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Single and Multispecies Cover Crop Effects on Corn Production and Economic Returns

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Abstract: The adoption of cover crops (CCs) has gained popularity in the continuous corn (*Zea mays* L.) production system due to their multiple benefits including scavenging or fixing nitrogen (N) in the soil. However, a CC's ability to develop early cover, scavenge N, and provide N to the following cash crop is species-dependent and affected by environment. A field study was conducted in three diverse environments to determine growth characteristics of nine CC treatments (i.e., monocultures or mixes of grasses, legumes, and brassica), and their effect on the following corn crop was compared to no cover crop treatment (noCC). Cover crops significantly differed for above-ground biomass, plant tissue carbon (C) and N concentrations, carbon to nitrogen ratio (C/N), and total N uptake (TNU). Among monocultures, grasses had the highest biomass and C/N ratio, and legumes had the highest N concentrations and TNU. Corn grain yield was highest following radish, whereas lowest corn yield was found following cereal rye + crimson clover mix in environment 1. Cover crops varied for C/N ratios in all three environments, but only affected corn plant height (PH) and grain yield in one environment. Cover crops belonging to the same species also exhibit different responses for characteristics measured, depending upon the environment. The expected returns were also variable, especially in CC mixes. The study provides valuable information on the species-specific functionality of CCs in continuous corn under variable environmental conditions. The information will benefit future studies to explore a high diversity mixture of CCs that may outperform across all three environments.

Keywords: *cereal rye, wheat, crimson clover, hairy vetch, radish, turnip*

Research Implications

- Cover crops provide multiple benefits and help with soil and water conservation.
- Cover crop mixes showed no improvement in the corn yield over the cover crop monocultures.
- Benefits of cover crops on corn production depend upon the environment.

Corn was ranked as the second main crop in Mississippi (MS) after soybean (*Glycine max* L.), with its economic value to the state estimated at $665 M in 2021 (USDA NASS 2021a). Corn was planted on 0.3 million ha in MS with total production of 3.2 million metric tons in 2021 (USDA NASS 2021a). Corn yields vary across MS because of crop and irrigation management practices. The non-irrigated corn yield in 2021 averaged 11.9 Mg ha^{-1} across MS. Irrigated corn is predominantly produced in the Delta region of the state with an average yield of 14.6 Mg ha^{-1} in 2021 (MSU 2021). Despite variable yield, the net returns across the state varied within ± $30, with the highest of $366 ha^{-1} and lowest of $336 ha^{-1} for irrigated and non-irrigated corn, respectively (Gregory 2020).

Farmers of the U.S. Mid-South made a quick shift from cotton to corn production with the introduction of the Farm Bill in 1995 (Sanchez

2016). Initially, the shift was from a continuous cotton production system to a continuous corn production system, until 2007. Corn production was increased from 121,000 ha in previous years to 376,000 ha in MS in 2007 with a 50% reduction in cotton acreage (USDA NASS 2021b). Corn yield was greatly increased primarily due to improved genetic and management practices (Duvick 2005). After 2007, biennial rotation of soybean and corn gained interest due to ease of management when compared to cotton. Cotton requires intensive efforts to manage foliage growth continuing even after it creates a seed, due to its indeterminate perennial growth habit. However, many corn farmers skip rotation and engage in corn monocropping, especially when the market returns for corn are higher (Wang and Ortiz-Bobea 2019).

Continuous corn production has a risk of yield drag due to cooler and wetter soils, nitrogen (N) immobilization, increased disease pressure, and allelopathy (Gentry et al. 2013). Past studies have reported a yield reduction ranging from 2 to 29% in continuous corn compared to corn following soybean (S-C) (Peterson and Varvel 1989; Porter et al. 1997; Wilhelm and Wortmann 2004). Among various factors, N immobilization plays a dominant role in yield penalty in continuous corn production compared to S-C rotation (Stanger and Lauer 2008). Long-term research in Iowa showed corn yields averaged only about 3.7 Mg ha^{-1} for continuous corn compared to 7.2 Mg ha^{-1} for S-C, when corn was not fertilized with N (Sawyer and Randall 2008). Therefore, cover crops (CCs) in a continuous corn production system can act as a rotational crop and may provide benefits like a two-year S-C rotation (Torbert et al. 1996; Dapaah and Vyn 1998; Gentry et al. 2013). Cover crops can substantially enhance N availability to subsequent corn in both till and no-till systems, however, their benefits are species-dependent. The species-specific N credits from legume and non-legume to corn were mainly quantified in terms of growth, biomass production, and yields in the past. For instance, Dapaah and Vyn (1998) reported that corn planted following ryegrass *(Lolium multiflorum* L.) was shorter in height with fewer leaves and less biomass compared to corn following red clover *(Trifolium pratense* L.). They also reported that corn yielded highest following red clover compared to ryegrass, oilseed radish *(Raphanus sativus* L.), and no cover crop (noCC). Torbert et al. (1996) reported a 7 to 22% increase in corn yield at the highest fertilizer N application level following crimson clover, compared with noCC. In addition, CCs help reduce nutrient losses from agricultural fields, improve water quality, and increase N supply for succeeding crops (Sanchez 2016). Martinez-Feria et al. (2016) reported that planting cereal rye reduced 26% nitrate-nitrogen (NO_3-N) losses without consistently reducing corn yields. Cover crops can be extremely beneficial in MS since its rainfall is greatest during the non-cash crop growing season from October to April (Tang et al. 2018), which can increase soil erosion, runoff losses, and nutrient leaching.

Cover crops used in the U.S. can generally be categorized into three groups: grasses, legumes, and brassica. Grasses produce a large volume of root biomass, are good in scavenging soil N, and fit well in a no-till system. However, they have a high carbon to nitrogen ratio (C/N) in their residues (Kaye et al. 2019). On the other hand, residues of legumes and brassica decompose more rapidly in the spring, due to a low C/N ratio compared with grasses (Kaye et al. 2019). Additionally, legumes are valued for their ability to fix N, which can benefit the succeeding crop. Multispecies CCs can have superior performance over monoculture CCs. For instance, a mix of grasses and legumes could allow quick soil cover and N scavenging by grasses, and N additions and quick residue break down by the legume. Hence, investigating region-specific selection, integration, and management of CCs in a continuous corn production system is crucial to determine the full potential of corn yield based on past advancements.

Cover crop benefits are long-term while the costs are upfront. Early CC performance is an important determinant in whether a farmer adopts the practice permanently or is discouraged by early results and prematurely drop the practice. These early results provide important information for conservation agencies sponsoring CC programs. Only about 30% of MS farmers have opted to implement CCs, according to a recent survey of irrigators in MS (Quintana-Ashwell et al. 2020). The overall objective of this study was to determine the effect of monocultures and multispecies overseeded CCs on the growth, yield, and quality of the following corn crop, and to estimate the production cost and expected returns from CC monocultures and multispecies mixes under diverse growing conditions. We hypothesized that CCs' performance and their effect on corn growth and development depend on the type of CCs.

Materials and Methods

Site Description and Experimental Layout

The experiment was conducted at two research sites for three years: Stoneville, MS (33°25'42.6"N, -90°57'13.5"W) in 2019-2020 and 2020-2021; and Starkville, MS in 2020-2021 (33°28'40.1"N, -88°47'13.2"W) (Table 1). The combinations of experimental site and year for the duration of CC or corn were referred to as environments. From this point in the article, environment 1 refers to Stoneville during 2019-2020, environment 2 refers to Stoneville during 2020-2021, and environment 3 refers to Starkville during 2020-2021 (Table 1). The dominant soil series at the Stoneville site was classified as Bosket very fine sandy loam (Fine-loamy, mixed, active, thermic Mollic Hapludalfs). Bosket very fine sandy loam is well-drained soil with moderately high saturated hydrologic conductivity and moderate permeability. The dominant soil series at the Starkville site was classified as Leeper silt clay loam (Fine, smectitic, nonacid, thermic Vertic Epiaquepts). Leeper silt clay loam is a somewhat poorly drained soil with very slow saturated hydraulic conductivity that occasionally causes flooding. The weather data for research sites were obtained from Mississippi State University's North Farm Starkville station and Stoneville West station of The Delta Agricultural Weather Center (MSU 2016). The data included average monthly temperatures, mean monthly solar radiations, and monthly total precipitation for three environments (Figure 1). The 30-year average annual minimum and maximum temperatures were 12.1°C and 23.6°C, respectively. The 30-year average annual precipitation received at the research site was 1406 mm.

