Agricultural & Environmental Letters

Research Letter

Harvesting Fertilized Rye Cover Crop: Simulated Revenue, Net Energy, and Drainage Nitrogen Loss

R. W. Malone,* J. F. Obrycki, D. L. Karlen, L. Ma, T. C. Kaspar,
D. B. Jaynes, T. B. Parkin, S. H. Lence, G. W. Feyereisen, Q. X. Fang,
T. L. Richard, and K. Gillette

Core Ideas

- Fertilizing winter rye increased estimated revenue and harvestable biomass.
- Fertilizing winter rye increased net energy production.
- Harvesting fertilized winter rye reduced simulated drainage N loss.
- Rye revenue in response to fertilizer rate plateaued at approximately 120 kg N ha^{-1}.
- Field studies are needed to evaluate fertilized/harvested rye cover crop.

Abstract: Harvesting fertilized rye (*Secale cereale* L.) cover crop has been suggested as a method to increase producer revenue and biofuel feedstock production, but drainage N loss impacts are currently unknown. Using the tested Root Zone Water Quality Model (RZWQM) across several N rates, spring application of 120 kg N ha^{-1} prior to winter rye harvest reduced drainage N loss by 54% compared with no cover crop and by 18% compared with planted rye that was neither fertilized nor harvested. Estimates of producer revenue and net energy were also positive, with 8.3 Mg ha^{-1} of harvested rye biomass. If confirmed by field studies, these results suggest that double-cropping fertilized rye is a promising strategy to increase producer revenue, increase net energy production, and reduce drainage N loss.

Substantial interest exists in (i) increasing feedstock for biofuel and bioproduct production (USDOE, 2011, 2016, 2017), (ii) reducing nitrogen (N) export to the environment (USEPA Science Advisory Board, 2007; Galloway et al., 2008; NAE, 2017), (iii) implementing sustainable intensification (Tilman et al., 2011; Garnett et al., 2013), and (iv) using cover crops to provide ecosystem services (Braat and de Groot, 2012; Costanza et al., 2014; Blanco-Canqui et al., 2015; Basche et al., 2016). These can be competing goals if increased biofuel production increases N export (Donner and Kucharik, 2008). Incorporating winter rye (*Secale cereale* L.)harvest into a corn (*Zea mays* L.)–cover crop–soybean [*Glycine max* (L.) Merr.] rotation could positively address all four goals and provide additional producer revenue.

Growing a winter rye cover crop can increase biofuel feedstock supplies without reducing food production (Baker and Griffis, 2009; Feyereisen et al., 2013; Shao et al., 2015; Jean et al., 2017) and can reduce N drainage loads (Strock et al., 2004; Kaspar et al., 2012; Kladivko et al., 2014; Malone et al., 2014a). Harvesting or grazing cover crops can also provide ecosystem services, thus enhancing the multifunctionality of the system (Blanco-Canqui et al., 2015).

Shao et al. (2015) showed that fertilizing and harvesting winter rye can increase feedstock supplies and producer revenue compared with unfertilized rye, but N losses to subsurface drainage and net energy potential of the system were not investigated. Studies have addressed various combinations of potential producer revenue, N loss to the environment, and net energy potential of agricultural systems that include harvested winter rye (e.g., Rotz et al., 2002; Igos et al., 2016; Ramcharan and Richard, 2017). But studies are needed that simultaneously address potential producer revenue, N loss to subsurface

R.W. Malone, J.F. Obrycki, D.L. Karlen, T.C. Kaspar, D.B. Jaynes, T.B. Parkin, and K. Gillette, USDA–ARS National Lab. for Agriculture and the Environment, Ames, IA; L. Ma, USDA–ARS, Rangeland Resources and Systems Research Unit, Fort Collins, CO; S.H. Lence, Dep. of Economics, Iowa State Univ., Ames, IA; G.W. Feyereisen, USDA–ARS, Soil and Water Management Research, St. Paul, MN; Q.X. Fang, Qingdao Agricultural Univ., Qingdao, People's Republic China; T.L. Richard, Dep. of Agricultural and Biological Engineering, Penn State Univ., University Park, PA.

