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Harvested winter rye energy cover crop: multiple benefits for North Central US

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Abstract

Cover crops (CCs) can reduce nitrogen (N) loss to subsurface drainage and can be reimagined as bioenergy crops for renewable natural gas production and carbon (C) benefits (fossil fuel substitution and C storage). Little information is available on the large-scale adoption of winter rye for these purposes. To investigate the impacts in the North Central US, we used the Root Zone Water Quality Model to simulate corn-soybean rotations with and without winter rye across 40 sites. The simulations were interpolated across a five-state area (IA, IL, IN, MN, and OH) with counties in the Mississippi River basin, which consists of ∼8 million ha with potential for rye CCs on artificially drained corn-soybean fields (more than 63 million ha total). Harvesting fertilized rye CCs before soybean planting in this area can reduce N loads to the Gulf of Mexico by 27% relative to no CCs, and provide 18 million Mg yr^{-1} of biomass-equivalent to 0.21 EJ yr^{-1} of biogas energy content or 3.5 times the 2022 US cellulosic biofuel production. Capturing the CO_2 in biogas from digesting rye in the region and sequestering it in underground geologic reservoirs could mitigate 7.5 million Mg CO_2 yr^{-1}. Nine clusters of counties (hotspots) were identified as an example of implementing rye as an energy CC on an industrial scale where 400 Gg yr^{-1} of rye could be sourced within a 121 km radius. Hotspots consisted of roughly 20% of the region's area and could provide ∼50% of both the N loss reduction and rye biomass. These results suggest that large-scale energy CC adoption would substantially contribute to the goals of reducing N loads to the Gulf of Mexico, increasing bioenergy production, and providing C benefits.

1. Introduction

Energy cover crops (CCs) such as winter rye are planted and harvested between two primary crops, resulting in three or four crops in two years; and can cost-effectively supply considerable biomass for biogas production without competing with food crops for land use (Feyereisen *et al* 2013, Herbstritt *et al* 2022, Launay *et al* 2022, Malone *et al* 2022). While conventional unharvested CCs provide numerous ecosystem services, harvesting the biomass has additional benefits (Blanco-Canqui *et al* 2020). These benefits include reduced nitrogen (N) loss in leaching and subsurface-drained corn-soybean systems (Heggenstaller *et al* 2008, Malone *et al* 2018, Launay *et al* 2022), potential for terrestrial carbon (C) storage (Ramcharan and Richard 2017, Valli *et al* 2017, Laboubee 2018, Dale *et al* 2020), fossil fuel substitution (Herbstritt *et al* 2022), and low-cost C capture and sequestration during biogas production (Wong *et al* 2022). Potential revenue from energy CCs could also incentivize CC adoption (Plastina 2020, Herbstritt *et al* 2022, Malone *et al* 2022). To expand on these studies, a regional assessment of the North Central US is needed to quantify potential benefits of this practice.

Studies using the Root Zone Water Quality Model (RZWQM) have shown that unharvested winter rye CCs adopted on a large scale across North Central US artificially-drained corn-soybean fields can substantially reduce N loads to the Mississippi River and Gulf of Mexico (Kladivko *et al* 2014, Malone *et al* 2014). Other studies in the North Central US showed that harvesting fertilized winter rye before a later-than-normal soybean planting can further reduce N loss to drainage compared with unharvested and unfertilized CCs, while potentially providing positive net energy and producer revenue (Malone *et al* 2018, 2022). These studies suggest that harvesting fertilized rye CCs on a large scale in US corn-soybean rotations would contribute to sustainable intensification of agriculture (Heaton *et al* 2013, Malone *et al* 2022, Schulte *et al* 2022), which is high on the global policy agenda and one of the grand challenges facing society (Tilman *et al* 2011, Garnett *et al* 2013, Petersen and Snapp 2015, Spiegal *et al* 2018, NAS 2021).

Few studies, if any, have quantified the impacts of large-scale adoption of energy CCs on N loss to artificial subsurface drainage and bioenergy potential. Here, the field-tested RZWQM (Gillette *et al* 2018, Malone *et al* 2020) and published analysis methods (Kladivko *et al* 2014, Malone *et al* 2014) were used to estimate potential rye yield and water quality benefits on land with artificial drainage for several scenarios of harvested and unharvested rye CC in corn-soybean rotations across the North Central US. Energy content and C benefit potential of digesting harvested rye to produce biogas were also estimated based on modeled biomass and literature values. To inform the implementation of rye as an energy CC, areas were identified that would be especially relevant 'hotspots' to reduce N loss and collect biomass for renewable natural gas (RNG).

2. Methods

The current study focused on the variations in winter rye growth and N loss reduction (NLR) to drainage with and without winter rye in corn-soybean rotations in the North Central US. Model adjustments for each location (e.g. fertilizer rates, primary crop growth calibration, and planting/harvest dates) were mostly specified by Malone *et al* (2014). Methods are briefly summarized here, including updates and differences from Malone *et al* (2014). Scenarios were modeled using the RZWQM calibration of Malone *et al* (2020), described more fully in Gillette *et al* (2018).