The experimental layout was a randomized complete block design, with four replications of ten CC treatments randomly planted in each environment. The ten treatments included in this study were: noCC, cereal rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* L.), radish (*Raphanus sativus* L.), cereal rye + crimson clover, wheat + crimson clover, hairy vetch + radish, and wheat + radish + turnip (*Brassica rapa* subsp. rapa L.). The seeding rates for cereal rye, wheat, crimson clover, hairy vetch,

Table 1. Dates for field operations and data collection during the experimental period.

Environments	Year	Location	Crop	Tillage	Planting	N-Fertilizer Split Application 1st	N-Fertilizer Split Application 2nd	Biomass Collection	Cover Crop Termination or Corn Harvest
1	2019	Stoneville	Cover crops	3 Oct. 2019	03 Oct. 2019	‡	‡	28 Feb. 2020	28 Feb. 2020
2	2020	Stoneville	Cover crops	3 Oct. 2020	07 Oct. 2020	‡	‡	10 Mar. 2021	11 Mar. 2021
3	2020	Starkville	Cover crops	1 Sep. 2021	16 Sep. 2021	‡	‡	10 Mar. 2021	24 Apr. 2021
1	2020	Stoneville	Corn	‡	03 Apr. 2020	29 Apr. 2020	05 May 2020	‡	03 Sep. 2020
2	2021	Stoneville	Corn	‡	16 Mar. 2021	05 Apr. 2021	14 May 2021	‡	17 Aug. 2021
3	2021	Starkville	Corn	‡	07 May 2021	28 May 2021	18 June 2021	‡	14 Sep. 2021

‡No data.

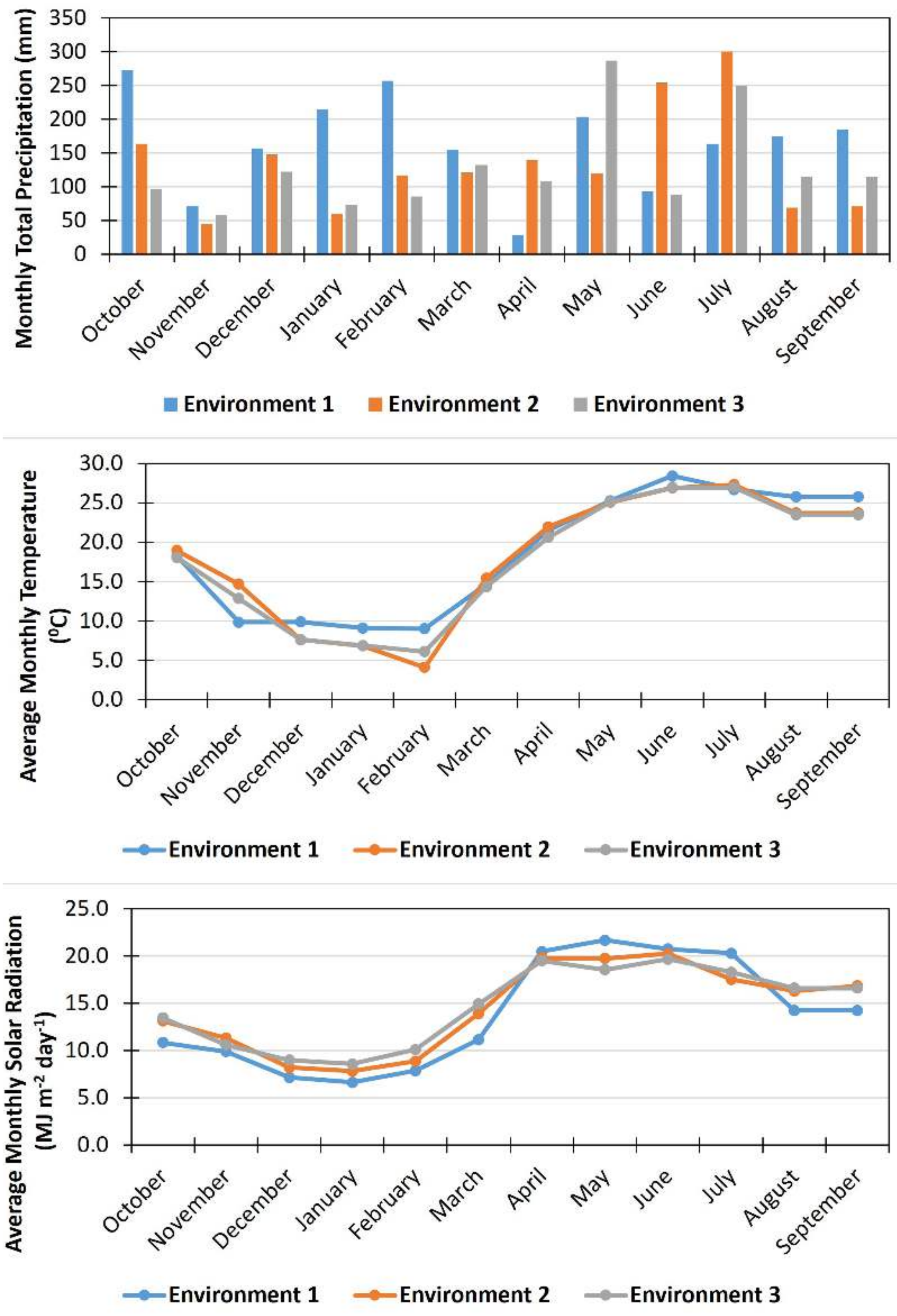

Figure 1. Monthly total precipitation, average monthly air temperature, and monthly solar radiation data recorded across three environments.

radish, hairy vetch + radish, and wheat + radish + turnip were 67.25, 67.25, 8.97, 22.47, 8.97, 11.21 + 4.48, and 44.83 + 4.48 + 2.24 kg ha^{-1}, respectively. Cereal rye + crimson clover and wheat + crimson clover CCs were planted at a seeding rate of 33.63 + 4.48 kg ha^{-1}. Each treatment plot was four rows wide with an inter-row spacing of 1.016 m in environments 1 and 2, and 0.965 m in environment 3. The plot size for every treatment was 4.06 m x 9.14 m in environments 1 and 2, and 3.86 m x 9.14 m for environment 3.

Field and Crop Management

The CCs were planted as monoculture or multispecies in fall 2019 and 2020 at Stoneville, and in fall 2020 at Starkville. The details of field and crop management at the three environments are given in Table 1. Tillage was performed in the experimental fields in the fall before aerial seeding or overseeding of CCs. The experiment fields were tilled using one pass of a stalk shredder, followed by at least two passes of disking, one pass of a field cultivator, and then finally hipped using a bedder roller. The CCs were overseeded on the ground after the tillage operations using a hand spreader. The CCs selected belonged to one of three groups based on species: grasses (cereal rye and wheat), legumes (hairy vetch and crimson clover), or brassica (radish and turnip). Cover crops in all three environments were terminated using Roundup Weathermax [glyphosate, N-(phosphonomethyl) glycine] at 1.89 kg a.e. ha^{-1}, 2,4-D (2,4-dichlorophenoxyacetic acid) at 0.80 kg a.e. ha^{-1}, and Scanner 0.25 v/v in the spring before planting corn.

Soil samples were collected from 0 to 30 cm depth in the fall before planting CCs, to analyse for physical and chemical soil properties of the field sites. The soil analysis results are reported in Table S1. Following the termination of CCs in the springs of 2020 and 2021 at the three environments, the corn cultivar Dekalb DK 70-27 (*DEKALB®*) was planted using a John Deere 1710 Maxemerge XP eight row seed drill. Fertilization, tillage, and weed management for corn were conducted according to Mississippi State University Extension Service recommendations. Nitrogen fertilizer was applied as preemergence and as a split application around V4-5 corn growth stage, while the phosphorus (P) and potassium (K) fertilizers were applied as a single application before tillage operations in the fall. Corn planted in environment 1 received NPK fertilizers at a rate of 278 kg N ha^{-1} as 32% urea ammonium nitrate (UAN), 20 kg P ha^{-1} as triple superphosphate (TSP), and 40 kg K ha^{-1} as Muriate of Potash (MOP). Environments 2 and 3 received a total of 263 kg N ha^{-1} as 32% UAN, 56 kg P ha^{-1} as TSP, and 112 kg K ha^{-1} as MOP. The biomass data were collected from both CCs and corn for all three environments (Table 1). The field sites received preemergence herbicide application of Lexar EZ [(S-Metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(1-methoxypropan-2-yl) acetamid + Mesotrion, 2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione + Atrazine, 6-Chloro-N^2-ethyl-N^4-(propan-2-yl)-1,3,5-triazine-2,4-diamine)] at 3.11 kg a.i. ha^{-1} plus scanner 0.25 v/v and a postemergence application of Halex GT [(S-Metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(1-methoxypropan-2-yl) acetamid + Glyphosate, N-(phosphonomethyl) glycine + Mesotrione, 2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione + Atrazine, 6-Chloro-N^2-ethyl-N^4-(propan-2-yl)-1,3,5-triazine-2,4-diamine)] at 2.21 kg a.i. ha^{-1} plus scanner 0.25 v/v for weed management.

