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Management Implications of a Rye Cover Crop on Nutrient Cycling and Soybean Production in Southeast South Dakota: Focus on Rye Seeding Rates and Termination Timing

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MANAGEMENT IMPLICATIONS OF A RYE COVER CROP ON NUTRIENT CYCLING AND SOYBEAN PRODUCTION IN SOUTHEAST SOUTH DAKOTA: FOCUS ON RYE SEEDING RATES AND TERMINATION TIMING

By:

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

MANAGEMENT IMPLICATIONS OF A RYE COVER CROP ON NUTRIENT CYCLING AND SOYBEAN PRODUCTION IN SOUTHEAST SOUTH DAKOTA: FOCUS ON RYE SEEDING RATES AND TERMINATION TIMING

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Winter rye (*Secale cereale* L.) has become an important cover crop in South Dakota; yet, concerns over negative impacts on cash crop yields is one important limitation to the widespread adoption of winter rye in cropping systems. Two field studies were implemented at the Southeast Research Farm near Beresford, SD investigating the impacts of five seeding rates (0-90 kg ha^{-1}) and termination timings (April 19th- May31st) with the objectives of examining the roles of winter rye management practices on soybean production and yield from nutrient cycling of nitrogen (N) and sulfur (S) in the agroecosystem. Plant, residue, and soybean samples were collected at critical points to observe changes in nutrient fluxes between sinks in the agroecosystem while fiber concentrations of rye and residue materials were analyzed to understand how management practices influenced the dynamics driving nutrient turnover. Delaying rye termination beyond May 13th resulted in dramatic increases in rye biomass leading to greater nutrient uptake and lower residue quality while seeding rate did not affect biomass production until 90 kg ha^{-1} was applied. Later termination dates and the 67-90 kg ha^{-1} seeding rates contributed to greater nutrient immobilization in crop residues and slower nutrient release as compared to earlier

terminations and the 22-45 kg ha^{-1} seeding rates. This resulted in a decreased soybean S in both studies at later terminations and higher seeding rates; however, high fertility soils at the research location contributed sufficient S to alleviate impacts on grain yield. Yield was unaffected by seeding rate treatment while later termination timings produced a yield advantage possibly as a result of delayed soybean development.

Chapter 1: Introduction

1.1 Cover Crop Benefits to Soil Health and Resilience

The age old challenge of agriculture is seeking ways to increase and intensify agricultural production to meet the needs of a growing population while maximizing environmental integrity understanding that agriculture itself has the potential to be a naturally degrading practice (Cassman, 2002; Foley et al., 2011; Ellis et al., 2013; Finney et al., 2016). While many solutions to this agricultural conundrum have been proposed, cover cropping has been one answer that has gained increasing amounts of traction due to its ability to improve ecological functioning and long-term sustainability of agroecosystems by building resiliency in agricultural systems (Morton and Abendroth, 2017; Rorick and Kladivko, 2017). Cover cropping has become an increasingly common practice in the Upper Midwest to build resiliency in soil systems as producers seek to capitalize on the range of ecosystem services provided from diversifying their cropping rotations (Singer and Nusser, 2007; CTIC, 2017). These ecosystem services include improved soil physical properties such as improved aggregation which can reduce erosion and improve internal water cycling and provision (Basche et al., 2016; Rorick and Kladivko, 2017). Higher levels of organic carbon, increased microbial communities, and improved nutrient cycling in soil systems have been observed in long term rye cover crop studies (Sarrantonio and Gallandt, 2008; McDaniel et al., 2014; Moore et al., 2014; Schipanski et al., 2014). Therefore, adding biomass from cover crops back into the soil system can be viewed as a long-term investment in soil health which creates a situation that stimulates microbiological activity, increases organic N pools and improves the natural ability of soils to provide resources to plants and withstand climatic variability (Ruffo et al., 2004).

1.2 A Changing nutrient management paradigm

While there are a range of ecosystem services that can be provided from cover crops and many of them are interrelated, this review will focus on nutrient cycling. The response to intensifying agricultural production has frequently been to increase the use of fertilizers to maximize crop production. Yet, a heavy use of inorganic fertilizer sources risk subjecting the ecosystem to nutrient saturation which leads to nutrient losses (Drinkwater and Snapp, 2007). N (Nitrogen), in particular, is the most susceptible to losses and of concern in nutrient cycling of agroecosystems. Reactive forms of nitrogen in fertilizers and a reliance on monocrop systems have resulted in a cascade of reactive nitrogen that has impacted a variety of terrestrial spheres causing degradation leading to losses in biodiversity, disruption of natural ecosystems, and contributing to global climate change (Galloway et al., 2003). Smil (1999) believes that only a small fraction of around 4 Tg ha^{-1} of N is accumulated in soil systems from the applied 170 Tg ha^{-1}. From this, a global nitrogen recovery rate is estimated at 50% with the remainder of the nitrogen being lost from the system (Smil, 1999). A major pathway that agriculture can take moving forward to decrease its dependence on reactive forms of nitrogen used in fertilization is to reduce the leakiness of the agroecosystem by recycling nutrients that are subject to loss pathways (Galloway et al., 2003). Therefore, improving nutrient recycling through additions of carbon to the soil can result in improved synchrony between N release and times of crop need (Cassman, 2002). This focus on carbon production stimulates microbially mediated processes that make use of the inherent soil nutrient sinks and improve the internal nutrient cycling capacity of agroecosystems (Drinkwater and Snapp, 2007). A fundamental shift in nutrient management in agriculture may be needed to shift away from thinking of nutrient management in inorganic terms and to begin viewing nutrient management as a primarily organic mediated process. Drinkwater and Snapp (2007) suggest the need for a change in our nutrient management paradigm to a kind of management that seeks to recombine the C, N, and P cycles.