The 40 sites used by Malone *et al* (2014) were used here, and indicated in figure 1 and specified in supplemental table S2. Historical weather data were updated to include 1961–2013 using the same databases. RZWQM was run for each site from 1961 to 2013; model results from 1972 to 2013 were used for analysis to allow an initialization period. Detroit, MI and Columbus, OH were not included in the current analysis because of missing weather records after 2005. For consistency with prior studies and because of its far southern location, Memphis, TN was only used for spatial interpolation and was not included in the management and results summaries.

Management is summarized in table 1 for the unharvested CC and no cover crop (NCC) scenarios, following Malone *et al* (2014) where the management was thoroughly described. For the current study, RZWQM was run at each site under several field management scenarios in addition to CC and NCC with all scenarios having (1) winter rye planted 3 d after simulated corn and soybean harvest and (2) corn fertilized 10 d after simulated emergence.

In addition to several intermediate scenarios, the primary simulated scenarios included NCC and CC, and fertilized winter rye with 90% of aboveground biomass harvested before late soybean planting (CC2_t_50 and CC2_nt_50). These are summarized in table 1 and supplemental figure S1. Scenarios include till and no-till (t and nt), corn and soybean planted in rotation at the typical date for each site (NCC and CC), rye chemically terminated (unharvested) and soybean planted 10 d later than CC (CC2), and rye harvested with either 0 or 50 kg N ha^{-1} fertilizer applied 31 March to rye before late soybean planting (0 and 50 at end of scenario name; Malone *et al* 2018, 2022). Rye was terminated before corn in all scenarios. The model did not apply 50 kg N ha^{-1} spring fertilizer in soybean years if the rye failed to overwinter, resulting in an average of 41 kg N ha^{-1} across sites for CC2_nt_50 (table 1). For the tilled scenarios (t), rye was terminated or harvested earlier to allow time for spring tillage, as discussed by Kladivko *et al* (2014) and Malone *et al* (2014). Rye was terminated or harvested either 3 or 13 d before soybean planting and 10 or 15 d before corn planting, depending on tillage (Malone *et al* 2014).

