11-yr corn–soybean rotation study in Iowa, Kaspar et al. (2004) concluded that yield was reduced in wet years compared with dry years on lower landscape positions probably due to waterlogging stress. Landscape position affected the movement of water in unsaturated soil zones at soil depths > 76 cm and modified plant-available water where toe slopes contained more water than the ridges and backslopes (Dymond et al., 2017). The spatial variability in crop performances due to topography is mainly attributed to the gradients in soil texture (owing to erosion and deposition), organic C, nutrients, soil microclimate, and thermal and hydraulic conductivities. These physical and chemical properties play an important role in dynamically modifying soil moisture and temperature regime, organic matter distribution, soil nutrients, and soil faunal activities. The movement of soil water in response to differences in hydraulic heads can potentially transport soil solutes and alter the nutrient composition of the soil, specific heat capacity, and microbial biota.

Core Ideas

- Topographic variations may affect cover crop and cash crops production.
- Cover crops produced more biomass and retained more N at the shoulder and backslope positions.
- Cereal rye increased the soybean yield at shoulder but not at backslope and footslope.
- Hairy vetch increased the corn yield except at the footslope position.

Most of the agronomic studies on yield, biomass, and N uptake of a CC-based corn–soybean production system has been conducted in small-scale plots on a relatively flat topography. Results extrapolated from small-scale studies mostly ignore spatial variability created by landscape positions on a larger scale. The significance of spatial variability at which CCs are implemented has been studied to a limited extent (Beehleret al. et al., 2017). Muñoz et al. (2014), Ladoni et al. (2015), Ladoni et al. (2016), and Muñoz et al. (2014) assessed the effects of landscape positions and red clover (*Trifolium pratense* L.) CC biomass on corn yields and reported greater accumulation of CC biomass on summit and depression landscape positions, whereas greater corn yields were recorded at sloped landscape positions. In another study involving CCs and landscape positions, red clover legume CC increased soil N content by 33.5% whereas a nonlegume CC, cereal rye, decreased soil N by 15% on flat landscape positions (i.e., summit and depressions) (Ladoni et al., 2015). Leuthold et al. (2021a) found that landscape positions did not affect the cover crop decomposition or residue N release. Another study by Leuthold et al. (2021b) reported a 6% increase in corn yield due to cereal rye CC in the backslope position, which was attributed to lower evaporation and runoff losses.

Since spatial and temporal variability plays an important role in CC performance, a better understanding of the interaction of CCs and landscape positions will help generate more site-specific management recommendations for producers. Therefore, the overall objective of this research was to assess the influence of CCs (i.e., cereal rye and hairy vetch) on corn and soybean production at three landscape positions including shoulder, backslope, and footslope. The specific

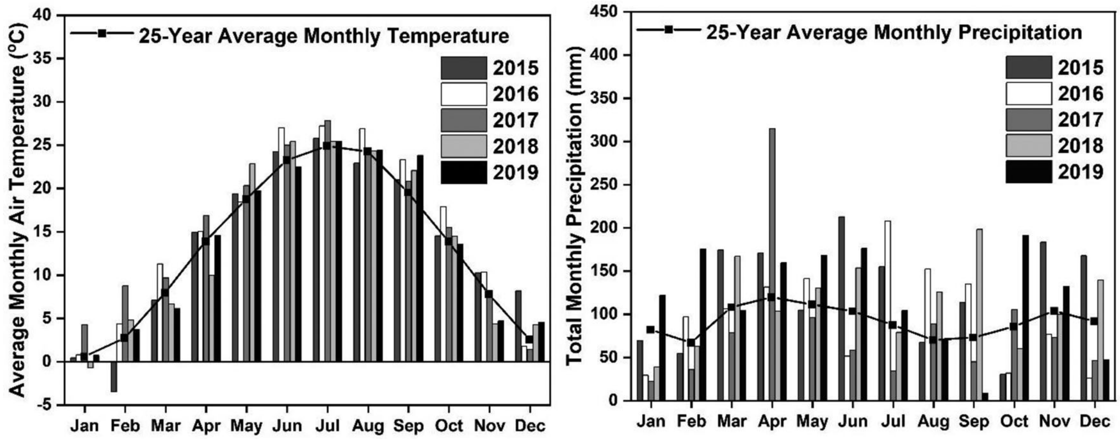

FIGURE 1 Mean monthly air temperature and total monthly precipitation received at the research site from 2015 to 2019. The black line is the 25-yr average monthly temperature and precipitation from 1990 to 2014

objectives were to quantify biomass accumulation, C:N ratio, and N uptake by CCs, corn, and soybean and to qualify crops yields as influenced by the use of CCs at three landscape positions. We hypothesized that incorporating CCs in a corn–soybean production system would improve grain yield irrespective of its landscape positions by increasing N uptake in plants.