1.3 Role of winter rye in nutrient cycling

Losses of soil nutrients are a major consideration in terms of environmental protection. Winter rye (*Secale cereale* L.) can play a role in recombining global C and N cycles through its exceptional ability to take up residual NO_3^- present in soil ecosystems following cash crop harvest (Kaspar et al., 2007). A thick, fibrous root system and prolific growth give rye an outstanding ability to soak up residual N in the soil system and makes it an advantageous choice over other winter cover crops (Sarrantonio and Gallandt, 2008; Yeo et al., 2014). Reduction in NO_3^- leaching vary widely by study, but can generally be estimated to be between 50% to 93% (Stute et al., 2007; Krueger et al., 2011; Yeo et al., 2014; Pantoja et al., 2016). The NO_3^- that is reduced from leaching losses can be found in the cover crop biomass through N uptake with this amount being equivalent to the reduction of NO_3^- leaching seen in fields (Kessavalou and Walters, 1999; Ruffo et al., 2004; Kaspar et al., 2007). Once terminated, the breakdown of rye residues leads to increases in OM levels and the N begins to cycle through the soil N pools (Ruffo et al., 2004). While much of the N recovered by rye is immobilized upon decomposition, this immobilization process prevents losses of N through leaching of NO_3^- or N_2O fluxes through denitrification. Management systems that return OM back to soils have higher levels of labile C which increases microbial activity. Microbes then immobilize N and re-release it creating a slow release of N throughout the growing season which results in tighter and more efficient N cycling systems (Burger and Jackson, 2003; McSwiney et al., 2010). McSwiney, et. al (2010) view this immobilization process as an N management tool for a more efficient use of fertilizer N. In a long-term study, Kuo (2000) observed initially a decrease in corn biomass production where rye was used as a cover crop. However, as larger pools of organic C and N were present in soils, gradual increases in corn biomass were seen (Kuo and Jellum, 2000). This suggests that priming the soil system with inputs of slow release organic materials can allow producers to reduce N fertilization in the long term due to the natural N supplying power of soils.

1.4 Cover crop adoption in South Dakota

The use of cover crops across the United States has been on the rise in recent years. The USDA-National Agricultural Statistics Survey (NASS) has reported 15,390,764 acres of cover crops planted in 2017 which is a 50% increase since 2012. South Dakota has followed the same trends with 2,154 farms planting a total of 281,649 acres of cover crops showing an 89% increase from 2012. Therefore, of the 19,813,517 acres of South Dakota cropland, 1.4% is under cover crops which is a rise from 0.78% of cropland acres using cover crops in 2012 (USDA-NASS, 2019). Winter cereal grains are the most commonly used cover crop with cereal rye being the most frequently planted species (CTIC, 2013;2017). A country wide survey in 2017 showed that commodity producers planted more rye than any other cover crop species (CTIC, 2017).

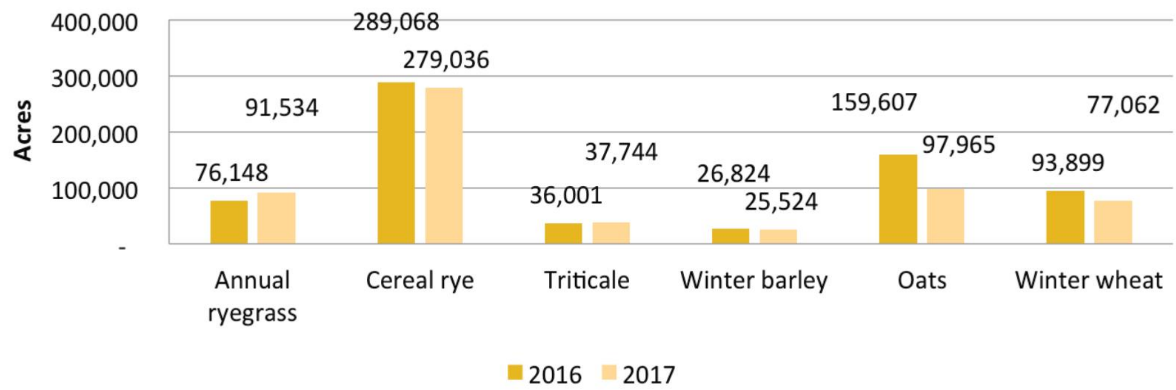


Figure 1.1 Acres of cereal grain used as cover crops among survey respondents in 2016 and 2017 (CTIC, 2017).

A 2018 survey in South Dakota showed that higher percentages of farmers who are using cover crops have used them for less than 3 years. The survey reported that 21.7% have planted cover crops for less than 3 years while 10.9% have had cover crops for over 10 years. Additionally, producers using cover crops for over 10 years have converted 45% of their land to include cover crops while those who are just beginning with cover crops only have incorporated less than 15% of their acres to cover crops. Producers who have used cover crops for longer periods of time have better perceptions of their impact on profitability with 40% of long-term cover crop users viewing it as profitable vs only 20% of new users (Wang, 2019). This data shows the changing perceptions among producers on how cover cropping can play a vital role towards profitability and sustainability in their cropping systems.

1.5 Fitting rye into corn and soybean rotations in South Dakota

While the cover crop species best suited to any particular situation is dependent entirely on the objectives of the producer; generally, cover crops best in otherwise fallow periods of the growing season as to not limit any cash cropping opportunities (Snapp et al., 2005). In a South Dakota corn and soybean rotation, this fallow period extends from corn harvest in October until soybean planting in May. Winter rye fits well into this corn and soybean rotation in the upper Midwest as it is a strongly winter hardy crop that can withstand late plantings and cold winters. With temperatures as low as 1.1°C rye is able to germinate and can produce vegetative growth with temperatures above 4°C (Sarrantonio and Gallandt, 2008; Appelgate et al., 2017). Rye can be expected to overwinter up to the Hardiness Zones of 3 (USDA-ARS, 2012) Reports have varied significantly on rye's effect on the following corn yields with studies showing both yield increases and decreases as a result of rye (Appelgate et al., 2017). However, results of studies in which rye has been planted after corn and ahead of soybeans have more consistently shown no differences in soybean yields (Thelen and Leep, 2002; Ruffo et al., 2004; De Bruin et al., 2005). The benefit to incorporating rye ahead of soybeans is that soybeans are able to remain competitive in low N environments which reduces the need to quickly cycle nitrogen back into the soil system for use of the cash crop (Wells et al., 2013). This allows for the potential to terminate rye later in the growing season resulting in higher biomass and higher uptake of N. This ability to terminate rye late in the growing season allows producers to stack multiple ecosystem services without seeing adverse effects on soybean yields suggesting that rye can be a strong choice following corn and preceding soybeans (Pantoja et al., 2015).

