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Short-run net returns to a cereal rye cover crop mix in a midwest corn–soybean rotation

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Abstract

Unsubstantiated economic returns are a major contributor to producers' reluctance to adopt cover crops. The objective of this study is to evaluate the direct short-run net returns to the producer of implementing a predominantly cereal rye (*Secale cereal* L.) cover crop mix into a Midwest corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation. Experimental agronomic data from field experiments in Lexington, IL, are used to calibrate economic simulations of the costs and benefits of cover crop adoption. Results indicate that net returns to cover crops, including current cost-share payments, were routinely negative. Returns to the soybean phase of the rotation were higher than corn given that the cover crop significantly reduced corn yield in 1 of 2 yr but did not significantly affect soybean yield. A scenario where cover crop biomass was hypothetically harvested and valued as a livestock feedstuff increased returns. However, further research is needed to validate the agronomic assumptions underlying this scenario. Finally, the breakeven subsidy that would make the producer indifferent to planting cover crops was estimated to be US\$13–\$23 kg^{-1} of nitrate saved from leaving the field each year (or approximately \$195–\$345 ha^{-1}). This is higher than current cost-share payments (\$140 ha^{-1}). In the short-run, incentivizing producers to adopt cover crops will likely require (i) improved recommendations for cover crop best management practices to eliminate current downside risk and (ii) higher cost-share payments or established markets to internalize cover crop benefits that accrue to society.

1 | INTRODUCTION

Planting cover crops in rotation between regular cash crop production periods is a practice that has been around for many years (Kell & McKee, 1936). However, the potential for cover crops to decrease agricultural nutrient losses and improve soil health has recently catapulted a reemergence of interest in the practice. Yet, for all of the attention surrounding cover crops, implementation remains sparse. According to the 2017 U.S. Census of Agriculture, cover crops were planted on 3% of harvested cropland hectares in Illinois, 8% in Indiana, and 4% in Iowa (U.S. Department of Agriculture, National Agricultural Statistical Service [USDA NASS], 2019).

Several recent studies have sought to identify why producers are reluctant to adopt cover crops (Arbuckle &

Abbreviation: CDF, cumulative density function.

Roesch-McNally, 2015; Conservation Technology Information Center [CTIC], 2017; Dunn et al., 2016; Roesch-McNally et al., 2017). Producers commonly identify matters such as a lack of familiarity with the practice, cover crop species selection, and time/labor constraints as barriers to cover crop adoption. However, economic return, or lack thereof, was the item most commonly selected (82% of respondents) as a major or minor concern to using cover crops (CTIC, 2017). This is not surprising given that economic returns to cover crop systems are largely unsubstantiated. Further, quantifying the direct and indirect costs and benefits associated with cover crop adoption in the short and long run can be complex (Bergtold, Ramsey, Maddy, & Williams, 2017; Roth, Ruffatti, O'Rourke, & Armstrong, 2018; Snapp et al., 2005).

Results from previous studies evaluating economic returns to cover crop adoption are mixed with respect to their profitability. These inconsistencies can be attributed to a variety of factors, including differences in the initial motivation for planting the cover crop, differences in production systems and cover crop management, and differences in geographies. As a result, Plastina, Liu, Sawadgo, Miguez, and Carlson (2018b) concluded that generic agronomic and economic recommendations should be avoided in favor of more regionalized and cover crop species-specific recommendations.

To date, little work has been done to quantify the direct short-run economic returns to producers of growing cover crops in Midwest row crop agriculture. The Midwest is an important corn and soybean production region and there is increasing attention on Midwest row crop agriculture as a major nonpoint source of nitrate pollution (Robertson & Saad, 2013). The work that has been done in the region has considered a variety of different approaches to quantifying cover crop costs and benefits. For example, Pratt, Tyner, Muth, and Kladivko (2014) and Roth et al. (2018) both provide estimates of the costs and benefits of cover crop adoption. In addition to conventional costs and benefits, including cover crop establishment, termination, and cash crop yield impacts, these authors also attempt to place a monetary value on additional cover crop benefits, such as increased soil organic matter, reduced compaction, reduced soil erosion, and reduced nitrate loading from subsurface drainage. While these aspects of cover adoption are all well established, they are commonly characterized as "indirect benefits" (Bergtold et al., 2017; Snapp et al., 2005). That is, they are positive externalities that accrue to landowners or society in general, but they are difficult to monetize as a line item on the producer's budget. The method of establishing value to be placed on measurable societal/environmental benefits, such as reduced nitrate loading and cover crop N scavenged, could be used as framework for future policy, but they are not directly available to producers currently, given the lack of an established market for cover crop benefits that accrue to society (Bergtold et al., 2017).

Core Ideas

- Expected net returns were consistently negative.
- Hypothetically harvesting and valuing cereal rye biomass increased net returns.
- Uncertain cash crop yield impacts are the biggest driver of cereal rye net returns.
- Current cost-share payments will not incentivize widespread cereal rye adoption.

Others have sought to quantify the economic costs and benefits of cover crop adoption using secondary producer data (Anderson, 2019; Monast, Sands, & Grafton, 2018; Plastina et al., 2018b, Plastina, Liu, Sawadgo, Miguez, & Carlson, 2018c; Plastina, Liu, F., W., & Carlson, 2018a). While these values serve as an informative baseline, reliance on producer records and expertise does not prove a causal relationship between cover crop adoption and reported cost and yield impacts (Monast et al., 2018). Further, the authors themselves acknowledge inherent biases that limit the representativeness of these results, including sample selection bias (Plastina et al., 2018a, 2018b, 2018c) and small sample sizes (Plastina et al., 2018b, 2018c). Therefore, there continues to be a lack of information on the net returns to the farmer from incorporating cover crops into a Midwest corn–soybean rotation.

The objective of this study is to evaluate the direct net returns of implementing a predominantly cereal rye cover crop mix into a Midwest corn–soybean rotation. Cereal rye is the most commonly selected cover crop among producers in the Midwest (CTIC, 2017), due to its low cost and ease of establishment after cash crop harvest and ability to enhance soil health and water quality. Primary experimental agronomic data collected from field experiments are used to parameterize distributions of the costs and benefits of cover crop adoption for a baseline scenario. In addition, experimental data are coupled with several assumptions based on the literature to characterize an additional scenario where cover crop biomass is hypothetically harvested and valued as a livestock feedstuff. These distributions are used as part of a stochastic Monte Carlo simulation to generate distributions of the net impact of cover crop adoption on the direct returns to the producer.

It is important to note that this study specifically focuses on direct short-run impacts. That is, we do not consider what has been previously characterized as indirect benefits (Bergtold et al., 2017; Snapp et al., 2005). Instead, we focus specifically on costs and returns that are directly measurable on the farmers budget. In addition, many of the soil health benefits associated with cover cropping are purported to accrue in the long run. Previous studies, such as Boyer, Lambert, Larson, and Tyler (2018) and Harmon, Boyer, Lambert, Larson, and Tyler

(2018), have considered the adoption of cover crops as a long-run investment decision using data from continuous long-run cover crop experiments. However, the experiment used in this study has only been conducted for 4 yr, limiting us to strictly short-run impacts. While this potentially overlooks benefits that will accrue in the longer run, the direct short-run impacts of cover crops on producer returns have implications for adoption decisions and policy design today.

Finally, the unique design of the agronomic experiment also allows us to link estimated producer returns with empirical estimates of the environmental/societal benefit of improved water quality through a breakeven subsidy kg^{-1} of abated nitrate load. That is, in the case that direct cover crop benefits do not offset the costs, we estimate how much value society would have to place on each kilogram of the reduction in nitrate loading to make the producer just indifferent between planting and not planting the cover crop. Although this value is not currently available to the producer, the idea of putting "a dollar value on the nitrate saved" is one that is commonly discussed (Roesch-McNally et al., 2017, p. 327). Therefore, by providing estimated distributions of producer returns and linking those returns with empirical measures of improved water quality, this research has important implications for producers, policymakers, and those influencing producer decision making related to cover crop adoption.