2 | MATERIALS AND METHODS

2.1 | Site description

The research site was located at the Southern Illinois University Farms, Carbondale, Illinois (37.70944˚ N, -89.26889˚ W). The 25-yr (1990–2014) average annual rainfall received at the study site was 1,067 mm, and the mean annual temperature was 12.6 ˚C. The dominant soil series was Bonnie silt loam (fine-silty, mixed, active, acid, mesic Typic Fluvaquents) at the footslope landscape position and Hosmer silt loam (fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs) at the shoulder and backslope landscape positions. The slope for the Hosmer soil series was 2–10%, whereas the slope for the Bonnie silt loam was 0–2%.

The total annual precipitation in 2015, 2016, 2017, 2018, 2019 was 148, 1,187, 960, 1,359, and 1,460 mm, respectively, at the study location (Figure 1). Among the years in which corn was grown, 2019 was wetter than 2017 with seasonal precipitation (May to September) of 529 mm in 2019 and 284 mm in 2017. The total precipitation during the soybean growing season (June to October) was 579 and 617 in 2016 and 2018, respectively.

Average daily maximum temperatures exceeded 25 ˚C from June to August, and average daily minimum temperatures dropped below freezing from January to February (Figure 1). Growing season temperature was slightly varied among years with the record high temperature in July 2017.

2.2 | Study design and landscape classification

A field with an area of 23 ha and a 10-yr history of no-tillage under a two-year corn–soybean rotation was selected for this research. The field was divided into twelve watersheds using a digital elevation model with a raster resolution of 1.219 × 1.219 m (Illinois Geospatial Data Clearinghouse, 2020) in ArcMap (Version 10.4.1, ESRI). Out of twelve delineated watersheds, six watersheds were randomly selected for this study based on area. Three watersheds were randomly assigned to corn–soybean rotation with CCs, and the remaining three were assigned to corn–soybean rotation without any CCs (Figure 2). It should be noted that the replications in Figure 2 are blocks. Within a replication, each watershed had a similar area and was randomly assigned to a no CC or CC rotation. Areas of watersheds ranged between 1.2 and 4.8 ha. The experimental design was a split-plot design with crop rotations as the main factor replicated three times. The crop rotations included in this study were: cereal rye—soybean–hairy vetch–corn (CC) and winter-fallow soybean–winter-fallow corn (NoCC). The split factor was landscape positions. The topographic position index tool (Evans, Williard, et al., 2016; Jenness, 2006) set to 125 m and a convergence index of 20 m in ArcMap were used in delineating three landscape positions within each watershed: shoulder, backslope, and footslope. Each landscape position was further split into three randomly selected sampling locations to capture the variability of treatments. In total, there were nine sampling locations per replication of a rotation treatment (three sampling locations per landscape position × three landscape positions).