1.6 Risks of rye to subsequent crop production

Rye has the potential to inhibit following crop production through mechanisms related to resource depletion as well as physical and chemical inhibition of germinating seedlings. Large quantities of biomass have the potential to interfere with seedling germination through reduced sunlight and heat reaching the soil surface as well as the production of benzoxazinoid compounds that inhibit plant growth (Mirsky et al., 2013). Winter rye grows prolifically in the springtime and significantly reduces soil NO_3^- and soil water. This depletion of soil resources can be a significant concern to producers due to potential risks towards subsequent cash crop production. Water usage of cover crops is most associated with grain yield reductions in dry years (Singer et. al 2005). As rye increases in biomass, higher concentrations of soil nutrients are taken up and held in rye tissues (Crandall et al., 2005). The main nutrient of concern is N; however, previous research has shown that S may also be immobilized by cover crop residues leaving the subsequent crop in a deficient state (Brockmueller et al., 2016; Sexton et al., 2017). Therefore, the synchronization between cover crop N and S release and cash crop uptake become essential to limiting nutrient stress and maintaining yield potential. Decomposition curves have shown that legumes quickly release lots of N while rye gradually releases lower amounts of N (Wagger, 1989; Sievers and Cook, 2018). Wagger (1989a) found that 8 weeks after desiccation, rye had released about 50% of the N while hairy vetch and crimson clover had released around 80% of total N (Ranells and Wagger, 1996). This data shows that grass cover crops likely will not be able to supply N in sufficient quantities to the following cash crop. Relationships between rye biomass and reductions in corn yield have been observed in previous studies which are likely a result of reduced N fertility as rye cover crops were unable to release enough N at times of plant need (Krueger et al., 2011; Pantoja et al., 2016). Options to prevent damage to subsequent crops are to synchronize nutrient release with cash crop needs or to grow a crop that is not dependent on soil supplied N (Sievers and Cook, 2018).

1.7 Overcoming rye risks through management

The rise in production of cover crops has led to an increase in research going into how to properly manage cover crops to maximize benefits while reducing risks to subsequent crops. In order to overcome these challenges, careful management of winter rye as a cover crop is needed to limit negative effects on the subsequent crop. Nutrient cycling occurs as soil microbes decompose organic materials releasing nutrients back into soil solution where they are available for crop uptake. Therefore, decomposition is an essential process to the turnover of nutrients. Decomposition is dependent on many factors external to the plant including temperature, soil moisture and microbe communities (Lupwayi et al., 2004; Ruffo et al., 2004). However, residue quality is the main plant based factor that impacts decomposition (Pantoja et al., 2016). Therefore, nutrient cycling is strongly predicted by the biomass produced and the quality of the residue upon termination as biomass determines the quantity of nutrients to cycle while quality determines the speed in which these nutrients will cycle. Higher quality materials will cycle nutrients back into the system quicker than lower quality materials (Martinez-Feria et al., 2016). Residue quality has several components that work together to effect the speed of nutrient turnover including the C:N ratio of the material, N concentration, and the fibrous components that make up the tissues (Lindsey et al., 2013). Lower C:N Ratios promote quicker decomposition and are affected by plant maturity and overall soil fertility (Lindsey et al., 2013). Rye cover crops tend to have higher C:N ratios and higher percentages of fiber composition than legume cover crops (Sievers and Cook, 2018) which leads to large differences in nutrient release (J.G Cobo, 2002; Harre et al., 2014; Sievers and Cook, 2018). Nitrogen concentration effects mineralization rates by influencing C:N ratios (Justes et al., 2009). Fiber components provide physical protection of nutrients from microbial decomposition resulting in slower release rates (Sievers and Cook, 2018). Fiber composition is increased as plants mature and is generally higher in grasses vs legume crops (Poffenbarger et al., 2015).

1.8 Managing rye cropping systems to promote nutrient turnover

Therefore, in order to impact nutrient cycling and soil nutrient release, management steps can be taken to alter residue quality to encourage turnover of soil nutrients. A variety of different management tools have been suggested in the literature. Rannels (1996) reported that modifying cropping systems to include bicultures of grasses and legumes may lower C:N ratios of the cover crop mixture by lowering the N competition in the soil system. However, many legume cover crops have had variable success overwintering due to the harsher winters in the Upper Midwest (Appelgate et al., 2017). Adding fertilizers to increase N content in the soil or planting rye after a legume crop may result in lower C:N ratios of rye due to higher concentrations of N present in the soil (Pantoja et al., 2016). Therefore, in N limited soils, rye C:N ratios can be predicted by biomass production (Brennan et al., 2013; Pantoja et al., 2016). Managing cover crop biomass includes both the burndown timing and seeding rates. Another option to manage residue quality is the termination time with earlier terminated crops taking up less nutrients, but also having lower residue quality to cycle nutrients quicker (Wagger, 1989; Alonso-Ayuso et al., 2014; Otte et al., 2019). Lastly, minimal research has been conducted on seeding rates as a management tool to effect residue quality in rye monoculture systems. Brennan and Boyd found that increasing rye seeding rates three fold resulted in an increase in dry matter production (Brennan. and Boyd, 2012a). Consequently, this increase in biomass production led to higher C:N ratios bringing about lower residue quality (Brennan et al., 2013).

1.9 Conclusion

From this review of the literature, we can conclude that there is need to recombine global C cycles with other soil nutrient cycles in order to promote tighter and more efficient nutrient cycling and provisioning. Winter rye can play an integral role in this process in the Upper Midwest due to its outstanding ability to fit into corn and soybean rotations. However, there are risks of depleting or sequestering soil resources if rye is not properly managed. Therefore, there is a need to synchronize rye nutrient release with the optimum uptake time of cash crops. Yet, the concern over the most limiting nutrient, N, can be limited by planting rye ahead of soybeans which is more resilient to low soil N conditions. However, with concerns about S immobilization in rye tissues, synchronization of S and soybean uptake is still of importance.

1.10 Objectives

After a comprehensive review of the literature, a field trial was set up with the following objectives:

1) Gain information on how the seeding rates and burndown timing of winter rye effect soil and plant nutrient status throughout the growing season and its ultimate impact on soybean grain yield.
2) Find a balance between maximizing ecosystem services and crop production with a seeding rate and burndown timing sweet spot that optimizes the relationship between biomass production and residue quality.