2 | MATERIALS AND METHODS

2.1 | Agronomic

Cash crop yield, cover crop aboveground biomass, cover crop aboveground biomass N, and annual total subsurface drainage nitrate loading data used in this study were produced in field experiments conducted during harvest years 2015–2018 in Lexington, IL (40.64° N, 88.72° W) at the Illinois State University Nitrogen Management Research Field Station. Soils are Drummer (fine-silty, mixed, superactive, mesic Typic Endoaquolls), El Paso (fine-silty, mixed, superactive, mesic Typic Endoaquolls), and Hartsburg (fine-silty, mixed, superactive, mesic Typic Endoaquolls) silty clay loams, all of which are poorly drained Mollisols with slopes of 0–2%, and are common in central Illinois region. These plots had previously been in an 8-yr rotation of strip-tilled corn and no-till soybean, and this experiment was a continuation of these cultural practices. According to the 2017 U.S. Census of Agriculture, approximately 43% of Illinois cropland was in some sort of conservation tillage (excluding no-till), 29% was in no-till, and 28% was in conventional tillage (USDA NASS, 2019). Additional context for the tillage practices used in this experiment can be found in Claassen, Bowman, McFadden, Smith, and Wallander (2018).

The treatment structure of the experiment was a 2 × 2 factorial. Treatments were arranged in a randomized complete block design with three replications. Each plot was 0.65 ha. Two N management systems, fall dominated (70% fall, 30% spring N application) and spring dominated (20% fall, 80% spring N application), were each applied to treatments with and without cover crops. The N timing treatment (fall vs. spring dominated) did not significantly influence any of the outcomes in this study. For this reason, the N timing treatment is ignored, and the experiment is analyzed as a one-way treatment with two levels, with and without cover crops, with six replications.

Cover crop treatments received a cover crop mix that was an 8% daikon radish [*Raphanus sativus* (L.)] and 92% cereal rye blend calculated by weight. The daikon radish provides rapid fall N uptake and biomass production and then winterkills. Cereal rye grows slower in the fall with some N uptake but is winter hardy allowing for rapid N uptake and biomass production in the spring. Cover crops were interseeded using a Hagie STS12 modified with an air seeding box at a rate of 84 kg ha^{-1} in late August and early September. Cover crop treatments were first established in September 2014 and cover crops are grown in the same plots each year. Spring termination of the cereal rye occurred 2–3 wk prior to planting using 2.34 L ha^{-1} glyphosate [N-(phosphonomethyl) glycine].

Spring aboveground cereal rye biomass sampling was conducted for each cover crop treatment prior to termination using a modified version of Dean and Weil's (2009) method. Cover crop biomass samples were oven dried at 60°C and ground to pass through a 1-mm sieve. The dry weight of each sample was used to calculate total cover crop biomass. Dried cover crop biomass was also analyzed for percent total N to determine the total cover crop N uptake.

Each plot was individually tile drained with its own independent controlled drainage structure and automated tile water monitoring system. The system collected up to a 200-ml sample every hour and formed a 600 ml composite every 3 h. Each plot hydrograph was analyzed and sampled to determine nitrate flow-weighted concentration and loading through subsurface drainage. For this study, annual total nitrate load is the cumulative annual load for the hydrologic year, where the hydrologic year was based on the average cover crop planting date. For example, total annual nitrate load for the 2015 cash crop harvest year includes total annual nitrate load from September 2014 through August 2015.

In corn years, the N rate in this study was the suggested maximum net return to N for central Illinois calculated by the Corn Nitrogen Rate Calculator of 224 kg ha^{-1} (Corn Nitrogen Rate Calculator, 2019). The N sources used to reach this application rate were anhydrous ammonia and diammonium phosphate (DAP). All fall anhydrous was applied with a N inhibitor, and application occurred only once soil temperatures fell below 10°C. All spring applications occurred

TABLE 1 Monthly average ambient air temperature and total monthly precipitation

Month	Avg. ambient air temperature						Total precipitation					
	2014	2015	2016	2017	2018	30 yr Avg.	2014	2015	2016	2017	2018	30 yr Avg.
	°C						mm					
Jan.		−4.6	−3.6	−1.0	−5.0	−3.8		39.9	15.7	37.6	7.6	57.5
Feb.		−8.3	−.4	3.9	−1.4	−2.1		13.7	19.1	13.0	85.1	51.8
Mar.		2.5	7.7	4.7	2.0	4.3		22.4	74.7	85.1	58.2	63.3
Apr.		11.4	10.5	13.1	6.3	10.9		60.2	67.1	95.5	39.6	90.7
May		18.0	16.6	16.0	21.4	17.1		131.6	102.9	73.9	35.1	108.1
June		21.5	23.2	22.6	23.2	22.2		179.1	102.4	95.0	163.3	100.5
July		22.3	23.2	23.15	22.2	23.9		139.2	157.0	32.8	60.7	98.3
Aug.		21.2	23.2	19.83	22.5	22.9		104.1	153.4	109.8	80.0	94.2
Sept.	17.7	20.3	20.5	18.9	20.4	18.8	98.8	69.1	78.5	37.6	36.6	83.4
Oct.	11.3	12.2	14.6	13.6	11.3	12.0	104.1	45.7	42.9	62.0	120.7	86.1
Nov.	0.6	7.0	7.3	4.5	1.1	4.9	41.9	100.1	66.0	39.1	37.8	78.2
Dec.	−0.1	4.2	−2.4	−2.9	0.4	−1.8	20.1	151.6	21.6	1.0	68.1	60.6

Note: Source: In-field weather station.

following corn planting as a side-dress anhydrous application near the V6 growth stage.

An in-field weather station was used to collect weather data. Monthly average ambient air temperature and monthly total precipitation are reported in Table 1 for each year of the experiment along with the 30-yr monthly averages.

Analysis of variance was performed using PROC GLIMMIX in SAS 9.4 (SAS Institute, 2016). Given that only one crop (corn or soybean) was grown in each year, separate models were estimated for corn and soybean to allow for treatment × year interactions. Corn and soybean yield, aboveground cover crop biomass, aboveground cover crop biomass N uptake, and annual total subsurface drainage nitrate load were the dependent variables and treatment, year, and treatment × year interactions were fixed effects. Homogeneity of variance and normality assumptions were tested. Violations of the homoscedasticity assumption are corrected using the EMPIRICAL statement to estimate heteroskedasticity consistent standard errors (SAS Institute, 2016). Violations of the normality assumption are corrected using a log transformation of the dependent variable using the LINK function. Least-squares means for each treatment are calculated and compared for statistical differences.

Data were also used to parameterize distributions of these variables for Monte Carlo simulations of net returns. Triangular distributions were used for all stochastic agronomic variables. Triangular distributions are often used in such cases with limited data because only the minimum, maximum, and most likely values are needed (Pratt et al., 2014). Observed minimums and maximums were used to calibrate the distributions, and the most likely value was computed using the formula for the mode of a triangular distribution, mode = 3 × mean – (minimum + maximum) (Back, Boles, & Fry, 2000).

2.2 | Economic

A partial budgeting approach is used to estimate distributions of net returns by isolating the costs and revenues that change with the introduction of cover crops. Conventional economic considerations including cover crop establishment and termination, as well as cash crop yield impacts, are considered. In addition, the unique design of the field experiment allows us to quantify several additional aspects of the cover crop system.