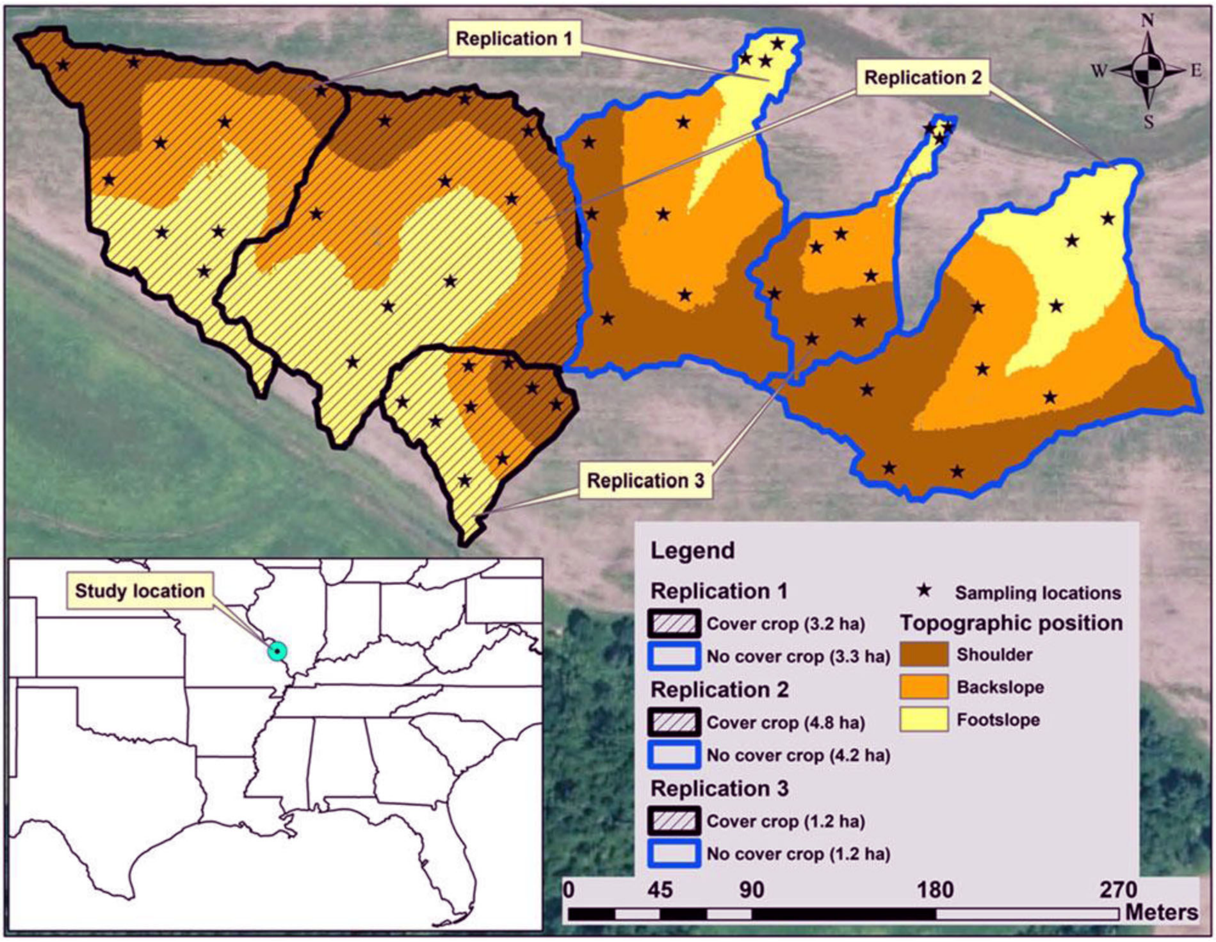

FIGURE 2 The research site for the watershed study in Carbondale, IL

TABLE 1 Dates of field operations and data collection from 2015 to 2019

Crop	NPK fertilizer application	Planting	Biomass collection	Harvest or termination[a]
Corn	30 Apr. 2015	3 May 2015	10 Sep. 2015	1 Oct. 2015
Cereal rye	–	5 Oct. 2015	15 Apr. 2016	18 Apr. 2016
Soybean	9 Apr. 2016	16 Jun. 2016	27 Sep. 2016	25 Oct. 2016
Hairy vetch	–	26 Oct. 2016	12 May 2017	12 May 2017
Corn	3 May 2017	19 May 2017	13 Sep. 2017	6 Oct. 2017
Cereal rye	–	13 Oct. 2017	7 May 2018	10 May 2018
Soybean	9 May 2018	5 June 2018	4 Oct. 2018	18 Oct. 2018
Hairy vetch	–	24 Oct. 2018	8 May 2019	13 Jun. 2019
Corn	25 Jun. 2019	12 Jun. 2019	15 Oct. 2019	18 Nov. 2019

Note. NPK, nitrogen, phosphorus, and potassium.

2.3 | Crop management

Planting, harvesting, and termination dates of CCs, corn, and soybean crops are provided in Table 1. In the NoCC rotation, winter weeds were allowed to grow, and no fall-residual herbicides were applied. Cereal rye CC was drilled at a seeding rate of 88 kg ha^{-1} after corn harvest in fall 2015 and 2017. Cereal rye was terminated in spring 2016 and 2018 using glyphosate at 0.95 kg a.e. ha^{-1}, saflufenacil at 0.04 kg a.i. ha^{-1}, methylated seed oil at 1% v/v, and diammonium sulfate at 1.5% v/v. Hairy vetch CC was planted after soybean harvest in fall 2016 and 2018 at a seeding rate of 28 kg ha^{-1}. Hairy vetch was terminated in spring 2017 and 2019 using glyphosate at 1.27 kg a.e. ha^{-1}, 2,4-D at 4.21 kg a.e. ha^{-1}, and diammonium sulfate at 2% v/v. Soybean and corn were planted using a John Deere plate planter 7200 at a row spacing of 76.2 cm and an average seeding rate of 346,000 and 79,000 seeds ha^{-1}, respectively. Nitrogen fertilizer application to corn was based on the maximum return-to-N calculator for southern Illinois (http://cnrc.agron.iastate.edu/nRate.aspx), and P and K fertilizers were broadcasted at single rate. About 222 kg N ha^{-1} as anhydrous ammonia, 34 kg P ha^{-1} as diammonium phosphate, and 56 kg K ha^{-1} as muriate of potash was applied to corn. Additionally, soybean received 160 kg K ha^{-1} in spring 2016 and 2018 before planting.

2.4 | Sampling and analysis

Dates of biomass sample collection are provided in Table 1. Aboveground CC biomass and weed biomass were taken for each sampling location and treatment before termination of cover crops from a 0.4-m^2 area using a PVC quadrat. The collected biomass samples were weighed, oven-dried at 60 ˚C to a constant weight, and weighed again to calculate the CCs' biomass tissue moisture content and aboveground dry matter yield. Weeds were not separated from CC biomass in CC treatments as their proportion in the total biomass was low (less than 0.2%). Winter annual weeds identified were common chickweed [*Stellaria media* (L.) Vill.], butterweed [*Packera glabella* (Poir.) C. Jeffrey], henbit (*Lamium amplexicaule* L.), and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.]. Dried CC biomass samples were ground using Wiley mill, passed through a 1-mm sieve, and analyzed for total C and N concentration using a CN soil-plant analyzer (Thermo Scientific FLASH 2000 Elemental Analyzer). The N retained in the CC biomass was calculated as the product of aboveground CC dry matter yield and its N concentration.