References

Alonso-Ayuso, M., J. L. Gabriel, M. Quemada, and A. Shrestha. 2014. The Kill Date as a Management Tool for Cover Cropping Success. PLoS ONE 9. doi:10.1371/journal.pone.0109587.

Appelgate, S. R., A. W. Lenssen, M. H. Wiedenhoeft, and T. C. Kaspar. 2017. Cover Crop Options and Mixes for Upper Midwest Corn–Soybean Systems. Agron. J. 109. doi:10.2134/agronj2016.08.0453.

Basche, A. D., T. C. Kaspar, S. V. 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. Agricultural Water Management 172:40-50. doi:10.1016/j.agwat.2016.04.006.

Brennan, E., and N. Boyd. 2012. Winter Cover Crop Seeding Rate and Variety Affects during Eight Years of Organic Vegetables: I. Cover Crop Biomass Production. Agronomy Journal 104:684-698. doi:10.2134/agronj2011.0330.

Brennan, E. B., N. S. Boyd, and R. F. Smith. 2013. Winter Cover Crop Seeding Rate and Variety Effects during Eight Years of Organic Vegetables: III. Cover Crop Residue Quality and Nitrogen Mineralization. Agron. J. 105:171-182. doi:10.2134/agronj2012.0258.

Brockmueller, B., C. Bolkema, M. Buiter, A. Huizenga, B. Rops, G. Williamson, et al. 2016. Rye cover crop grown ahead of soybeans--2016 season--A first look at impacts on soybean nutrient uptake. Southeast South Dakota Exp. Farm Annual Progress Report 2016:34-39.

Burger, M., and L. E. Jackson. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biol. Biochem. 35:29-36. doi:10.1016/S0038-0717(02)00233-X.

Cassman, K. G. 2002. Agroecosystems, Nitrogen-Use Efficiency, and Nitrogen Management. Ambio 31:132-140.

Crandall, S. M., M. L. Ruffo, and G. A. Bollero. 2005. Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn. Plant Soil 268:209-219. doi:10.1007/s11104-004-0272-x.

CTIC. 2013. 2012-2013 Cover Crop Survey. June 2013 Survey Analysis. Joint Publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program. Retrieved from https://www.sare.org/Learning-Center/Topic-Rooms/Cover-Crops/Cover-Crop-Surveys. (accessed 28 February 2020).

CTIC. 2017. Report of the 2016-17 national cover crop survey. Joint Publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. Retrieved from https://www.sare.org/Learning-Center/Topic-Rooms/Cover-Crops/Cover-Crop-Surveys. (accessed 28 February 2020).

De Bruin, J., P. Porter, and N. Jordan. 2005. Use of a Rye Cover Crop following Corn in Rotation with Soybean in the Upper Midwest. Agron. J. 97:587-598. doi:10.2134/agronj2005.0587.

Drinkwater, L. E., and S. S. Snapp. 2007. Nutrients in Agroecosystems: Rethinking the Management Paradigm. In: D. L. Sparks, editor Advances in Agronomy. Academic Press. p. 163-186.

Ellis, E. C., J. O. Kaplan, D. Q. Fuller, S. Vavrus, K. Klein Goldewijk, and P. H. Verburg. 2013. Used planet: a global history. Proc Natl Acad Sci U S A 110:7978-7985. doi:10.1073/pnas.1217241110.

Finney, D. M., C. M. White, and J. P. Kaye. 2016. Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. Agron. J. 108:39-52. doi:10.2134/agronj15.0182.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, et al. 2011. Solutions for a cultivated planet. Nature 478:337-342. doi:10.1038/nature10452.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, et al. 2003. The Nitrogen Cascade. BioScience 53:341-356. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO2.

Harre, N., J. Schoonover, and B. Young. 2014. Decay and Nutrient Release Patterns of Weeds Following Post-Emergent Glyphosate Control. Weed Science 62:588-596. doi:10.1614/WS-D-14-00058.1.

J.G Cobo, E. B., D.C.L. Kass, R.J. Thomas. 2002. Decomposition and Nutrient Release by Green Manures in a Tropical Hillside Agroecosystem. Plant Soil 240:331-342.

Justes, E., B. Mary, and B. Nicolardot. 2009. Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: parameterization of the residue decomposition module of STICS model for mature and non mature residues. Plant Soil 325:171-185. doi:10.1007/s11104-009-9966-4.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. J. Environ. Qual. 36:1503-1511. doi:10.2134/jeq2006.0468.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye Cover Crop and Gamagrass Strip Effects on NO3 Concentration and Load in Tile Drainage. J. Environ. Qual. 36:1503-1511. doi:10.2134/jeq2006.0468.

Kessavalou, A., and D. T. Walters. 1999. Winter Rye Cover Crop Following Soybean Under Conservation Tillage: Residual Soil Nitrate. Agron. J. 91:643-649. doi:10.2134/agronj1999.914643x.

Krueger, E., T. Ochsner, P. Porter, and J. Baker. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agron. J. 103:316-323. doi:10.2134/agronj2010.0327.

Kuo, S., and E. Jellum. 2000. Long-term winter cover cropping effects on corn (Zea mays L.) production and soil nitrogen availability. Biol. Fertil. Soils 31:470-477.

Lindsey, L., K. Steinke, D. Warncke, and W. Everman. 2013. Nitrogen Release from Weed Residue. Weed Sci. 61:334-340. doi:10.1614/WS-D-12-00090.1.

Lupwayi, N., G. Clayton, J. O'Donovan, K. Harker, T. Turkington, and W. Rice. 2004. Decomposition of crop residues under conventional and zero tillage. Can. J. Soil Sci. 84:403-410.

Martinez-Feria, R. A., R. Dietzel, M. Liebman, M. J. Helmers, and S. V. Archontoulis. 2016. Rye cover crop effects on maize: A system-level analysis. Field Crops Res. 196:145-159. doi:10.1016/j.fcr.2016.06.016.

McDaniel, M. D., L. K. Tiemann, and A. S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24:560-570. doi:10.1890/13-0616.1.

