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A. Plastina
Iowa State University

J. Acharya
Iowa State University

F. M. Marcos
Iowa State University

M. R. Parvej
Iowa State University

M. A. Licht
Iowa State University

See next page for additional authors

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Authors

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Corresponding author:
A. Plastina; Email: plastina@iastate.edu

Does grazing winter cereal rye in Iowa, USA, make it profitable?

A. Plastina[1], J. Acharya[2], F. M. Marcos[3], M. R. Parvej[3,4], M. A. Licht[3] and A. E. Robertson[2]

[1]Department of Economics, Iowa State University, Ames, IA, USA; [2]Department of Plant Pathology, Entomology, and Microbiology, Iowa State University, Ames, IA, USA; [3]Department of Agronomy, Iowa State University, Ames, IA, USA and [4]Louisiana State University Ag Center, Scott Research & Extension Center, Winnsboro, LA, USA

Abstract

Unproven economic returns at the farm level are a major barrier to large-scale adoption of cover crops. The objective of this study was to evaluate the short-run private net returns to producers implementing a cereal rye (*Secale cereale* L.) cover crop preceding the no-till corn (*Zea mays* L.) phase of a US Midwest corn–soybean (*Glycine max* [L.] Merr.) rotation in an integrated crop and cow–calf operation. We used experimental agronomic data from six location-years in Iowa to estimate private net returns to cereal rye across alternative scenarios in a partial budget framework. Net returns in the absence of grazing averaged −\$123.74 ha^{-1} and were negative for 82.2% of the treatments, while net returns under partial grazing averaged −\$15.24 ha^{-1} and were negative for 54.8% of the treatments. Early-broadcast cereal rye produced higher biomass and larger net cost savings in the livestock enterprise than late-drilled cereal rye, but it also resulted in higher corn yield penalties. In the no-grazing scenario, net losses for early-broadcast cereal rye were \$165.97 ha^{-1} larger, on average, than for late-drilled cereal rye. Our findings should raise awareness about the low probability of obtaining positive annual private net returns to cereal rye in Iowa in the absence of sizable targeted financial incentives, and inform the policy discussion on the cost-effectiveness of government-sponsored conservation programs.

Introduction

Despite the numerous environmental benefits associated with cover crop use, such as reducing erosion, improving infiltration, mitigating nutrient loading in surface waters, and improving soil health (Dabney, Delgado and Reeves, 2001; Kaspar, Radke and Laflen, 2001; Snapp et al., 2005; Tonitto, David and Drinkwater, 2006; Schnepf and Cox, 2006; Kaspar and Singer, 2011), many farmers in the Midwestern United States are still reluctant to include cover crops in their production practices. Across four surveys (Werblow and Watts, 2013; Werblow and Myers, 2014, 2015, 2016), US farmers reported establishment, time or labor required, increased management, and species selection as the greatest challenges to using cover crops. The Iowa Farm and Rural Life Poll (Arbuckle, 2016) reported potential economic impacts had moderate-to-very strong influence on changes in 74% of producers' management practices, and 57% of them agreed with the statement 'pressure to make profit margins makes it difficult to invest in conservation practices'.

In Iowa, which is the largest producer of corn (*Zea mays* L.) and second-largest producer of soybeans (*Glycine max* L.) in the United States, cover crops were implemented in 4% of all tillable area in 2017 (USDA, 2019a). While research on a wide range of winter-hardy cover crop species is ongoing, cereal rye (*Secale cereale* L.) is the only species documented to consistently grow well enough throughout Iowa to provide substantial water quality benefits. Yet, an ongoing concern for many farmers is that cover crops may reduce yields of the following cash crop (Arbuckle and Roesch-McNally, 2015). A study of no-till plots in Iowa showed cereal rye reduced corn yields by 6% (Pantoja et al., 2015). However, Marcillo and Miguez (2017) concluded from a meta-analysis that cover crops did not generally reduce subsequent corn yields, particularly in the upper Midwest region. Martinez-Feria et al. (2016) did not find consistent corn yield declines following cover crops in Iowa, while Seifert, Azzari and Lobell (2018, 2019) reported corn yield increases of 0.71% in the Midwest, based on satellite panel data. Small but statistically significant positive effects of cover crops on active carbon and soil stability in Midwestern states were reported by Wood and Bowman (2021), but their economic implications were not evaluated. The peer-reviewed literature based on survey methods (Plastina et al., 2018a, 2018b, 2018c), field experiments (Thompson et al., 2020), and simulations from physical models (Marcillo et al., 2019) concluded net returns to cover crops in the US Midwest were predominantly negative, even after accounting for cost-share payments.

Cover crop biomass in early spring can reduce an integrated production system's dependence on stored feed (Lundy, Loy and Bruene, 2018; Phillips et al., 2019), and thus reduce feed costs. Furthermore, early spring cover crop biomass might allow for adjusting calving dates to optimize labor use and reduce the impact of mud at calving and calf scours (Sellers et al., 2019). In 2019, cattle and calves in Iowa accounted for 14.3% of the state's total cash receipts from agricultural commodities and 5% of total cash receipts from cattle and calf production in the United States (USDA, 2021). According to Sellers et al. (2019), feed costs accounted, on average, for 63% of the direct costs of cow–calf production in Iowa, and stored feed represented 71% of feed costs. Despite the relevance of this livestock enterprise, the literature on feed cost savings stemming from grazing aboveground cover crop biomass is scant. A survey of Iowa farmers reported feed cost savings from grazing or harvesting cover crop biomass before corn ranging from \$7.4 to \$247.1 ha^{-1}, and averaging \$86.5 ha^{-1} (Plastina et al., 2018c, p.24). A hypothetical harvest of cover crop biomass in Lexington, Illinois, would have generated \$122.2 ha^{-1} in feedstuff value, on average (Thompson et al., 2020). However, the extra revenue would have been insufficient to offset the additional costs in the cropping system, leaving farmers with annual private losses of −\$173.7 ha^{-1} in the absence of cost-share payments (Thompson et al., 2020). Furthermore, making hay with cereal rye biomass harvested in the early spring can be a major challenge in the US Midwest, given its high moisture content (Blanco-Canqui et al., 2020). Projected net returns to grazed cereal rye in the corn phase of a corn–soybean rotation in Iowa, based on a physically driven model of corn yields and cereal rye biomass, averaged −\$30.5 ha^{-1} in the absence of cost-share payments and cereal rye termination costs, and −\$64.0 ha^{-1} with termination costs (Marcillo et al., 2019). Malone et al. (2022) suggested harvesting cereal rye for forage between mid-May and early June before planting soybeans in the north-central United States could be economically viable, particularly if producers did not observe soybean yield losses from the double-cropping alternative (Gesch, Archer and Berti, 2014; Nafziger et al., 2016).

The goal of the present study was to evaluate the annual private net returns to cereal rye as a winter cover crop in the no-till corn phase of an integrated corn–soybean and cow–calf system in Iowa. We conducted the evaluation in two stages. First, the net returns to cereal rye in the crop system were calculated using experimental agronomic data from Marcos et al. (2023) and local average prices in a partial budget framework. Partial budgets captured the differences between total profits from no-till corn production in fields planted to cereal rye in the fall, and total profits from no-till corn production in fields left fallow over the winter. Second, using data on cereal rye biomass collected from the experimental plots and local average prices, we simulated the hypothetical net cost savings from grazing cows in the cover-cropped fields for a typical cow–calf enterprise. We calculated the annual net returns to cereal rye in an integrated crop–livestock operation as the direct sum of the net returns in the crop system and the net cost savings in the cow–calf enterprise. Note that partial budgets captured short-term 'direct' effects of adding cereal rye to the crop rotation. We did not include 'indirect' benefits from cover crop use in our analysis, such as reduced soil erosion or nitrate loading from subsurface drainage (Roth et al., 2018; Bergtold et al., 2017; Snapp et al., 2005), because they do not affect the private net returns to farming in the short-run.

The present study simulated private net returns to cereal rye by planting date and method, seeding rate, and termination date using experimental field data, and estimated feed cost savings from grazing cereal rye biomass in a cow–calf enterprise.

Materials and methods

Private net returns to cereal rye in no-till corn enterprise

Agronomic data from six location-years Marcos et al. (2023) and price data were used to evaluate the net returns to cereal rye preceding no-till corn in a partial budget framework. Treatment factors for the agronomic experiment included planting date-method, seeding rate, and target termination date. A comprehensive field study including all factors under analysis was implemented at a central Iowa research farm and supplemented with smaller studies at outlying research farms located in northwest and southeast Iowa. Each research farm is representative of a different soil type and weather pattern. Table 1 describes the main characteristics of the replicated treatments in each location-year. All treatment plots were 15.2 m long by 9.1 m wide.

The comprehensive field study in central Iowa utilized a split-split-plot design with six replications. The main plot treatment was the cereal rye planting method: broadcast or drill. Following Iowa State University (ISU) recommendations (Conservation Learning Group, 2020), the subplot treatment was cereal rye target termination date: early and late termination dates targeted, respectively, 14 and 3 days before planting (DBP) corn. The sub-sub-plot treatment was seeding rate: high, medium, low, and zero. The seeding rates were 0.82, 1.65, and 2.47 million pure live seed (PLS) ha^{-1} for drilled cereal rye; and 1.65, 2.47, and 3.28 million PLS ha^{-1} for broadcast cereal rye. At the outlying farms, the three non-zero seeding rates were compared in the two seeding methods, but all treatments were terminated according to the 14 DBP target. Treatments were replicated six times at the outlying farms.