At physiological maturity, aboveground corn and soybean biomass samples were collected by manually harvesting plants from 3-m row length from all sampling locations. The collected plant biomass samples were weighed (moist weight) and chopped using a chopper. A handful of chopped subsamples was weighed and dried at 60 ˚C to calculate tissue moisture content and aboveground dry matter yield for grain crops. Dried biomass subsamples were then ground to pass a 1-mm sieve using Wiley-Mill and analyzed for C and N content. Nitrogen uptake by corn and soybean plants was calculated by multiplying percent N in the subsample with dry matter yield. Corn and soybean yields were determined using a John Deere combine equipped with an AgLeader yield monitoring system. Yield measurements were taken by grain flow sensors, with each measurement covering an area of about 2 × 6 m (2 m is an average forward distance traveled by a combine in 1 s, and 6 m is the width of the reaper). The yield was determined by correcting the grain moisture content to 15 and 13% for corn and soybean, respectively.

2.5 | Statistical analysis

Data were analyzed in SAS 9.4 statistical software (SAS Institute Inc.) for normality and log-transformed if needed based on Shapiro-Wilk and Kolmogorov-Smirnov tests of normality before analysis. The original data were presented in Tables 2 and 3. Data were analyzed using the GLIMMIX procedure in SAS. Crop rotations, landscape positions, and their interactions were set as fixed effects, whereas replication, landscape position, and year of data collection were treated as random effects. Treatment means were separated at $\alpha = .05$ using *T*-grouping of least squares mean differences.

Analysis of covariance was used to estimate the contribution of cover crop biomass to soybean and corn yield within each landscape position. In this analysis, the cereal rye biomass and crop yields were correlated separately for each landscape position. The analysis of covariance combines variance and regression analyses, which were determined in SAS using a generalized linear model. Soybean or corn yield were dependent variables, whereas cereal rye or hairy vetch biomass were independent variables. The landscape positions were considered categorical variables. The comparisons between landscape positions were performed at the lower quartile, median, and upper quartile of the covariate using *T*-grouping of least squares mean differences set at $\alpha = .05$ (Figure 3). Additionally, the covariate model included an independent effect of the intercept and slope for the CC at each landscape position.

3 | RESULTS

3.1 | Effect of cereal rye CC and topography on soybean

3.1.1 | Cereal rye

Soybean followed cereal rye CC in summer 2016 and 2018. Table 2 presents the biomass moisture, C and N concentration, and biomass or yield of these two crops under three landscape positions. Averaged across the years and landscape positions, weed biomass in NoCC plots (weeds) retained more moisture and N concentration than in CC plots (Table 2). Landscape positions affected N concentration in cereal rye-dry matter yield, its CN ratio, and N uptake but not the moisture content and C concentration. Dry matter yield and N uptake were affected by the interaction between landscape positions and CC treatments ($P < .05$, Table 2). The dry matter yield of CC treatment at the shoulder and backslope positions was 1,413 and 1,048 kg ha^{-1} more than the NoCC treatment on the same landscape positions. In the CC treatment, the dry matter production was greatest at the shoulder position and decreased by 985 and 1,609 kg ha^{-1} at the backslope and

TABLE 2 Comparison of biomass moisture, biomass carbon (C), and nitrogen (N) concentration, C:N ratio, dry matter yield, biomass N uptake, seed yield, and moisture collected from three landscape positions in rotations with and without cover crops (CC and NoCC) for cereal rye and soybean

		Cereal rye2015–2016 and 2017–2018						Soybean2016 and 2018							
Rotation[a]	LP[b]	Moisture[c]	C	N	C:N ratio	Dry matteryield	N uptake	Moisture[c]	C	N	C:N ratio	Dry matter yield	N uptake	Seed yield	Seed moisture
		g kg^{-1}				kg ha^{-1}		g kg^{-1}				kg ha^{-1}		Mg ha^{-1}	g kg^{-1}
CC		793b	387	12.6b	31a	1,852a	23a	452	463	31.6	15	5,265	168	2.96	157
NoCC		812a	381	14.2a	27b	1,172b	17b	430	462	31.2	15	5,037	158	2.97	154
	Shoulder	811	381	13.8a	28b	2,010a	27a	433	462	31.8	15	5,343	173	3.18a	157a
	Backslope	802	387	13.7a	29b	1,207b	17b	451	462	31.3	15	5,240	165	3.14a	153b
	Footslope	795	385	12.7b	31a	1,319b	16b	437	463	31.1	16	4,870	151	2.58b	156ab
CC	Shoulder	805	382	12.8	30	2,716a	35a	428b	463	31.7	15	5,703a	187a	3.33a	158
CC	Backslope	787	389	12.8	31	1,731b	22b	465a	462	31.6	15	5,554a	176a	3.19ab	154
CC	Footslope	787	391	12.2	32	1,107 cd	13 cd	462a	464	31.5	16	4,538b	140b	2.36d	157
NoCC	Shoulder	816	380	14.8	26	1,303bc	20bc	439ab	462	31.8	15	4,983ab	159ab	3.04b	156
NoCC	Backslope	818	385	14.6	27	683d	10d	438ab	462	30.6	16	4,927ab	153ab	3.08ab	151
NoCC	Footslope	803	379	13.2	29	1,530bc	21bc	412b	462	31.2	16	5,202ab	162ab	2.80c	156
Source of variation	df[d]	*p* values													
Rotation (R)	1	.0257	.1275	<.0001	<.0001	.0036	.0314	.0843	.6124	.6355	.8619	.4371	.3160	.8844	.4591
LP	2	.2252	.4879	.0019	.0002	<.0001	<.0001	.1449	.7680	.6262	.6280	.2164	.1199	<.0001	.0467
R × LP	2	.5116	.4994	.3908	.9039	<.0001	<.0001	.0124	.7830	.7184	.6278	.0284	.0363	<.0001	.8929