McSwiney, C. P., S. S. Snapp, and L. E. Gentry. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecol. Appl. 20:648-662. doi:10.1890/09-0077.1.

Mirsky, S. B., M. R. Ryan, J. R. Teasdale, W. S. Curran, C. S. Reberg-Horton, J. T. Spargo, et al. 2013. Overcoming Weed Management Challenges in Cover Crop—Based Organic Rotational No-Till Soybean Production in the Eastern United States. Weed Technol. 27:193-203. doi:10.1614/WT-D-12-00078.1.

Moore, E. B., M. H. Wiedenhoeft, T. C. Kaspar, and C. A. Cambardella. 2014. Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage–Soybean Cropping Systems. Soil Sci. Soc. Am. J. 78:968-976. doi:10.2136/sssaj2013.09.0401.

Morton, L. W., and L. J. Abendroth. 2017. Crops, climate, culture, and change. J. Soil Water Cons. 72:47A-52A. doi:10.2489/jswc.72.3.47A.

National Agricultural Statistic Services (USDA-NASS). 2019. Census of Agriculture, United States Summary and State Data. Volume 1. Geographic Area Series. Part 51. AC-17-A-51. U.S. Department of Agriculture-National Agricultural Statistics Service, Washington, DC.

Otte, B., S. Mirsky, H. Schomberg, B. Davis, and K. Tully. 2019. Effect of Cover Crop Termination Timing on Pools and Fluxes of Inorganic Nitrogen in No-Till Corn. Agron. J. doi:10.2134/agronj2018.10.0699.

Pantoja, J. L., K. P. Woli, J. E. Sawyer, and D. W. Barker. 2015. Corn Nitrogen Fertilization Requirement and Corn–Soybean Productivity with a Rye Cover Crop. Soil Sci. Soc. Am. J. 79:1482-1495. doi:10.2136/sssaj2015.02.0084.

Pantoja, J. L., K. P. Woli, J. E. Sawyer, and D. W. Barker. 2016. Winter Rye Cover Crop Biomass Production, Degradation, and Nitrogen Recycling. Agron. J. 108:841-853. doi:10.2134/agronj2015.0336.

Poffenbarger, H. J., S. B. Mirsky, R. R. Weil, J. E. Maul, M. Kramer, J. T. Spargo, et al. 2015. Biomass and Nitrogen Content of Hairy Vetch–Cereal Rye Cover Crop Mixtures as Influenced by Species Proportions. Agron. J. 107. doi:10.2134/agronj14.0462.

Ranells, N. N., and M. G. Wagger. 1996. Nitrogen Release from Grass and Legume Cover Crop Monocultures and Bicultures. Agron. J. 88:777-882. doi:10.2134/agronj1996.00021962008800050015x.

Rorick, J. D., and E. J. Kladivko. 2017. Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. J. Soil Water Conserv. 72:260.

Ruffo, M., D. Bullock, and G. Bollero. 2004. Soybean Yield as Affected by Biomass and Nitrogen Uptake of Cereal Rye in Winter Cover Crop Rotations. Agron. J. 96:800-805. doi:10.2134/agronj2004.0800.

Sarrantonio, M., and E. Gallandt. 2008. The Role of Cover Crops in North American Cropping Systems. J. Crop Prod. 8:53-74. doi:10.1300/J144v08n01_04.

Schipanski, M. E., M. Barbercheck, M. R. Douglas, D. M. Finney, K. Haider, J. P. Kaye, et al. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125:12-22. doi:10.1016/j.agsy.2013.11.004.

Sexton, P., D. Auch, and B. Rops. 2017. Burndown timing for a rye cover crop raised ahead of corn--A preliminary study. Southeast South Dakota Exp. Farm Annual Progress Report 2017:19-21.

Sievers, T., and R. L. Cook. 2018. Aboveground and Root Decomposition of Cereal Rye and Hairy Vetch Cover Crops. Soil Sci. Soc. Am. J. 82. doi:10.2136/sssaj2017.05.0139.

Singer, J. W., and S. M. Nusser. 2007. Are cover crops being used in the US corn belt? J. Soil Water Conserv. 62:353-358.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycles 13:647-662. doi:10.1029/1999gb900015.

Snapp, S. S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, et al. 2005. Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. Agron. J. 97:322-332. doi:10.2134/agronj2005.0322a.

Stute, J., K. Shelly, D. Mueller, and T. Wood. 2007. Planting winter rye after corn silage: Managing for forage. Retrieved from https://fyi.extension.wisc.edu/forage/planting-winter-rye-after-corn-silage-managing-for-forage/. (accessed 13 January 2020).

Thelen, K. D., and R. H. Leep. 2002. Integrating a Double-Cropped Winter Annual Forage into a Corn-Soybean Rotation. Crop Manage. 1. doi:10.1094/cm-2002-1218-01-rs.

USDA-ARS. 2012. Plant Hardiness Zone Map. Retrieved from https://planthardiness.ars.usda.gov/PHZMWeb/. (accessed 26 February, 2020).

Wagger, M. G. 1989. Time of Desiccation Effects on Plant Composition and Subsequent Nitrogen Release from Several Winter Annual Cover Crops. Agron. J. 81:236-241. doi:10.2134/agronj1989.00021962008100020020x.

Wang, T. 2019. Cover Crop Usage in South Dakota is on the Rise. Retrieved from https://extension.sdstate.edu/cover-crop-usage-south-dakota-rise. (accessed February 19, 2020).

Wells, M. S., S. C. Reberg-Horton, A. N. Smith, and J. M. Grossman. 2013. The Reduction of Plant-Available Nitrogen by Cover Crop Mulches and Subsequent Effects on Soybean Performance and Weed Interference. Agron. J. 105:539-545. doi:10.2134/agronj2012.0396.

Yeo, I., S. Lee, A. Sadeghi, P. C. Beeson, W. Hively, G. McCarty, et al. 2014. Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model. Hydrol. Earth Syst. Sci. 18:5239-5253. doi:10.5194/hess-18-5239-2014.

Chapter 2: Winter rye cover crop seeding rate effects on nutrient cycling and production of the following soybean crop.