Stochastic net returns are evaluated for three scenarios. In the baseline scenario, net returns are:

$$\widetilde{NR}_{Baseline} = \Delta\tilde{Y}^{l}_{corn} \times \tilde{P}_{corn} - EstC_{cc} - TermC_{cc} + CS \quad (1)$$

where $\Delta\tilde{Y}^{l}_{corn}$ is stochastic change in corn yield from planting cover crops when cover crop biomass is left (l) in the field, $\tilde{P}_{corn}$ is stochastic corn price, $EstC_{cc}$ is cover crop establishment cost (i.e., seed and planting), $TermC_{cc}$ is cover crop termination cost (i.e., additional herbicide costs above normal pre-plant burndown application [Plastina et al., 2018a]), and CS is a potential cost-share payment based on Environmental Quality Inventives Program (EQIP) payments (U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS], 2019).

Potential fertilizer cost savings associated with nitrogen cycling from the cover crop residue back to the soil for cash crop use are commonly discussed as a potential benefit of a cover crop system (Bergtold et al., 2017; Pratt et al., 2014; Roth et al., 2018; Snapp et al., 2005). However, surveys conducted by Plastina et al. (2018a), 2018c) indicate that producers rarely credit their N program following a cover crop. Therefore, in the second scenario, potential fertilizer cost savings are added to the net return equation:

$$\widetilde{NR}_{N\,Saving} = \Delta\tilde{Y}^{l}_{corn} \times \tilde{P}_{corn} - EstC_{cc} - TermC_{cc} + \left(\tilde{N}_{cc} \times \tilde{N}_{avail} \times \tilde{P}_{n}\right) + CS \quad (2)$$

where $\tilde{N}_{cc}$ is stochastic aboveground cover crop biomass nitrogen uptake, $\tilde{N}_{avail}$ is stochastic plant available N, or the effective percentage of aboveground cover crop biomass N that is available to the following cash crop, and $\tilde{P}_{n}$ is stochastic N price. Although research focused on understanding the timing of cover crop N mineralization is ongoing, it appears as though only a small portion of the mineralized cover crop nitrogen is actually available to the subsequent cash crop given the nature of the cover crop residue in terms of C/N ratio (Bergström & Kirchmann; 2004; Ranells & Wagger, 1997).

Finally, previous literature has also suggested that valuing cover crop biomass as a livestock feedstuff may increase the likelihood of positive economic returns (Crowley, Van Es, Gomez, & Ryan, 2018; Gabriel, Garrido, & Quemada, 2013; Milliron, Karsten, & Beegle, 2019; Plastina et al., 2018a, 2018c). Therefore, the third scenario is one in which aboveground cover crop biomass is hypothetically harvested and valued as a livestock feedstuff:

$$\widetilde{NR}_{CC\,Biomass} = \Delta\tilde{Y}^{h}_{corn} \times \tilde{P}_{corn} - EstC_{cc} + \left(\tilde{Y}_{cc} \times \tilde{P}_{cc}\right) - HarvC_{cc} \quad (3)$$

where $\Delta\tilde{Y}^{h}_{corn}$ is stochastic change in corn yield from planting cover crops when cover crop biomass is harvested (h), $\tilde{Y}_{cc}$ is stochastic cover crop aboveground biomass, $\tilde{P}_{cc}$ is stochastic cover crop biomass price, or the value of the cover crop as a livestock feedstuff, and $HarvC_{cc}$ is cover crop harvest cost (i.e., mowing, raking, and baling). It is important to point out that while empirical measures of cover crop biomass were collected in the agronomic experiment, there were no treatments where cover crop biomass was actually harvested from the entire plot. Therefore, cash crop yield impacts following cover crop biomass harvest are based on assumptions informed by the literature. Notice also that fertilizer cost savings in Eq. [2] are not included in Eq. [3]. By removing the cover crop biomass from the field, the producer forgoes the potential fertilizer cost savings associated with aboveground cover crop N captured in Eq. [2]. $TermC_{cc}$ is also not included in Eq. [3] given that harvest of the cover crop in the reproductive growth stage is assumed to terminate growth. Finally, CS is not included in Eq. [3] given that harvesting of cover crops generally inhibits the producer from qualifying for EQIP cost-share payments (M. Eastman, NRCS, personal communication, 2019).

All other costs and revenues are assumed to not change with the implementation of cover crops. However, it is important to point out that there are likely additional indirect costs associated with harvesting cover crop biomass that are not accounted for in this analysis. Mainly, the cost of hauling, storing, and marketing harvested cover crop biomass are not accounted for here given that these costs will vary widely from one farm to the next. When interpreting the results for this scenario, it is important for individual producers to consider how these costs may influence the returns on their farm.

Scenarios one through three are also evaluated for soybean by substituting stochastic changes in soybean yield from planting cover crops, $\Delta\tilde{Y}^{l}_{bean}$ and $\Delta\tilde{Y}^{h}_{bean}$, and stochastic soybean price, $\tilde{P}_{bean}$. We also evaluate net returns to a 50–50 corn–soybean rotation by weighting the relevant returns for each crop by .5.

Corn and soybean price distributions were calibrated using USDA monthly Illinois corn and soybean price data from the last 10 yr, 2009–2018 (USDA-NASS, 2019). Data are fit to a lognormal distribution. (Table 2). Anhydrous ammonia price was used as the price of N for the fertilizer cost savings scenario in this study. Ten years of monthly prices were collected and use to calibrate a lognormal distribution (U. S. Department of Agriculture, Agricultural Markeing Service [USDA AMS], 2019) (Table 2). Finally, the PennState Extension (2019) Feed Value Calculator was used to generate 10 yr of monthly cereal rye biomass prices as a function of historical corn and soybean meal prices. These prices were also fit to a lognormal distribution (Table 2). The correlation feature in @Risk was used to maintain the observed correlations among these four prices (corn, soybean, fertilizer, and cereal rye biomass) in the simulation (Palisade Corporation, 2016). @Risk's correlation feature uses a "distribution-free" approach based on Spearman rank order correlations (Iman & Conover, 1982). First, randomly generated rank scores are generated for each variable and iteratively rearranged to achieve the desired correlations. Second, random numbers are generated for each variable and paired with the corresponding rank score resulting in random variables with the desired underlying Spearman rank order correlations. Simulations were set up and run in @Risk with 5000 iterations (Palisade Corporation, 2016).

Deterministic costs for cover crop establishment, termination, and harvest operations are based on as-applied rates and relevant costs (Table 2). Cover crop establishment costs include seed cost of \$1.04 kg^{-1} and air seeding cost of \$30 ha^{-1}. Cover crop termination costs include glyphosate cost of \$6 L^{-1}. Again, given the assumption that all hectares without cover crops receive a pre-plant burndown herbicide application (Plastina et al., 2018a), only the additional herbicide cost above the pre-plant burndown rate is considered in the partial budgeting approach. Harvesting cover crop biomass includes costs for mowing, raking, and baling of \$130 ha^{-1}. Finally, a fixed cost-share payment based on 2018 Illinois EQIP cover crop mix rate of \$140 ha^{-1} is applied to the relevant scenarios (USDA NRCS, 2019).