Data Collection and Analysis

Above-ground biomass samples of CCs and winter weeds (noCC) were collected from a 0.19 m^2 area before CC termination by clipping all plant biomass above the ground (Table 1). The samples collected were dried at 60°C until the constant dry weight was achieved. Dried samples were weighed, ground using a Wiley Mill (Thermo Scientific), and sifted using a 0.5 mm sieve. Sieved subsamples were analysed for C and N concentrations using dry combustion followed by gas chromatography (Flash 2000, organic elemental analyser, Thermo Scientific). The total N uptake (TNU) was then calculated by multiplying the N concentration with dry weight. The C/N ratio was also determined by dividing C concentration by the N concentration of the sample.

At physiological maturity, the mean plant height (PH) of corn was recorded from 1-m row length from each plot at all three environments. A FieldScout CM 1000 Chlorophyll Meter was used for measuring the chlorophyll index, a measure of relative greenness, of the ear leaf. Corn yield, test weight, and moisture were determined by harvesting the middle two rows along the entire plot length using a plot combine (Kincaid 8xp; Haven, KS) equipped with a harvest master H_2 yield monitor (Juniper Systems; Logan, UT). The grain yield obtained was adjusted to 15.5% grain moisture before data analysis. Grain samples of 500 to 600 g were collected at the time of harvesting from each plot to analyse for grain quality, including oil, protein, and starch content with Near-infrared (NIR) spectroscopy using the Foss Infratec 1241 grain analyzer (Hilleroed, Denmark). After analysing grain quality, the grain samples were also used to measure seed index (SI) by measuring the weight of 100 grains.

Statistical and Economic Analysis

Data collected during the season were analysed using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC). The CC and environment were considered as fixed effects and replication as random effects. The environmental effect was significant for all the traits but protein (Table 2). Therefore, data were reanalysed to determine the influence of CCs on corn growth and development for each environment separately (Tables 3 and 4). Post hoc differences were determined using Fisher's Least Significant Difference ($\alpha = 0.05$). The expected farm revenue was calculated by multiplying the yields under each treatment by the average (average of two years, 2020 and 2021) bid price for corn reported by the U.S. Department of Agriculture (USDA) Economics, Statistics and Market Information System (ESMIS) for county elevators in Greenville, MS, at \$221.65 Mg^{-1}. Partial budget analyses were performed to compare the profitability implications of different CC treatments to the returns and variability associated with the noCC system. The production cost estimates were obtained from the 2022 crop planning budgets published by the Mississippi State University's Department of Agricultural Economics (MSU 2022), which employed prices for the year 2021. Since the corn planning budgets for corn are only generated for production on 76.2 and 95.5 cm row spacing, a space factor was created, and the budget was adjusted to account for 101.6 cm row spacing. The relationship between risk and returns exploited the variability reported for the yields to calculate the variability in returns.

Results

Weather Data

The highest average monthly temperature was in July for Environments 2 and 3, whereas it was in June for environment 1. The lowest average monthly temperature was in February for all three environments (Figure 1). The average monthly temperature in June was 1.5^{o}C higher in environment 1 than environments 2 and 3. The average monthly temperature in December and January was 2.2^{o}C higher in environment 1 than the other two environments. Similarly, the monthly temperature in February was also 4.9 and 2.9^{o}C higher in environment 1 than the environments 2 and 3, respectively.

Average monthly solar radiation was lower for environment 1 than the other environments from October to March (Figure 1). However, solar radiation was higher in environment 1 than the other two environments in May and July. The total monthly precipitation from October to September was 367 and 445 mm greater for environment 1 (1,978 mm) than environments 2 (1,611 mm) and 3 (1,533 mm), respectively (Figure 1). The monthly total precipitation received during the CC growing season from October to March was 473 and 559 mm higher in environment 1 (1,129 mm) than environments 2 (656 mm) and 3 (569 mm), respectively. January and February accumulated at least 100 mm more precipitation in environment 1 than the other two environments. The highest environmental variation in monthly total precipitation occurred in January, February, June, and July.

Cover Crop Biomass, Plant Tissue Nitrogen, Carbon, and C/N Ratios

Environments 1 and 3 had significant variation in CC biomass, N, C, and C/N ratio, but environment 2 exhibited only variation for C/N ratio (Table 3).

Biomass. In environment 1, all CC monocultures and mixtures had 2092 to 4830 kg ha^{-1} greater biomass production than noCC, except crimson clover, hairy vetch, and wheat + crimson clover mix (Table 4). No differences in biomass were observed among wheat, cereal rye, and radish, and on average they were 82% higher in biomass production than the crimson clover and hairy vetch legume CCs (Table 4). Growing hairy vetch in a mix with radish resulted in greater biomass production than the hairy vetch monoculture whereas growing wheat in a mix with crimson clover had lower biomass (1259 kg ha^{-1}) compared to growing wheat as monoculture (2405 kg ha^{-1}). No differences were observed in between cereal rye and radish biomass when planted as monocultures or as a mix.

Except monoculture hairy vetch and crimson clover, all other CCs planted whether as monoculture or mix had greater biomass production than noCCs in environment 3 (Table 4). The biomass of legume monoculture CCs (crimson clover and hairy vetch) was 62% less than the average biomass of wheat, cereal rye, and radish monocultures. Among CC mixes, crimson clover legume when planted with cereal rye showed a 64% increase in biomass than monoculture crimson clover (Table 4). Cereal rye + crimson clover had the highest biomass production in environment 3, however, it was not significantly different from the wheat + radish + turnip mix and wheat, radish, and cereal rye monocultures CCs. Further, no differences were observed in biomass when grasses and brassica were planted as mix or as single species in all three environments (Table 4). In contrast, wheat showed a 33% decline in biomass when mixed with crimson clover than its monoculture although the difference was not significant.

Plant Tissue Nitrogen Concentration and Uptake. Significant differences in N concentrations among CCs were observed in environments 1 and 3 (Table 3). The lowest plant tissue N concentration was obtained for weeds in noCC treatment. In the case of CC monoculture, radish consistently maintained higher N in both environments 1 and 3 (Table 4). In environment 1, radish planted as monoculture had 49, 57, 70, and 77% higher N concentrations than cereal rye, wheat, crimson clover, and hairy vetch monocultures, respectively (Table 4). Crimson clover, hairy vetch, and noCC showed the lowest N, averaging 9 g kg^{-1} for environment 1. In environment 3, radish and hairy vetch had

Table 2. P-values from statistical analysis showing the effects of cover crops and environments on data collected during the studies conducted in Mississippi.

Source of Variation	Cover Crop					Corn								
	Biomass	**C†**	**N**	**C/N**	**TNU**	**PH**	**CI**	**GM**	**TW**	**SI**	**Yield**	**Oil**	**Protein**	**Starch**
E	0.0082	<0.0001	<0.0001	<0.0001	0.0017	<0.0001	0.0013	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.7844	<0.0001
CC	0.0900	<0.0001	<0.0001	<0.0001	0.0203	0.0178	0.2345	0.3970	0.9500	0.4400	0.5542	0.5300	0.4809	0.7100
E × CC	0.3748	<0.0001	<0.0001	0.0964	0.2235	0.6014	0.7007	0.5432	0.9700	0.0900	0.0485	0.6100	0.4933	0.9000

E, environment; CC, cover crop; C, carbon concentration; N, nitrogen concentration; C/N, carbon to nitrogen ratio; TNU, total nitrogen uptake in biomass; PH, plant height; CI, Chlorophyll index; GM, grain moisture; TW, test weight; SI, 100 seed weight. P-values showing significant differences have been underlined and where interaction is significant, only interaction p-values have been underlined.

Table 3. P-values from statistical analysis showing the cover crop effects on the data collected during the experiment and separated for each environment.