2.1 Abstract

In response to the increased popularity of winter rye (*Secale cereale* L.) as a cover crop, proper management is necessary to maintain a balance between achieving cover crop benefits without compromising the following crop yield. A study implemented at the Southeast Research Farm near Beresford, SD examined the effects of five rye seeding rates on nutrient cycling and the nutrient status of the following soybean crop. Plant, residue, and soil samples were taken at four critical points during the growing season to provide a snapshot of current nutrient status and to observe their flow between major nutrient sinks in the agroecosystem. Plant and residue biomass samples were taken and measured for nutrient concentration and fibrous composition. The 90 kg ha^{-1} treatment yielded the highest rye biomass and nutrient uptake with no difference recorded between the 22, 45, and 67 kg ha^{-1} seeding rate treatments. Higher seeding rates trended towards lower rye residue quality in 2019 leading to slower decomposition of crop residues at higher seeding rates. No difference was observed in the fibrous materials in 2018 with low C:N ratios being the main factor driving quick nutrient turnover and decomposition among all treatments. No difference in soybean nutrient composition or yield was observed. These results suggest that under these conditions, lower seeding rates of rye could be used to achieve the same cover crop benefits while cycling nutrients quicker in the agroecosystem.

2.2 Introduction

In response to concerns regarding resource management, researchers and farmers are trying to adapt system wide approaches that conserve land resources and biodiversity while still maximizing yield and profit. Winter rye cover crops have fit this role in many parts of the Upper Midwest due to their suite of ecosystem services and strong adaptability to commonly practiced cropping systems (Power, 2010; Schipanski et al., 2014; Appelgate et al., 2017). Yet, several barriers to adoption exist including concerns over cost of establishment, N dynamics, residue management, and inconsistent results which have prevented winter rye from gaining a more prominent influence in the Midwestern agricultural setting (Singer and Nusser, 2007; Bergtold et al., 2019; Thompson et al., 2020). While ecosystem services are strongly predicted by plant biomass and residue quality, proper management of rye biomass and residues are an important step in reducing the potential risks to soybean production (Finney et al., 2016). Management approaches suggested in the literature to balance rye biomass with residue quality have included the use of bicultures (White et al., 2017), N fertilizers (Ryan et al., 2011), termination timing (Otte et al., 2019), and managing seeding rates (Brennan et al., 2013). Seeding rate management is important as it offers the potential for a direct reduction in input costs for producers. A more complete understanding of the interrelated dynamics between cover crop seeding rates, residue quality, and nutrient turnover can help producers make management decisions that maximize cover crop services while minimizing cost of establishment and adverse effects on cash crop yields.

Current management practices regarding seeding rates in the Upper Midwest vary widely by location, producers' goals, and management style with the Natural Resource Conservation Service (NRCS) suggesting between 45 to 180 kg ha^{-1} (Casey, 2012). Generally, lower seeding rates of around 67 kg ha^{-1} are encouraged when rye is used as a cover crop with the intention of nutrient cycling (USDA and SARE, 1992). South Dakota State University Extension suggests seeding rates of 45 kg ha^{-1} when used within corn and soybean cropping systems (Karki, 2019)

There is some discrepancy in the literature about the ability of increased seeding rates to raise total rye biomass. Brennan and Boyd (2012) saw increased biomass from increasing seeding rates three-fold. On the contrary, other studies have observed neutral effects in biomass production which were attributed to rye tillering compensating for lower planting densities or N limitations at higher seeding rates (Boyd et al., 2009; Ryan et al., 2011). Residue quality has generally been observed to decrease with higher seeding rates (Reddy et al., 2003). Caravetta (1990) noted lower concentrations of NDF and lignin in sorghum planted at reduced densities. Brennan et al. (2013) saw increases in C:N ratios as seeding rates increased which was attributed to lower N concentration in rye at higher seeding rates. Both C:N ratio and fibrous components have been shown to be effected by the availability of N in the system (Liu et al., 2016; Pantoja et al., 2016; Ogden et al., 2018).

The general paradigm for decomposition shows that the interactions between environment, litter quality, and microbial communities are the driving forces behind decomposition of crop residues (Bradford et al., 2016). Cover crops can actively effect decomposition rates by creating priming effects in which biotic and abiotic factors in the rhizosphere induce decomposition (Wichern et al., 2007; Fustec et al., 2010) or through plant litter legacy effects that can enhance (Varela et al., 2014) or impede decomposition (Barel et al., 2019). Decomposition rates are very tightly connected to residue quality (Duval et al., 2016; Chatterjee and Acharya, 2020). Therefore, factors effecting residue quality of rye tissues will impact the speed of decomposition and nutrient cycling.

While winter rye has trended towards either reducing corn yields (Hunter et al., 2019; Waring et al., 2020) or having neutral effects (Marcillo and Miguez, 2017), rye has more consistently been shown to have limited effect on soybean production (Ruffo et al., 2004; De Bruin et al., 2005; Waring et al., 2020). Risks to following soybean yields have been attributed to excess crop residues inhibiting germination, increased water use of rye, and nutrient sequestration (Ruffo et al., 2004; Mirsky et al., 2009). While soybean yields will be less impacted by timely turnover of crop residue N as compared to corn, adequate and timely release could be important for S availability. Previous research at the SDSU Southeast Research Farm has shown that soybeans could have lower sulfur content thereby incurring a risk to both grain yield and quality (Brockmueller et al., 2016; Sexton et al., 2017). From a review of the literature, it would be expected that higher seeding rates would increase nutrient uptake of N and S while lowering the residue quality of the rye tissues. We hypothesized that higher seeding rates will increase biomass production drawing down soil inorganic pools of N and S and increasing nutrient uptake in rye tissues which will lead to reduced residue quality and slower N and S cycling in the agroecosystem. Therefore, the objectives of this study were to: (1) Find practical information on rye seeding rates in relation to rye biomass and residue quality; (2) Observe how rye biomass and quality related to key indicators of decomposition; (3) Track concentrations of N and S throughout the growing season in the major nutrient sinks in the agroecosystem; (4) Observe the effects of rye seeding rates on soybean nutrient composition and yield.