Supplemental material is available online for this article.
Agric. Environ. Lett. 3:170041 (2018)
doi:10.2134/ael2017.11.0041

Received 30 Nov. 2017.
Accepted 10 Jan. 2018.

*Corresponding author (rob.malone@ars.usda.gov).

Abbreviations: CC, cover crop; CCH, unfertilized harvested cover crop; CCH_L_*x*, late harvest of fertilized cover crop; DM, dry matter; NCC, no cover crop.

drainage, and net energy potential of corn–soybean systems in the US Midwest that include harvested and fertilized double-cropped winter rye.

The Root Zone Water Quality Model (RZWQM) has been used to investigate crop yield and nitrate leaching in China (Sun et al., 2018), where the model validation was described in a previous study (Sun et al., 2016). The model has been thoroughly tested in Iowa for numerous subsurface drained corn–soybean systems (Thorp et al., 2007, 2008; Malone et al., 2010, 2014b; Fang et al., 2012), including several with winter rye as a cover crop (Li et al., 2008; Qi et al., 2011; Malone et al., 2014a; Gillette et al., 2018).

This study (i) simulates the effects of harvesting a winter rye cover crop within a corn–soybean rotation on drainage N loss in central Iowa using the field-tested RZWQM reported by Gillette et al. (2018), (ii) estimates producer revenue at different fertilizer-N rates for rye biomass production, and (iii) estimates the net energy potential of rye for selected N rates.

Methods

We modeled the no cover crop (NCC) and winter rye cover crop (CC) scenarios using the same input parameters as Gillette et al. (2018). That study used RZWQM to simulate winter rye growth, N uptake, corn and soybean yield, drainage N loss, and N_2O emissions reasonably well compared with 9 yr (2002–2010) of observed central Iowa data. Other RZWQM studies suggested the model could acceptably predict winter wheat (*Triticum aestivum* L.) biomass and N uptake at different N fertilizer rates (Supplemental Table S1; Saseendran et al., 2004; Hu et al., 2006; Fang et al., 2008). Therefore, additional scenarios include (i) unfertilized harvested cover crop (CCH), where winter rye was harvested rather than killed before planting soybean on 15 May, and (ii) late harvest of fertilized cover crop (CCH_L_*x*), where rye was fertilized with various N rates (*x*) from 0 to 160 kg N ha^{-1} in early April and harvested before planting soybean on 5 June. For CCH and CCH_L_*x*, the aboveground rye biomass was harvested before planting corn on 1 May. The rye fertilizer date minimized simulated N loss to drainage and maximized yield. Corn and soybean were harvested on 1 October, which is after crop maturity and somewhat early for central Iowa, and the rye cover crop was planted on 5 October. The early harvest dates simulated the common practice of aerial seeding of rye before harvest because RZWQM allows only one crop at a time (Malone et al., 2014a), which resulted in additional winter rye growth, additional N uptake, reduced N loss in drainage, and little change in simulated main crop yield (<1%) compared with later planting. Aerial (broadcast) seeding can provide water quality benefits (Fisher et al., 2011) but can also be less reliable and cost more than seed incorporation after harvest (Fisher et al., 2011; Wilson et al., 2014). Corn was planted in even years, and soybean was planted in odd years. Model scenarios are summarized in Supplemental Table S2.

Producer revenue for harvested rye cover crop (ryer, \$ ha^{-1}) grown prior to soybean from 2001 to 2010 was estimated following Aizpurua et al. (2010), using the equation ryer = (ryeh × ryep) − (fertc × Nrate), where ryeh is predicted rye harvest (Mg ha^{-1}), ryep is net price without considering fertilizer costs (\$ Mg^{-1}), fertc is fertilizer cost (\$ kg^{-1}), and Nrate is the amount applied on 6 April (kg N ha^{-1}). A low estimate for producer revenue was calculated using a high fertilizer N cost estimate (fertc = \$1.33 kg^{-1}; IFB, 2017) and low net rye price estimate (ryep = \$75 Mg^{-1}). This net rye price estimate combined a low estimate of rye product value for ethanol plus byproducts provided by Shao et al. (2015) of \$150 Mg^{-1} (dry matter [DM]) minus a high rye feedstock cost estimate provided by Baker and Griffis (2009) of \$75 Mg^{-1} for delivering rye biomass to the farm gate that included planting and harvesting costs. In comparison, Roley et al. (2016) estimated the costs associated with nonharvested winter rye cover crops as \$151 ha^{-1} yr^{-1} (seeds, planting, kill, additional management or equipment, etc.).