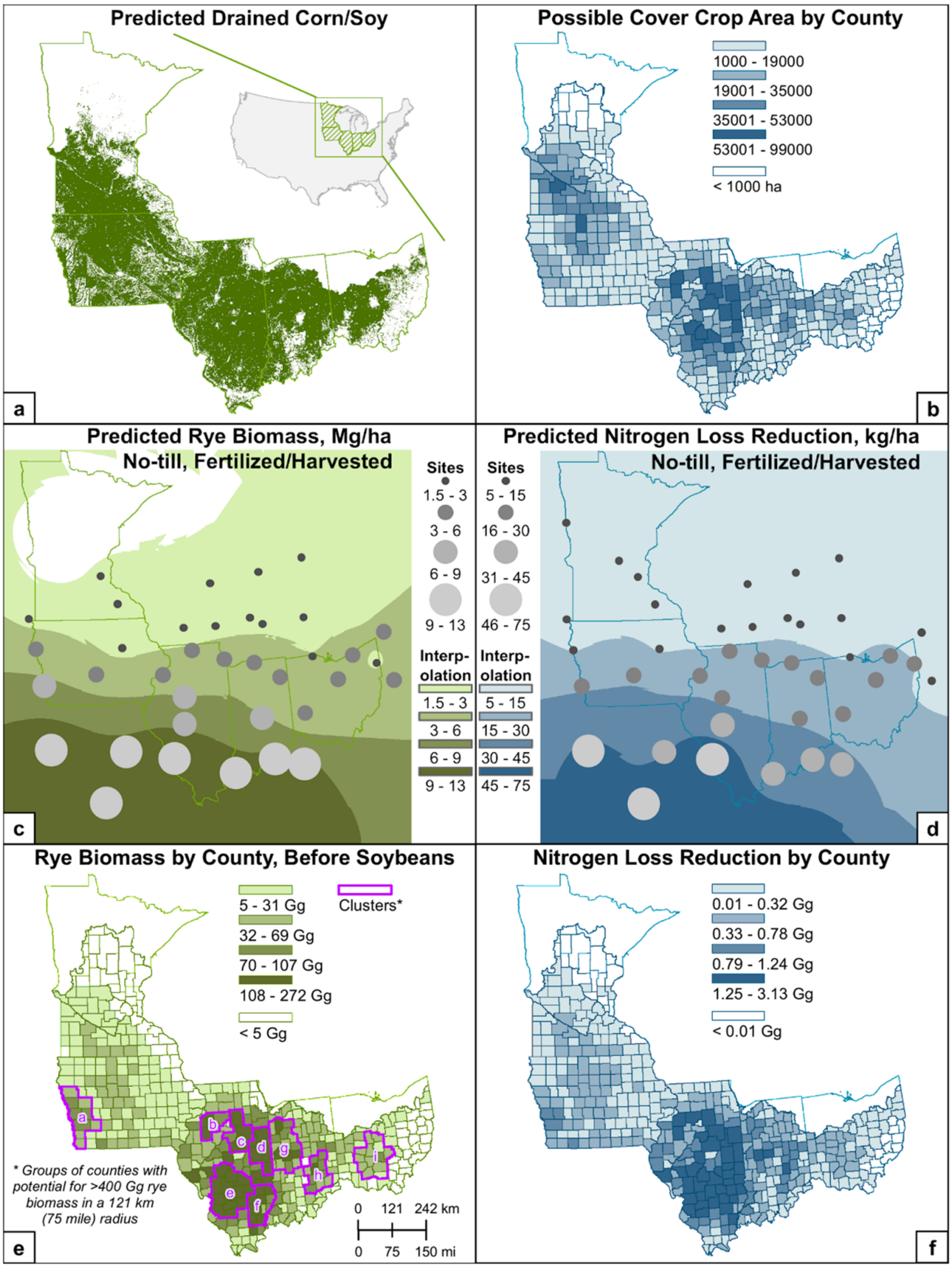

Figure 1. Maps of North Central US showing distributions related to fertilized and harvested rye biomass (RB) and the resulting N loss reduction (NLR) in artificially drained crop land in corn-soybean rotations with no-till or spring tillage. Panels (a)–(f) (top left to bottom right): (a). Distribution of drained soils in soybean-corn rotation (2016 and 2017 national land cover datasets) within the Upper Mississippi Watershed in the five states used for this study (30 m × 30 m pixels); (b). Drained soils in corn/soy rotation, with intensive fall tillage area removed, summed by county; (c). Modeled and interpolated (ordinary spherical 2-dimensional kriging) average annual RB for soybean years only (modeled sites are represented by circles and were omitted if less than 1.5 Mg ha^{-1}); (d). Modeled and interpolated average annual NLR for both phases of corn-soybean rotation (modeled sites are represented by circles and were omitted if less than 5 kg N ha^{-1}); (e). County averages (RB interpolation × area, accounting for tillage types) of harvested RB in soybean years in the Mississippi River Basin, including clusters of counties where more than 400 Gg of rye might be sourced from within 121 km; (f). County averages (NLR interpolation × area, accounting for tillage types) of NLR in the Mississippi River Basin.

Table 1. RZWQM-simulated management and results summary. Averaged over 42 years and all 40 sites except Memphis for each modeled scenario. The 'test' site (NCC_test and CC_test) is the central Iowa site used for model calibration and testing (Malone *et al* 2020). Management timeline for four scenarios (CC_nt, CC_t, CC2_nt_50, CC2_t_50) is illustrated in supplemental figure S1.

Management, rye growing degree days (GDD), and model results	Model scenarios											
	No cover crop, till (t) and no-till (nt)		Unharvested cover crop (CC)		Unharvested late terminated CC2		Harvested late terminated CC2, unfertilized (0) and fertilized (50)				Model testing	
	NCC_nt	NCC_t	CC_nt	CC_t	CC2_nt	CC2_t	CC2_nt_0	CC2_t_0	CC2_nt_50	CC2_t_50	NCC_test	CC_test
	Management (planted, harvested, terminated, fertilized, tilled)											
Rye-soy terminated	Nd	Nd	19-May	09-May	29-May	19-May	29-May	19-May	29-May	19-May	Nd	04-May
Soy-rye planted	22-May	22-May	22-May	22-May	01-Jun	01-Jun	01-Jun	01-Jun	01-Jun	01-Jun	14-May	14-May
Soy-rye harvested	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	13-Oct	28-Sep	28-Sep
Rye-corn planted	Nd	Nd	16-Oct	16-Oct	16-Oct	16-Oct	16-Oct	16-Oct	16-Oct	16-Oct	Nd	30-Sep
Rye-corn terminated	Nd	Nd	22-Apr	17-Apr	22-Apr	17-Apr	22-Apr	17-Apr	22-Apr	17-Apr	Nd	20-Apr
Corn-rye planted	02-May	02-May	02-May	02-May	02-May	02-May	02-May	02-May	02-May	02-May	02-May	02-May
Corn-rye harvested	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	18-Oct	05-Oct	05-Oct
Rye-soy planted	Nd	Nd	21-Oct	21-Oct	21-Oct	21-Oct	21-Oct	21-Oct	21-Oct	21-Oct	Nd	15-Oct
Corn-rye fert. (kg N ha^{-1})	153	153	153	153	153	153	153	153	153	153	203	203
Soy-rye fert. (kg N ha^{-1})	0	0	0	0	0	0	0	0	41	41	27	27
Rye harvested (yes/no)	No	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No
Tilled (yes/no)	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	No
	Rye growing degree day (GDD, 0 C basis; included fall, winter, and spring)											
Rye-soy GDD	Nd	Nd	1032	905	1176	1036	1176	1036	1176	1036	Nd	843
Rye-corn GDD	Nd	Nd	817	763	815	761	815	761	815	761	Nd	847
	Model results (above ground rye biomass, corn and soybean yield, drainage N loss)											
Rye-soy biom. (kg ha^{-1})	Nd	Nd	3164	2149	3871	2769	3319	2497	5168	3974	Nd	1798
Rye-corn biom. (kg ha^{-1})	Nd	Nd	1619	1230	1549	1186	1348	1069	1373	1087	Nd	2446
Soy yield (kg ha^{-1})	2469	2538	2520	2602	2464	2539	2483	2546	2476	2539	2809	2879
Corn yield (kg ha^{-1})	6557	6713	6652	6769	6638	6767	6613	6731	6623	6745	10 901	10 848
Drain. N loss (kg ha^{-1})	44.4	44.3	25.3	24.8	23.9	23.4	20.8	21.1	21.2	22.0	49.4	20.0