Cereal rye was established in mid-September in standing soybean (R7 growth stage; Pedersen and Licht, 2014) for broadcast plots using a high clearance boom applicator. Soon after soybean harvest in mid to late October, drill plots were seeded in both 2019 and 2020 using a John Deere 750 10-feet no-till grain drill with a 19 cm row spacing. Since the different seeding dates have a confounding effect with the alternative planting methods, we refer to 'early-broadcast' *vs* 'late-drill' as our main seeding 'date-method' treatments in the remainder of the article. Early planting and late termination of cover crops has been associated with better establishment and biomass production (Ruis et al., 2019) and higher ecosystem services (Hively et al. (2009).

At all locations, May 1 was targeted as the ideal planting date for corn, but actual planting dates were affected by weather conditions. Consequently, cereal rye termination targeting 14 DBP actually occurred 19–39 DBP in 2019, and 10–13 DBP in 2020; while the 3 DBP target actually resulted in termination 13 DBP in 2019 and 2 DBP in 2020. Corn nitrogen management consisted of 168 kg N ha^{-1} applied mostly at the time of V4 to V6 corn stage (Abendroth et al., 2011), except for the southeast farm where a mistake by the field manager resulted in an application of 190.5 kg ha^{-1} in 2019. All locations utilized ISU recommendations for phosphorous and potassium fertilizer (Sawyer et al., 2006; Mallarino, Sawyer and Barnhart, 2013) as well as for weed management (Hodgson, Licht and Sisson, 2020). The agronomic data used for the present study include kg of cereal rye

Table 1. Commonalities in experimental design variables by location-year

Variable	Northwest		Central		Southeast	
	2018/19	2019/20	2018/19	2019/20	2018/19	2019/20
Farm characteristics						
GIS coordinates	42.92550, −95.52738	42.92992, −95.53869	42.01187, −93.74021	42.01324, −93.74108	41.19312, −91.48019	41.20399, −91.49428
Soil types	Primghar, silty clay loam, 0–2% slope	Primghar, silty clay loam, 0–2% slope	Nicollet, loam, 1–3% slope	Clarion, loam, Bemis moraine, 2–6% slope	Mahaska, silty clay loam, 0–2% slope	Tainter, silty clay loam, 0–2% slope
Cereal rye						
Type	Elbon	Elbon	Elbon	Elbon	Elbon	Elbon
Planting dates: broadcast	9/27/2018	9/16/2019	9/17/2018	9/5/2019	9/13/2018	9/9/2019
Planting dates: drill	10/22/2018	10/18/2019	10/29/2018	10/16/2019	10/26/2018	10/17/2019
Chemical termination (liters ha^{-1})^	Roundup Power Max (2.92 l) + Power House (1.97 l)		Glyphosate (2.56 l)	Roundup Power Max (2.56 l)	Glyphosate (2.34 l) + 2-4D (2.34 l)	Roundup Power Max (2.34 l) + Radar LV (2.34 l)
Termination dates: 14DBP	4/25/2019	4/29/2020	4/26/2019	4/21/2020	4/25/2019	4/21/2020
Termination dates: 3DBP	NA	NA	5/3/2019	5/2/2020	NA	NA
Corn						
Planting date	5/14/2019	5/12/2020	5/16/2019	5/4/2020	6/3/2019	5/1/2020
Harvest date	10/30/2019	10/14/2020	11/1/2019	11/1/2020	11/6/2019	10/20/2020
Seeds ha^{-1}	86,487		86,487		84,016	88,958
Seed type	P0157AMXT s.st.	P0589AMXT s.st.	P1197AM std.st.		P1197AMXT s.st.	P1108Q s.st.
Yield in check plots, mt ha^{-1}: mean (StDev)	14.12 (0.55)	14.24 (1.18)	11.59 (1.39)	9.61 (1.73)	13.43 (0.40)	13.79 (0.40)
Herbicide program						
1st application, rate ha^{-1}	Harness (2.63 l)		Glyphosate (1.90 l) + Corvus (0.41 l)	Laudis (0.22 l) + Buctril (0.44 l)	Zidua (0.24 l) + Atrazine (1.68 kg) + Roundup (2.34 l) + 2-4-D (0.58 l)	Zidua (0.24 l) + Atrazine (1.68 kg) + Roundup (2.34 l)
1st application date	5/23/2019	5/15/2020	5/16/2019	6/18/2020	6/3/2019	5/1/2020
2nd application, rate ha^{-1}	Realm Q (0.29 l) + Power House (1.97 l) + Roundup Power Max (2.92 l) + Interlock (0.37 l)		Impact (0.07 l)	None	Roudup (2.34 l)	Halex GT (4.68 l) + Atrazine (0.56 kg)
2nd application date	6/19/2019	6/9/2020	6/20/2019	None	7/3/2019	6/8/2020
Fertilization program						
1st application, rate ha^{-1}	DAP 18-46-0 + 0-0-60 potash (32.5 kg N, 82.94 kg P, 107.6 kg K)	MAP 11-52-0 + 0-0-60 potash (19.1 kg N, 82.94 kg P, 107.6 kg K)	Urea as starter (33.63 kg)		MAP (224.17 kg) and 22-104-120 potash (224.17 kg)	0-0-156 potash (291.42 kg)

(*Continued*)

Table 1. (*Continued.*)

Variable	Northwest		Central		Southeast	
	2018/19	2019/20	2018/19	2019/20	2018/19	2019/20
1st application date	11/15/2018	11/13/2019	5/16/2019	5/4/2020	4/3/2019	12/19/2019
2nd application, rate ha^{-1}	Urea as starter 2 × 2 (33.63 kg)		UAN sidedress 32-0-0 (134.5 kg)		UAN sidedress 32-0-0 (190.5 kg)	UAN sidedress 32-0-0 (168.1 kg)
2nd application date	5/14/2019	5/12/2020	7/15/2019	6/15/2020	6/26/2019	6/3/2020
3rd application, rate ha^{-1}	UAN sidedress 32-0-0 (134.5 kg)		None	None	None	None
3rd application date	6/11/2019	6/2/2020	None	None	None	None

Notes: NA, not applicable; DBP, days before planting; ^ control plots (no cereal rye) were also sprayed with the same chemicals to provide consistent exposure across treatment plots.

biomass in November and on the date of termination; as well as corn planting date, harvesting date, and yield. The full agronomic experiment is described in detail in Marcos et al. (2023).

Table 2 lists the relevant prices and costs from 2018 to 2020 used in our analysis. We estimated cereal rye seed costs using average prices paid by our project manager in 2018 and 2019. To estimate no-till planting costs at farm scale, we assumed machinery field efficiencies for broadcasting and drilling cereal rye seeds at 12.14 and 2.06 ha h^{-1}, respectively (Hanna, 2016). The costs of purchased inputs for corn production reflect average prices from a number of specialized websites (e.g., https://farmtrade.com, https://ranchwholesale.com, https://fbn.com) and personal communications with input dealers in Iowa. We derived machinery and labor costs for the no-till corn phase from crop production budgets published by ISU (Plastina, 2018, 2019, 2020). While operators in Iowa are typically able to outsource multiple farm activities by hiring custom work, the present analysis assumed farm operators implemented all production activities with owned machinery. Since hiring custom work would typically be more expensive to farmers (because the service provider would have to recover the depreciation of their machinery and generate a profit margin), we consider our estimates optimistic and close to the upper bound of the actual distribution of net returns.

Data on cereal rye biomass were collected in the fall during rye's vegetative dormancy period, and on the date of termination in the spring. We only collected fall samples for early-broadcast seeds because rye had emerged only in these treatments, but we collected spring samples for both planting date-methods. However, while in spring 2019 we sampled all plots as planned, changes in experimental field protocols during the spring of 2020 due to the COVID-19 pandemic resulted in only four out of six replications sampled for biomass in 2020. Since the northwest farm did not broadcast cereal rye seeds correctly in the fall of 2019, data on those early broadcast treatments were excluded from the analysis. Pandemic protocols were more lenient in the summer of 2020, and we collected corn yield data from all plots (even those not sampled in the spring).

We estimated net returns to cereal rye as the difference between total profits from no-till corn production preceded by cereal rye (treated plots) and total profits from no-till corn production in plots with no winter cover crops (untreated plots). Since we base our analysis on agronomic data collected from controlled field experiments, all field preparation, crop protection, and fertilization practices were identical across treated and untreated plots in each location-year. Hence, the only difference between treated and untreated plots affecting the calculation of private net returns per hectare (NR) were cereal rye planting costs (S), and differences in harvesting costs (ΔH) and corn revenue (ΔR):

$$NR_{mra} = \Delta R_{mra} - \Delta H_{mra} - S_{mr}, \qquad (1)$$

where $m = \{B \equiv \text{early-broadcast};\ D \equiv \text{late-drill}\}$ indexes planting date-methods; $r = \{\ L \equiv \text{low};\ M \equiv \text{medium};\ H \equiv \text{high}\}$ indexes seeding rates; and $a = \{3\ \text{DBP},\ 14\ \text{DBP}\}$ indexes target termination date. All economic assumptions were described in Table 2.