The FEAT model (Camargo et al., 2013) was used to estimate the energy inputs associated with rye production. This included 6.6 GJ ha^{-1} for the 120 kg ha^{-1} N fertilizer treatment, based on a conversion factor of 54.8 GJ Mg^{-1} N. Adjusting phosphorus (P) and potassium (K) rates for expected harvested yield, the energy embedded in P, K, seed, on farm fuel use, and transportation of inputs are an additional 5.1 and 4.5 GJ ha^{-1} for CCH_L_120 and CCH_L_0, respectively.

Results and Discussion

Winter Rye Growth, Potential Revenue, and Nitrogen Uptake

Simulated annual (2001–2010) biomass of pre-soybean–harvested rye averaged 2.2, 3.7, and 6.4 Mg ha^{-1} for CCH, CCH_L_0, and CCH_L_60, respectively (Fig. 1). The simulated biomass response to fertilizer N was consistent with field results published by Shao et al. (2015), where winter rye biomass increased from 5.9 to 8.5 Mg ha^{-1} as fertilizer rates increased from 0 and 60 kg N ha^{-1} (Supplemental Table S1). We speculate that our simulated yields were lower because the average temperature October through May in central Iowa was lower than the Pennsylvania site (Malone et al., 2014a; PSC, 2017).

Average annual pre-soybean producer revenue obtained by harvesting 90% of the simulated winter rye biomass increased from \$276 ha^{-1} at a N rate of 0 (CCH_L_0) to a maximum of \$468 ha^{-1} at a rate of 140 kg N ha^{-1}, while the revenue plateaued around \$465 at a rate of approximately 120 kg N ha^{-1} (Fig. 1). The producer return to N at 120 kg N ha^{-1} was then \$189 ha^{-1} with a harvested rye biomass of 8.3 Mg ha^{-1} (Fig. 1). The predicted average annual soybean yield was only reduced by 4% for CCH_L_120 compared with NCC (results not shown). Similarly, soybean yield was reported to be 7% less following small grain forage and planting 3 wk later than full-season soybean that followed no winter crop (Nafziger et al., 2016). Studies at a greater US latitude have reported more substantial reduction in soybean yield and producer revenue from double-cropped biofuel systems when planting soybean in late June to mid-July (Gesch et al., 2014). The 4% soybean yield reduction (0.13 Mg ha^{-1}) reduced revenue \$52 ha^{-1} assuming soybean prices were