TABLE 2 Parameter values for Monte Carlo simulation of net returns to cover crops

Variable	Unit	Deterministic value	Parameters for triangular distributions of stochastic agronomic variables: Minimum	Most likely	Maximum	Parameters for lognormal distributions of stochastic price variables: Mean	SD
Distributions based on results from agronomic experiment							
Corn yield change cover crop biomass left in the field ($\Delta\tilde{Y}^{l}_{corn}$)	Mg ha^{-1}		−3.46	−1.58	.44		
Soybean yield change cover crop biomass left in the field ($\Delta\tilde{Y}^{l}_{bean}$)	Mg ha^{-1}		−.61	−0.30	.45		
Cover crop nitrogen uptake ($\tilde{N}_{cc}$)	kg ha^{-1}		5.63	42.83	83.42		
Cover crop biomass ($\tilde{Y}_{cc}$)	Mg ha^{-1}		0.15	1.11	2.51		
Total annual nitrate load change cover crop biomass left in the field (ΔN_{load})	kg ha^{-1}yr^{-1}		−50.35	−15.02	2.06		
Distributions based on informed assumptions							
Corn yield change cover crop biomass harvested ($\Delta\tilde{Y}^{h}_{corn}$)	Mg ha^{-1}		−3.46	0.00	0.44		
Soybean yield change cover crop biomass harvested ($\Delta\tilde{Y}^{h}_{bean}$)	Mg ha^{-1}		−0.61	0.00	0.45		
Plant available nitrogen ($\tilde{N}_{avail}$)	%		0.00	0.10	0.15		
Secondary data							
Corn price ($\tilde{P}_{corn}$)	\$ Mg^{-1}					138.00	9.30
Soybean price ($\tilde{P}_{bean}$)	\$ Mg^{-1}					331.00	52.85
Nitrogen price ($\tilde{P}_{n}$)	\$ kg^{-1}					0.56	0.13
Cereal rye cover crop biomass feedstuff price ($\tilde{P}_{cc}$)	\$ Mg^{-1}					135.00	11.63
Cover crop establishment cost ($EstC_{cc}$)	\$ ha^{-1}	117.00					
Cover crop termination cost ($TermC_{cc}$)	\$ ha^{-1}	16.00					
Cover crop harvest cost ($HarvC_{cc}$)	\$ ha^{-1}	130.00					
Cost-share payment	\$ ha^{-1}	140.00					

2.3 | Breakeven subsidy per kilogram of abated nitrate load

Previous research has established the impact of production agriculture on the environment and society in general (e.g., Tegtmeier & Duffy, 2004). Specifically, the impact on water quality outcomes is well documented given increasing attention on N leaching from agricultural fields as a contributor to the hypoxic zone in the Gulf of Mexico (Alexander, Smith, & Schwarz, 2000; Keeler et al., 2012, 2016; Kladivko et al., 2014; Robertson & Saad, 2013; Roley, Tank, Tyndall, & Witter, 2016; Ruffatti, Roth, Lacey, & Armstrong, 2019). Therefore, we attempt to link direct producer returns with the indirect water quality benefits provided by the cover crop through a breakeven subsidy kg^{-1} of abated nitrate load.

Specifically, total annual tile nitrate load for each plot in the agronomic experiment is used to quantify the environmental/societal benefit associated with improved water quality from reduced nitrate loading. Previous research has routinely validated water quality improvements from cover crops (e.g., Feyereisen, Wilson, Sands, Strock, & Porter, 2006; Kaspar, Jaynes, Parkin, Moorman, & Singer, 2012; Ruffatti et al., 2019). However, attempts to monetize this societal benefit have fallen short given the difficulty of valuing these kilograms of N without an established market for cover crop benefits that accrue to society (Bergtold et al., 2017). Therefore, instead of attempting to value the reduction in nitrate loading directly, we determine how much value society would have to place on each kilogram of nitrate saved from leaving the field each year in order for the cover crop to break even from the producer's perspective. That is, the breakeven subsidy kg^{-1} of abated nitrate load ($\tilde{S}_{BE}$) is:

$$\tilde{S}_{BE} = \begin{cases} \frac{\widetilde{NR}-CS}{\Delta\tilde{N}_{load}} & if\ \widetilde{NR} - CS < 0\ and\ \Delta\tilde{N}_{load} < 0 \\ 0 & otherwise \end{cases} \quad (4)$$

where $\Delta\tilde{N}_{load}$ is stochastic change in total annual nitrate load. Notice, for the purpose of estimating $\tilde{S}_{BE}$ the EQIP cost-share payment (CS) is subtracted from the estimated net returns where relevant. The purpose of EQIP payments is to provide financial assistance to agricultural producers to deliver environmental benefits such as improved water quality (USDA NRCS, 2019). Thus, to avoid redundancy in the estimation of the societal value provided by cover crops, current cost-share payments are subtracted from scenarios where they were originally included for the estimation of the breakeven subsidy kg^{-1} of abated nitrate load.

3 | RESULTS AND DISCUSSION

3.1 | Agronomic

3.1.1 | Corn yield

A significant treatment × year interaction was identified in the corn yield ANOVA model (Table 3). Least-squares mean corn yield for each treatment and year are reported in Table 4. Results indicate that the presence of cover crops significantly reduced corn yield in 2017, but not in 2015. The spring of 2017 was characterized by warmer than average temperatures and above average precipitation (Table 1), resulting in ideal growing conditions for the cereal rye cover crop. While previous literature is mixed with respect to the impact of cover crops on corn yield, our finding that cereal rye before corn may reduce corn yield in some years is certainly not unique (Hunter et al., 2019; Krueger, Ochsner, Porter, & Baker, 2011; Marcillo & Miguez, 2017; Singer & Kohler, 2005). Adaptive N fertilizer management and improved cover crop management, including species selection, the timing of cover crop termination, cover crop biomass removal, etc., may mitigate potential cash crop yield impacts. However, these management adaptations are also generally associated with additional costs. The reality is that producers growing cover crops take on the risk of reductions in corn yield relative to a non-cover crop check, which in some cases may be quite large, up to 20%, until best management practices for cover crop management are identified and verified as economically advantageous.

Using this data, the impact of cover crops on corn yield is fit to a triangular distribution ranging from –3.46 to +0.44 Mg ha^{-1}, with a most likely corn yield change of –1.58 Mg ha^{-1} (Figure 1i; Table 2). The agronomic experiment used in this study did not include treatments where cover crop biomass was actually harvested. Therefore, actual cash crop yield impacts in scenarios where cover crop biomass is harvested were not observed. For the purposes of our simulation, the hypothetically harvested cover crop biomass scenario is assumed to have cash crop yield impacts with the same range of outcomes as scenarios where cover crop biomass is left in the field. However, the most likely value in the triangular distribution is set to zero, indicating that negative cash crop yield impacts would be mitigated in scenarios where the aboveground cover crop biomass is harvested and removed from the field. For example, the corn yield change following a harvested cereal rye cover crop has a triangular distribution ranging from –3.46–+.44 Mg ha^{-1}, with a most likely corn yield change of .00 Mg ha^{-1} (Table 2). In the literature, the potential for corn yield reductions in cover crop fields increases as cover crop biomass increases, especially for cereal rye (e.g., see meta-analysis by Miguez & Bollero, 2005). Increased biomass is associated with more mature cover crops and greater C/N ratios, which has been proven to decrease N availability due to microbial immobilization. Additionally, greater cover crop biomass can result in greater soil moisture at the crop seeding depth due to a reduction in soil moisture evaporation. Greater soil moisture could result in cooler soil temperatures and slower seed germination. Thus, the removal of the aboveground cereal rye biomass could mitigate the negative effects on the seedling environment and decrease the potential for negative crop yield impacts.

3.1.2 | Soybean yield

The year main effect was statistically significant in the soybean yield ANOVA model, but the treatment main effect and treatment × year interaction were not (Table 3). Therefore, soybean yields varied from year to year, but were not influenced by the presence of cover crops. This is consistent with previous research which has found soybean yields to be more resilient to a cereal rye cover crop than corn (Hunter et al., 2019; Singer & Kohler, 2005). Least squares mean soybean yield for each treatment and year are reported in Table 4. Fitting soybean yield change data when cover crop biomass is left in the field to a triangular distribution resulted in a range of –0.61– +.45 Mg ha^{-1} and a most likely value of –.30 Mg ha^{-1} (Figure 1iii; Table 2). Similar to corn, the soybean yield change distribution when the cover crop biomass is hypothetically harvested and removed from the field is not observed. Based on previous literature we assume that the distribution would maintain the same range of outcomes as when cover crop biomass was left in the field, but the most likely soybean yield change is set to .00 Mg ha^{-1} (Figure 1iii; Table 2).