We calculated the difference in corn revenue as the product of the mean yield difference in metric tons per hectare (mt ha^{-1}) between treated and untreated plots in each location-year, ΔY, and the corn price: $\Delta R = \Delta Y \times\ \$198.81\ \text{mt}^{-1}$. The harvesting cost difference wascalculated as the product of the mean yield

Table 2. Economic assumptions

Activity	Description	Unit	Value	Sources
Cereal rye planting				
Seed	22.68 kg bag with 43,387 seeds kg^{-1}	\$ bag^{-1}	25.00	Average purchase prices 2018–2019
Broadcasting	Variable costs of broadcast seeder	\$ ha^{-1}	4.32	Average costs from Plastina (2018, 2019)
Drilling	Variable costs of 3.05 m no-till grain drill	\$ ha^{-1}	19.03	Average costs from Plastina (2018, 2019)
Corn harvesting				
Hauling	Variable costs for hauling corn to on-farm grain bin	\$ mt^{-1}	1.50	Average costs from Plastina (2019, 2020)
Drying	Variable costs for drying corn with propane gas	\$ mt^{-1}	5.91	Average costs from Plastina (2019, 2020)
Store grain	Variable costs for moving corn from grain cart to on-farm grain bin with auger	\$ mt^{-1}	0.75	Average costs from Plastina (2019, 2020)
Corn price	Average price received by farmers in Iowa over 2019/20 and 2020/21	\$ mt^{-1}	198.81	USDA (2022)
Livestock production				
Hay price	Average price paid for hay in Iowa, March-May 2019 and 2020	\$ mt^{-1}	147.16	USDA (2021)
Hay dry matter	Estimated dry matter of hay when fed	Percent	84.50	Sellers et al. (2019)
Solar electric fence charger	Market price for new charger for 16.1 km of fence	\$ unit^{-1}	200.00	Various online farm implement stores
Fence posts	Market price for *T*-shaped fence posts	\$ unit^{-1}	4.00	Various online farm implement stores
Barbed wire	Market price for barbed wire	\$ km^{-1}	198.85	Various online farm implement stores
Useful life of removable fence	Expected useful life of removable fence	Years	4.00	Authors’ assumption
Herd size	Number of 567 kg lactating cows in the operation	Heads	48.00	Authors’ assumption
Daily cow consumption	Daily cow consumption in percent of own weight	Percent	4.00	USDA (2009)
Cover crop area	Area planted to cereal rye prior to corn	Ha	64.75	Authors’ assumption
Fencing labor	Labor to install and remove fence Mar–May	Hours season^{-1}	32.00	Authors’ assumption
Maintenance	Labor to repair fences, refill waterers, move cows	Hours day^{-1}	0.57	Authors’ assumption
Feedlot labor	Labor to feed herd in feedlot, remove manure	Hours day^{-1}	2.22	Authors’ assumption
Hourly wage	Average hourly rate for farm labor	\$ h^{-1}	14.33	Average costs from Plastina (2018, 2019, 2020)

difference and the variable cost to haul corn from the field to on-farm storage, dry it to a 14% moisture level, and store it until sold: $\Delta H = \Delta Y \times \$8.15\ \text{mt}^{-1}$.

Cereal rye planting costs were defined as a function of the seeding rate (*srate*) and the variable portion of machinery costs and labor costs specific to each seeding method (V_m):

$$S_{mr} = \$25.4065 \times srate_{mr} + V_m, \tag{2}$$

where $\$25.4065 = \$25\ \text{bag}^{-1} \times 1{,}000{,}000\ \text{seeds}/(22.68\ \text{kg bag}^{-1} \times 43{,}387\ \text{seeds kg}^{-1})$; $V_B = \$5.50\ \text{ha}^{-1} = \$4.32\ \text{ha}^{-1} + \$14.33\ \text{h}^{-1}/12.14\ \text{ha h}^{-1}$; and $V_D = \$25.99\ \text{ha}^{-1} = \$19.03\ \text{ha}^{-1} + \$14.33\ \text{h}^{-1}/2.06\ \text{ha h}^{-1}$. The seeding rates, in million seeds ha^{-1}, were $srate_{Br} = \{0.82, 1.65, 2.47\}$ and $srate_{Dr} = \{1.65, 2.47, 3.28\}$.

Private net cost savings in cow–calf enterprise

Cost savings from grazing cereal rye are highly dependent on the type of livestock, herd size, proximity of the feedlot to the field, and total available biomass. In Iowa, farms selling between 20 and 99 cattle and calves in 2017 sold an average of 47 heads per farm and accounted for 40% of all farms with sales of cattle and calves in the state (USDA, 2019a).

We focused on a typical Iowa cow–calf production system with 48 cows feeding on dry hay in a feedlot during winter and early spring. Furthermore, we assumed cereal rye was planted on 64.75 ha arranged in the shape of a square adjacent to the feedlot; that a removable electrified fence along the perimeter and a pre-owned and fully depreciated waterer were installed in the early spring and removed the day before rye termination. The temporary fence was assumed to consist of two lines of barbed wire held in place by removable T-shaped posts placed 6.1 m apart, and electrified with a solar electric fence charger. These assumptions were in line with our intention to generate upper bound estimates of net returns.

Private net cost savings in the cow–calf operation, *NCS*, were dependent onwith fencing costs, *F*, net daily labor savings, *L*, daily hay cost savings, *H*, and number of grazing days, *G*:

$$NCS_{mra} = (L + H) \times G_{mra} - F. \tag{3}$$

We calculated annual fencing costs as the sum of (a) \$11.31 ha^{-1} from the linear depreciation over four years of 425 T-shaped posts, 5180 m of barbed wire, and a solar electric fence charger; (b) \$1.85 ha^{-1} in materials to repair the fence; and (c) \$7.08 ha^{-1} for 32 h of labor to install and remove the electric fence and waterer each spring: F = \$20.23 ha^{-1}.

Net daily labor savings, *L*, were calculated as the saved labor from not feeding cows in the feedlot (2 h G^{-1}) and not collecting, hauling, and spreading manure accumulated over the spring (0.22 h G^{-1}), minus the extra labor hours spent repairing the fence (2 h week^{-1}) and refilling the waterer (2 h week^{-1}): L =\$14.33 h^{-1} × 1.65 h G^{-1}/64.75 ha = \$0.37 ha^{-1} G^{-1}.

Assuming each cow consumes 4% of its body weight (including spoilage) and their average weight is 567 kg, the daily target herd consumption, *K*, was 1.0886 mt of cereal rye biomass (i.e., K =1.0886 mt G^{-1}). The calculation of daily hay cost savings, *H*, assumed hay dry matter at 84.5% of hay weight, and the price of hay at \$147.16 mt^{-1}: H =1.0886 mt G^{-1} × \$147.16 mt^{-1} × 84.5%/64.75 ha^{-1} = \$2.93 ha^{-1} G^{-1}.

Although our field experiments collected rye biomass data at two points in time (at most), *G* varied with the amount of biomass available on each day of the spring. We estimated *G* for the 21 treatments with both fall and spring biomass data using a two-step approach. First, we calculated the average daily growth rate of the biomass, *x*, between the date when vegetative dormancy broke, *d*, and the spring sampling date, *T*, as

$$x = (B^S/B^F)^{d-T} - 1, \tag{4}$$

where B^S is spring biomass; B^F is fall biomass; and the subscripts $\{m, r, a\}$ were excluded for simplicity of exposition. This equation solves the following compounded growth equation relating the fall biomass to the spring biomass, $B^S = B^F(1+x)^{(T-d)}$, for observed B^S, B^F, T, and d. The break in vegetative dormancy was documented on April 3, 2019, and March 4, 2020, for all locations. Then, we estimated the number of grazing days as:

$$G = \ln\left(\frac{64.75 \times x \times B^S}{K} + 1\right) - \ln(1+x), \tag{5}$$

where ln( ) indicates the natural logarithm of the expression inside the parenthesis. This equation solves the equality 64.75 × $B^S = K/x[(1+x)^G - 1]$, which requires that the target herd consumption volume, *K*, be available across the 64.75 ha each of the *G* days preceding termination date, subject to the restrictions that: (a) spring biomass be larger than or equal to the target herd consumption volume (i.e., $64.75 \times B^S \geq K$, otherwise $G = 0$); and (b) that the number of grazing days could not exceed the total number of days between the breaking of vegetative dormancy and termination (i.e., $G \leq (T-d)$), otherwise, some grazing days would take place in the fall, which would reduce the soil and water quality benefits of cover cropping. Although the latter effect is beyond the scope of this study, the environmental benefits of cover crops are typically major drivers of the adoption decision. For the late-drilled treatments, the number of grazing days was estimated using the average daily growth rate of cereal rye, *x*, calculated for the early-broadcast-equivalent treatment (same location, year, seeding rate, and target termination date). Since we did not collect biomass data for broadcast cereal rye in the northwest farm in 2019/20, we excluded the northwest farm from the 2019/20 feed-cost savings analysis.

Private net returns to cereal rye in an integrated crop and cow–calf system

The net returns to cereal rye preceding no-till corn in an integrated cow–calf system, *NRI*, were calculated as the direct sum of net returns from the corn partial budget and the net cost savings from the livestock operation:

$$\begin{aligned} NRI_{mra} = NR_{mra} + NCS_{mra} = \$190.66 \\ \times \Delta Y_{mra} - S_{mr} + \$3.30 \times G_{mra} - \$20.23. \end{aligned} \tag{6}$$

NRI_{mra} did not include a termination-cost-saving term because grazing is not an effective termination method for cover crops and rye was chemically terminated. We did not introduce adjustments to crop fertilization costs based on livestock manure left on soil surface while grazing, because volatile losses can reduce the fertilizer replacement value by as much as 85% (ISU Extension and Outreach, 2016). Recent research on short-term soil physical responses to grazing and cover crops in an integrated crop–livestock agroecosystem in South Dakota (Singh et al., 2022) concluded grazing cover crops did not cause substantial compaction or physical damage to the soil. Consequently, in the absence of similar local guidelines for Iowa, we assumed that hoof activity from livestock grazing in the spring had no significant effect on subsequent corn yields. Depending on the assumptions regarding the effects of cereal rye on corn yields, and the amount of cereal rye biomass left in the field by termination date, we developed three scenarios: no-grazing, full-grazing, and partial-grazing.

No-grazing scenario

This scenario was used as the baseline to measure any gains from grazing cereal rye biomass since it excluded the net cost savings from the livestock enterprise. We measured net returns to cereal rye in the no-grazing scenario as $NRI^{No}_{mra} = NR_{mra}$.