Note. The same letter within a column indicates no significant difference for a given factor or combination of factors ($p = .05$).

[a]CC, cover crop (cereal rye—soybean–hairy vetch–corn); NoCC, no cover crop (winter-fallow soybean–winter-fallow corn. [b]LP, landscape positions. [c]Moisture, aboveground biomass moisture. [d]Numerator degrees of freedom.

TABLE 3 Comparison of mean biomass moisture, carbon (C), biomass nitrogen (N), C:N ratio, dry matter yield, biomass N uptake, grain yield, and grain moisture collected from three landscape positions in rotations with and without cover crops (CC and NoCC) for hairy vetch and corn

		Hairy vetch2016–2017 and 2018–2019						Corn2017 and 2019							
Rotation[a]	**LP**[b]	**Moisture**[c]	**C**	**N**	**C:N ratio**	**Dry matter yield**	**N uptake**	**Moisture**[c]	**C**	**N**	**C:N ratio**	**Dry matter yield**	**N uptake**	**Grain yield**	**Grain moisture**
		g kg^{-1}				kg ha^{-1}		g kg^{-1}				kg ha^{-1}		Mg ha^{-1}	g kg^{-1}
CC		716a	401	22.3a	19b	2,646a	57a	566	398	8.7	50	20,530	181	9.52	172
NoCC		628b	401	17.3b	24a	990b	16b	562	408	8.6	51	21,426	188	8.27	174
	Shoulder	689	402	21.4a	20b	2,255a	49a	575	401	9.3a	47	21,923	202a	9.25a	172b
	Backslope	666	402	20.7a	20b	1,690b	35b	555	403	8.0b	53	20,682	164b	8.79ab	171b
	Footslope	661	397	17.3b	24a	1,508b	26b	562	405	8.7ab	51	20,329	188ab	8.65b	175a
CC	Shoulder	745a	402	24.5	18	3,356a	77a	568	393c	9.3	46	22,521a	203a	10.82a	170b
CC	Backslope	730a	404	23.1	18	2,731b	59b	565	403ab	8.3	53	20,626a	173ab	10.00ab	171b
CC	Footslope	674b	395	19.1	22	1,850c	35c	563	398bc	8.4	51	18,442b	166ab	7.74bc	175a
NoCC	Shoulder	633c	403	18.2	23	1,154c	20c	581	408ab	9.3	48	21,325a	201a	7.67bc	175a
NoCC	Backslope	603d	401	18.4	22	650d	12d	545	402bc	7.7	54	20,033ab	154b	7.31c	172ab
NoCC	Footslope	649bc	399	15.5	27	1,166c	17c	560	412a	8.9	50	22,921a	210a	9.84ab	174a
Source of variation	df[d]	*p* values													
Rotation (R)	1	.0380	.8142	.0003	.0012	.0044	.0005	.7940	.1417	.9472	.6611	.3971	.4090	.1609	.1174
LP	2	.1582	.1305	<.0001	<.0001	.0008	.0004	.3777	.2290	.0087	.0705	.1639	.0139	.0228	.0134
R × LP	2	.0025	.4934	.2600	.7124	.0002	.0021	.4784	.0070	.4298	.8505	.0133	.0087	.0045	.0428

Note. The same letter within a column indicates no significant difference for a given factor or combination of factors ($p = .05$).
[a]CC, cover crop (cereal rye—soybean–hairy vetch–corn); NoCC, no cover crop (winter-fallow soybean—winter-fallow corn. [b]LP, landscape positions. [c]Aboveground biomass moisture. [d]Numerator degrees of freedom.