Notes: 'Nd' is not determined; 'rye-soy terminated' and 'rye-corn terminated' indicate termination or harvest dates for rye before soybean or corn planting; 'corn-rye fertilized' and 'soy-rye fertilized' indicate fertilizer applied in corn or soybean years; 'rye-soy biomass' (harvested for four scenarios) and 'rye-corn biomass' (not harvested) indicate total in-field above-ground biomass of rye at termination or harvest before soybean or corn planting; the first crop listed in each crop pair (e.g. rye-soy, soy-rye) is the crop terminated, planted, or harvested on that date, while the second crop in the listed pair will be the following crop.

Till and no-till scenarios NCC and CC have soybean, corn, and rye planting and termination within 1 or 2 d of Malone *et al* (2014) for treatments where the earlier study planted rye after the typical main crop harvest dates for the sites (table 1 and Malone *et al* 2014). For example, average rye termination was 22 April compared with 24 April in Malone *et al* (2014), partly because Detroit, MI had a relatively late corn planting (11 May) in the previous analysis and was not included in the current analysis.

Average annual NLR from rye CC (e.g. NCC_nt minus CC2_nt_50) and harvested rye biomass across five states draining to the Mississippi River (IA, IL, IN, MN, and OH) were calculated in ArcGIS (ESRI, Redlands, CA). Methods were similar to Kladivko *et al* (2014) where they were thoroughly described. Briefly, data from the 2016–2017 National Cropland Data Layer (CDL; USDA, 2016; 2017) were used to identify areas of corn-soybean rotations, and soils with a moderate to severe wetness limitation (non-irrigated capability [NIRR] class 2, 3, or 4; NIRR subclass 'w') in the NRCS SSURGO (Soil Survey Staff 2022) database were overlaid on these to determine probable drained corn-soybean area in each county. This is likely a low estimate for the drained area, with drainage often installed on a whole field that includes soils with different wetness limitations (Jame *et al* 2022). Results were checked against other methods (e.g. TDMost-PD, Jame *et al* 2022; AgTile, Gökkaya *et al* 2017, Valayamkunnath *et al* 2020) and determined to be acceptable, falling between other published predictions and comparable to US Census of Agriculture statewide estimates for IA and IL (USDA 2017).

Estimates of the proportion of each county under no-till or tilled management were obtained from the Operational Tillage Information System (Regrow 2017). Tilled corn-soybean areas that could transition to spring till and adopt CCs were adapted from Kladivko *et al* (2014). On average, approximately 20% of the corn-soybean area was assumed unlikely to adopt cover cropping because of intensive fall tillage (<30% residue cover on soil) after corn harvest. The area used for analysis (e.g. drained and considered capable of supporting CCs) has increased by ∼10% across the region compared with Kladivko *et al* (2014) even though they included continuous corn, but the current analysis does not (see supplemental table S1). This is due to improved accuracy in the CDL (Lark *et al* 2017), reclassification of SSURGO data, and greater adoption of no-till, mulch, and spring-till practices (Zulauf and Brown 2019). Rye biomass and drainage nitrate loss estimates from the RZWQM scenarios were interpolated using ordinary spherical kriging and averaged by county. These interpolated values for the tilled and no-tilled scenarios were multiplied by the predicted area available for tilled or no-tilled CCs to estimate harvestable rye biomass and NLR across the region.

Winter rye can be converted to biogas, a mixture of methane (CH_4) and carbon dioxide (CO_2), through anaerobic digestion, and the biogas then separated with the CH_4 usable as RNG (USEPA 2020, Launay *et al* 2022). We estimated bioenergy production assuming that rye biomass prior to soybean planting could provide 11.3 GJ RNG Mg^{-1} rye biomass feedstock (Herbstritt *et al* 2022). Carbon benefits of this system include (1) soil carbon storage from unharvested aboveground and belowground biomass, which can be roughly estimated as 0.3 Mg CO_2 ha^{-1} yr^{-1} assuming roots are 30% of the total CC biomass and contribute proportionally more soil C sequestration than aboveground biomass (Blanco-Canqui *et al* 2020) and soil C sequestration potential of growing unharvested CCs can range from 0.2 to 0.5 Mg C ha^{-1} yr^{-1} or roughly 0.7–2.0 Mg CO_2 ha^{-1} yr^{-1} (Poeplau and Don 2015, Abdalla *et al* 2019, McClelland *et al* 2021); (2) substituting biogenic for fossil C emissions by switching from natural gas to RNG; and (3) geologic C storage of the byproduct CO_2 stream associated with biogas separation to RNG, assuming biogas is 60% CH_4 and 40% CO_2 on a molar basis (NREL 2013) and 100% of the biogas CO_2 is captured and stored. Approximately 73.3% of the total dry rye biomass is converted to biogas (Valli *et al* 2017, Herbstritt *et al* 2022) while 26.7% remains as digestate. Existing and emerging gas separation technologies that upgrade biogas to biomethane and separate the CO_2 stream include amine scrubbing, water scrubbing, pressure swing adsorption units, membrane units, and cryogenic technologies can achieve close to 100% carbon capture (Bauer *et al* 2013, Varing *et al* 2023).