Full-grazing scenario

We based the full-grazing scenario on naïve assumptions that optimal timing of grazing decisions secured full use of cereal biomass produced during the spring, $G^{Full}_{mra} \equiv G_{mra}$, and the agronomic effect of the fully grazed cereal rye on corn yields was null, $\Delta Y_{mra} = 0$:

$$NRI^{Full}_{mra} = -S_{mr} + \$3.30 \times G^{Full}_{mra} - \$20.23. \tag{7}$$

This scenario was only intended to serve as an extreme hypothetical benchmark and was the least plausible of the three scenarios.

Partial-grazing scenario

For the partial-grazing scenario, we assumed that 90% of B^S was effectively grazed in the spring, leaving only 10% of the biomass on the field by termination date, $B' = 0.1 \times B^S$; and yield differences between treated and untreated plots were a function of B'. Replacing B^S by $(1 - B')$ in the equation for G and leaving all other variables unchanged, we calculated $G_{mra}^{Partial} \le G_{mra}^{Full}$.

Furthermore, we represented the statistical relationship between total cereal rye biomass at time of termination and percent corn yields differences between treated and untreated plots as

$$\begin{aligned}\%\Delta Y_{mra} = \alpha + \beta_1 \ln{(64.75 \times B_{mra}^S)}^{-1} \\ + \beta_2 \ln{(64.75 \times B_{mra}^S)}^{-2} + \mu_{mra},\end{aligned} \tag{8}$$

where $\%\Delta Y_{mra}$ was the observed percent difference between the average corn yield for treatment $\{m, r, a\}$ and the average corn yield in the corresponding check plots; α, β_1, β_2 were the parameters of the model to be estimated; and, μ_{mra} was a random disturbance with zero mean and finite variance.

We used the estimated parameters $\{\hat{\alpha}, \hat{\beta}_1, \hat{\beta}_2\}$ and the residuals $u_{mra} = \%\Delta Y_{mra} - \hat{\alpha} + \hat{\beta}_1 \ln{(64.75 \times B_{mra}^S)}^{-1} + \hat{\beta}_2 \ln{(64.75 \times B_{mra}^S)}^{-2}$ to project the percent difference in yields between treated and untreated plots for each level of B'_{mra} as follows:

$$\begin{aligned}\widehat{\%\Delta Y}_{mra} = \hat{\alpha} + \hat{\beta}_1 \ln{(64.75 \times B_{mra}^S)}^{-1} \\ + \hat{\beta}_2 \ln{(64.75 \times B_{mra}^S)}^{-2} + u_{mra}.\end{aligned} \tag{9}$$

Then, we derived the differences between treated and untreated plots using $\Delta\hat{Y}_{mra} = Y_{mra} \times \widehat{\%\Delta Y}_{mra}$, where Y_{mra} indicated the average corn yield in the check plots for treatment $\{m, r, a\}$. In summary, we calculated the net returns to cereal rye in the partial grazing scenario as:

$$\begin{aligned}NRI_{mra}^{Partial} = \$190.66 \times \Delta\hat{Y}_{mra} - S_{mr} \\ + \$3.30 \times G_{mra}^{Partial} - \$20.23.\end{aligned} \tag{10}$$

Results

We pooled observations across years (to emulate farmers' production uncertainty when deciding whether to plant cereal rye) and across locations (to maximize degrees of freedom in our statistical analyses). We evaluated treatment effects in each of the variables of interest within and across factors $\{m, r, a\}$ applying analysis of variance (ANOVA) and adjusted P-values from Tukey's honestly significant difference tests with 95% family-wise confidence level in R Version 4.0.0. (R Core Team, 2017). Levene and Shapiro–Wilk tests were used to check for homogeneity of variance and normality of the residuals, respectively. When the hypothesis of normal residuals was rejected, we applied the non-parametric Kruskal–Wallis rank sum test (Hollander and Wolfe, 1973) to compare the location parameters of the distribution of an observed variable across groups.

No-grazing scenario

Corn yield differences between treated and check plots, ΔY, averaged -0.292 mt ha^{-1} across the 45 treatments (Table 3). ΔY averaged -0.760 mt ha^{-1} across the 29 treatments (64.4%) with $\Delta Y < 0$, and 0.555 mt ha^{-1} across the other 16 treatments (35.6%). While ΔY averaged 0.113 mt ha^{-1} across late-drilled plots, it averaged -0.755 mt ha^{-1} across early-broadcast plots. Furthermore, 90.5% of the early-broadcast plots showed $\Delta Y < 0$, but only 41.7% of the late-drilled plots did.

The mean corn yield difference between late-drilled plots and their corresponding check plots was 0.868 mt ha^{-1} higher than the mean corn yield difference between early-broadcast plots and their corresponding check plots (adj. P-value = 0.0015). While higher seeding rates and delayed termination were associated with more negative mean yield differences between treated and check plots (Table 3), those effects were not statistically significant in an ANOVA of ΔY.

Private net returns in the no-grazing scenario, NRI^{No}, averaged $-\$123.74$ ha^{-1} across the 45 treatments (Table 4). NRI^{No} was negative for 37 treatments (82.2%), averaging $-\$174.88$ ha^{-1}, and positive for 18 treatments (17.8%), averaging \$112.75 ha^{-1}. Most of the negative net returns came from plots with early-broadcast cereal rye (20 *vs* 17 plots), which produced more biomass and suffered larger corn yield penalties than late-drilled plots, as discussed in the next subsection.

Net returns were \$165.96 ha^{-1} less negative in late-drilled plots, on average, than in early-broadcast plots (adj. P-value = 0.0015), driven by corn yield differences across planting date-methods (Table 4). The average net loss across early-broadcast plots where $NRI^{No} < 0$ was almost twice in magnitude as the average net loss across late-drilled plots where $NRI^{No} < 0$: $-\$223.52$ *vs* $-\$117.65$ ha^{-1}. Slightly less than one-third of the late-drilled plots (29.2%) had positive NRI^{No} and averaged \$127.01 ha^{-1}.

Full-grazing scenario

The estimated number of grazing days for 48 lactating cows across 64.75 ha planted to cereal rye ranged from 2.4 to 50.7 days, and averaged 18.0 days, based on a mean biomass availability of 0.870 mt ha^{-1} on termination date (Table 5).

Due to high correlation between biomass and grazing days (Pearson correlation coefficient = 0.6589), we measured the treatment effects on the former (observed) variable. Furthermore, since the Shapiro–Wilk (P-value = 0.020) test and the Levene test for homogeneity of variance (P-value < 0.001) rejected normality of the ANOVA residuals, we evaluated the treatment effects on B^S with the Kruskal–Wallis rank-sum test (Table 6). Planting date-method, termination date, their interaction, and the interaction between planting date-method and seeding rate had statistically significant effects on biomass availability. Biomass in early-broadcast plots was, on average, 1.1 mt ha^{-1} higher (P-value < 0.001) than in late-drilled plots (Table 5). A target termination date of 3 DBP was associated with an extra 0.9 mt ha^{-1} of rye biomass (P-value = 0.055) than a target termination date of 14 DBP. The difference in mean biomass produced across early-broadcasting and late-planting is significantly higher (P-value < 0.001) for a 3 DBP target termination date (2.3 mt ha^{-1}) than for a 14 DBP target termination date (0.6 mt ha^{-1}). Termination date was the only factor with a statistically significant effect on the variability of biomass across early-broadcast plots (P-value = 0.005): a 3 DBP target termination date was associated with 1.8 mt ha^{-1} higher biomass than a 14 DBP target termination date. Seeding rates had a relatively larger effect on biomass in late-drilled than in early-broadcast plots (P-value = 0.002): the mean biomass differences between high seeding rates and low seeding rates were 0.2 mt ha^{-1} for late-drilled rye and 0.1 mt ha^{-1} for early-broadcast rye.

As shown in the last four columns of Table 5, early-broadcast plots produced 14.6 more grazing days than late-drilled plots

Table 3. Descriptive statistics of corn yield differences between treated and untreated plots, ΔY

		All observations				Negative yield difference		Positive yield difference	
Treatment	*N*	Mean difference (mt ha^{-1})	StDev (mt ha^{-1})	Min (mt ha^{-1})	Max (mt ha^{-1})	% of *N*	Mean difference (mt ha^{-1})	% of *N*	Mean difference (mt ha^{-1})
All	45	−0.292	0.895	−2.852	2.089	64.4%	−0.760	35.6%	0.555
Planting date-method									
B	21	−0.755	0.732	−2.852	0.317	90.5%	−0.852	9.5%	0.168
D	24	0.113	0.837	−1.765	2.089	41.7%	−0.584	58.3%	0.611
Seeding rate									
L	15	−0.133	0.670	−1.447	0.886	66.7%	−0.467	33.3%	0.535
M	15	−0.348	0.764	−1.654	1.290	66.7%	−0.741	33.3%	0.437
H	15	−0.395	1.202	−2.852	2.089	60.0%	−1.105	40.0%	0.671
Termination date									
14	33	−0.248	0.852	−2.852	2.089	63.6%	−0.672	36.4%	0.495
3	12	−0.414	1.035	−1.765	1.290	66.7%	−0.989	33.3%	0.737
Planting date-method × seeding rate									
B × L	7	−0.544	0.674	−1.447	0.317	85.7%	−0.688	14.3%	0.317
B × M	7	−0.753	0.596	−1.654	0.019	85.7%	−0.881	14.3%	0.019
B × H	7	−0.968	0.934	−2.852	−0.282	100.0%	−0.968	0.0%	n/a
D × L	8	0.227	0.436	−0.239	0.886	50.0%	−0.137	50.0%	0.590
D × M	8	0.005	0.746	−1.131	1.290	50.0%	−0.530	50.0%	0.541
D × H	8	0.107	1.236	−1.765	2.089	25.0%	−1.584	75.0%	0.671
Planting date-method × termination date									
B × 14	15	−0.695	0.730	−2.852	0.019	93.3%	−0.746	6.7%	0.019
D × 14	18	0.124	0.778	−1.403	2.089	38.9%	−0.525	61.1%	0.538
B × 3	6	−0.905	0.783	−1.654	0.317	83.3%	−1.150	16.7%	0.317
D × 3	6	0.078	1.079	−1.765	1.290	50.0%	−0.721	50.0%	0.877
Seeding rate × termination date									
L × 14	11	−0.139	0.574	−1.403	0.696	72.7%	−0.376	27.3%	0.491
M × 14	11	−0.370	0.606	−1.377	0.522	63.6%	−0.709	36.4%	0.223
H × 14	11	−0.234	1.264	−2.852	2.089	54.5%	−1.024	45.5%	0.714
L × 3	4	−0.116	0.996	−1.447	0.886	50.0%	−0.834	50.0%	0.602
M × 3	4	−0.288	1.222	−1.654	1.290	75.0%	−0.814	25.0%	1.290
H × 3	4	−0.836	1.033	−1.765	0.455	75.0%	−1.267	25.0%	0.455