3.1.3 | Spring aboveground cover crop biomass

A significant year main effect was identified in the spring aboveground cover crop biomass ANOVA model (Table 3), indicating that cover crop biomass production varied from

TABLE 3 Analysis of variance for cover crop treatment and year effects on corn yield, soybean yield, cover crop above ground biomass, cover crop aboveground biomass N, and total annual nitrate load

Source of variation	df	Corn yield	df	Soybean yield	df	Cover crop biomass[a]	df	Cover crop biomass N†	df	Nitrate load
Treatment (T)[b]	1	***	1	ns[b]	–	–	–	–	1	***
Year (Y)	1[c]	***	1[c]	***	3	***	3	***	3	***
T × Y	1	***	1	ns[d]	–	–	–	–	3	ns[d]
Total	23		23		23		23		47	

***Significant at the 0.01 probability level.

[a]Aboveground cover crop biomass and aboveground cover crop biomass N were only available for the cover crop treatments and thus there is only a year main effect.

[b]The two treatments are with and without cover crops.

[c]The experiment was conducted over the harvest years 2015–2018. However, because of the corn–soybean rotation, corn yield and soybean yield data were each only available in 2 of the 4 yr.

[d]Not statistically significant.

TABLE 4 Least-squares mean corn yield, soybean yield, spring cereal rye aboveground cover crop biomass, spring cereal rye aboveground cover crop biomass nitrogen, and total annual nitrate load

	Harvest year				
Variable/treatment	2015	2016	2017	2018	Avg.
Corn yield, Mg ha^{-1}[a]					
No cover crop	12.97a		12.91a		12.95a
Cover crop	12.51a		10.31b		11.41b
Soybean yield, Mg ha^{-1}[a]					
No cover crop		4.01a		4.38a	4.20a
Cover crop		3.83a		4.26a	4.05a
Spring cereal rye aboveground cover crop biomass, Mg ha^{-1}[b]	1.11b	1.22b	2.20a	0.50c	1.26
Spring cereal rye aboveground cover crop biomass N, kg ha^{-1}[b]	53.53b	31.39c	74.55a	16.39d	43.96
Total annual nitrate load, kg ha^{-1} yr^{-1}[a, c]					
No cover crop	41.58a	51.06a[d]	40.23a	8.86a	29.49a
Cover crop	36.77a	22.59a[d]	14.76b	4.24b	15.10b

[a]For corn yield, soybean yield, and total annual nitrate load different letters within a column denote significant differences between treatments in a given year at the $p \le .05$ level.

[b]For spring cereal rye aboveground cover crop biomass and spring cereal rye aboveground cover crop biomass nitrogen different letters within a row denote significant differences between years at the $p \le .05$ level.

[c]Total annual nitrate load is the cumulative annual load for the hydrologic year (where the hydrologic year was based on the average cover crop planting date–September). For example, 2015 represents the cash crop harvest year but includes total annual nitrate load from September 2014 through August 2015.

[d]Test for difference in cover crop and no cover crop total annual nitrate load means in 2016 has a $p = .07$.

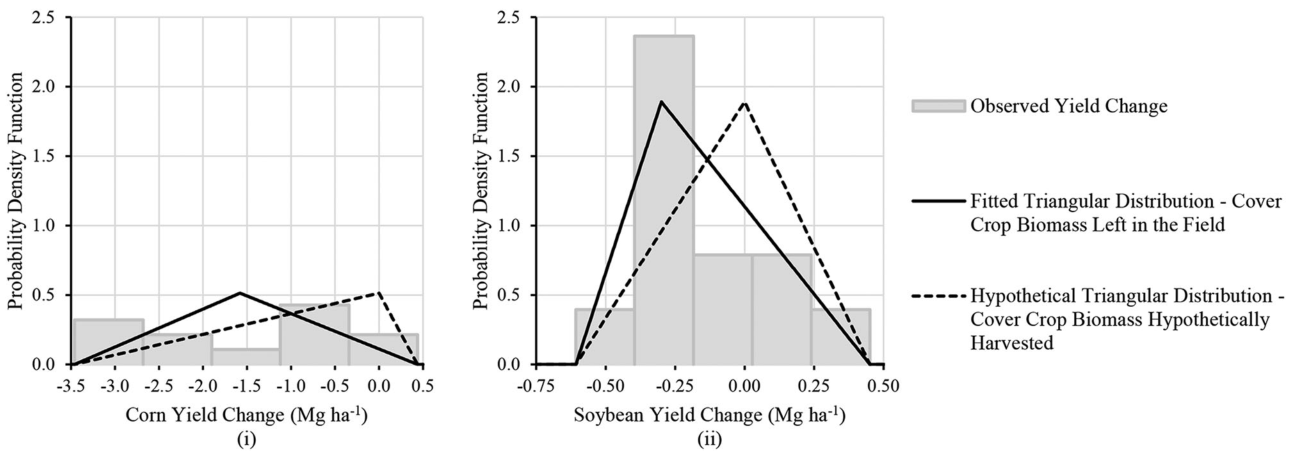

FIGURE 1 Probability density functions of (i) corn yield change associated with cover crops and (ii) the soybean yield change associated with cover crops

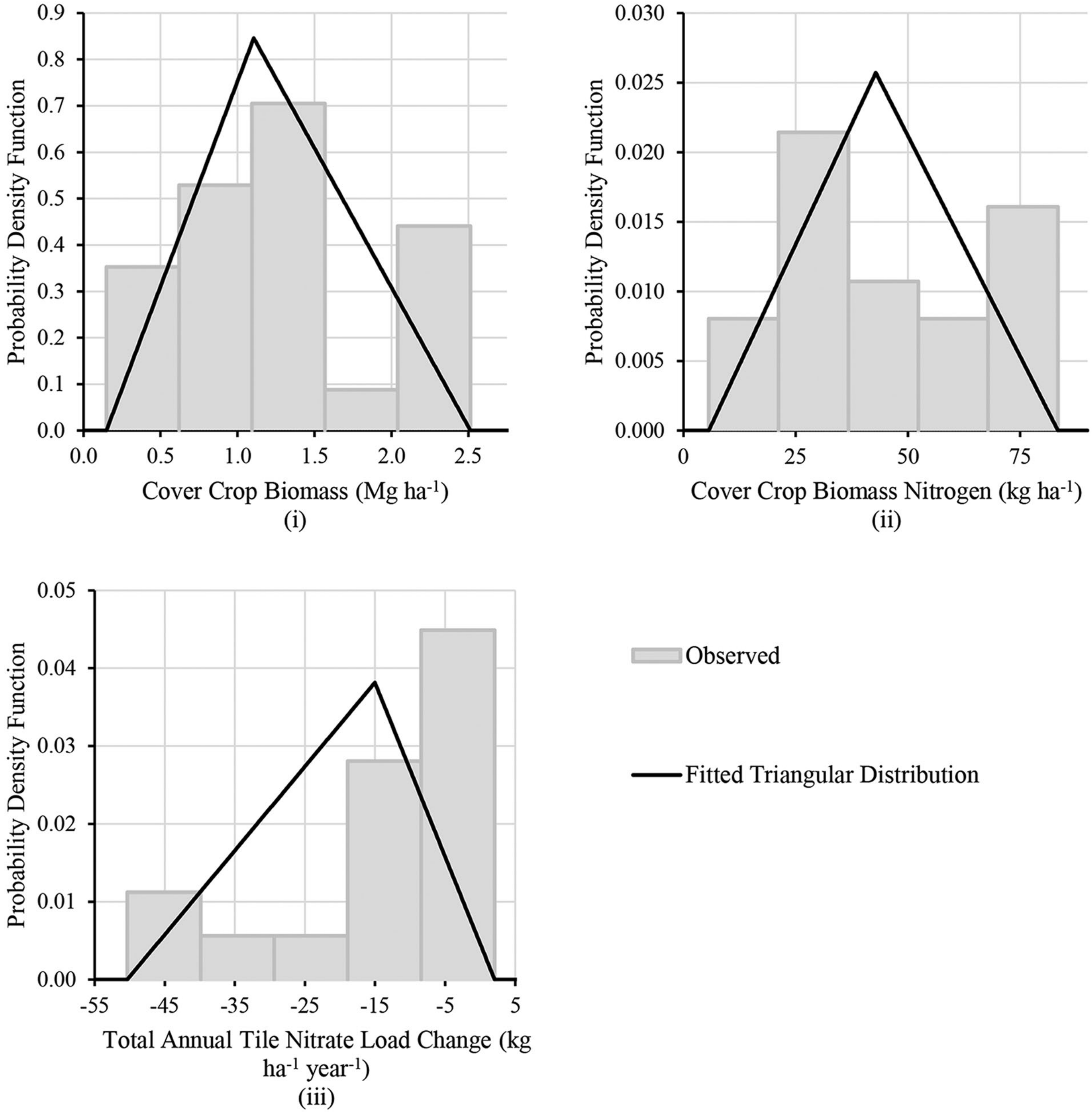

FIGURE 2 Probability density functions of (i) aboveground spring cereal rye cover crop biomass, (ii) aboveground spring cereal rye cover crop biomass nitrogen, and (iii) the change in total annual tile nitrate load