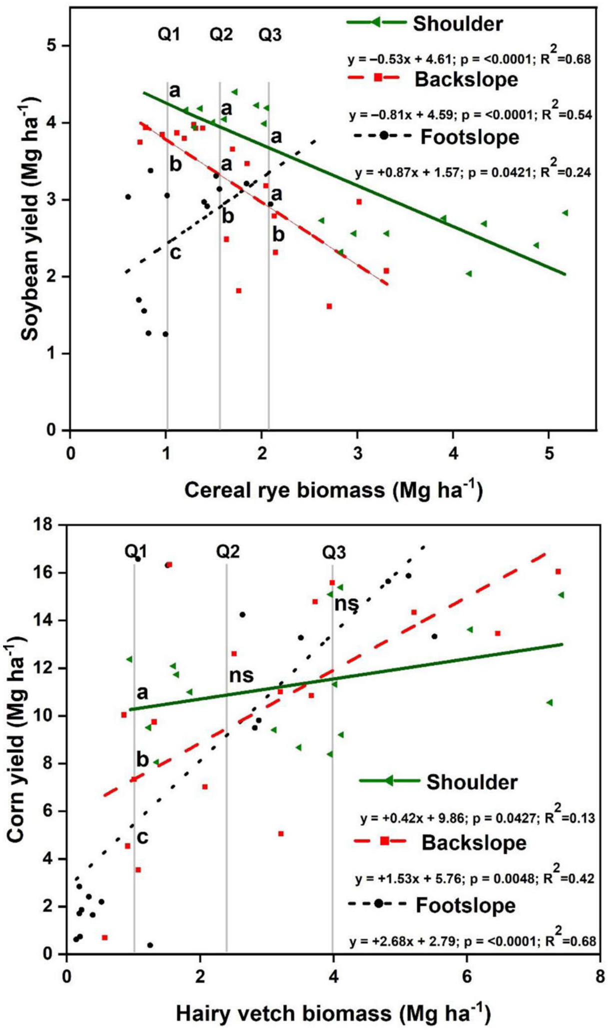

FIGURE 3 Effect of (a) cereal rye biomass on soybean yield and (b) hairy vetch biomass on corn yield at three landscape positions. Green (solid line), red (dashed line), and black (dotted line) indicate a linear relationship between grain yield and cover crop (CC) biomass. Comparisons between landscape positions were performed at first (Q1), second (Q2), and third (Q3) quartiles of the covariate indicated as vertical gray lines. Different letters within the same value of CC biomass indicate a statistically significant difference between landscape positions at $p = .05$, and ns indicates nonsignificant

footslope positions, respectively, compared with the shoulder position. However, the dry matter yield at the backslope position was less than the other two landscape positions in the NoCC treatments. A similar trend was obtained for N uptake by the cereal rye in this study. There were no significant differences between the dry matter yields of cereal rye and weeds and N uptake in the CC and NoCC treatments, respectively, at the footslope position.

3.1.2 | Soybean

Interaction between landscape positions and CC treatment revealed that the average soybean dry matter moisture content was 50 g kg^{-1} more in the CC than NoCC treatment at the footslope position. The soybean dry matter and N uptake under NoCC were not affected by landscape position, whereas the soybean dry matter yield and N uptake were greater at the shoulder and backslope than the footslope landscape position in the CC treatments (Table 2). Soybean seed yield at shoulder and backslope was greater (0.24 to 0.97 Mg ha^{-1}, respectively) compared with the footslope position. When compared with the NoCC treatments, cereal rye CC increased soybean yield by 0.29 Mg ha^{-1} at the shoulder position, but it reduced yield by 0.44 Mg ha^{-1} at the footslope position (Table 2).

A significant correlation was found between the CC biomass production and soybean yield (Figure 3) within each topographic position. Soybean yield was linearly and positively related with the cereal rye biomass within the footslope position. At the footslope position, every 1 Mg ha^{-1} increase in cereal rye biomass increased soybean yield by 0.87 Mg ha^{-1}. In contrast, soybean yield was negatively related to the cereal rye biomass within the shoulder and backslope positions (Figure 3). An increase in cereal rye biomass by 1 Mg ha^{-1} at the shoulder and backslope positions reduced soybean yield by 0.53 and 0.81 Mg ha^{-1}, respectively. Soybean yield differed significantly among three landscape positions at the lower, median, and upper quartiles of the covariate, which corresponds to 1.0, 1.6, and 2.1 Mg ha^{-1} of the cereal rye biomass, respectively. Soybean yield was in the order of shoulder > backslope > footslope for the first quartile of the covariate up to 1 Mg ha^{-1} biomass of cereal rye. Soybean yield varied between landscape positions in the second quartile, having equal yield on the shoulder and backslope and lower yield on the footslope. However, a linear but opposite slope of soybean yield-cereal rye biomass relations for three landscape positions resulted in an equally greater soybean yield on shoulder and footslope than the backslope in the upper quartile of the covariate.

3.2 | Effect of hairy vetch and topography on corn

3.2.1 | Hairy vetch

Hairy vetch was grown after soybean harvest during winter in 2016 and 2018 followed by corn in the summer of 2017 and 2019. To separate its effect on crop rotation, the hairy vetch–corn component of the complete crop rotation (cereal rye–soybean–hairy vetch–corn) was analyzed for yield and linked attributes (Table 3). Since hairy vetch can fix atmospheric

N_2 into its root nodules, its N concentration is higher than the nonlegumes, including broadleaf weeds, as proven by our results. The C:N ratio was lower for the hairy vetch CC than the weeds in the NoCC treatment. An interaction between the rotation and landscape position showed that the hairy vetch dry matter production was 625 to 1,506 kg ha^{-1} greater at the shoulder position compared with the backslope and footslope position, respectively, in the CC treatment. Backslope had lower weed infestation than that in shoulder and footslope positions, as indicated by the lowest dry matter in NoCC plots (Table 3). No significant differences were obtained between CC and NoCC treatments for dry matter production at the footslope landscape position. However, the hairy vetch dry matter production was 2,202 and 2,081 kg ha^{-1} greater at the shoulder and backslope landscape positions, respectively, in the CC treatments compared with NoCC treatments. The N uptake by hairy vetch followed the same trend as the dry matter yield in the CC and NoCC treatments.