Notes: B, early-broadcast; D, late-drill; L, low seeding rate; M, medium seeding rate; H, high seeding rate; 3 = target termination date 3 days before planting; 14 = target termination date 14 days before planting.

(25.3 *vs* 10.7 days), on average, and a 3 DBP target termination date was associated with 8.8 extra grazing days over a 14 DBP target termination date (24.3 *vs* 15.5 days). Early-broadcast plots with a 3 DBP target termination date produced the largest number of grazing days (35.5 days) among the four possible combinations of planting date-methods and termination dates, while late-drilled plots with a 14 DBP termination date produced the lowest number of grazing days (9.8 days). On late-drilled plots, high seeding rates produced, on average, 4.9 extra grazing days than low seeding rates (13.1 *vs* 8.2 grazing days with 3.28 *vs* 1.65 million seeds ha^{-1}, respectively); but the difference was only 3.4 extra grazing days on early-broadcast plots (27.0 *vs* 23.6 grazing days with 2.47 *vs* 0.82 million seeds ha^{-1}, respectively). Appendix Table A4 reports the information used to calculate grazing days by treatment in the full-grazing scenario.

Net cost savings in the cow–calf enterprise, *NCS*, ranged from −\$12.21 to \$146.69 ha^{-1}, and averaged \$39.15 ha^{-1} (Appendix Table A5). In 35 out of 42 treatments, or 83.3% of the time, the estimated cost savings from grazing cereal rye more than offset the extra fencing costs, resulting in net cost savings to the cow–calf operation. All the early-broadcast plots and two-thirds of the late-drilled plots experienced net cost savings (averaging \$63.22

Table 4. Descriptive statistics of net returns to cereal rye in the no-grazing scenario, NRI^{No}

		All observations				Negative net returns		Positive net returns	
Treatment	*N*	Mean ($ ha^{-1})	StDev ($ ha^{-1})	Min ($ ha^{-1})	Max ($ ha^{-1})	% of *N*	Mean ($ ha^{-1})	% of *N*	Mean ($ ha^{-1})
All	45	−$123.74	$173.74	−$632.86	$309.52	82.2%	−$174.88	17.8%	$112.75
Planting date-method									
B	21	−$212.26	$144.78	−$632.86	$12.96	95.2%	−$223.52	4.8%	$12.96
D	24	−$46.29	$161.56	−$425.32	$309.52	70.8%	−$117.65	29.2%	$127.01
Seeding rate									
L	15	−$72.49	$127.93	−$323.43	$122.33	73.3%	−$124.40	26.7%	$70.24
M	15	−$134.57	$145.69	−$383.72	$177.99	86.7%	−$171.39	13.3%	$104.76
H	15	−$164.16	$229.31	−$632.86	$309.52	86.7%	−$221.08	13.3%	$205.77
Termination date									
14	33	−$115.32	$164.32	−$632.86	$309.52	84.8%	−$156.94	15.2%	$117.75
3	12	−$146.90	$203.44	−$425.32	$177.99	75.0%	−$230.67	25.0%	$104.42
Planting date-method × seeding rate									
B × L	7	−$151.36	$128.56	−$323.43	$12.96	85.7%	−$178.75	14.3%	$12.96
B × M	7	−$211.77	$113.61	−$383.72	−$64.72	100.0%	−$211.77	0.0%	n/a
B × H	7	−$273.63	$178.09	−$632.86	−$142.75	100.0%	−$273.63	0.0%	n/a
D × L	8	−$3.48	$83.07	−$92.34	$122.33	62.5%	−$59.18	37.5%	$89.34
D × M	8	−$67.01	$142.15	−$283.59	$177.99	75.0%	−$124.27	25.0%	$104.76
D × H	8	−$68.38	$235.62	−$425.32	$309.52	75.0%	−$159.76	25.0%	$205.77
Planting date-method × termination date									
B × 14	15	−$200.80	$144.44	−$632.86	−$56.33	100.0%	−$200.80	0.0%	n/a
D × 14	18	−$44.09	$147.74	−$356.29	$309.52	72.2%	−$106.33	27.8%	$117.75
B × 3	6	−$240.89	$155.10	−$387.83	$12.96	83.3%	−$291.66	16.7%	$12.96
D × 3	6	−$52.90	$213.99	−$425.32	$177.99	66.7%	−$154.43	33.3%	$150.16
Seeding rate × termination date									
L × 14	11	−$73.67	$109.82	−$315.10	$86.09	81.8%	−$106.23	18.2%	$72.84
M × 14	11	−$138.73	$115.55	−$330.92	$31.53	90.9%	−$155.76	9.1%	$31.53
H × 14	11	−$133.56	$241.07	−$632.86	$309.52	81.8%	−$208.97	18.2%	$205.77
L × 3	4	−$69.25	$190.13	−$323.43	$122.33	50.0%	−$206.15	50.0%	$67.64
M × 3	4	−$123.12	$233.02	−$383.72	$177.99	75.0%	−$223.49	25.0%	$177.99
H × 3	4	−$248.31	$196.98	−$425.32	−$1.97	100.0%	−$248.31	0.0%	n/a

Notes: B, early-broadcast; D, late-drill; L, low seeding rate; M, medium seeding rate; H, high seeding rate; 3 = target termination date 3 days before planting; 14 = target termination date 14 days before planting.

and \$25.90 ha^{-1}, respectively), and only one-third of the late-drilled plots experienced extra net costs (averaging −\$6.57 ha^{-1}).

Private net returns to cereal rye in the full-grazing scenario, NRI^{Full}, averaged −\$28.91 ha^{-1} across all treatments, and −\$45.27 ha^{-1} for 34 out of 42 treatments (81.0%) with $NRI^{Full} < 0$ (Table 7). The average net return for the remaining 19.0% of treatments where $NRI^{Full} > 0$ was \$40.66 ha^{-1}. All but one of the late-drilled plots and two-thirds of the early-broadcast plots experienced negative net returns, averaging −\$55.47 and −\$30.70 ha^{-1}, respectively. Only one late-drilled plot and one-third of the early-broadcast plots obtained positive net returns, averaging \$1.76 and \$46.22 ha^{-1}, respectively.

For the subset of early-broadcast plots, only termination date had a marginally statistically significant effect on net returns (P-value = 0.062): plots with a 3 DBP termination date obtained a \$46.71 ha^{-1} higher average net return than plots with a 14 DBP termination date (\$28.30 *vs* −\$18.41 ha^{-1}); and, while only 20% of the treated plots obtained positive net returns in the latter group, two-thirds of the plots in the former group did.

For the subset of late-drilled plots, only seeding rate had a negative and marginally statistically significant effect on net returns (P-value = 0.081): the higher the seeding rate, the more negative the net returns to late-drilled cereal rye.

Table 5. Descriptive statistics of spring biomass, B^S, and grazing days in the full-grazing scenario, G^{Full}

		Biomass on termination date, B^S				Estimated number of grazing days, G^{Full}			
Treatment	N^	Mean (mt ha^{-1})	StDev (mt ha^{-1})	Min (mt ha^{-1})	Max (mt ha^{-1})	Mean (days)	StDev (days)	Min (days)	Max (days)
All	42	0.870	1.026	0.043	4.320	18.0	12.9	2.4	50.7
Planting date-method									
B	21	1.416	1.187	0.144	4.320	25.3	13.1	7.2	50.7
D	21	0.323	0.348	0.043	1.224	10.7	7.7	2.4	27.3
Seeding rate									
L	14	0.812	1.151	0.043	4.320	15.9	13.7	2.4	50.7
M	14	0.821	0.897	0.063	3.268	18.2	13.2	3.6	47.9
H	14	0.976	1.084	0.077	4.273	20.0	12.5	4.4	48.6
Termination date									
14	30	0.606	0.558	0.043	1.833	15.5	10.7	2.4	37.3
3	12	1.528	1.563	0.116	4.320	24.3	16.2	5.3	50.7
Planting date-method × seeding rate									
B × L	7	1.407	1.413	0.144	4.320	23.6	15.1	7.2	50.7
B × M	7	1.308	1.011	0.156	3.268	25.4	13.3	8.1	47.9
B × H	7	1.534	1.286	0.192	4.273	27.0	12.6	10.2	48.6
D × L	7	0.217	0.215	0.043	0.544	8.2	6.4	2.4	18.4
D × M	7	0.333	0.408	0.063	1.197	10.9	8.8	3.6	27.3
D × H	7	0.419	0.408	0.077	1.224	13.1	8.0	4.4	26.3
Planting date-method × termination date									
B × 14	15	0.907	0.548	0.144	1.833	21.3	10.2	7.2	37.3
D × 14	15	0.305	0.388	0.043	1.224	9.8	7.8	2.4	27.3
B × 3	6	2.689	1.442	1.240	4.320	35.5	14.9	21.3	50.7
D × 3	6	0.366	0.245	0.116	0.714	13.1	7.3	5.3	22.0
Seeding rate × termination date									
L × 14	10	0.477	0.528	0.043	1.678	12.7	10.4	2.4	37.3
M × 14	10	0.633	0.613	0.063	1.833	16.0	11.5	3.6	36.7
H × 14	10	0.710	0.563	0.077	1.500	17.9	10.6	4.4	37.1
L × 3	4	1.650	1.895	0.116	4.320	24.0	19.2	5.3	50.7
M × 3	4	1.290	1.395	0.147	3.268	23.6	17.5	6.5	47.9
H × 3	4	1.642	1.819	0.200	4.273	25.3	16.9	8.1	48.6

Notes: B, early-broadcast; D, late-drill; L, low seeding rate; M, medium seeding rate; H, high seeding rate; 3 = target termination date 3 days before planting; 14 = target termination date 14 days before planting; ^ 2019/20 treatments in the northwest farm were excluded due to the unavailability of biomass data.