To identify the most promising energy CC 'hotspots', we assumed an industrial-scale liquid biofuel facility required roughly 400 Gg yr^{-1} of biomass (Lambert and Middleton 2010, Bals and Dale 2012, Darr and Shah 2014). Biogas plants in the US are currently much smaller and often sized for individual farms, but biogas facilities in other countries process up to 400 Gg yr^{-1} of feedstock (Hansen *et al* 2019). We determined hotspots where 400 Gg yr^{-1} could be sourced within a 75 mile (121 km) radius (Bain *et al* 2003, Wendt *et al* 2014) by identifying the most promising clusters of contiguous counties.

3. Results and discussion

3.1. Average annual results for the different scenarios

The average annual results across the 40 sites were as follows (table 1). Simulated N loss to drainage ranged from 20.8 kg N ha^{-1} (CC2_nt_0) to 44.4 kg N ha^{-1} (NCC_nt) and above ground rye biomass at termination before soybean planting ranged from 2149 (CC_t) to 5168 kg ha^{-1} (CC2_nt_50). NLR was nearly 45% with CCs (CC_nt and CC_t compared

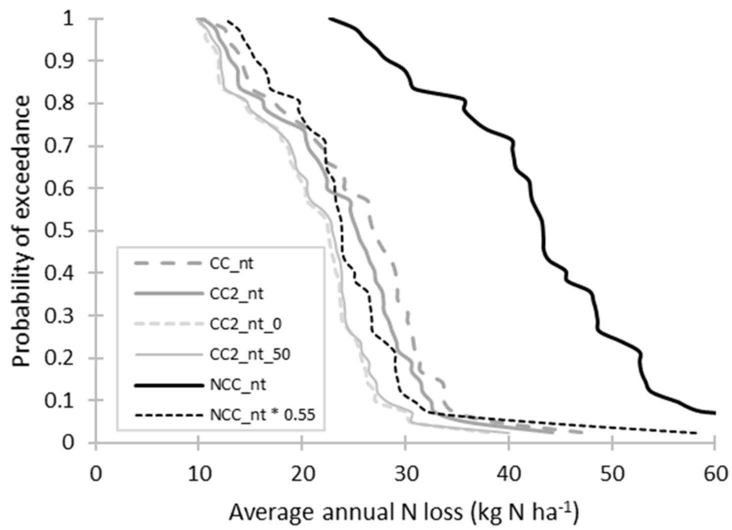

Figure 2. RZWQM estimated distributions for average annual N loss to drainage across the 40 sites with no-till ($n = 42$ years), sorted from highest to lowest N loss. Y-axis is the cumulative probability (1/42 years is the lowest probability and matches the highest N loss). The NCC_nt * 0.55 line indicates the 45% goal set by the Gulf Hypoxia Task Force to reduce N loads from the Mississippi River Basin.

with NCC_nt and NCC_t). Later unharvested rye termination and soybean planting (CC2_nt and CC2_t) further reduced NLR by an additional 6% (1.4 kg N ha^{-1}) compared with earlier termination (CC_nt and CC_t). Harvesting 90% of above-ground rye before soybean planting (CC2_nt_0 and CC2_t_0) further reduced NLR more than 10% (more than 2.0 kg N ha^{-1}) compared with unharvested rye (CC2_nt and CC2_t). Compared with CC2_nt_0 and CC_t_0, applying early spring fertilizer to rye (CC2_nt_50 and CC2_t_50) increased the average annual above-ground biomass yield prior to soybean planting by more than 50% (e.g. 3319–5168 kg ha^{-1} in no-till) while NLR increased by less than 5% (<1.0 kg N ha^{-1}). Average annual drainage N losses across the 40 sites for CC2_nt_0 and CC2_nt_50 were consistently lower than the other no-till scenarios (figure 2).

The results of fertilized and harvested rye in corn-soybean systems were similar to Malone *et al* (2018) where RZWQM was used to simulate these effects in a Central IA no-till system. For example, with rye fertilized at 0 and 60 kg N ha^{-1}, rye yield increased by more than 2000 kg ha^{-1} while N loss to drainage only slightly increased. In a Central IA field study, applying 60 kg N ha^{-1} to rye significantly increased rye biomass and the associated above-ground N uptake compared with unfertilized rye (Malone *et al* 2022).