Data Collected	Environment 1	Environment 2	Environment 3
Cover Crop			
Biomass	<0.0001	0.3731	<0.0001
Carbon (C) Concentration	<0.0001	0.5402	<0.0001
Nitrogen (N) Concentration	<0.0001	0.2715	<0.0001
Carbon / Nitrogen Ratio	<0.0001	0.0108	0.0003
Total Nitrogen Uptake	<0.0001	0.1209	<0.0001
Corn			
Plant Height	0.0163	0.6855	‡
Chlorophyll Index	0.1272	0.3556	‡
Grain Moisture	0.6249	0.9206	0.4200
Yield	0.0232	0.4292	0.2674
Test Weight	0.6230	0.0195	0.9700
Seed Index	0.1181	0.8221	0.0226
Oil	0.5131	0.5763	0.3200
Protein	0.8321	0.6280	0.3528
Starch	0.8167	0.0311	0.7700

P-values showing significant differences have been underlined.
‡No data collected.

an average of 20% greater N concentrations than crimson clover, wheat, and cereal rye (Table 4). A CC mix of hairy vetch + radish showed no change for N concentration from radish monoculture in environment 1, while the N concentration of this mix declined by 21% compared to the hairy vetch and radish monocultures in environment 3. The N concentration of cereal rye + crimson clover mix was greater than monocultures of cereal rye and crimson clover in environments 1 and 3. The three-way mix of wheat + radish + turnip had a slight improvement in N concentration compared to monoculture wheat in environment 1. No differences were observed for N concentration among CC monocultures, mixtures, and noCC in environment 2 and they averaged 24.1 g kg^{-1} across all treatments (Table 4).

Like biomass, CCs showed a significant difference for TNU in environments 1 and 3 (Table 3). In both environments, the decreasing order of TNU in the CC monocultures was in the order of: brassica > grasses > legumes. Among CC monocultures, radish (172.8 kg ha^{-1}) and cereal rye (63.3 kg ha^{-1}) had higher TNU followed by wheat (34.8 kg ha^{-1}) in environment 1, whereas significantly lower TNU was found in hairy vetch, crimson clover, and noCC (Table 4). Total nitrogen uptake was similar among all mixes except for wheat + crimson clover, which had 122 and 145 kg ha^{-1} lower TNU than the wheat + radish + turnip and hairy vetch + radish mixes, respectively in environment 1 (Table 4). In environment 3, the highest TNU was obtained in the CC mix of cereal rye + crimson clover (200.24 kg ha^{-1}), while the lowest was obtained in noCC (32.36 kg ha^{-1}) (Table 4). The combination of cereal rye + crimson clover outperformed for TNU among all treatments, except wheat + radish + turnip and radish (Table 4). All other CC mixes showed no improvement in TNU over CC monocultures. Among CC mixes in environment 3, the lowest TNU accumulated was in the wheat + crimson clover mix. The trend of low TNU for wheat + crimson clover mix was similar to that of environment 1 (Table 2).

Carbon to Nitrogen Ratio (C/N). Cover crops significantly differed for C/N ratios in all three environments, with the highest being in grasses and the lowest in single-planted or mix of hairy vetch

Table 4. Cover crops biomass production, C and N concentration, C/N ratio, and total nitrogen uptake as affected by the cover crop treatments in three environments.

Treatment	Biomass kg ha^{-1}	C g kg^{-1}	N g kg^{-1}	C/N ratio	TNU kg ha^{-1}
			Environment 1		
No Cover Crop	313±101c†	98.7±80b	9.3±7d	7.78±1f†	3.64±1c
Cereal Rye	3,584±1,600a	256.8±50a	18.0±3c	14.07±1ab	63.26±23ab
Wheat	2,405±660a	249.8±13a	15.6±8cd	15.72±1a	34.81±17b
Crimson Clover	765±634bc	123.5±40b	10.5±3d	11.77±1bcd	7.92±1c
Hairy Vetch	489±295bc	88.7±20b	8.0±2d	10.18±1def	4.71±4c
Radish	4,831±1,194a	321.1±10a	35.0±2a	8.96±1def	172.82±41a
Cereal Rye + Crimson Clover	4,247±382a	288.3±40a	21.8±4b	13.34±1abc	91.98±16ab
Wheat + Crimson Clover	1,259±750b	268.1±50a	18.8±4c	14.44±1ab	23±16b
Hairy Vetch + Radish	4,764±1,611a	311.0±10a	35.0±4a	8.77±1ef	168.35±52a
Wheat + Radish + Turnip	5,143±3369a	278.9±20a	26.0±5b	10.79±1cde	144.63±19a
			Environment 2		
No Cover Crop	1,423±1,074	268.2±10.2	21.9±1.1	12.89±2.14abcd	32.85±35.45
Cereal Rye	2,035±731	349.7±2.0	24.6±0.5	14.60±2.41ab	52.77±32.32
Wheat	1,940±822	267.3±3.9	17.5±0.2	15.26±1.37a	34.57±17.59
Crimson Clover	1,809±255	256.1±6.0	19.0±0.6	14.08±2.45abc	33.56±9.99
Hairy Vetch	2,415±280	306.9±5.2	27.9±3	10.92±1.37d	67.73±12.52
Radish	1,733±751	299.4±6.0	25.0±0.3	11.67±1.28cd	45.37±22.23
Cereal Rye + Crimson Clover	2,521±1,085	312.9±5.1	24.0±0.7	13.11±2.35abcd	57.81±11.51
Wheat + Crimson Clover	1,352±444	293.2±9.5	2.6±0.9	13.29±1.41abcd	29.10±11.01
Hairy Vetch + Radish	2,583±1,240	308.5±3.3	28.0±0.3	10.94±0.47d	70.25±30.36
Wheat + Radish + Turnip	2,590±1,342	310.5±2.8	24.6±0.3	12.64±0.73bcd	65.15±35.11
			Environment 3		
No Cover Crop	1,744±1,242f	327.0±3.4e	17.0±0d	18.78±0.1a	32.36±28.00e
Cereal Rye	5,617±861abc	395.0±0.8a	24.8±0c	16.09±0.2abc	140.89±36.05bc
Wheat	5,807±1,705abc	399.4±1.3a	24.0±5c	17.34±0.4ab	134.60±34.56bc
Crimson Clover	2,498±637ef	366.0±1.1cd	24.2±5c	15.68±0.3bc	62.85±29.26ed
Hairy Vetch	3,452±934def	384.0±1.9abc	29.2±3ab	13.31±0.2cd	103.68±36.57cd
Radish	5,442±1,569abc	369.9±0.8bcd	31.5±3a	11.80±0.1d	171.15±50.18ab
Cereal Rye + Crimson Clover	6,940±1,539a	391.9±0.9ab	32.0±7a	14.89±0.5bc	200.24±73.93a
Wheat + Crimson Clover	3,879±1,943cde	393.2±0.6a	28.0±1abc	15.53±0.1bc	101.31±57.30cd
Hairy Vetch + Radish	4,463±1,260bcd	358.6±1.9d	24.0±1c	11.14±0.1d	143.34±39.31bc
Wheat + Radish + Turnip	5,737±564abc	365.1±0.7cd	26.0±3bc	13.78±0.1cd	154.66±30.75abc

†The same letter within a column indicates no significant difference for a given factor or combination of factors ($\alpha = 0.05$). Note: C, carbon concentration; N, nitrogen concentration; C/N, carbon to nitrogen ratio; TNU, total nitrogen uptake in cover crop biomass. The values are means ± standard deviation.

and radish (Tables 3 and 4). The average C/N ratio of grasses was 33% higher than the average C/N ratio obtained in the mix of hairy vetch + radish across all environments (Table 4). The comparison of noCC plots with treatments was highly variable for C/N ratios among environments. For instance, noCC had the lowest C/N ratio in environment 1, whereas environments 2 and 3 had comparable C/N ratios between noCC and CCs. Overall, the CC mixtures did not exhibit any improvement over CC monocultures for C/N ratio.

Corn Growth, Grain Yield, and Quality

Plant Height. In environment 1, corn PH was 8% higher following radish than grasses (wheat and cereal rye) (Table 5). Corn following radish showed a 6% increase in PH compared to corn following crimson clover. No differences in PH were observed between corn following legumes or grasses. The cereal rye + crimson clover CC mixture produced stunted corn plants compared to other CC monocultures and mixtures. In environment 1, corn following CC showed a wide range of PH, varying from 217.4 to 242.3 cm. Also, the noCC had a comparable effect on PH (228.6 cm). Corn height in environment 2 had a narrow range (10.1 cm) of variation among CC treatments.

Grain Yield. Like PH, yield differences among treatments were only significant in environment 1 (Table 3). Cereal rye + crimson clover reduced corn grain yield by 24% compared to the noCC. Corn yields differed by 25.7% among CCs, with the highest following radish (11,520 kg ha^{-1}) and the lowest following the cereal rye + crimson clover mixture (8,561 kg ha^{-1}) (Table 5). The CC mixes over the CC monocultures showed no improvement in the yield.