Partial-grazing scenario

On average, across all treatments, the number of grazing days in the partial-grazing scenario was slightly less than one day (0.92) lower than in the full-grazing scenario. The fitted model from Equation (8) was statistically significant (F-statistic P-value < 0.001) and explained 30.87% of the variability in $\%\Delta Y$ (Table 8). As shown in Figure 1, the fitted percent difference in corn yields between treated and untreated plots was positive for low levels of spring biomass (following an increasing and then decreasing pattern) and then turned negative (and increasingly so) for higher levels of spring biomass. We obtained the projected percent corn yield difference for each (unobserved) level of spring biomass in the partial-grazing model, $\widehat{\%\Delta Y}_{mra}$, using the estimated coefficients from Table 8 and substituting B^S_{mra} for B'_{mra} and u_{mra} for μ_{mra} in the statistical model. To avoid using the estimated model to predict values of the independent variable outside of the observed range of dependent variables, we imposed the condition that $\widehat{\%\Delta Y}_{mra} = u_{mra}$ when $(1 - B'_{mra}) < \min(B^S) = 42.61\ \mathrm{kg\,ha^{-1}}$ of dry matter. In other words, we assumed when the biomass left in the field on termination date (not grazed) was very small, cereal rye did not affect corn yields in the treated plot and any difference between corn yields in the treated plot and the check plot was caused by variables other than cereal rye biomass. This condition was binding for 19 treatments.

Table 6. Kruskal–Wallis rank-sum tests on spring biomass, B^S

Factor by planting date-method	Chi-square	DF	*P*-value	
All planting date-methods				
Planting date-method	17.33	1	<0.001	***
Seeding rate	1.47	2	0.480	
Termination date	3.69	1	0.055	.
Planting date-method × seeding rate	19.22	5	0.002	**
Planting date-method × termination date	21.94	3	<0.001	***
Seeding rate × termination date	5.40	5	0.369	
Early-broadcast				
Seeding rate	0.20	2	0.905	
Termination date	7.85	1	0.005	**
Seeding rate × termination date	8.46	5	0.133	
Late-drill				
Seeding rate	2.87	2	0.238	
Termination date	1.36	1	0.243	
Seeding rate × termination date	4.39	5	0.494	

Notes: Significance codes: '***' 0.001; '**' 0.01; '*' 0.05; '.' 0.1.

The projected yield differences,$\Delta\hat{Y}_{mra}$, obtained by multiplying corn yield in the corresponding check plot by $\%\widehat{\Delta Y}_{mra}$, were, on average, 0.410 mt ha^{-1} higher than under the no-grazing scenario. Eighteen treatments experienced a 0.219 mt ha^{-1} yield decline, and 24 treatments experienced a 0.883 mt ha^{-1} yield increase in the partial-grazing scenario, on average, with respect to the no-grazing scenario (Appendix Table A6).

Net returns in the partial-grazing scenario, $NRI^{Partial}$, averaged −$15.24 ha^{-1} across all treatments (Table 9), and were, on average, $13.66 ha^{-1} less negative than NRI^{Full} and $108.50 ha^{-1} less negative than NRI^{No}. However, dispersion of net returns around the mean (measured by the coefficient of variation, CV) in the partial-grazing scenario was higher than in the full-grazing and no-grazing scenarios (CVs of 9.40 *vs* 1.51 and 1.40, respectively). The average net return across the 23 treatments where $NRI^{Partial} < 0$ amounted to −$116.27 ha^{-1}, which was $58.61 ha^{-1} less negative than for treatments where $NRI^{No} < 0$, but $71.00 ha^{-1} more negative than the treatments where $NRI^{Full} < 0$.

The average net return across the 19 treatments where $NRI^{Partial} > 0$ amounted to $107.05 ha^{-1}, which was $5.70 ha^{-1} lower than for the treatments where $NRI^{No} > 0$, and $66.39 ha^{-1} higher than the treatments where $NRI^{Full} > 0$. No statistically significant differences were found in $NRI^{Partial}$ across agronomic treatments.

Slightly more than half of the early-broadcast plots (52.4%) obtained positive net returns to cereal rye, averaging $98.15 ha^{-1}, while only 38.1% of the late-drilled plots did, averaging $110.30 ha^{-1}. A higher biomass availability in the spring generated with lower planting costs in the early-broadcast plots resulted in more economical grazing days and a higher probability of breaking-even than in late-drilled plots.

Discussion

Effects of farming practices on private net returns to cereal rye

Our findings have multiple implications for farm management. First, the statistical relationship between higher cereal rye biomass in the spring and lower subsequent corn yields showcases the trade-off faced by farmers between producing higher environmental services and incurring economic losses. Private net returns to cereal rye in the no-grazing scenario were negative for 82.2% of the treatments and averaged −$174.88 ha^{-1} for those treatments. In the absence of large financial incentives (subsidies, cost-share payments, or payments for ecosystem services) our findings suggest cover crops will not be adopted at large scale in Iowa.

Second, average net returns were significantly less negative in late-drilled plots than in early-broadcast plots in the no-grazing scenario, as higher rye biomass negatively affected corn yields relatively more in the latter than in the former plots. This suggests Iowa farmers would be more likely to break even if the planting date-method combination could be adjusted to achieve their environmental goals while minimizing corn yield losses. Late-broadcasting cereal rye (which was not explored in this study) could produce similar or even higher net returns than late-drilling, given the lower expenses associated with the former planting method.

Third, since seeding rates and target termination dates were not statistically significant factors affecting net returns to cereal rye in the no-grazing scenario, farmers could benefit from further research exploring the use of lower seeding rates and flexible termination dates to minimize costs subject to achieving their environmental goals. Marcillo et al. (2019) reported less negative private net returns to cereal rye at lower seeding rates.

Fourth, our finding that 45.2% of the plots under partial grazing obtained average net returns of $107.05 ha^{-1} suggests that cereal rye could be profitable to a sizeable share of the integrated row–crop and cow–calf production systems in Iowa when the rye biomass is used as forage. Figure 2 illustrates the relation between $NRI^{Partial}$ and total biomass produced by termination date (both grazed and left in the field). It seems to suggest that in order to be profitable while providing ground cover and its associated environmental benefits, cereal rye had to produce a total biomass of at least 2 mt ha^{-1} and possibly 3 mt ha^{-1} by

Table 7. Descriptive statistics of net returns to cereal rye in the full-grazing scenario, NRI^{Full}

	All observations					Negative net returns		Positive net returns	
Treatment	*N*	Mean (\$ ha^{-1})	StDev (\$ ha^{-1})	Min (\$ ha^{-1})	Max (\$ ha^{-1})	% of *N*	Mean (\$ ha^{-1})	% of *N*	Mean (\$ ha^{-1})
All	42	−\$28.91	\$43.66	−\$94.47	\$99.13	81.0%	−\$45.27	19.0%	\$40.66
Planting date-method									
B	21	−\$5.06	\$44.75	−\$75.72	\$99.13	66.7%	−\$30.70	33.3%	\$46.22
D	21	−\$52.75	\$26.67	−\$94.47	\$1.76	95.2%	−\$55.47	4.8%	\$1.76
Seeding rate									
L	14	−\$15.00	\$44.92	−\$58.90	\$99.13	78.6%	−\$33.47	21.4%	\$52.71
M	14	−\$28.58	\$43.48	−\$76.49	\$69.35	78.6%	−\$45.78	21.4%	\$34.47
H	14	−\$43.13	\$40.95	−\$94.47	\$50.87	85.7%	−\$55.63	14.3%	\$31.87
Termination date									
14	30	−\$37.17	\$35.79	−\$94.47	\$55.16	86.7%	−\$46.82	13.3%	\$25.52
3	12	−\$8.24	\$55.45	−\$82.35	\$99.13	66.7%	−\$40.26	33.3%	\$55.80
Planting date-method × seeding rate									
B × L	7	\$9.89	\$49.86	−\$44.00	\$99.13	57.1%	−\$22.23	42.9%	\$52.71
B × M	7	−\$4.73	\$43.95	−\$61.92	\$69.35	71.4%	−\$26.95	28.6%	\$50.83
B × H	7	−\$20.36	\$41.51	−\$75.72	\$50.87	71.4%	−\$41.25	28.6%	\$31.87
D × L	7	−\$39.90	\$20.95	−\$58.90	−\$6.30	100.0%	−\$39.90	0.0%	n/a
D × M	7	−\$52.44	\$28.94	−\$76.49	\$1.76	85.7%	−\$61.47	14.3%	\$1.76
D × H	7	−\$65.90	\$26.48	−\$94.47	−\$22.32	100.0%	−\$65.90	0.0%	n/a
Planting date-method × termination date									
B × 14	15	−\$18.41	\$34.53	−\$75.72	\$55.16	80.0%	−\$31.37	20.0%	\$33.44
D × 14	15	−\$55.93	\$26.60	−\$94.47	\$1.76	93.3%	−\$60.05	6.7%	\$1.76
B × 3	6	\$28.30	\$52.92	−\$35.12	\$99.13	33.3%	−\$26.70	66.7%	\$55.80
D × 3	6	−\$44.78	\$27.55	−\$82.35	−\$6.30	100.0%	−\$44.78	0.0%	n/a
Seeding rate × termination date									
L × 14	10	−\$25.71	\$34.03	−\$58.90	\$55.16	90.0%	−\$34.69	10.0%	\$55.16
M × 14	10	−\$35.75	\$37.86	−\$76.49	\$32.30	80.0%	−\$48.95	20.0%	\$17.03
H × 14	10	−\$50.05	\$34.71	−\$94.47	\$12.87	90.0%	−\$57.04	10.0%	\$12.87
L × 3	4	\$11.76	\$62.69	−\$49.64	\$99.13	50.0%	−\$27.97	50.0%	\$51.49
M × 3	4	−\$10.66	\$57.40	−\$66.91	\$69.35	75.0%	−\$37.33	25.0%	\$69.35
H × 3	4	−\$25.82	\$55.62	−\$82.35	\$50.87	75.0%	−\$51.38	25.0%	\$50.87