year to year as expected. Least squares mean cover crop biomass for each year are reported in Table 4. When fit to a triangular distribution, aboveground cover crop biomass has a range of .15–2.51 Mg ha^{-1} and a most likely value of 1.11 Mg ha^{-1} (Figure 2i; Table 2). These values are representative of the aboveground cover crop biomass observed in previous literature. For example, in a meta-analysis of 194 cover crop studies, Marcillo and Miguez (2017) reported an average aboveground cover crop biomass of 1.2 Mg ha^{-1} and a range of 0.6–3.0 Mg ha^{-1}.

3.1.4 | Spring aboveground cover crop biomass nitrogen

A significant year main effect was identified in the ANOVA model for spring aboveground cover crop biomass N, indicating that cover crop N uptake varied from year to year (Table 3). Least squares mean N uptake for each year are reported in Table 4. These data are fit to a triangular distribution with a range of 5.63–83.42 kg ha^{-1} and a most likely value of 42.83 kg ha^{-1} (Figure 2ii; Table 2).

In addition to the amount of cover crop N uptake, it is also critical to understand the mineralization of cover crop N and its availability to the subsequent cash crop. While empirical estimates of these values were not collected in the present study, other research is used to calibrate these values here. Although work is ongoing in this area, current data suggests that while the majority (>95%) of cereal rye cover crop N is mineralized (Roth et al., 2018), only around 10% of that N is available to the subsequent cash crop (Bergström & Kirchmann; 2004; Ranells & Wagger, 1997). Therefore, cereal rye biomass N available to the subsequent cash crop is characterized by a triangular distribution with a range of 0–15%, with a most likely value of 10% (Table 2).

3.2 | Economic

Simulated net returns to cover crop adoption are generated for each of the three scenarios (baseline, with fertilizer cost savings, and with hypothetically harvested cover crop biomass) as cumulative density functions (CDFs) for corn, soybean, and a 50–50 corn–soybean rotation. Results for the baseline scenario and the scenario with fertilizer cost savings were nearly identical given the relatively low proportion of aboveground cereal rye biomass N that is actually available to the subsequent cash crop– differences <\$3 ha^{-1} across the entire distribution. For this reason, the scenario with fertilizer costs savings is dropped from the analysis, and the baseline scenario is compared directly with the scenario with hypothetically harvested cereal rye biomass. More research is needed to understand how and when the N contained in aboveground cereal rye biomass becomes available before producers can confidently adjust their N management programs and credit these savings as a cover crop benefit. Therefore, the current tendency of most producers to not adjust N management following cereal rye as reported by Plastina et al. (2018a)) is likely sensible.

Looking at the corn phase of the corn–soybean rotation, net returns to cover crops ranged from –\$600–+\$200 ha^{-1} (Figure 3i). Expected net returns are around –\$345 ha^{-1} when cover crop biomass is left in the field and no cost-share payment is received, –\$204 ha^{-1} when cover crop biomass is left in the field and a \$140 ha^{-1} cost-share payment is received, and –\$216 ha^{-1} when cereal rye biomass is hypothetically harvested and valued as a livestock feedstuff (Table 5). Despite expected negative net returns, CDFs also indicate that positive economic returns are possible about 3% of the time in the baseline scenario with a cost-share payment and 4% of the time when cover crop biomass is harvested and valued as a livestock feedstuff. These results are largely consistent with the sentiment of Plastina et al. (2018a)) that positive returns are most often associated with cost-share payments and additional value generated by harvesting or grazing cover crops. Nonetheless, our results indicate that these probabilities of positive returns are small.

The large economic losses associated with cover crop adoption before corn are the largely the result of potentially large negative corn yield impacts. It is commonly recommended that starter N be applied or a significant portion of the total N rate be applied as pre-plant to offset N immobilization to achieve at least equal yield in a scenario where corn is planted following a cereal rye cover crop. However, this recommendation was not adhered to in this study because the researchers were investigating the worst case scenario for corn following cereal rye. Thus, had this common recommendation been followed in this study then equal yields may have been achieved. However, it is also important to note that this practice has associated costs. Therefore, further research is needed to determine the effect of starter fertilizer on cash crop yields following a cereal rye cover crop and the subsequent profitability of this recommendation.

Returns to the soybean phase of the corn–soybean rotation were higher than the corn phase (Figure 3ii). In particular, the left tail of the distribution shifts drastically to the right. This difference is largely the result of no significant difference in soybean yield between treatments with and without cover crops in both of the soybean years in this study, eliminating the severe downside risk experienced with corn. Expected net returns to cover crops for the soybean phase are around –\$183 ha^{-1} when cover crop biomass is left in the field and no cost-share payment is received, –\$43 ha^{-1} when cover crop biomass is left in the field and a \$140 ha^{-1} cost-share payment is received, and –\$94 ha^{-1} when cereal rye biomass is hypothetically harvested and valued as a livestock feedstuff (Table 5). The probabilities of positive economic returns are 28% in the baseline scenario with cost-share payment and 18% when cover crop biomass is hypothetically harvested and valued as a livestock feedstuff. Therefore, economic losses are still likely, but to a lesser extent than corn.

Finally, results for corn and soybeans above are combined into a single CDF for each scenario representing the common cultural practice of a 50–50 corn–soybean rotation. Net returns to incorporating cover crops into the corn–soybean rotation range from –\$500 to +200 ha^{-1} (Figure 3iii). Expected net returns for the rotation are –\$264 ha^{-1} when cover crop biomass is left in the field and no cost-share payment is received, –\$124 ha^{-1} when cover crop biomass is left in the field and a \$140 ha^{-1} cost-share payment is received, and –\$155 ha^{-1} when cereal rye biomass is hypothetically harvested and valued as a livestock feedstuff (Table 5). The probabilities of positive economic returns are 4% in the baseline scenario with cost-share payment and 5% when cover crop biomass is hypothetically harvested and valued as a livestock feedstuff.