Grain Quality. Cover crops affected grain quality in environments 2 (test weight (TW) and starch concentration (SI)) and 3 (Table 3). In environment 2, the starch concentration was lowest in the cereal rye + crimson clover CC mix, which was not significantly different from wheat, crimson clover, and wheat + radish + turnip (Table 5). Overall, the average starch concentration among all three environments was within ± 10 of 700 g kg^{-1}, which is close to the standard for grain quality analysis (U.S. Grain Council 2021). In environment 1, no differences were observed in corn TW following grass, legume, and brassica species. However, hairy vetch + radish increased TW by 1.6% than monoculture radish (Table 5). Also, TW was significantly increased (1.6%) by crimson clover + wheat mixture compared to their monoculture stands. Hairy vetch + radish mix showed higher TW than other CC mixes except for crimson clover + wheat mix. Overall, environments 1 and 2 had higher TW in all treatments, including noCC, than the standard set for corn grain quality (72.08 kg hL^{-1}). Environment 3 showed lower TW than the set standard averaging 61.59 kg hL^{-1}. In environment 3, corn following cereal rye or hairy vetch showed lower SI (35.7g) than other single-species CC treatments (38.1 g). Further, the study did not show any improvements in SI with planting multispecies CCs. Unlike TW, corn in environment 1 had the lowest SI of 30.5 g compared to a ~37 g average for the other two environments (Table 5).

Risk and Profit Analysis

The estimated production costs and profits for each treatment in each environment are summarized in Table 6. Table 7 shows the profitability ranking of each treatment in each environment, while table 8 summarizes the overall risk-return combinations for each treatment. The noCC showed the highest level of expected profits overall ($649.50 ha^{-1}), although it was most profitable only under environment 2 ($746.89 ha^{-1}), while it showed the third-highest expected profits under environments 1 ($769.68 ha^{-1}) and 3 ($531.99 ha^{-1}). Crimson clover CC showed the second highest overall returns at $502.94 ha^{-1}, ranking second highest for environment 1 ($785.77 ha^{-1}), fifth for environment 2 ($477.88 ha^{-1}), and fourth for environment 3 ($347.11 ha^{-1}).

Radish monoculture showed the third overall highest returns at $398.07 ha^{-1}, ranking highest in environment 1 with $810.16 ha^{-1}, fourth in environment 2 with $563.73 ha^{-1}, and eighth in environment 3 with an expected loss of $222.03 ha^{-1}. Fourth overall was hairy vetch with $368.18 ha^{-1} followed by cereal rye with $352.41 ha^{-1}. The least profitable overall, in descending order, were wheat with $329.88 ha^{-1}, hairy vetch + radish mix with $320.38 ha^{-1}, wheat + radish + turnip mix with $316.99 ha^{-1}, cereal rye + crimson clover mix

Table 5. Corn production as affected by the cover crop monoculture and mixtures in three environments.

Treatments	Plant Height cm	Chlorophyll Index	Grain Moisture g kg^{-1}	Grain Yield kg ha^{-1}	Test Weight kg hl^{-1}	Seed Index g	Oil g kg^{-1}	Starch g kg^{-1}	Protein g kg^{-1}
Environment 1									
No Cover Crop	229±7abc[†]	369.08±36.55	176.3±6.7	11,230±781ab	73.33±1.20	30.27±0.89	44.8±4.9	702±1	89.0±3.5
Cereal Rye	226±5bc	3.1667.17±9.16	179.0±5.7	9,838±692bc	72.50±0.60	30.51±2.06	40.5±8.8	705±17	88.0±1.2
Wheat	217±20cd	316.50±27.57	172.5±3.6	10,311±1,682ab	72.88±0.73	30.20±2.02	40.3±4.1	705±12	88.8±4.1
Crimson Clover	227±4bc	351.67±29.14	175.3±9.5	11,427±517ab	73.33±0.32	32.18±1.59	38.0±6.6	710±12	85.8±1.7
Hairy Vetch	229±10abc	350.50±40.51	170.3±16.0	11,100±853ab	72.50±1.67	30.61±2.20	35.5±4.6	716±7	88.0±3.9
Radish	242±7a	360.75±31.37	176.3±3.5	11,520±1,761a	73.43±0.82	32.18±1.48	43.5±8.5	701±15	89.3±3.3
Cereal Rye + Crimson Clover	212±6d	307.00±34.77	173.8±3.4	8,561±1,258c	72.85±0.80	28.46±0.92	38.3±3.8	711±11	92.0±1.4
Wheat + Crimson Clover	229±10abc	357.42±32.78	175.3±6.8	10,390±940ab	73.33±0.68	30.34±2.61	40.0±5.3	703±10	89.5±1.9
Hairy Vetch + Radish	232±12ab	363.67±24.66	181.8±6.7	10,661±950ab	73.36±0.98	32.19±2.92	41.3±3.4	705±8	89.8±1.2
Wheat + Radish + Turnip	223±6bcd	379.92±84.26	171.0±8.1	9,911±1.101abc	73.56±0.54	29.01±1.62	37.0±5.7	703±16	89.0±1.6
Environment 2									
No Cover Crop	212±6	478.33±89.63	203.3±2.9	11,602±465	74.68±0.73abc	36.95±2.81	37.8±0.5	698±1ab	94.0±7.1
Cereal Rye	205±6	365.08±110.91	205.0±3.5	9,514±1,285	73.68±1.80bcd	36.96±1.63	37.8±0.9	697±2abc	97.0±3.4
Wheat	211±11	363.50±39.11	201.0±9.0	9,899±1,013	73.49±0.36d	36.99±1.69	38.3±0.5	695±2bcd	101.2±5.2
Crimson Clover	202±8	420.92±59.56	201.5±11.8	10,466±1,194	73.58±0.54cd	35.30±3.96	38.3±0.5	695±2bcd	99.3±2.1
Hairy Vetch	213±5	352.58±118.69	205.3±4.9	10,586±951	74.58±0.22abcd	37.73±0.36	38.8±0.5	696±2abc	99.8±3.4
Radish	215±18	424.50±114.62	200.3±9.5	10,852±2,301	74.36±1.17bcd	37.45±1.97	38.5±1.0	697±3abc	98.5±4.3
Cereal Rye + Crimson Clover	203±7	395.75±70.58	206.8±5.5	9,847±1,441	73.91±0.73bcd	38.44±0.89	38.0±0.8	693±1d	14.3±4.2
Wheat + Crimson Clover	208±12	377.25±29.08	203.3±3.3	11,143±1,825	74.74±0.66ab	36.81±1.55	38.0±0.8	697±2abc	99.8±4.0
Hairy Vetch + Radish	211±14	399.08±41.18	201.0±5.2	11,506±1,159	75.58±0.68a	37.22±2.14	38.5±0.5	699±2a	96.3±5.2
Wheat + Radish + Turnip	206±12	409.67±49.40	200.3±9.7	10,577±1,267	73.87±1.09bcd	37.35±2.27	38.0±0.8	695±2cd	101.0±4.2
Environment 3									
No Cover Crop	.	.	187.0±9.4	10,599±2,280	63.55±3.64	38.02±1.24a	37.0±1.1	705±2	98.5±6.4
Cereal Rye	.	.	183.5±7.7	10,946±513	56.53±11.92	36.2±1.70bc	35.5±0.5	707±6	98.5±4.9
Wheat	.	.	184.5±8.3	9,672±3,225	64.12±9.48	38.1±0.63a	37.3±1.8	708±4	100.3±7.3
Crimson Clover	.	.	190.5±6.2	9,859±3,133	65.35±6.69	37.98±2.22a	37.0±1.1	708±5	97.0±5.1
Hairy Vetch	.	.	187.0±12.2	9,629±2,684	63.48±5.20	35.25±1.59c	35.8±1.2	711±5	96.8±8.0
Radish	.	.	178.0±12.6	7,105±3,140	51.484±18.26	37.33±3.07a	37.5±1.0	703±5	99.8±4.5
Cereal Rye + Crimson Clover	.	.	212.0±5.3	11,438±1,421	65.55±7.40	37.75±0.46ab	37.3±1.5	709±2	97.3±3.2
Wheat + Crimson Clover	.	.	190.5±11.9	6,421±4,408	63.80±9.94	35.86±1.30bc	36.5±0.5	709±8	99.3±5.7
Hairy Vetch + Radish	.	.	188.0±4.5	7,238±3,140	54.76±13.98	37.41±0.30abc	36.0±0.0	709±4	99.0±4.6
Wheat + Radish + Turnip	.	.	192.3±4.9	9,115±3,422	67.27±12.15	37.49±1.71ab	37.0±1.0	706±4	99.0±8.5

[†]The same letter within a column indicates no significant difference for a given factor or combination of factors ($\alpha = 0.05$). The values are means ± standard deviation.