As an indication of the reliability of the simulations across the 40 sites, the NCC and unharvested CC results (NCC_nt and CC_nt) were reasonable compared with model testing (NCC_test and CC_test; table 1) and Malone *et al* (2014) as discussed in supplementary text 1. Model limitations and uncertainties are discussed in supplemental text 2, such as one soil simulated across the region and model only tested at one site without fertilizing rye CC.

3.2. Harvested rye biomass, bioenergy, and carbon benefits across the region

Rye yield and NLR across the region were estimated using CC2_nt_50 and CC2_t_50. These fertilized scenarios showed (1) a large increase in rye yield and only a small increase in N loss compared with no additional fertilization (CC2_nt_0 and CC2_t_0) and (2) no reduction in soybean yield compared with NCC_nt (table 1). Positive net energy and potentially higher net revenue with fertilized vs unfertilized harvested rye CCs was previously reported (Malone *et al* 2018, 2022).

The average annual above-ground rye biomass across the sites before soybean planting was over 3000 kg ha^{-1} and appears acceptable for harvest (CC2_nt_50 and CC2_t_50; table 1; figure 1(c)). This assumes (1) to maintain soil ecosystem services, 750–1000 kg ha^{-1} of rye should remain in the field and (2) site-years where more than 1000 kg ha^{-1} rye could be collected are likely acceptable for harvest (Blanco-Canqui *et al* 2020). While leaving ~1000 kg ha^{-1} of rye in the field for soil ecosystem services is recommended, the overall system may be optimized if larger amounts are harvested when considering economics, N loss to drainage and N removal in biomass (Malone *et al* 2018), and the overall C benefit and fossil gas substitution with biogas production (Herbstritt *et al* 2022, Launay *et al* 2022). Further, the digestate produced when digesting rye for biogas can be used as a soil amendment and partial substitution for chemical fertilizers produced with fossil fuels. Typically, digestate retains almost all of the original feedstock

Table 2. Regional results summary. Total renewable natural gas (RNG) equivalent from converting rye biomass to RNG (11.3 GJ RNG Mg^{-1} rye; Herbstritt *et al* 2022). N loss reduction is from (NCC_nt + NCC_t) minus (CC2_nt_50 + CC_t_50), interpolated from the 40 sites. Sequesterable CO_2 in biogas is produced during digestion of rye.

	State/region					
Item	Illinois	Indiana	Iowa	Ohio	Minnesota	Total for region
Area evaluated (ha)	14 595 351	9093 586	14 574 441	16 742 678	8705 831	63 708 888
Area for cover crops (ha)	2873 790	1559 988	1664 086	1179 667	632 306	7909 836
Rye biomass (Mg)	9684 810	4173 327	2771 433	1117 299	745 991	18 492 859
N loss reduction (NLR, Mg)	112 547	47 182	34 784	12 418	9557	216 488
N loss without cover crops (Mg, NCC_nt + NCC_t)	181 716	83 170	70 635	26 551	34 694	396 766
Natural gas consumption (GJ, USEIA 2020)	$1.22 \times 10^{+9}$	$9.18 \times 10^{+8}$	$4.18 \times 10^{+8}$	$1.30 \times 10^{+9}$	$5.22 \times 10^{+8}$	$4.31 \times 10^{+9}$
Total RNG equivalent (GJ)	$1.09 \times 10^{+8}$	$4.27 \times 10^{+7}$	$3.13 \times 10^{+7}$	$1.26 \times 10^{+7}$	$8.43 \times 10^{+6}$	$2.09 \times 10^{+8}$
RNG vs. natural gas consumption (%)	9.0	5.1	7.5	1.0	1.6	4.8
Sequesterable CO_2 from biogas (Mg)	3910 784	1685 214	1119 121	451 172	301 236	7467 526

N in the form of ammonium (NH_4), all of the phosphorus (P), about 30% of the C, and is often a more predictable and plant-available nutrient source than other organic fertilizers like manure (Möller and Müller 2012, Al Seadi *et al* 2013, Koszel and Lorencowicz 2015, Walsh *et al* 2018, Doyeni *et al* 2021, Launay *et al* 2022). Accordingly, while some site-years with the current simulations had less than 1000 kg ha^{-1} rye harvested and less rye remaining in the field than recommended, 90% of the above-ground rye biomass was harvested for all site-years (Feyereisen *et al* 2013, Malone *et al* 2018).

From the estimated drained corn-soybean area in no-till or spring till (figures 1(a) and (b)) and RZWQM estimated rye yield (figure 1(c)), the average annual rye biomass collected prior to soybean planting was 18.5 million Mg (dry basis) assuming that 50% of the area is in soybean (figure 1(e); table 2). In comparison, Feyereisen *et al* (2013) reported approximately 151 million Mg of rye harvested (with approximately 4 Mg ha^{-1} on average) prior to both corn and soybean in all non-irrigated US corn-soybean rotations, as well as continuous corn. Counties with high rye biomass potential are strongly correlated with higher potential for drained corn-rye-soybean area (figures 1(b) and (e); $R^2 = 0.80$). Temperature also has clear effects on rye CC impact across the region (Malone *et al* 2014), such as higher biomass per unit area in the southern regions (figure 1(c)).