3.2.2 | Corn

When data were averaged over rotations, the N concentration in aboveground corn biomass was 1.3 g kg^{-1} greater at the shoulder landscape position than at the backslope, whereas the footslope was intermediate between them (Table 3). Interaction between rotation and topography showed that all treatments were equally effective in retaining N in corn biomass except for NoCC treatment on the backslope position. Within the NoCC rotation, N uptake at the backslope position was 47 and 56 kg ha^{-1} lower than the shoulder and footslope positions, respectively. Hairy vetch increased corn yield at the shoulder and backslope positions by 3.15 and 2.69 kg ha^{-1}, respectively, compared with the NoCC rotation (Table 3). Figure 3 shows that the hairy vetch biomass affected corn yield positively ($P < .05$). Corn yield at the backslope and footslope was more dependent on hairy vetch biomass than at the shoulder landscape position at the lower quartile of the covariate, which corresponds to 1.0 Mg ha^{-1} of the hairy vetch biomass. Hairy vetch biomass greater than 2.2 Mg ha^{-1} equally increased the corn yield with an increase in biomass for all landscape positions in the middle and upper quartiles of the covariate.

4 | DISCUSSION

4.1 | Effect of cereal rye CC and topography on soybean

In the CC treatments, the CC biomass included >80% by mass of cereal rye, which indicates a reason for lower N concentration of the CC biomass than that of the NoCC treatment. In the NoCC treatment, most weeds were broadleaves, mixed with some grasses, and broadleaf weeds contain greater N concentration than C3 species like cereal rye. Dhakal et al. (2020) reported 14 to 32 g N kg^{-1} in broadleaf weed tissues. Cereal rye has been reported to have low tissue N content ranging from 5 to 12 g N kg^{-1} (Poffenbarger et al., 2015; Sievers & Cook, 2018). Production of high cereal rye biomass might have diluted the N concentration of the CC biomass on the shoulder landscape position, where the CC dry matter productivity was significantly greater than on the backslope and footslope positions. Singh et al. (2019) explained that the shoulder positions had relatively better growing conditions than the backslope and footslope due to availability of sufficient soil moisture with good drainage and nutrient-rich condition, especially soil N. The high erodibility of the backslope and the poor drainage and high N leaching in the footslope position might be potential reasons for low cereal rye biomass production in these landscape positions, especially without CC (Singh et al., 2019).

In the CC rotation, soybean dry matter, seed yield, and N uptake were greater at the shoulder and backslope positions compared with the footslope, given that the production of cereal rye biomass was also greater in the shoulder and backslope positions. When cereal rye biomass and soybean yield were correlated individually for each topographic position, cereal rye biomass negatively affected the soybean grain yield within the shoulder and backslope positions. Cereal rye slowly decomposes and releases N to the soil after termination and can immobilize N for microbial degradation. Since the topsoil layer of the shoulder and backslope positions dry out faster than the footslope (Sariyildiz et al., 2005; Singh et al., 2019), the low soil moisture content could have extended the duration of N immobilization. The thick cereal rye residue on the shoulder could even worsen the nutrient availability to the crops during first few weeks after termination. Other potential reasons for reducing soybean yield with increasing cereal rye biomass at the shoulder and backslope positions might be due to lower plant stand (Reddy, 2001), slower canopy closure, toxic effects due to allelopathy, and lower soil temperature (Johnson et al., 1998; Reddy, 2001). Singh et al. (2020c) reported a lag in canopy closure of the soybean in the CC plots compared with NoCC treatment plots in the study conducted in southern Illinois. The lower landscape position can retain water long enough to allow thick CC residue to fully decompose and release nutrients to the soil. This favored a growing condition where an increase in cereal rye residue increased the soybean yield at the footslope region, as seen by the positive relationship between grain yield and mass of CC residue. However, the soybean yield was severely limited by the waterlogging condition and subsequent anaerobic stress (Singh et al., 2019). Strategies that allow cereal rye to mature would increase its biomass and crop grain yield at footslope landscape position. Dymond et al. (2017) suggested that although topography is a major driver of plant-available water in the soil, CC roots may reach deep soil layers, variably deplete soil water, and ultimately change soil-water regime. Despite having a negative relation between cereal rye residue and soybean seed yield at the shoulder and backslope positions, the CC treatment had higher soybean seed yield than the NoCC treatment at the shoulder position (Table 2). Figure 3 suggested that early termination of the cereal rye at the shoulder and backslope would increase the soybean yield. Nevertheless, the other soil and topographic factors might have compensated for the soybean yield in the shoulder and backslope as we did not control the CC biomass to fit the model that builds a relationship between CC performance and cash crop yield. Low-density cereal rye may allow broadleaf weeds to grow on a bare surface, which could contribute to the total surface residue that helps maintain the soil N status and ultimately the soybean productivity. The comparable grain yield of soybean obtained from the NoCC treatment from all landscape positions indicate that the cereal rye cover may not be necessary on the backslope positions, and a site-specific approach would be needed for cover cropping in heterogeneous areas.