Table 6. The estimated production costs and profits for the cover crop monoculture and mixture treatments in three environments.

Cover Crop Treatments	Grain Revenue	Production Cost	Expected Profit	Profit Standard Deviation
	---------- $ ha^{-1} ----------			
		Environment 1		
No Cover Crop	2,489.21	1,719.53	769.68	173.11
Cereal Rye	2,180.73	1,778.24	402.49	153.38
Wheat	2,285.43	1,787.66	497.77	372.82
Crimson Clover	2,532.90	1,747.13	785.77	114.59
Hairy Vetch	2,460.40	1,850.92	609.48	189.07
Radish	2,553.54	1,743.38	810.16	390.33
Cereal Rye + Crimson Clover	1,897.56	1,769.84	127.72	278.84
Wheat + Crimson Clover	2,302.91	1,775.77	527.14	208.35
Hairy Vetch + Radish	2,363.05	1,812.94	550.11	210.57
Wheat + Radish + Turnip	2,196.77	1,795.32	401.45	244.04
		Environment 2		
No Cover Crop	2,571.56	1,824.67	746.89	103.07
Cereal Rye	2,108.71	1,864.46	244.25	284.82
Wheat	2,194.15	1,877.38	316.77	224.54
Crimson Clover	2,319.87	1,841.99	477.88	264.65
Hairy Vetch	2,346.51	1,946.87	399.65	210.79
Radish	2,405.45	1,841.72	563.73	510.02
Cereal Rye + Crimson Clover	2,182.67	1,859.09	323.57	319.40
Wheat + Crimson Clover	2,469.84	1,876.76	593.08	404.52
Hairy Vetch + Radish	2,550.43	1,917.21	633.22	256.90
Wheat + Radish + Turnip	2,344.45	1,891.17	453.28	280.84
		Environment 3		
No Cover Crop	2,347.57	1,815.58	531.99	505.10
Cereal Rye	2,424.43	1,857.78	566.64	113.70
Wheat	2,142.28	1,875.30	266.97	714.29
Crimson Clover	2,183.60	1,836.48	347.11	694.13
Hairy Vetch	2,132.61	1,938.17	194.45	594.54
Radish	1,573.56	1,795.59	-222.03	321.41
Cereal Rye + Crimson Clover	2,533.29	1,847.58	685.71	314.75
Wheat + Crimson Clover	1,422.16	1,833.96	-411.80	976.41
Hairy Vetch + Radish	1,603.15	1,867.42	-264.27	695.67
Wheat + Radish + Turnip	2,018.89	1,857.27	161.63	757.97

Table 7. The profitability ranking of the cover crop monoculture and mixture treatments in three environments with 1 as the most profitable and 10 as the least profitable.

Cover Crop Treatments	---------- **Profitabilty Ranking** ----------			
	Environment 1	***Environment 2***	***Environment 3***	***Overall***
No Cover Crop	3	1	3	1
Cereal Rye	8	10	2	5
Wheat	7	9	5	6
Crimson Clover	2	5	4	2
Hairy Vetch	4	7	6	4
Radish	1	4	8	3
Cereal Rye + Crimson Clover	10	8	1	9
Wheat + Crimson Clover	6	3	10	10
Hairy Vetch + Radish	5	2	9	7
Wheat + Radish + Turnip	9	6	7	8

Table 8. The overall risk-return combinations for cover crop monoculture and mixture treatments.

Cover Crop Treatments	**Average Profit**	**Profit difference‡**	**Risk-return equivalent††**	**Risk-adjusted Compensation†**
	---------- $ ha^{-1} ----------			
No Cover Crop	649.50	-	649.50	-
Cereal Rye	352.41	-297.09	495.47	143.06
Wheat	329.88	-319.62	955.85	625.97
Crimson Clover	502.94	-146.56	910.20	407.26
Hairy Vetch	368.18	-281.32	805.56	437.38
Radish	398.07	-251.44	1,239.29	841.22
Cereal Rye + Crimson Clover	316.35	-333.16	820.48	504.14
Wheat + Crimson Clover	205.10	-444.41	1,601.43	1,396.33
Hairy Vetch + Radish	320.38	-329.12	1,177.42	857.04
Wheat + Radish +Turnip	316.99	-332.51	905.04	588.05
All Cover Crops	345.82	-303.68	1,010.56	664.74
Cover Crop Monocultures	390.82	-258.69	890.77	499.96
Cover Crop Mixtures	287.82	-361.68	1,143.84	856.01

‡Profit difference = (Average profit from cover crop treatment) - (Average profit from no cover crop treatment).
†Risk-adjusted compensation = risk-return equivalent - average profit.
††Risk-return equivalent indicates the returns that a cover crop treatment needs to show to be equivalent to the no cover crop treatment which offers the best risk-return ratio.

at \$316.35 ha^{-1}, and wheat + crimson clover mix at \$205.10 ha^{-1}.

The results were highly variable depending on the agro-climatic conditions of the site. This fact indicated that a "one size fits all" approach is inadequate to make CC decisions and expected returns should not be the only factor to be considered to make the optimal choice of CC species or mix of species. The variability of expected returns, which provides a measure of risk, should also be considered in the decision.

Table 6 and Figure 2 show the implicit trade-offs between expected returns and their variability. This is an important insight to consider when crafting incentives for farmers to adopt CCs and any associated policies. As a group, single-species treatments produced higher returns and lower return variability than mixed species treatments. This implies that incentive programs aiming at encouraging multi-species CCs should provide larger payments than those for single-species programs. Indeed, the Environmental Quality Incentives Program (EQIP) in MS (program code 340) offers a larger incentive for multi-species CCs (\$157.70 ha^{-1}) than single-species CCs (\$128.92 ha^{-1}), with contracts that can extend up to five years. However, our estimates show that these incentives cover less than half the expected losses with respect to the noCC scenario—and even a lower proportion of the risk-return equivalents.

Discussion

The study supported the hypothesis that CC performance and consequent benefits on corn growth, yield, and quality were highly regulated by environmental factors such as precipitation and temperature. The average monthly temperatures, solar radiations, and total precipitation recorded during the study period followed the annual patterns of long-term historical data (1989-2018) recorded by the National Weather Services for MS (https://www.weather.gov/wrh/Climate?wfo=jan). Yang et al. (2020) reported ~60% of annual precipitation accumulated during the offseason (October to April) for 80 consecutive years (1938-2017) in MS, while a lower proportion of the annual rainfall accumulated during the cash crop season, similar with the yearly trends for precipitation reported in the present study. Yang et al. (2020) also classified the historical 80-year rainfall pattern accumulated in the CC growth period (October to April) into three groups, dry (mean = 540 mm), normal (mean = 771 mm), and wet (mean = 1,029 mm). Likewise, the rainfall accumulated during the CC period in the present study was highly