Notes: B, early-broadcast; D, late-drill; L, low seeding rate; M, medium seeding rate; H, high seeding rate; 3 = target termination date 3 days before planting; 14 = target termination date 14 days before planting.

Table 8. Statistical model of percent change in corn yield differences between treated and untreated plots, $\%\Delta Y$

Parameters	Estimate	Std. error	*t* value	Pr(>|*t*|)
α	−61.42	24.11	−2.548	0.0146*
β_1	569.31	272.82	2.087	0.0430*
β_2	−1262.59	747.33	−1.689	0.0985

Notes: Significance codes: '***' 0.001; '**' 0.01; '*' 0.05; '.' 0.1. Residual standard error: 6.799 on 42 degrees of freedom. Multiple R^2: 0.3083, *F*-statistic: 9.358 on 2 and 42 DF, *P*-value: 0.0004354.

termination date. However, this is a testable hypothesis that should be further explored with a larger sample size.

Finally, our methodology could serve as the basis for future research to develop local guidelines to maximize private net returns to cereal rye in integrated crop and livestock systems, with expanded models also accounting for forage quality, actual herd behavior and associated weight gain, soil compaction issues, manure quantity and quality during grazing. For example, while cereal rye can be a very high-quality forage for cattle when grazed appropriately, farmers should be aware of local risks for grass tetany, ergot poisoning, and nitrate toxicity (Iowa Beef Center,

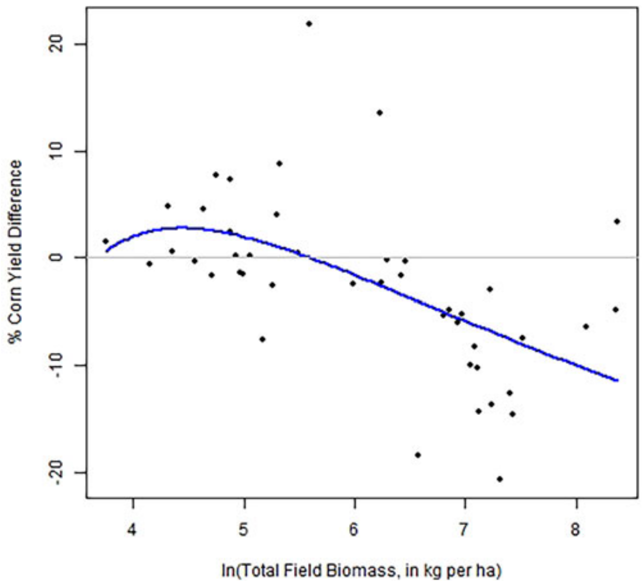

Figure 1. Fitted and observed percent changes in corn yield differences, %Δ*Y*, *vs* total field biomass, ln $(64.75 \times B^S)$.

2018), as well as herbicide carry over from the soybean phase of the crop rotation (Hartzler, Anderson and Vittetoe, 2017).

Cost-share programs and social net returns to cereal rye

Our findings also have multiple implications for policy analysis. Since the USDA considers grazing livestock on cereal rye a good farming practice in Iowa, implementing this practice does not impact farmers' ability to receive government payments or subsidies or their amounts (USDA, 2019b). If the average incentive of \$83.59 ha^{-1} from the USDA Environmental Quality Incentives Program (EQIP) to plant cereal rye in Iowa (Sawadgo and Plastina, 2018; Myers, Weber and Tellatin, 2019) had been applied to all treated farms in our analysis, the percent of plots that would have generated positive net returns in the no-grazing scenario would have increased from 17.8 to 42.2%. While this seems like a substantial achievement, it is relevant to highlight that even under such a generous incentive, 57.8% of the treatments would have incurred annual net losses. Even after doubling the cost-share incentive to \$167.19 ha^{-1}, 37.8% of the treatments would have not broken-even in the no-grazing scenario. In the partial-grazing scenario, cost-share incentives to plant cereal rye of \$83.59 and \$167.19 ha^{-1} would have

Table 9. Descriptive statistics of net returns to cereal rye in the partial-grazing scenario, $NRI^{Partial}$

		All observations				Negative net returns		Positive net returns	
Treatment	*N*	Mean (\$ ha^{-1})	StDev (\$ ha^{-1})	Min (\$ ha^{-1})	Max (\$ ha^{-1})	% of *N*	Mean (\$ ha^{-1})	% of *N*	Mean (\$ ha^{-1})
All	42	−\$15.24	\$143.21	−\$323.18	\$328.65	54.8%	−\$116.27	45.2%	\$107.05
Planting date-method									
B	21	−\$7.96	\$141.56	−\$323.18	\$328.65	47.6%	−\$124.67	52.4%	\$98.15
D	21	−\$22.53	\$147.96	−\$254.99	\$327.09	61.9%	−\$109.81	38.1%	\$119.30
Seeding rate									
L	14	\$18.05	\$119.87	−\$136.87	\$328.65	50.0%	−\$68.86	50.0%	\$104.95
M	14	−\$28.76	\$137.17	−\$228.44	\$292.48	57.1%	−\$122.16	42.9%	\$95.77
H	14	−\$35.01	\$172.29	−\$323.18	\$327.09	57.1%	−\$151.86	42.9%	\$120.79
Termination date									
14	30	−\$27.61	\$126.62	−\$323.18	\$327.09	56.7%	−\$111.57	43.3%	\$82.18
3	12	\$15.68	\$180.86	−\$254.99	\$328.65	50.0%	−\$129.58	50.0%	\$160.94
Planting date-method × seeding rate									
B × L	7	\$26.86	\$158.12	−\$136.87	\$328.65	57.1%	−\$76.64	42.9%	\$164.85
B × M	7	−\$3.35	\$97.73	−\$144.86	\$122.18	42.9%	−\$98.78	57.1%	\$68.22
B × H	7	−\$47.37	\$170.28	−\$323.18	\$131.12	42.9%	−\$214.60	57.1%	\$78.04
D × L	7	\$9.24	\$77.11	−\$131.78	\$103.79	42.9%	−\$58.48	57.1%	\$60.03
D × M	7	−\$54.18	\$172.36	−\$228.44	\$292.48	71.4%	−\$136.20	28.6%	\$150.87
D × H	7	−\$22.65	\$187.00	−\$254.99	\$327.09	71.4%	−\$114.23	28.6%	\$206.28
Planting date-method × termination date									
B × 14	15	−\$26.14	\$121.28	−\$323.18	\$130.98	46.7%	−\$127.10	53.3%	\$62.21
D × 14	15	−\$29.09	\$136.01	−\$228.44	\$327.09	66.7%	−\$100.70	33.3%	\$114.15
B × 3	6	\$37.50	\$188.42	−\$144.86	\$328.65	50.0%	−\$118.99	50.0%	\$193.98

(*Continued*)

Table 9. (*Continued.*)

	All observations					Negative net returns		Positive net returns	
Treatment	*N*	Mean ($ ha^{-1})	StDev ($ ha^{-1})	Min ($ ha^{-1})	Max ($ ha^{-1})	% of *N*	Mean ($ ha^{-1})	% of *N*	Mean ($ ha^{-1})
D × 3	6	−$6.14	$187.93	−$254.99	$292.48	50.0%	−$140.18	50.0%	$127.90
Seeding rate × termination date									
L × 14	10	−$9.53	$89.72	−$136.87	$130.98	60.0%	−$68.36	40.0%	$78.70
M × 14	10	−$52.75	$97.69	−$228.44	$61.04	60.0%	−$114.58	40.0%	$39.99
H × 14	10	−$20.55	$181.52	−$323.18	$327.09	50.0%	−$159.82	50.0%	$118.72
L × 3	4	$87.00	$170.99	−$71.86	$328.65	25.0%	−$71.86	75.0%	$139.95
M × 3	4	$31.20	$214.93	−$144.98	$292.48	50.0%	−$144.92	50.0%	$207.33
H × 3	4	−$71.17	$165.37	−$254.99	$131.12	75.0%	−$138.60	25.0%	$131.12

Notes: B, early-broadcast; D, late-drill; L, low seeding rate; M, medium seeding rate; H, high seeding rate; 3 = target termination date 3 days before planting; 14 = target termination date 14 days before planting.

brought the share of profitable farms to 69.0 and 90.5%, respectively.