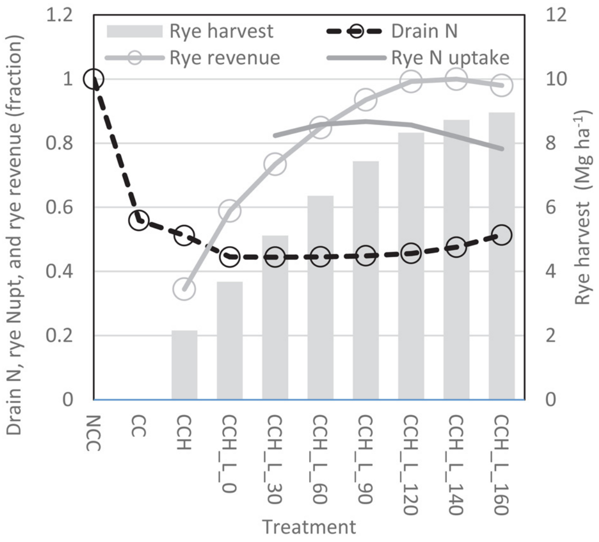

Fig. 1. Average annual 2001–2010 RZWQM results. Includes 90% of above ground rye biomass which was harvested before soybean (Mg ha^{-1}); nitrate N in drainage (fraction of maximum, which was 56.3 kg N ha^{-1} for NCC); total aboveground N uptake by pre-soybean rye minus N uptake of CCH_L_0 (fraction of N applied); and potential revenue from pre-soybean rye (fraction of maximum, which was \$468 ha^{-1} for CCH_L_140). NCC = no winter rye cover crop; CC = unharvested and unfertilized cover crop; CCH = unfertilized harvested cover crop; CCH_L_*x* = late harvest of fertilized winter rye grown prior to late soybean planting (*x* indicates the rye fertilizer rate, kg N ha^{-1}). Corn was planted in even years on 1 May, and soybean was planted in odd years on either 15 May (NCC, CC, and CCH) or 5 June (CCH_L_*x*).

\$400 Mg^{-1} (DM). This all suggests strongly positive revenue for harvesting fertilized rye. Corn yields were predicted to be reduced <1% for CCH_L_120 compared with NCC (results not shown).

The model-approximated fertilizer rate for maximum revenue of between 120 and 140 kg N ha^{-1} was low compared with previously published recommendations for full-season winter rye fertilization (Fowler et al., 1989; Bland et al., 2013) partly because of the values used for ryep and fertc and because the winter rye was terminated before maturity. Additionally, when the winter rye was sown, simulated soil nitrate N to a depth of 90 cm for CCH_L_0 was <60 kg ha^{-1} each year. At an initial soil nitrate level of 60 kg N ha^{-1} in the surface 90 cm of soil, Cui et al. (2013) reported optimal N rates for winter wheat in the North China Plain to be about 176 kg N ha^{-1}.

Although cellulosic markets for bioenergy feedstock have not yet developed, winter rye biomass can be used within the livestock feed industry. The average monthly rye silage prices in Pennsylvania during 2016 ranged from \$178 to \$247 Mg^{-1} (DM) (Ishler, 2017), and prices were estimated at \$160 Mg^{-1} DM in Wisconsin (Barnett and Rankin, 2014). Anderson et al. (2016) reported US hay prices of about \$96 Mg^{-1} DM. Therefore, even with planting, fertilizing, and harvesting costs, the producer revenue associated with incorporating rye into the cropping system appears positive.

The simulated aboveground N uptake fraction, calculated as [(CCH_L_x – CCH_L_0)/Nrate x], where x equals the N fertilizer applied in April, ranged from 0.78 to 0.87 (Fig. 1). This is higher than the <50% reported by Read et al. (2011) but lower than the >94% reported by Gu et al. (2016) for winter wheat (Supplemental Table S1). Furthermore, Gu et al. (2016) reported growing season N mineralization at their site exceeded 147 kg N ha^{-1} while October to May simulated mineralization for CCH_L_0 was <70 kg N ha^{-1}. These results, along with the results reported by Gillette et al. (2018) for unfertilized rye at this site, suggest the simulated N uptake by winter rye was reasonable. Furthermore, Fang et al. (2008) and Hu et al. (2006) reported that RZWQM can simulate the effects of different N application rates on N uptake by winter wheat (Supplemental Table S1).

Drainage Nitrate Loss and Net Energy

Compared with “business as usual” (NCC) for 2001 through 2010, where average drainage N loss was 56.3 kg ha^{-1}, planting unfertilized winter rye and killing it without harvesting (CC) reduced drainage N loss by 44% (Fig. 1). Harvesting the rye 20 d later without April fertilizer application (CCH_L_0) decreased N loss by 56%. Using the same model parameters as the current study, Gillette et al. (2018) concluded that “RZWQM reasonably simulated the relative effects of winter rye on N loss in drain flow over the nine year period [of field data] compared to the no cover crop system.”