When comparing the three scenarios evaluated, the baseline scenario with a cost-share payment consistently produced

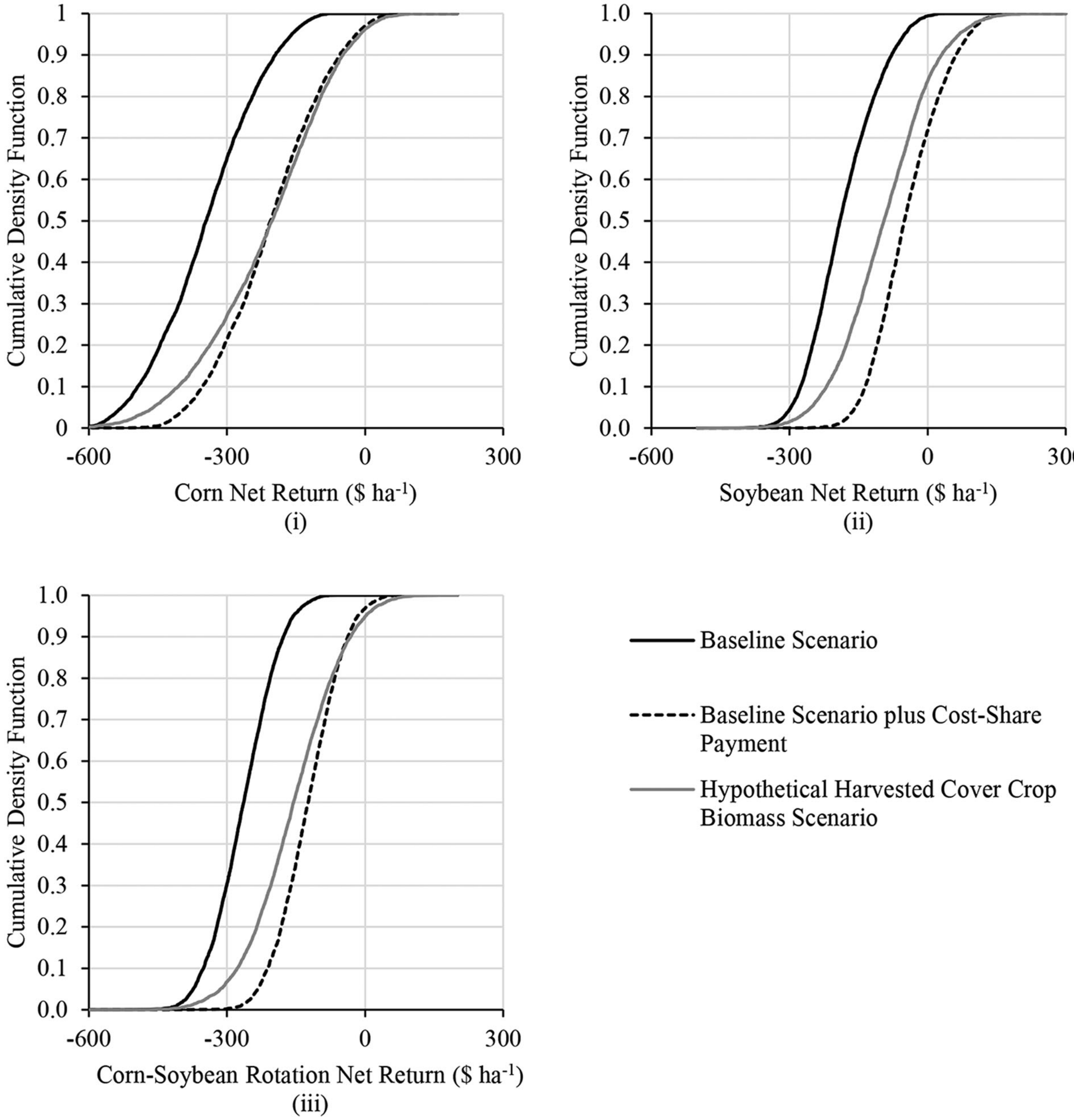

FIGURE 3 Cumulative density functions of net returns to cover crops for (i) the corn phase of the corn–soybean rotation, (ii) the soybean phase of the corn–soybean rotation, and (iii) a 50–50 corn–soybean rotation

the highest expected net returns in our simulations. However, it is important to point out that producers are generally only eligible for these cost-share payments for 2 yr. Therefore, it is important to look to other practices or management strategies that may contribute to increasing returns to the cover crop system. In our analysis, the scenario in which cereal rye biomass is hypothetically harvested and valued as a livestock feedstuff produced net returns that were only slightly lower than the baseline scenario with a cost-share payment. This is consistent with previous literature which has indicated improved economic returns to cover crops in scenarios where the biomass is harvested and valued as a livestock feedstuff (Crowley et al., 2018; Gabriel et al., 2013; Milliron et al., 2019; Plastina et al., 2018a), but this is the first study to validate these claims using partial empirical agronomic data that links cover crop biomass production with other aspects of the cover crop system for a Midwest corn–soybean rotation. However, it is important to point out that the agronomic experiment did not include treatments where cover crop biomass was actually harvested from the entire plot. Therefore, further research is need to validate the assumptions in this analysis with respect to the impact of harvesting the cover crop on cash crop yield impacts and the environmental trade off in terms of tile nitrate loss reductions.

TABLE 5 Summary statistics of net return distributions

Crop/Scenario	Net return			
	Mean	Median	25th Percentile	75th Percentile
	US$ ha^{-1}			
Corn				
Baseline scenario	−345	−346	−425	−265
Baseline scenario plus cost-share payment	−204	−206	−285	−125
Hypothetical harvested cover crop biomass scenario	−216	−202	−308	−114
Soybean				
Baseline scenario	−183	−191	−238	−131
Baseline scenario plus cost-share payment	−43	−51	−98	9
Hypothetical harvested cover crop biomass scenario	−94	−95	−163	−28
Corn–soybean rotation				
Baseline scenario	−264	−264	−311	−218
Baseline scenario plus cost-share payment	−124	−124	−171	−78
Hypothetical harvested cover crop biomass scenario	−155	−156	−221	−89

In addition, it is also important to point out that there are likely indirect costs to harvesting cover crop biomass that are not accounted for in this analysis. For example, cover crop biomass harvest is occurring in the spring when the availability of labor and machinery may be constrained due to cash crop planting operations. Further, costs of hauling, storing, and marketing harvested cover crop biomass are not accounted for here. For those feeding directly to owned livestock, hauling costs will be minimal, they likely already have storage for the feedstuff, and they would have no marketing costs. On the other hand, these costs may be substantial for some farms, in particular those operating in regions with less demand for livestock feed, if they need to store the product, find/create a market for the product, and physically haul the product to said market. Ultimately, when interpreting the results presented here it is important to consider the impact of this scenario on whole farm management for the individual producer as well as the supply and demand for livestock forage in the local market region as these factors could have large implications on economic feasibility.

3.3 | Breakeven subsidy per kilogram of abated nitrate load

Significant treatment and year main effects were identified in the annual total tile nitrate load ANOVA model (Table 3). Least squares mean annual total nitrate load for each treatment and year are reported in Table 4. Results indicate that the presence of cover crops reduced annual total nitrate load in each of the 4 yr and the reduction was statistically significant ($p \leq .05$) in two of those years (2017 and 2018) and marginally significant in 2016 ($p = .07$). These results validate previous findings that cover crops reduce nitrate loading. However, the amount of nitrate load reduction fluctuates from year to year. Hence, we use these data to parameterize a stochastic nitrate load reduction distribution. When fitting the distribution, observations from 2015 are excluded given that the tile system was installed just prior to the start of the hydrologic year in September of 2014 influencing oxygen influx into the soil resulting in altered N mineralization and nitrification rates, as well as altered flow of water through the soil profile. In addition, one observation of the change in total annual nitrate load in 2016 was confirmed to be an outlier by Grubb's test (Grubbs, 1950) and was also excluded from fitting the distribution. This resulted in a triangular distribution for the change in total annual nitrate load ranging from –50.35–+2.06 kg ha^{-1} yr^{-1} with a most likely value of –15.02 kg ha^{-1} yr^{-1} (Figure 2iii; Table 2). These values are representative of the change in total annual nitrate load observed in previous literature focused on Midwest corn and soybean production (Kaspar, Jaynes, Parkin, & Moorman, 2007; Kaspar et al., 2012).