4.2 | Effect of hairy vetch and topography on corn

Cover crops help to build the organic matter and enrich soil N (Bargués Tobella et al., 2014). Additionally, incorporation of CC residue to the soil increases recovery of soil P in the subsequent cash crops (Nziguheba et al., 2000), which could also affect the crop yield in the CC plots. Incorporating hairy vetch in a corn production system provided available N equivalent to the N provided by 62 kg fertilizer N ha^{-1} (Power et al., 1991). Although the hairy vetch CC treatment produced a significant amount of aboveground biomass and accumulated the highest amount of N in its mass, it did not increase the corn biomass or yield on the footslope landscape position over NoCC treatments. This indicates either that the soil condition was not limiting the crop yield or that the CC couldn't change the soil nutrient pool during summer, which could be because a legume CC such as hairy vetch rapidly loses its mass and releases N into the soil within the first two weeks of termination before corn establishes its root system, especially with high soil moisture conditions (Sievers & Cook, 2018; Singh et al., 2020b). The low performance of corn in CC treatments at the footslope landscape position might be attributed to the prolonged waterlogged condition in July as the water was retained longer than in NoCC plots. Relatively high clay content and clay had a negative role in draining the water, which may create a less favorable environment for crops near the rooting zone (Jiang & Thelen, 2004).

The cover crop did affect corn yield on the backslope, which indicates an influence of CC residue on soil and water. Cover crop residue slows down the movement of water that potentially carries nutrients and prevents severe erosion, especially in areas like backslope. A meta-analysis conducted by Meyer et al. (2018) came up with an average estimate of 27- to 32-mm reduction in drained water from CC-treated row crop plots over a bare surface. Clay fragipan underneath the A-B horizon in our study might have resisted the downward movement of water and solutes, which could have exacerbated the runoff from the bare backslope surface. The backslope soil might have developed a thinner surface horizon than the shoulder and footslope due to erosion, which could lead to greater water runoff and low soil productivity (Wright et al., 1990). Hairy vetch CC might have improved soil physical and hydraulic properties and provide nutrients necessary for corn production. Kravchenko and Bullock (2000) observed changes in plant-available water with elevation and indicated water as the major reason for corn yield variability during extreme weather conditions. Overall, topographic positions of a landscape should be considered when choosing hairy vetch as a winter crop in a corn–soybean-based cropping system. Legume CCs may not provide benefits when incorporated at lower topographic areas compared with the upper landscape positions. As suggested by Muñoz et al. (2014), a simple linear relationship established between CC biomass and cash crop yield (Figure 3) may not fully explain soil and climatic variability. To consider the fact that multiple factors simultaneously interact with each other, a hierarchical path analysis would be better to account for the experimental factors such as soil, topography, management practices, and crop performances (Muñoz et al., 2014).

5 | CONCLUSION

It is undoubtedly true that cover cropping can benefit crop production in various ways, but care should be given in selecting the type of CC and landscape position. Cereal rye can provide ground cover by producing significant aboveground biomass at the shoulder and backslope positions than at the footslope due to gradients in soil moisture and nutrient condition, but cereal rye did not add yield benefit to the soybean when compared with the NoCC treatment at the backslope and footslope positions. Results showed that the cereal rye–soybean rotation would be ideal for the shoulder position. However, with proper drainage, if the cereal rye biomass increases on the footslope, it could potentially increase the soybean grain yield, as indicated by the linear relations between CC biomass and grain yield. It was evident that the hairy vetch–corn system can increase grain yield significantly over NoCC rotation on the shoulder and backslope positions, but not on the footslope, possibly due to poor growing conditions at the footslope position that can limit establishment of the CC and, subsequently, the cash crop yield.

Strategies that allow CCs to grow for longer periods at the footslope would increase their biomass and cash crop yield. Our study suggests that the legume CC should be planted on shoulder and backslope positions, whereas the footslope should have nonlegume CC or can be left fallow during winter. However, if proper subsurface drainage can be ensured for the footslope position, then CCs might perform better on the footslope landscape positions. Overall, topography-specific management of the CC would optimize crop productivity.

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AUTHOR CONTRIBUTIONS

Gurbir Singh: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Writing – original draft; Writing – review & editing. Madhav Dhakal: Writing – review & editing. Gurpreet Kaur: Writing – original draft; Writing – review & editing. Jon E. Schoonover: Methodology; Project administration; Writing – review & editing. Karl W. J. Williard: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Gurbir Singh https://orcid.org/0000-0002-4013-3460
Madhav Dhakal https://orcid.org/0000-0003-3082-5225
Gurpreet Kaur https://orcid.org/0000-0003-0766-3336

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