Applying a fertilizer rate of 120 kg N ha^{-1} to harvested winter rye (CCH_L_120) reduced the simulated drainage N loss 54% compared with NCC and 18% compared with CC (Fig. 1). The N loss with CCH_L_120 was not greater mostly because of high average annual calendar year total N uptake of all crops (soybean, corn, and rye, roots and aboveground) compared with NCC (345 vs. 254 kg N ha^{-1}) and less annual net mineralization compared with CC (97 vs. 144 kg N ha^{-1}). The simulated winter rye N uptake and biomass seem reasonable as discussed above. The scenario CCH_L_120 had lower mineralization compared with CC because of rye (and thus N) harvest and removal. More thorough discussions of the RZWQM simulated annual N budget for CC and NCC were reported previously (Li et al., 2008; Malone et al., 2014a; Gillette et al., 2018). Importantly, this reduction in N loss represents an additional economic benefit that, albeit not directly captured by the producer, accrues to society as a whole in the form of improved water quality (Grizzetti et al., 2011; Wang et al., 2014).

The energy output of 8.3 and 3.7 Mg ha^{-1} harvested rye biomass (CCH_L_120 and CCH_L_0; Fig. 1) were estimated at 145.2 and 64.7 GJ ha^{-1} based on a conversion factor of 17.5 GJ Mg^{-1} DM rye (Feyereisen et al., 2013). The net energy ratios (output/input) taking into account energy inputs associated with rye for CCH_L_120 and CCH_L_0 are both strongly positive at 12 and 14, with net energy per hectare of 133.5 and 60.2 GJ ha^{-1}, respectively. The 4% reduced soybean yield for CCH_L_120 compared with NCC only reduced total energy output an additional 4.4 GJ ha^{-1}, assuming a conversion factor of 23.8 GJ Mg^{-1} DM soybean. With increased rye yield from N fertilizer application, the regional energy potential is greater than predicted by Feyereisen et al. (2013), who concluded double cropping unfertilized winter rye across the US corn–soybean belt could provide a major energy resource.

Acknowledgments

USDA is an equal opportunity provider and employer. Participation of John F. Obrycki on this project was supported in part by an appointment to the Agricultural Research Service (ARS) Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) managed by ORAU under DOE contract number DE-SC0014664. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of USDA, ARS, DOE, or ORAU/ORISE.

References

Aizpurua, A., J.M. Estavillo, A. Castellón, A. Alonso, G. Besga, and M.A. Ortuzar-Iragorri. 2010. Estimation of optimum nitrogen fertilizer rates in winter wheat in humid Mediterranean conditions: II. Economically optimal dose of nitrogen. Commun. Soil Sci. Plant. Anal. 41(3):301–307. doi:10.1080/00103620903460815

Anderson, W., M.B. Parker, J.E. Knoll, and R.C. Lacy. 2016. Fertilization ratios of N–P_2O_5–K_2O for Tifton 85 bermudagrass on two coastal plain soils. Agron. J. 108(4):1542–1551. doi:10.2134/agronj2015.0585

Baker, J.M., and T.J. Griffis. 2009. Evaluating the potential use of winter cover crops in corn–soybean systems for sustainable co-production of food and fuel. Agric. For. Meteorol. 149(12):2120–2132. doi:10.1016/j.agrformet.2009.05.017

Barnett, K., and M. Rankin. 2014. Pricing standing small grains for forage. Wisconsin Cooperative Extension. http://fyi.uwex.edu/forage/economics/.

Basche, A.D., T.C. Kaspar, S. Archontoulis, D.B. Jaynes, T.J. Sauer, T.B. Parkin, et al. 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manage. 172:40–50. doi:10.1016/j.agwat.2016.04.006

Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, et al. 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron. J. 107(6):2449–2474. doi:10.2134/agronj15.0086

Bland, D.E., S. Yong, K.L. Flanders, and B.M. Cunfer. 2013. Rye. In: Southern small grains resource management handbook. University of Georgia College of Agricultural and Environmental Sciences Cooperative Extension. https://secure.caes.uga.edu/extension/publications/files/pdf/B%201190_3.PDF.