If used as an RNG feedstock, the winter rye from this five-state region could provide approximately 0.21 EJ of energy. In 2020 these five-states used approximately 4.4 EJ of energy from fossil natural gas (USEIA 2020); harvested rye could provide 5% of this region's natural gas consumption (table 2) and substitute 11.2 million Mg CO_2 that would otherwise be emitted from burning fossil natural gas. Most RNG is currently marketed in the transportation sector as cellulosic biofuel (ANL 2020), similar to fuel ethanol. The 0.21 EJ this region could produce from rye is equivalent to 8.8 billion l of fuel ethanol, roughly 1/8 of current US fuel ethanol production or 3.5 times the 2022 total US cellulosic biofuel production of 2.5 billion l (ethanol equivalent energy basis; USDOE 2021, USEIA 2022, USEPA 2023). While the market for winter rye as an energy feedstock is currently limited partly because this is a relatively new management practice (Launay *et al* 2022), interest is growing for these systems to produce biogas from agricultural biomass and convert it into RNG (Pleima 2019). Also, industrial scale RNG facilities using agricultural residues and winter crops are operating in the North Central US and Europe (e.g. Pleima 2019, Dale *et al* 2020, Verbio AG 2022). See supplemental text 3 for more details.

Beyond the fossil fuel substitution potential of RNG, energy CCs present a carbon negative climate mitigation opportunity from storing C in soil and capturing the byproduct CO_2 stream that is produced from biogas separation into RNG. The potential net carbon negativity is dependent on decisions across the supply chain, which should be assessed in future research (Fajardy and Mac Dowell 2018). Research modeling emissions to the farm gate found substantially lower emissions per ha and per MJ for winter rye compared to corn grain (Carmargo *et al* 2013). We did not consider the dilute CO_2 produced during RNG combustion, but if captured this could provide further carbon benefits. Generating biogas from energy CCs in the five-state region could yield roughly 7.5 million Mg CO_2 yr^{-1} (2.0 million Mg of C; table 2), which could be used in the food and beverage industry (e.g. meat processing, food preservation, beverage carbonation) or stored in underground geologic reservoirs (Sandalow et al 2021, Farghali et al 2022, Herbstritt et al 2022, Wong et al 2022). Pipelines are proposed across the North Central US to transport CO_2 captured from ethanol and other industrial facilities to locations where it can be geologically sequestered (Eller 2021).

While carbon capture and storage in geologic reservoirs is expected to be permanent (NETL 2010, Alcalde et al 2018), the permanence of soil C storage from CCs in terrestrial ecosystems is less certain. The soil C contribution of CCs is expected to decrease over time as soil C levels saturate (Qin et al 2016). However, CC roots and remaining above ground biomass after rye harvest could significantly improve the carbon benefits of bioenergy CCs in the near term by sequestering more than 2 million Mg CO_2 yr^{-1} in the region (0.3 Mg CO_2 ha^{-1} yr^{-1} times 7.9 million ha available for CCs in the five state region, see Methods).

3.3. NLR across the region

Given the estimated drained corn-soybean area (figures 1(a) and (b)) and the RZWQM estimated NLR (figure 1(d)), the potential reduction in N load to the Mississippi River from growing fertilized winter rye as an energy CC averaged 216 million kg yr^{-1} (figure 1(f); table 2). The Gulf Hypoxia Task Force set a goal to reduce total N loads from the Mississippi River basin by 45% by 2035, compared with the baseline loads between 1980 and 1996 (USEPA 2014, USGS 2021). The CC2_nt_50 scenario compared with NCC_nt consistently reduced annual N loss to drainage across the 40 sites more than 45% (figure 2). To achieve this 45% N reduction goal, 12 states with water discharging to the Mississippi River were tasked with developing strategies to reduce the N load to the Gulf of Mexico (USEPA 2008). The load reduction determined here from only five of these twelve states could substantially contribute to this goal. Assuming 813 million kg N as a baseline load transported annually to the Gulf of Mexico by the Mississippi River (2001–2005 water years, USEPA 2007), a 27% reduction can be achieved (216/813 = 27%). In comparison, a 19% reduction was reported by Kladivko et al (2014) where continuous corn was included in the analysis and the rye CC was unharvested. While the current analysis did not include continuous corn, delayed harvest of fertilized rye CCs resulted in less N loss compared with unfertilized and unharvested rye terminated earlier (e.g. CC2_nt_50 vs. CC_nt, table 1). Also, the potential area estimated for implementing energy CCs in the five states increased, as mentioned in the section 2.

CCs will play an important role in meeting the North Central US Nutrient Reduction Strategies (Feyereisen et al 2022). Under medium or high levels of conservation practice implementation, CCs might be needed on 9.7–14.7 million ha in three states (IA, IL, MN). This level of implementation will be a challenge without economic incentives (Singer et al 2007, Plastina et al 2020). In areas where forage is not in high demand, the potential to harvest biomass, as described here, may result in additional revenue for producers and increase adoption (Herbstritt et al 2022, Malone et al 2022).