2.3 Materials and Methods

2.3.1 Site description and field history

Two field experiments were conducted from the fall of 2017 to the fall of 2018 (2018 growing season) and from the fall of 2018 until the fall of 2019 (2019 growing season) at the Southeast Research Farm in Clay county near Beresford, SD (43°02'N, 96°53'W). Monthly average temperature and cumulative precipitation are shown in figure 2.1. The experimental plots were located within a corn-soybean-small grain rotation under no-till management that included artificial drainage with tile lines. No fertilizer applications were applied during the experiment. Initial soil classifications and nutrient data are presented in table 2.2.

During the 2018 growing season, the experiment was located on Egan (Fine-silty, mixed, superactive, mesic Udic Haplustolls)-Trent (Fine-silty, mixed, superactive, mesic Pachic Haplustolls) silty clay loams, 0-2% slopes and an Egan-Clarno (Fine-loamy, mixed, superactive, mesic Typic Haplustolls) -Tetonka (Fine, smectitic, mesic Argiaquic Argialbolls) complex with 0-2% slopes (USDA-NRCS, 2020). The 2019 growing season was on an Egan-Clarno-Tetonka complex with 0-2% slopes.

At both experimental locations corn was planted the previous season. Two growing seasons prior to the experiment had a split of soybeans and oat so that all current plots were evenly subject to a ½ split of soybeans and oats. The last fertilizer application was applied to corn in the season prior to the experimental year. In 2017, fertilizer was applied preplant at a rate of 175 kg ha^{-1} of N, 22 kg ha^{-1} of S, and 68 kg ha^{-1} of P. In 2018, 222 kg ha^{-1} of N was applied to this site with 55 kg ha^{-1} being applied preplant and the remainder being side dressed. No sulfur, phosphorus, or potassium was applied based on soil test levels.

Initial soil samples were taken prior to spring rye growth by collecting six soil cores using a hand probe with a diameter of 12.7 mm in March 2018 and November 2018. Soil samples were then air dried, ground and sieved by passing through a 2-mm screen. Tests were run to report NO_3- using the Nitrate Electrode method, P by the Olsen method, K was extracted with 1 *M* of NH_4OAc, pH and EC were measured using a 1:1 extraction, Zn through the diethylenetriaminepentaacetic acid (DTPA) extraction, and S by the Monocalcium Phosphate Extraction procedure as described by Manjula and Gelderman (2015).

2.3.2 Experimental Design

A Randomized Complete Block Design was utilized with five treatments replicated four times. The location of the trial changed from the 2018 growing season to the 2019 growing season in order to follow the rotation. Plot sizes were 4.57 m in width across both seasons and 73.0 m and 51.2 m in length for the 2018 and 2019 growing seasons respectively. Treatments were different winter rye seeding rates of 0, 22, 45, 67, and 90 kg ha^{-1}.

2.3.3 Crop Management

All agronomic management activities for the 2018 and 2019 growing seasons are listed in table 2.1. Winter rye, Rymin, (Minnesota Agricultural Exp. Station, St. Paul, MN) was drilled (JD 750, John Deere, Moline, IL) into standing corn stubble in the fall prior to the start of the experiment.

During the 2018 growing season, rye was terminated with a burndown mix of 2.34 L ha^{-1} of glyphosate, 0.29 L ha^{-1} of Metribuzin, 0.15 L ha^{-1} of Flumioxazin, 2% UAN v/v, and 0.25% non-ionic surfactants (NIS) v/v. In 2019 a burndown mix of 2.34 L ha^{-1} glyphosate and 1.17 L ha^{-1} of metolachlor was used to terminate rye. Soybean varieties AS2733 (Asgrow Seed Co LLC, Creve Coeur, MO) were planted on 19 cm rows and 19EA32 (Stine Seed Co, Adel, IA) using 76 cm row widths were planted in 2018 and 2019 respectively at 350,000 seeds ha^{-1}. Herbicide was applied during the soybean growing season using a mix of 0. 73 L ha^{-1} of Fomesafen, 0.44 L ha^{-1} of Clethodim, 0.02 L ha^{-1} of cloransulam-methyl, 1% v/v of UAN, and 1% v/v of Crop Oil Concentrate (COC) in 2018 and a mix of 2.34 L ha^{-1} of glyphosate, 0.022 L ha^{-1} of cloransulam-methyl, 2.5% Urea Ammonium Nitrate (UAN) v/v and 1% COC v/v in 2019.

2.3.4 Cover crop, plants, and residue sampling

Four sampling dates were used to collect plant and residue samples with the first two occurring during the rye growing season and the final two occurring during the soybean growing season. The first sampling date collected initial rye biomass and corn residues. This was targeted for the 1st week of May, although cold, wet conditions in 2018 delayed rye development and subsequently the sampling date. The 2nd sampling date corresponded with rye termination and collected rye biomass and corn residues. The third and fourth sampling dates were taken at soybean GS R3 and R6 respectively for soybean plant and crop residue samples. At the 4th sampling, any senesced leaves from soybeans were separated from crop residues and bagged separately for further analysis. Plant heights were recorded at these times by averaging three randomly selected plants per plot. Soybean plant samples were subsampled using a chipper in the 2018 season and by selecting ten representative plants in 2019. Soybean leaf tissues were collected only in 2019 by randomly selecting seven trifoliate leaves located at the first fully mature node from the top of plant at the R3 growth stage. All rye biomass, crop residues, soybean plants, and senesced leaves were collected by hand with two frames of 0.28 m^2 in each plot. The frame size was adjusted to 0.22 m^2 for the 2019. These samples were then oven dried in a forced air oven at 60°C to a constant weight and dry weight was measured and converted to kg ha^{-1}. Dried samples were ground first with a Thomas-Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a sieve size of 2-mm, and a subsample was then ground through a UDY mill (UDY Corporation, Fort Collins, CO) to pass through a mesh size of <1-mm.

2.3.5 Soil Sampling

Soil samples were taken from each plot using a hand probe of 12.7 mm diameter and divided between depths of 0-15 cm and 15-61 cm to be analyzed separately. Soil samples were taken for all sampling dates excluding the 1st sampling date. Upon completion of soil sampling, soil was air dried and ground. Samples were then ground to pass through a sieve size of 2-mm.