Braat, L.C., and R. de Groot. 2012. The ecosystem services agenda: Bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosyst. Serv. 1:4–15. doi:10.1016/j.ecoser.2012.07.011

Camargo, G.T., M.R. Ryan, and T.L. Richard. 2013. Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool. Bioscience 63:263–273. doi:10.1525/bio.2013.63.4.6

Costanza, R., R. de Groot, P. Sutton, et al. 2014. Changes in the global value of ecosystem services. Glob. Environ. Change 26:152–158. doi:10.1016/j.gloenvcha.2014.04.002

Cui, Z., X. Chen, and F. Zhang. 2013. Development of regional nitrogen rate guidelines for intensive cropping systems in China. Agron. J. 105(5):1411–1416. doi:10.2134/agronj2012.0398

Donner, S.D., and C.J. Kucharik. 2008. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. Proc. Natl. Acad. Sci. USA 105:4513–4518. doi:10.1073/pnas.0708300105

Fang, Q., L. Ma, Q. Yu, R.W. Malone, S.A. Saseendran, and L.R. Ahuja. 2008. Modeling nitrogen and water management effects in a wheat–maize double-cropping system. J. Environ. Qual. 37:2232–2242. doi:10.2134/jeq2007.0601

Fang, Q.X., R.W. Malone, L. Ma, D.B. Jaynes, K.R. Thorp, T.R. Green, et al. 2012. Modeling the effects of controlled drainage, N rate, and weather on nitrate loss to subsurface drainage. Agric. Water Manage. 103:150–161. doi:10.1016/j.agwat.2011.11.006

Feyereisen, G.W., G.G.T. Camargo, R.E. Baxter, J.M. Baker, and T.L. Richard. 2013. Cellulosic biofuel potential of a winter rye double crop across the US corn–soybean belt. Agron. J. 105(3):631–642. doi:10.2134/agronj2012.0282

Fisher, K.A., B. Momen, and R.J. Kratochvil. 2011. Is broadcasting seed an effective winter cover crop planting method? Agron. J. 103:472–478. doi:10.2134/agronj2010.0318

Fowler, D.B., J. Brydon, and R.J. Baker. 1989. Nitrogen fertilization of no-till winter wheat and rye. I. Yield and agronomic responses. Agron. J. 81:66–72. doi:10.2134/agronj1989.00021962008100010012x

Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney, et al. 2008. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. Science 320:889–892.

Garnett, T., M.C. Appleby, A. Balmford, I.J. Bateman, T.G. Benton, P. Bloomer, et al. 2013. Sustainable intensification in agriculture: Premises and policies. Science 341:33–34. doi:10.1126/science.1234485

Gesch, R.W., D.W. Archer, and M.T. Berti. 2014. Dual cropping winter camelina with soybean in the northern Corn Belt. Agron. J. 106:1735–1745. doi:10.2134/agronj14.0215

Gillette, K., R.W. Malone, T.C. Kaspar, L. Ma, T.B. Parkin, D.B. Jaynes, Q.X. Fang, J.L. Hatfield, G.W. Feyereisen, and K.C. Kersebaum. 2018. N loss to drain flow and N2O emissions from a corn–soybean rotation with winter rye. Sci. Total Environ. 618:982–997. doi:10.1016/j.scitotenv.2017.09.054

Grizzetti, B., F. Bouraoui, G. Billen, H. van Grinsven, A.C. Cardoso, V. Thieu, J. Garnier, C. Curtis, R. Howarth, and P. Johnes. 2011. Nitrogen as a threat to European water quality. In: M.A. Sutton, C.M. Howard, J.W. Erisman, G. Billen, A. Bleeker, P. Grennfelt, H. van Grinsven, and B. Grizzetti, editors, European nitrogen assessment. Cambridge Univ. Press, Cambridge, UK. p. 405–433. doi:10.1017/CBO9780511976988.020

Gu, L., T. Liu, J. Wang, P. Liu, S. Dong, B. Zhao, et al. 2016. Lysimeter study of nitrogen losses and nitrogen use efficiency of northern Chinese wheat. Field Crops Res. 188:82–95. doi:10.1016/j.fcr.2015.10.014

Hu, C., S.A. Saseendran, T.R. Green, L. Ma, X. Li, and L.R. Ahuja. 2006. Evaluating nitrogen and water management in a double-cropping system using RZWQM. Vadose Zone J. 5(1):493–505. doi:10.2136/vzj2005.0004

Igos, E., K. Golkowska, D. Koster, B. Vervisch, and E. Benetto. 2016. Using rye as cover crop for bioenergy production: An environmental and economic assessment. Biomass Bioenergy 95:116–123. doi:10.1016/j.biombioe.2016.09.023

Iowa Farm Bureau (IFB). 2017. Fertilizer prices. https://www.iowafarmbureau.com/Article/Fertilizer-Prices-73889 (accessed 3 Mar. 2017).