3.4. Hotspots

Identifying hotspots for N management and spatially targeting practices could improve (1) the cost-effectiveness of conservation measures, (2) networks of informed advisors and new infrastructure and technologies, and (3) social acceptability and adoption through a neighborhood effect (Roy et al 2021). Identifying hotspots would also help in siting bioenergy facilities to minimize feedstock transportation distance. Biogas systems benefit from economies of scale in capital costs but experience diseconomies of sourcing increasingly distant feedstocks to feed larger facilities (Richard 2010). A 10 km shift in siting bioenergy facilities with carbon capture and storage can increase supply chain emissions by up to 13.1% (Freer et al 2022) but the necessity of optimal siting concerns may be negated in locations where biomass supply and geologic storage can be co-located (Sanchez and Callaway 2016). Bioenergy facilities must be optimally sited to reduce the energy and cost associated with transporting cellulosic feedstocks and CO_2 when coupled with carbon capture to be competitive with fossil fuels and to achieve a net-negative carbon balance across their supply chains.

Within this five state region, a small fraction of the overall area (e.g. 20%) contributed a large fraction of the cumulative NLR and rye biomass (nearly 60%, point A, figure 3). Hotspots consist of nine clusters (figure 1(e)) occupying 19% of the total area, while contributing 49% of the biomass and 48% of the NLR. The cluster of counties in Southwestern IL (cluster e) consists of ~2 million ha (20 000 km^2) and could produce more than 2000 Gg yr^{-1} rye biomass. Each cluster could support between one and five large industrial facilities using 400 Gg yr^{-1} rye biomass, taking advantage of the high density of potential energy CC implementation and the benefits that hotspots entail as listed above. While large industrial biogas facilities have some advantages, farm scale digesters are currently commercially viable at the scale of 2000 cow dairies, which is equivalent to 7.5 Gg yr^{-1} rye biomass, so these clusters could support between 50 and 250 farm-scale digesters. Counties outside these hotspots were estimated to produce rye biomass of more than 30 Gg yr^{-1}, where smaller facilities may be possible (figure 1(e)). See supplemental text 4 for more discussion concerning smaller biogas facilities.

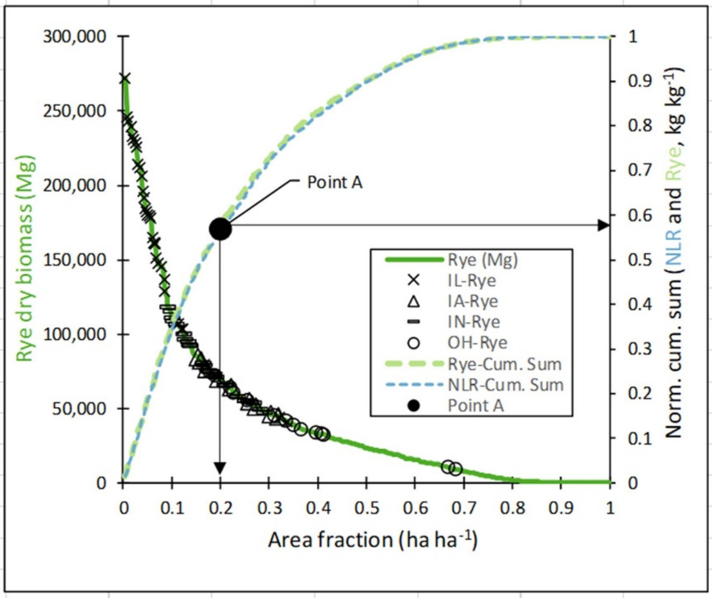

Figure 3. Distributions for fertilized and harvested rye biomass and nitrogen loss reduction (NLR) from figures 1(e) and (f). *X*-axis is the cumulative fraction of county area normalized by dividing by total cumulative sum (ha ha^{-1}). *Y*-axes are the county-by-county NLR or rye biomass sorted from highest to lowest. Right axis is the normalized cumulative sum (kg kg^{-1}); the left axis is the rye biomass for each individual county. Symbols indicate each state's hot spot counties. The total area sum of all counties is 63 708 888 ha. The total cumulative biomass harvested and NLR adding all 432 counties from figures 1(e) and (f) are 1.85×10^7 Mg and 2.16×10^8 kg.

4. Conclusions

This study illustrates the potential of energy CCs implemented on a large scale to address the goals of intensifying agricultural production, increasing cellulosic bioenergy production, providing carbon benefits, and reducing the negative environmental impacts of agriculture. Information regarding producer participation is needed, and pilot programs in key locations could help in this respect. Field trials and further modeling studies will clarify how the components of primary crop yield, rye yield, and N losses vary with soil characteristics, climate, and management. These results with additional studies will help advance policies and guidelines to optimize the goals of environmental quality, bioenergy production, carbon benefits, crop yields, and farm profits.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare that they have no conflict of interests.

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