Simulated breakeven values for the subsidy kg^{-1} of abated nitrate load are reported in Figure 4 for the 50–50 corn–soybean rotation baseline scenario. Notice that a small percentage of the breakeven values equal zero. This may occur for one of two reasons. Either the net returns to producing the cover crop (excluding current cost-share payments) are greater than zero and thus no additional subsidy is necessary for the farmer to break even, or the change in total annual tile nitrate load is greater than or equal to zero (indicating cover crops did not reduce nitrate loading) and thus there is no basis for subsidizing cover crop adoption. In the baseline scenario, only .5% of the simulated breakeven values equal zero, and all of these were the result of the change in total annual nitrate load greater than or equal to zero. The other thing to notice is that the histogram in Figure 4 indicates the potential for

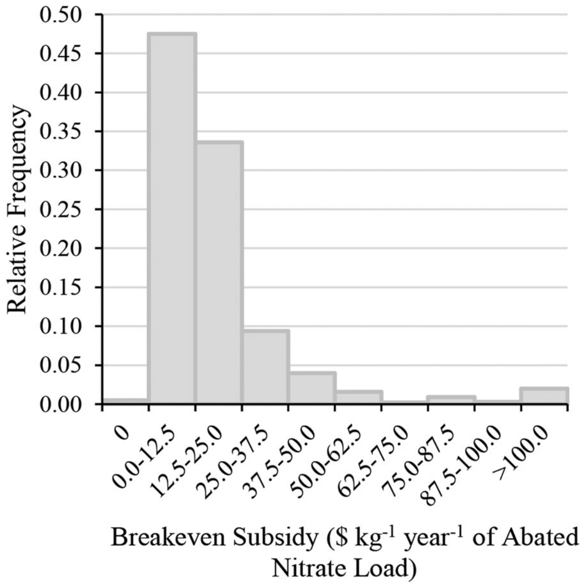

FIGURE 4 Relative frequency histogram of the breakeven subsidy kg^{-1} of abated nitrate load for the 50–50 corn–soybean rotation baseline scenario

breakeven values greater than \$100 kg^{-1} yr^{-1}. The long right tail of the distribution is a result of the change in total annual tile nitrate load distribution approaching and crossing zero. That is, given that the change in tile nitrate load is the denominator of the breakeven subsidy kg^{-1} of abated nitrate load formula in Eq. [4], small negative values of the change in total annual nitrate load result in potentially high breakeven values.

Focusing on the rest of the distribution, the expected breakeven value for the baseline scenario is \$23 kg^{-1} of nitrate yr^{-1}. That is, the producer would have to receive \$23 for each kilogram of nitrate the cover crop prevents from leaching out of subsurface drainage each year to just offset the net loss from growing the cover crop. However, because of the right skew of the distribution, the median breakeven value is just \$13 kg^{-1} yr^{-1}, and there is a 48% chance that the breakeven value is less than \$12.50 kg^{-1} yr^{-1}.

It is important to put these values in to context by comparing them with current Illinois EQIP cover crop payment rates. However, current payment rates are fixed \$ ha^{-1} payments of \$140 ha^{-1} yr^{-1} and are not based on actual reductions in nitrate loading. An ad hoc conversion of the estimated \$ kg^{-1} breakeven value to a \$ ha^{-1} payment using the average reduction in nitrate loading from our data of 15 kg ha^{-1} is instructive and indicates current payment rates around \$195–\$354 ha^{-1} yr^{-1}. These values are generally higher that what is currently available to producers through the EQIP program. Therefore, based on the results of our simulation, higher cost-share payments are likely necessary to incentivize widespread cover crop adoption among Midwest corn and soybean producers. While current EQIP payments appear to be sufficient to offset the costs of cover crop establishment and termination, they are insufficient to offset the potential short-run yield losses observed in our data.

4 | CONCLUSIONS

This study uses experimental agronomic data from Illinois to examine the direct short-run economic returns of implementing a predominantly cereal rye cover crop mix into a Midwest corn–soybean rotation. The results presented here shed light on several important aspects of the discussion surrounding cover crop economics, but should be interpreted conditional on the cultural practices of the agronomic experiment and the limited distribution of observed weather conditions. For example, planting density, N rates, and soil types are all representative of a typical central Illinois farms. Tillage practices (strip-till corn and no-till soybean) are not necessarily the predominant system, but are well represented in the 2017 U.S. Census of Agriculture. Finally, our simulations are based on 4 yr of data, and because of the corn–soybean rotation that includes only two corn years and two soybean years. While this is certainly a limitation of the current study, the range of agronomic outcomes appears to be generally consistent with previous literature providing confidence to our results.

Our results indicate that the short-run expected net returns to cover crops are consistently negative in all of the scenarios evaluated, including the baseline scenario that includes a currently available cost-share payment of \$140 ha^{-1}. Consistent with previous research, a scenario where cover crop biomass is hypothetically harvested and valued as a livestock feedstuff increased net returns almost as much as the \$140 ha^{-1} cost-share payment. Since harvesting cover crop biomass would generally disqualify producers from receiving cost-share payments and NRCS EQIP payments are only available for 2 yr, this may be a strategy to increase cover crop returns once a producer has exhausted their EQIP participation. However, more research is need to validate the assumptions in this analysis with respect to the impact of harvesting the cover crop on cash crop yield impacts and the environmental trade off in terms of tile nitrate loss reductions.

In our simulations, the impact of cover crops on the subsequent cash crop yield is currently the biggest influencer of cover crop returns. At best, in our analysis cover crops did not significantly impact cash crop yields, with actual yield changes varying around zero. However, the potential for significant negative cash crop yield impacts still exists, especially for corn following a predominantly cereal rye cover crop mix. Improved recommendations for cover crop best management practices and adaptive fertilizer management that can reduce currently large downside risk without increasing the overall rate of Nn applied are prudent to incentivize widespread adoption.

Finally, we also attempt to estimate the value of water quality benefits provided by the cover crop required for the producer to breakeven when adopting cover crops. Expected breakeven values are around \$13–\$23 kg^{-1} yr^{-1} depending on the measure of central tendency used. An ad hoc conversion of these values to \$ ha^{-1} based on the mean change in total annual nitrate load (15 kg^{-1} ha^{-1}) allows us to compare our estimated breakeven subsidy kg^{-1} of abated nitrate load with currently available cost-share payments. Results indicate that estimated breakeven values of \$195–\$345 ha^{-1} are generally higher than current NRCS EQIP payments of \$140 ha^{-1}. Therefore, based on the results of our simulation, higher cost-share payments are likely necessary to incentivize widespread cover crop adoption among Midwest corn and soybean producers. Similarly, established markets to internalize cover crop benefits that accrue to society would also allow for more efficient transmission of market signals from society to producers.

It is important for those designing policy aimed at incentivizing cover crop adoption to consider more than just the direct costs of establishment and termination. Two main considerations emerge from this research. First, we find that typical cost share rates (e.g., from EQIP) are likely insufficient to compensate producers in the face of expected yield losses from cover crop adoption. Second, our simulation results suggest cover crop adoption may influence higher moments of the producer's net cash flows (variance, skewness, etc.), at least in the short run. Increased yield variability over time can influence producers' average production history and hence can negatively affect crop insurance premiums. Designing effective incentives therefore requires accounting for risk and uncertainty in producers' adoption decisions. In particular, risk averse producers (whose utility decreases with the variability of net income) may require even larger cost-share rates to compensate them for changes in yield variability and for larger insurance premiums. Alternatively, policy designers may consider developing tools to better share the risk of cover crop adoption, for example, through specialized crop insurance policies that indemnify conservationist landowners from yield losses while the practice becomes established. We leave questions of optimal incentive design for future research.

It is also important to emphasize that our analysis considers only the short-run effects of cover crop adoption. Yield losses and uncertainty may dissipate with greater producer experience, improvements in soil structure, and other factors. In this case, optimal incentives for cover crop adoption would change over time. Further research is needed to better understand yield dynamics from continuous cover crop use.

Finally, better aligning program dollars with the stated objective of improved water quality outcomes can be achieved through linking direct producer returns with empirical evidence of reductions in nitrate loading. In this paper, we offer a framework for linking these aspects of the cover crop system that result in a breakeven subsidy kg^{-1} of abated nitrate load that makes the producer just indifferent between planting and not planting the cover crop.

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