Ishler, V. 2017. Feed price list. Penn State Extension. http://extension.psu.edu/animals/dairy/business-management/copy_of_feed-price-list.

Jean, M., D. Pennington, M. Quigley, and K. Thelen. 2017. Improving biomass and ethanol yield by intercropping a winter cereal with corn. Agron. J. 109:2530–2536. doi:10.2134/agronj2017.03.0129

Kaspar, T.C., D.B. Jaynes, T.B. Parkin, T.B. Moorman, and J.W. Singer. 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agric. Water Manage. 110:25–33. doi:10.1016/j.agwat.2012.03.010

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, et al. 2014. Cover crops in the upper midwestern USA: Potential adoption and reduction of nitrate leaching in the Mississippi River basin. J. Soil Water Conserv. 69(4):279–291. doi:10.2489/jswc.69.4.279

Li, L., R.W. Malone, L. Ma, T.C. Kaspar, D.B. Jaynes, S.A. Saseendran, K.R. Thorp, Q. Yu, and L.R. Ahuja. 2008. Winter cover crop effects on nitrate leaching in subsurface drainage as simulated by RZWQM-DSSAT. Trans. ASABE 51:1575–1583. doi:10.13031/2013.25314

Malone, R.W., D.B. Jaynes, T.C. Kaspar, K.R. Thorp, E.J. Kladivko, L. Ma, D.E. James, J.W. Singer, X.K. Morin, and T.D. Searchinger. 2014a. Cover crops in the upper Midwest USA: Simulated effect on nitrate leaching with artificial drainage. J. Soil Water Conserv. 69:292–305. doi:10.2489/jswc.69.4.292

Malone, R.W., D.B. Jaynes, L. Ma, B.T. Nolan, D.W. Meek, and D.L. Karlen. 2010. Soil-test N recommendations augmented with PEST-optimized RZWQM simulations. J. Environ. Qual. 39(5):1711–1723. doi:10.2134/jeq2009.0425

Malone, R.W., B.T. Nolan, L. Ma, R.S. Kanwar, C. Peterson, and P. Heilman. 2014b. Effects of tillage and application rate on atrazine transport to subsurface drainage: Evaluation of RZWQM using a six-year field study. Agric. Water Manage. 132:10–22. doi:10.1016/j.agwat.2013.09.009

Nafziger, E.D., M.B. Villamil, J. Niekamp, F.W. Iutzi, and V.M. Davis. 2016. Bioenergy yields of several cropping systems in the US Corn Belt. Agron. J. 108:559–565. doi:10.2134/agronj2015.0203

National Academy of Engineering (NAE). 2017. Manage the nitrogen cycle. http://www.engineeringchallenges.org/challenges/nitrogen.aspx (accessed 27 Sept. 2017).

Pennsylvania State Climatologist (PSC). 2017. Home page. http://climate.psu.edu/ (accessed 27 Sept. 2017).

Qi, Z., M.J. Helmers, R.W. Malone, and K.R. Thorp. 2011. Simulating long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics for a corn–soybean crop system. Trans. ASABE 54(5):1575–1588. doi:10.13031/2013.39836

Ramcharan, A.M., and T.L. Richard. 2017. Carbon and nitrogen environmental trade-offs of winter rye cellulosic biomass in the Chesapeake watershed. Agric. Syst. 156:85–94. doi:10.1016/j.agsy.2017.05.017

Read, J.J., G.E. Brink, M.R. McLaughlin, and K.R. Sistani. 2011. Nitrogen and winter cover crop effects on spring and summer nutrient uptake. Grass Forage Sci. 66(3):381–390. 10.1111/j.1365-2494.2011.00792.x

Roley, S.S., J.L. Tank, J.C. Tyndall, and J.D. Witter. 2016. How cost-effective are cover crops, wetlands, and two-stage ditches for nitrogen removal in the Mississippi River basin? Water Resour. Econ. 15:43–56. doi:10.1016/j.wre.2016.06.003

Rotz, C.A., G.W. Roth, and W.L. Stout. 2002. Economic and environmental implications of small grain production and use on Pennsylvania dairy farms. Appl. Eng. Agric. 18:417–428.