Additionally, it is important to consider the differential impact of the same EQIP incentive across high- *vs* low-biomass producing practices, conceptually represented in our study through late-drilled *vs* early-broadcast plots, respectively. In the no-grazing scenario, 66.7% of the plots with low-biomass and 14.3% of the plots with high-biomass would have obtained positive net returns after receiving EQIP payments. This comparison should inform policy discussions on the cost-effectiveness of public programs

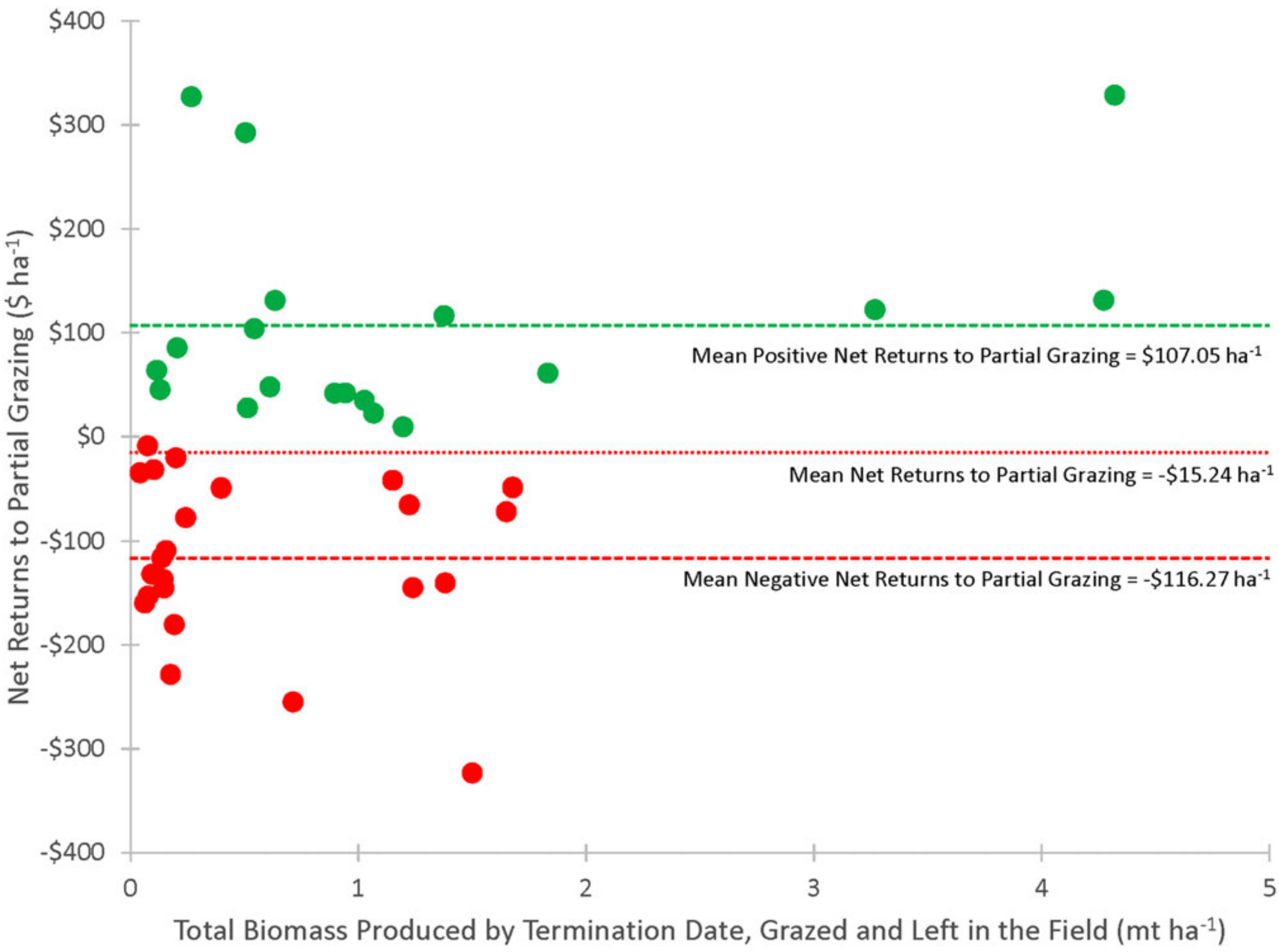

Figure 2. Net returns to partial grazing versus total biomass produced by termination date (grazed and left in the field).

to achieve environmental goals, and induce research on the social net returns to alternative cover cropping methods targeting high-biomass production.

Under partial grazing, the differential impact of an \$83.59 ha^{-1} EQIP payment on private net returns across high- *vs* low-biomass plots would have been much smaller: 66.7% of the low-biomass plots and 71.4% of the high-biomass plots would have obtained positive private net returns. However, further research is still needed to understand the social net returns to cereal rye planted for forage.

Other variables affecting net returns to cereal rye

Several caveats apply to our analysis. First, despite the large number of data points from experimental plots (324 observations), our analysis relied on homogeneous economic variables across location-years. While this seemed appropriate to evaluate the differential effects of agronomic practices on annual private net returns to cereal rye, our results might overstate the percent of treatments that would have generated losses to real farming operations, simply because farmers who anticipate losses might not plant cover crops.

Second, we relied on a fixed combination of herd size and area planted to cereal rye to estimate private net returns that were representative of a sizable portion of integrated farms in Iowa. Since the relationships between herd size, planted area, and net returns are non-linear, further analysis beyond the scope of this study would be required to develop practical guidelines to optimize the addition of cereal rye to integrated crop–livestock systems.

Third, while we incorporated fixed fencing costs into the analysis, we did not incorporate the opportunity cost of capital associated with the fencing equipment and the planting of 64.75 ha of cereal rye. This was an intentional choice to estimate the upper bound of net returns to cereal rye. Adding opportunity costs to our study will only reduce the calculated net returns.

Fourth, we calculated net returns to cereal rye only for no-till corn due to its higher environmental desirability than conventional tillage. However, no-till only accounts for 31% of tillable cropland in Iowa (USDA, 2019a). The net returns to simultaneously shifting from a conventional tillage system with fallow land in winter to a no-till system with winter cover crops could become positive if savings from tillage practices (elimination of chisel plow, deep rip, and moldboard plow) offset the negative net returns to cereal rye. Al-Kaisi et al. (2015) found that no-till corn and soybean systems in Iowa were consistently less profitable across 7 locations, 10 years, and multiple rotations, than their conventional counterparts. Deines et al. (2023) reported that cover cropping practices implemented across the US Corn Belt caused average corn and soybeans yield losses of 5.5 and 3.5%, respectively, in 2019–2020.

Fifth, cereal rye planting dates and methods had confounded effects in our study. Future research including full factorial designs of planting dates (early and late) and methods (broadcast and drill) should help identify their separate unique effects.

Experimental vs *survey data*

The major advantages of our experimental approach over survey-based studies are that all agronomic practices were strictly controlled and documented (eliminating the noise from recollection of information by respondents) and plot characteristics were observable to researchers. In comparison, survey data are typically subject to sample selection bias, rely on farmers' recollections of costs and implemented practices, and pool responses across potentially different farms and production systems.

However, advantages of our experimental approach came at the expense of excluding behavioral responses to weather events, market trends, and other variables that affect profitability in real life. Additionally, our analysis relied on agronomic data obtained from small experimental plots that we extrapolated to a per-hectare basis.

Finally, our study did not consider fertilizing cereal rye, as proposed by Malone et al. (2022) for double-cropping soybean with cereal rye and mechanically harvesting the cereal rye biomass for hay. Potential extensions of our research include fertilization of cereal rye with a combination of manure and commercial fertilizers in the fall, and harvesting rather than grazing cereal rye biomass.

Conclusion

On a two-year study across three locations in Iowa, we found that in the absence of grazing, planting cereal rye as a cover crop followed by no-till corn was very likely to generate negative private net returns, averaging −\$123.74 ha^{-1}.

While early-broadcasting was less costly than late-drilling cereal rye, it produced more biomass, negatively affecting subsequent corn yields and private net returns in the no-grazing scenario. Net losses in early-broadcast plots were \$165.96 ha^{-1} more negative, on average, than net losses in late-drilled plots in the absence of grazing. Since seeding rate and termination date did not have significant effects on private net returns in the no-grazing scenario, further research should be undertaken to assess the cost-effectiveness of alternative cover cropping practices to achieve desirable environmental effects at minimum cost.

In the partial grazing scenario, a higher availability of rye biomass during the spring was associated with higher private cost savings in the livestock enterprise, and lower amounts of rye biomass left on the field prior to corn planting resulted in improved corn yields with respect to the no-grazing scenario. Consequently, mean private net returns to cereal rye were less negative in the partial-grazing scenario than in the no-grazing scenario, and the likelihood of obtaining positive net returns in the former was more than twice the likelihood in the latter scenario (45.2 *vs* 17.8%). However, even in the more favorable scenario, average private net returns to cereal rye were negative at −\$15.24 ha^{-1}.

Our findings should inform farmers, advisors, extension specialists, researchers, and policy makers about the low probability of consistently obtaining positive annual private net returns to cereal rye in Iowa in the absence of substantial targeted financial incentives, even in an integrated crop–livestock operation. Further research should evaluate whether the environmental benefits from scaling-up the use of cereal rye as a winter cover crop would justify larger financial incentives for cereal rye adoption, and whether our results hold under agronomic trials that included actual rather than simulated grazing effects.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170523000388.

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Competing interests. None.

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