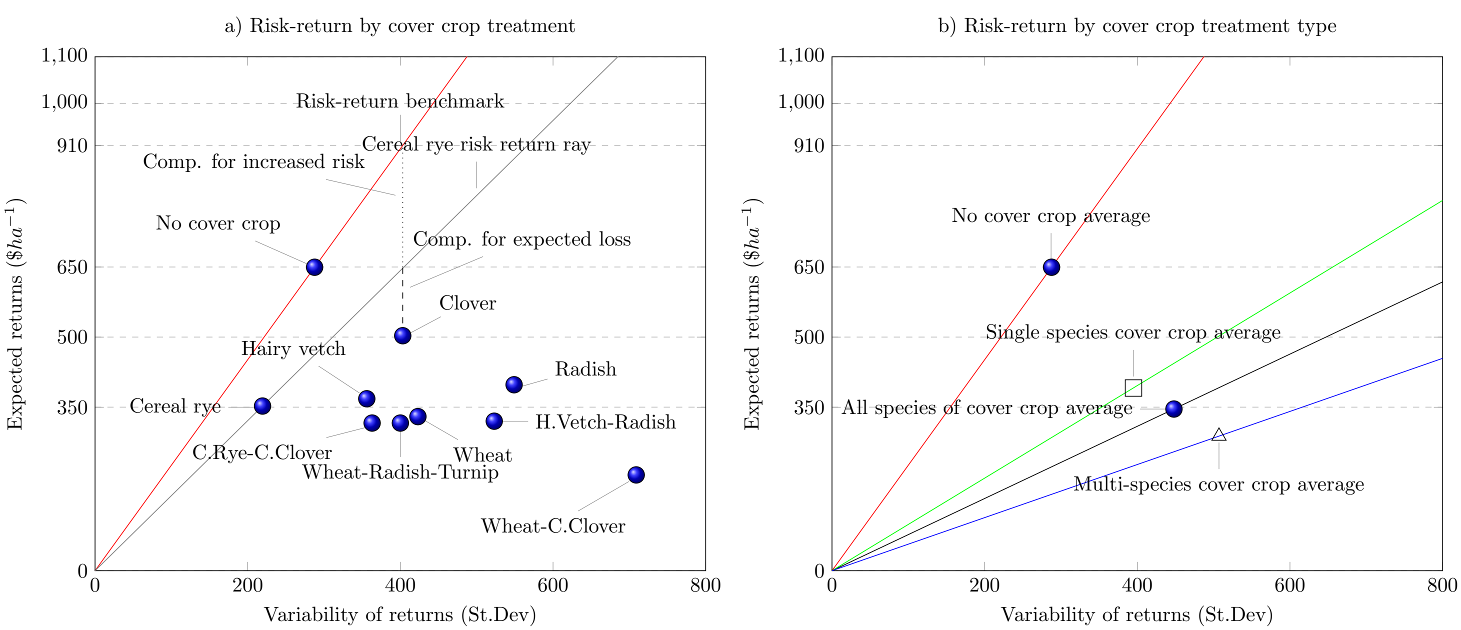

Figure 2. Illustration of farm profits compared to their variability across cover crop monocultures and mixture treatments. Notice: Cereal rye-crimson clover mixture is risk-reducing when compared to the no-cover crop treatment.

variable across the three environments compared to temperature and solar radiation. The CCs season from October to April accumulated 1,157 mm, 795 mm, and 677 mm rainfall in environments 1, 2, and 3, respectively. Cover crops are considered a potential tool for improving soil water dynamics by reducing runoff and subsequently improving soil water storage, thus mitigating the impact of rainfall variability on following crop yield (Yang et al. 2020). However, Yang et al. (2020) concluded that coefficient of variation in corn yields substantially decreases from dry to wet CC periods. Significant improvement in corn yields by CC than noCC treatment was observed only in the dry group that accumulated mean rainfall ≤ 540 mm (Yang et al. 2020). In the present study, rainfall accumulation during the CC period in all three environments was > 540 mm. Hence, the low coefficient of variation in corn yields under high rainfall conditions during the CC seasons in the present study might have attributed to no difference in corn yield between noCC and CC treatments in all three environments. Similarly, other studies have correlated the rainfall amount and CC efficiency in water conservation to improve subsequent cash crop yield (Qi et al. 2011; Martinez-Feria et al. 2016). However, previous studies have mostly simulated the impact of CCs on soil nutrients, water dynamics, and subsequent cash crop productivity using only one type of CC species (Qi et al. 2011; Martinez-Feria et al. 2016; Yang et al. 2020). The present study is unique in that it quantified the impact of different CC species on subsequent cash crops across different rainfall patterns. This study has also recognized the degrees of phenotypic plasticity among CC species to changing weather patterns. In the present study, differential rainfall accumulation during CC season (October to April) among the three environments might have contributed to variable biomass, C and N concentration, C/N ratio, and Total N among treatments. High rainfall during CC season in environment 1 resulted in lower biomass production (hairy vetch and crimson clover) in legumes possibly due to poor stand establishment and root growth, and consequently, lower N and TN which were not statistically different from noCC. Legumes under low rainfall scenarios in environment 3 had significantly higher N and TN than noCC. A controlled environment study conducted by Munyon et al. (2021) reported that specie-specific changes in CC performance to environmental challenges like temperature and drought are likely associated with changes in biochemical and physiological processes. The present study proposes future studies to intensively investigate phenotypic plasticity of CCs in relation to dynamic weather patterns to determine site-specific suitability of CC species.

Drought and excessive rainfall are the second most influential cause of loss in corn production in the U.S., however, the impact can vary with the time of their occurrence relative to the corn growth stage (Li et al. 2019). Rainfall received during the cropping season (May to September) was not different (± 40 mm) among the three environments (averaging 830 mm) but the high variability in monthly total precipitation recorded in corn cropping season, especially July, might have played a significant role in the differential response of corn to CCs among the three environments. The rainfall received in July was lowest in environment 1 (164 mm) and highest in environment 2 (300 mm), although average air temperature was not very different (< 1^{o}C). Environment 2 received greater rainfall during the peak growing period in July, when the corn is usually at tasselling and silking stages (R1 growth stage), than the other two environments, which might have resulted in higher corn yield in environment 2 (averaging 10,599 kg ha^{-1}). Consistent with the present study, the effects of mean precipitation in July positively impacted corn yield across several locations in the U.S. (Thomson 1969; Asghari and Hanson 1984). According to the model developed from 25 years of historical data by USDA's Economic Research Service (ERS), a decline in corn yield below the 25-year average with reductions in July precipitation exceeded yield gain above averages from equal magnitudes of increase in July precipitation (Westcott and Jewison 2013). The average high precipitation in July can also alleviate the determinant effect of high temperatures on corn yield (Hendrick and Scholl 1943; Gilmore and Rogers 1958), perhaps primarily because of the higher water use efficiency of corn in wet summers compared to normal or dry summers (Yang et al. 2020). The recommended rate of N application may not be economically significant to increase grain yield under rainfall deficit conditions in July (Pattey et al. 2001). Corn grain quality parameters had differential sensitivity to weather patterns in the present study. Like previous studies, this study proposes a weather component inclusion in process-based models to accurately access CC benefits and subsequent growth of corn (Pattey et al. 2001; Munyon et al. 2021).

The present study also recognized the innate differences among CCs based on their growth characteristics and benefits to the following corn crop. Consistent with past studies, our study found greater biomass and C/N ratios with monoculture of grasses (wheat or cereal rye) compared to the monoculture of legumes (crimson clover or hairy vetch) (Kaye et al. 2019; Munyon et al. 2021). Also, radish planted as a monoculture CC exhibited higher biomass but a lower C/N ratio than legume monoculture in two out of the three environments. Overall, radish outperformed among CCs and benefits corn yield in a monoculture stand. A CC mix could be more beneficial than single-species CCs in balancing early cover and N scavenging along with fast decomposition of residues and N availability to cash crop (Finney et al. 2016; White et al. 2017). The present study also recognized the weather influence on functionality of different CCs within same groups, rarely studied in the past. For instance, hairy vetch had a ~20% greater N concentration than crimson clover in environment 3, while no significant difference was found between them in the other two environments. The addition of turnip to a mixture of wheat and radish did not significantly improve the parameters measured. Therefore, future studies should explore the significance of CC mixes consisting of different species as high-diversity mixtures are used more often by farmers (Hamilton 2016).

Economic analysis at this early stage indicates that farmers looking to adopt CC practices should expect both financial losses and increased risks in almost every case. Although the long-term benefits of CCs are well documented (Qi et al. 2011; Martinez-Feria et al. 2016; Sanchez 2016), the outcomes of the first few years can strongly encourage or discourage farmers to continue their programs. Consequently, our data suggest that existing incentive programs compensate for approximately half of the expected losses during the earlier stages of adoption. Furthermore, our estimates provide a range of incentive values that could induce adoption of CCs at a faster rate by minimizing farmer concerns about expected losses and increased risks.

Conclusion

The present study provided information on the benefits of growing winter CCs during a fallow period in MS's continuous corn production system. The CC species had innate differences in growth characteristics (biomass, C/N ratios, total N) and subsequently affected corn growth, yield, and quality. However, the functionality of CC treatments was highly influenced by weather patterns among the three environments. Mixed CC treatments exhibited balanced N scavenging and N credits but less stable returns than single-species treatments. The information will be helpful to farmers for the selection of species in a CC mix to balance biomass, N scavenging, and N availability to the following corn crop under variable rainfall patterns. The study also proposes future studies to explore resilience in the functionality of a high-diversity mixture under diverse weather conditions.

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References

Asghari, M. and R.G. Hanson. 1984. Nitrogen, climate, and previous crop effect on corn yield and grain N[1]. *Agronomy Journal* 76(4): 536-542.

Dapaah, H.K. and T.J. Vyn. 1998. Nitrogen fertilization and cover crop effects on soil structural stability and corn performance. *Communications in Soil Science and Plant Analysis* 29(17-18): 2557-2569.

Duvick, D.N. 2005. Genetic progress in yield of United States maize (*Zea mays* L.). *Maydica* 50(3): 193-202.

Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. *Agronomy Journal* 108(1): 39-52.

Gentry, L.F., M.L. Ruffo, and F.E. Below. 2013. Identifying factors controlling the continuous corn yield penalty. *Agronomy Journal* 105(2): 295-303.

Gilmore Jr., E.C. and J.S. Rogers. 1958. Heat units as a method of measuring maturity in corn. *Agronomy Journal* 50(10): 611-615.

Gregory, E. 2020. 2020 Row-Crop Returns Summary. Publication Number: P3422. Mississippi State University Extension Service, Starkville, MS. Available at: http://extension.msstate.edu/publications/2020-row-crop-returns-summary. Accessed February 25, 2022.

Hamilton, A.V. 2016. Maximizing the on-farm benefits of cover crops: Comparing management intentions and ecosystem service provisioning. MS Thesis, The Pennsylvania State University, State College, Pennsylvania.

Hendrick, W.A. and J.C. Scholl. 1943. Techniques in Measuring Joint Relationship. The Joint Effects of Temperature and Precipitation on Crop Yield. North Carolina Agricultural Experiment Station Technology Bulletin 74.

Kaye, J., D. Finney, C. White, B. Bradley, M. Schipanski, M. Alonso-Ayuso, M. Hunter, M. Burgess, and C. Mejia. 2019. Managing nitrogen through cover crop species selection in the U.S. mid-Atlantic. *PloS ONE* 14(4): e0215448.

Li, Y., K. Guan, G.D. Schnitkey, E. DeLucia, and B. Peng. 2019. Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. *Global Change Biology* 25(7): 2325-2337.

Martinez-Feria, R.A., R. Dietzel, M. Liebman, M.J. Helmers, and S.V. Archontoulis. 2016. Rye cover crop effects on maize: A system-level analysis. *Field Crops Research* 196: 145-159.

Mississippi State University (MSU). 2016. Delta Agricultural Weather Center. Mississippi State University Extension Service, Stoneville, MS. Available at: http://deltaweather.extension.msstate.edu/. Accessed February 25, 2022.

Mississippi State University (MSU). 2021. MSU Corn Hybrid Demonstration Program. Mississippi State University Extension Service, Starkville, MS. Available at: http://www.mississippi-crops.com/wp-content/uploads/2021/10/CornDemo_Summary_2021.pdf. Accessed February 25, 2022.

Mississippi State University (MSU). 2022. Budget Report 2022. Department of Agricultural Economics. Available at: https://www.agecon.msstate.edu/whatwedo/budgets.php. Accessed February 25, 2022.

Munyon, J.W., R. Bheemanahalli, C.H. Walne, and K.R. Reddy. 2021. Developing functional relationships between temperature and cover crop species vegetative growth and development. *Agronomy Journal* 113(2): 1333-1348.

Pattey, E., I.B. Strachan, J.B. Boisvert, R.L. Desjardins, and N.B. McLaughlin. 2001. Detecting effects of nitrogen rate and weather on corn growth using micrometeorological and hyperspectral reflectance measurements. *Agricultural and Forest Meteorology* 108(2): 85-99.

Peterson, T.A. and G.E. Varvel. 1989. Crop yield as affected by rotation and nitrogen rate. III. Corn. *Agronomy Journal* 81(5): 735-738.

Porter, P.M., J.G. Lauer, W.E. Lueschen, J.H. Ford, T.R. Hoverstad, E.S. Oplinger, and R.K. Crookston. 1997. Environment affects the corn and soybean rotation effect. *Agronomy Journal* 89(3): 442-448.

Qi, Z., M.J. Helmers, R.W. Malone, and K.R. Thorp. 2011. Simulating long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics for a corn-soybean crop system. *Transactions of the ASABE* 54(5): 1575-1588.

Quintana-Ashwell, N., D.M. Gholson, L.J. Krutz, C.G. Henry, and T. Cooke. 2020. Adoption of water-conserving irrigation practices among row-crop growers in Mississippi, USA. *Agronomy* 10(8): 1083.

Sanchez, I.I. 2016. Evaluation of winter cover crops on nutrient cycling, soil quality and yield for production systems in the Mid-South. Master's Thesis, Louisiana State University, Baton Rouge, LA.

Sawyer, J.E. and G.W. Randall. 2008. Nitrogen rates. In: UMRSHNC (Upper Mississippi River Sub-basin Hypoxia Nutrient Committee). *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*, L.G. Bundy, A.P. Mallarino, and L.W. Good (Eds.). ASABE, St. Joseph, MI, pp. 59-71.

Stanger, T.F. and J.G. Lauer. 2008. Corn grain yield response to crop rotation and nitrogen over 35 years. *Agronomy Journal* 100(3): 643-650.

Tang, Q., G. Feng, D. Fisher, H. Zhang, Y. Ouyang, A. Adeli, and J. Jenkins. 2018. Rain water deficit and irrigation demand of major row crops in the Mississippi Delta. *Transactions of the ASABE* 61(3): 927-935.

Thompson, L. 1969. Weather and technology in the production of corn in the U.S. corn belt. *American Society of Agronomy* 14(3): 453-456.

Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. 1996. Winter legume cover crop benefits to corn: Rotation vs. fixed-nitrogen effects. *Agronomy Journal* 88(4): 527-535.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA NASS). 2021a. 2020 State Agriculture Overview. Available at: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=MISSISSIPPI. Accessed February 25, 2022.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA NASS). 2021b. Mississippi Corn Historical Data. Available at: https://quickstats.nass.usda.gov/#132E3E85-0D93-3D6C-8C47-B429E27B8CE0. Accessed February 25, 2022.

U.S. Grain Council. 2021. *Corn Harvest Quality Report*. Available at: https://grains.org/wp-content/uploads/2021/12/2021-22-USGC-Corn-Harvest-Report.pdf. Accessed February 25, 2022.

Wang, H. and A. Ortiz-Bobea. 2019. Market-driven corn monocropping in the U.S. Midwest. *Agricultural and Resource Economics Review* 48(2): 274-296.

Westcott, P. and M. Jewison. 2013. Weather Effects on Expected Corn and Soybean Yields. United States Department of Agriculture, Economic Research Service, Feed Outlook No. FDS-13G-01. Available at: https://www.ers.usda.gov/publications/pub-details/?pubid=36652. Accessed February 25, 2022.

White, C.M., S.T. DuPont, M. Hautau, D. Hartman, D.M. Finney, B. Bradley, J.C. LaChance, and J.P. Kaye. 2017. Managing the trade-off between nitrogen supply and retention with cover crop mixtures. *Agriculture, Ecosystems & Environment* 237: 121-133.

Wilhelm, W. and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. *Agronomy Journal* 96(2): 425-432.

Yang, W., G. Feng, J.J. Read, Y. Ouyang, J. Han, and P. Li. 2020. Impact of cover crop on corn-soybean productivity and soil water dynamics under different seasonal rainfall patterns. *Agronomy Journal* 112(2): 1201-1215.

Supplementary Data

Table S1. Soil properties at the three sites used in this study.

Soil Properties	Units	Environment 1 Stoneville Fall 2019	Environment 2 Stoneville Fall 2020	Environment 3 Starkville Fall 2020
Cation Exchange Capacity	cmol (+) kg^{-1}	9.13	7.76	7.79
pH_s		6.57	6.23	6.25
Organic Matter	g kg^{-1}	8.6	9.3	7.7
Bulk Density	g cm^{-3}	1.38	1.37	1.46
Nitrogen Release	kg ha^{-1}	37.26	40.35	35.02
NH_4-N	mg kg^{-1}	5.2875	5.5875	5.475
NO_3-N	mg kg^{-1}	<0.5	1.37	1.4
Bray I Phosphorus	mg kg^{-1}	16.375	18.625	61.25
Phosphorus*	mg kg^{-1}	17.13	20.88	40.5
Potassium*	mg kg^{-1}	106.38	102.75	143.38
Calcium*	mg kg^{-1}	1166.88	971	928
Magnesium*	mg kg^{-1}	222.5	158.13	169.5
Sulphur*	mg kg^{-1}	9.125	4.25	4.25
Boron*	mg kg^{-1}	0.25	0.23	<0.2
Sodium*	mg kg^{-1}	37.5	17.13	10.88
Aluminium*	mg kg^{-1}	322.75	311.63	298.75
Iron*	mg kg^{-1}	145.5	155.13	208.75
Manganese*	mg kg^{-1}	23	23.13	27.13
Copper*	mg kg^{-1}	1.27	0.96	0.94
Zinc*	mg kg^{-1}	1.53	1.06	1.18

*Mehlich III extractable