Saseendran, S.A., D.C. Nielsen, L. Ma, L.R. Ahuja, and A.D. Halvorson. 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-wheat. Agron. J. 96(3):615–630. doi:10.2134/agronj2004.0615

Shao, X.J., K. DiMarco, T.L. Richard, and L.R. Lynd. 2015. Winter rye as a bioenergy feedstock: Impact of crop maturity on composition, biological solubilization and potential revenue. Biotechnol. Biofuels 8:35. doi:10.1186/s13068-015-0225-z

Strock, J.S., P.M. Porter, and M.P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern US Corn Belt. J. Environ. Qual. 33(3):1010–1016. doi:10.2134/jeq2004.1010

Sun, M., Z. Huo, Y. Zheng, X. Dai, S. Feng, and X. Mao. 2018. Quantifying long-term responses of crop yield and nitrate leaching in an intensive farmland using agro-eco-environmental model. Sci. Total Environ. 613–614:1003–1012. doi:10.1016/j.scitotenv.2017.09.080

Sun, M., X. Zhang, Z. Huo, S. Feng, G. Huang, and X. Mao. 2016. Uncertainty and sensitivity assessments of an agricultural–hydrological model (RZWQM2) using the GLUE method. J. Hydrol. 534:19–30. doi:10.1016/j.jhydrol.2015.12.045

Thorp, K.R., D.B. Jaynes, and R.W. Malone. 2008. Simulating the long-term performance of drainage water management across the midwestern United States. Trans. ASABE 51(3):961–976. doi:10.13031/2013.24534

Thorp, K.R., R.W. Malone, and D.B. Jaynes. 2007. Simulating long-term effects of nitrogen fertilizer application rates on corn yield and nitrogen dynamics. Trans. ASABE 50(4):1287–1303. doi:10.13031/2013.23640

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. USA 108:20260–20264. doi:10.1073/pnas.1116437108

USDOE. 2011. US billion-ton update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes, leads, ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf.

USDOE. 2016. 2016 billion-ton report: Advancing domestic resources for a thriving bioeconomy. Vol. 1: Economic availability of feedstocks. M.H. Langholtz, B.J. Stokes, and L.M. Eaton, leads, ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi:10.2172/1271651

USDOE. 2017. 2016 billion-ton report: Advancing domestic resources for a thriving bioeconomy. Vol. 2: Environmental sustainability effects of select scenarios from volume 1. R.A. Efroymson, M. H. Langholtz, K.E. Johnson, and B. J. Stokes, editors, ORNL/TM-2016/727. Oak Ridge National Laboratory, Oak Ridge, TN. doi:10.2172/1338837

USEPA Science Advisory Board. 2007. Hypoxia in the northern Gulf of Mexico. EPA-SAB-08-003. USEPA. https://yosemite.epa.gov/sab/sabproduct.nsf/C3D2F27094E03F90852573B800601D93/$File/EPA-SAB-08-003complete.unsigned.pdf.

Wang, G.L., Y.L. Ye, X.P. Chen, and Z.L. Cui. 2014. Determining the optimal nitrogen rate for summer maize in China by integrating agronomic, economic, and environmental aspects. Biogeosciences 11:3031–3041. doi:10.5194/bg-11-3031-2014

Wilson, M.L., D.L. Allan, and J.M. Baker. 2014. Aerially seeding cover crops in the northern US Corn Belt: Limitations, future research needs, and alternative practices. J. Soil Water Conserv. 69:67A–72A. doi:10.2489/jswc.69.3.67A