2.3.6 Soybean Harvest

Plant height measurements and stand counts were recorded at soybean harvest. The harvested area during the 2018 season was 1.5 m in width and 11.9 m in length, whereas, in 2019, the area harvested was 3 m wide by 51 m long. All plots were harvested using a research plot combine (2065, Kincaid Equipment Manufacturing, Haven, KS) to determine grain yield. Yield was converted into kg ha^{-1} and adjusted to 13.0% moisture content. Test weight and grain moisture were measured using a Steinlite Moisture Meter (SL95, Atchison, KS). A subsample of soybean grain was collected and ground through a KnifeTec (Tecator, Höganäs, Sweden).

2.3.7 Laboratory Analysis

Rye and crop residue samples were analyzed for fiber composition by proximate analysis according to the procedure described by Van Soest for fiber analysis (Van Soest, 1963) to determine the percentage of Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), Acid Detergent Lignin (ADL), and Crude Fiber (CF) using an Ankom 200 Fiber Analyzer (Van Soest, 1963). Concentrations of Hemicellulose were calculated by subtracting ADF from NDF. Cellulose fractions were calculated by subtracting ADL from ADF. Total carbon and nitrogen were analyzed for all plant, residue, leaf tissue samples, and grain samples using a dry combustion analyzer (Bremner, 1996). Additionally, nutrient concentrations were analyzed using Inductively coupled plasma mass spectrometry (ICP) at Ward Labs in Kearney, NE.

Soil samples were analyzed for NO_3-N, Olsen P, K, Zn, and S. All nutrients were analyzed to the 0-15 cm depth while NO_3-N and S were also analyzed to a depth of 61 cm. Additionally, organic matter, pH, and electrical conductivity were measured for all samples.

2.3.8 Statistical Analysis

Statistical analysis was done using RStudio statistical software version 3.5.1 (R Core Team, 2018). A two-way ANOVA using a linear model was used to test all independent variables. Model assumptions and potential outliers were tested using the Shapiro-Wilk normality test, examining residuals plots using the ggResidpanel package (Goode and Rey, 2019) and calculating the standardized residuals. All effects were considered to be fixed effects. Fishers Protected LSD was calculated using the agricolae package (Felipe de Mendiburu, 2017) at a $p < 0.05$ level for mean separation. Further data analysis was conducted using correlations while principle component analysis was conducted using the ggbiplot package in R (Vincent, 2011).

2.4 Results

2.4.1 Weather

Winter rye biomass production, root exploration of the soil, and enhancement of N recovery are greatly dependent on accumulated growing degree days with fall planting dates and spring temperatures being important indicators of rye growth and development (Mirsky et al., 2009; Farsad et al., 2011; Kantar and Porter, 2014) . Therefore, both fall and spring weather conditions in 2018 and 2019 impacted biomass production and quality trends leading to yearly differences in the ability of rye to cycle nutrients in these systems.

Weather conditions throughout this study were characterized by abnormally wet conditions. October 2017 saw 114 mm of rain measuring 66 mm higher than the 65-year average for October rainfall (Figure 2.1). This wet month during the critical time for corn harvest and subsequent rye planting delayed winter rye sowing. The following spring brought below average temperatures in the month of April with a monthly average of 6.1°C lower than the 66-year average. A late fall planting date combined with a cooler than average April resulted in slower growth and development of winter rye which led to lower than expected biomass of higher quality at the time of termination in 2018. As the growing season progressed, moisture was well above normal with the biggest rainfall events occurring in June and September 2018. 2018 ended the year well above average with 234 mm more precipitation than the 66-year average.

The 2019 season finished 180 mm above the 67-year average resulting in a wetter than average growing season. Much of this increased rainfall fell during planting season in the month of May which was 75 mm above average. This excess of springtime moisture created challenging planting conditions across the region and delayed rye termination and soybean planting. By the time of rye termination, rye had accumulated 765 and 1172 growing degree days in 2018 and 2019 respectively (Figure 2.2).

2.4.2 Rye Biomass

While no stand count data was recorded in 2018, stand counts observed in the spring of the 2019 shows clear differentiation between seeding rate treatments (Figure 2.3). No difference in the number of plants lost between the fall and spring counts were noted between treatments. There was an average of 25% mortality rate for rye which became proportionally smaller as seeding rates increased (Table 2.3). Likely a stretch of cold weather in February 2019 resulted in some winter kill and reduction of stand. Plant heights measured at the time of rye termination noted a correlation between planting density and plant height (Figure 2.3). At the initial sampling, we observed general increases in dry matter production as seeding rate increased (Table 2.4). This is in agreement with other studies who have noted increases in biomass by seeding rate at earlier stages in rye growth (Boyd et al., 2009; Brennan. and Boyd, 2012a). At the time of rye termination, no differences in rye dry matter production were observed between the 22, 45, and 67 kg ha^{-1} treatments in either 2018 or 2019 despite differences in year when pooled across treatments (Figure 2.4). The 90 kg ha^{-1} treatment yielded the highest quantity of biomass by out yielding the lower treatments by 104% and 43% in 2018 and 2019 respectively.

2.4.3 Rye residue quality

Rye N concentration is significant ($p=<0.03$) at the time of termination when pooled across year showing the trend that higher seeding rates reduced the concentration of N in the rye tissue (Table 2.5). While this trend was significant in 2019 but not 2018 likely reflecting the difference in biomass present between the two years.

As expected, rye N concentration was observed to be highly correlated with C:N ratio (Figure 2.5). This high R^2 value suggests that N dynamics in the plant are the driving factor in C:N ratio changes while C components have little variation between treatments (Pantoja et al., 2016). While N concentration was significantly different by year, the treatment by year interaction was not significant showing that the 90 kg ha^{-1} treatment had a lower N concentrations than the 22-67 kg ha^{-1} treatments (Table 2.5). These trends mirror those of rye biomass suggesting that overall biomass reflected changes in the C:N ratio (Figure 2.6), (Martinez-Feria et al., 2016).

In 2018, no difference in fiber composition was observed in measurements of NDF, ADF, CF, hemicellulose, cellulose, or lignin (Table 2.6). Fiber components of rye in 2019 tended to increase as seeding rates increased. Cellulose (R^2 = 0.71) and lignin (R^2 = 0.38) correlated with total rye dry matter at the time of termination in 2019 (Figure 2.7) while no correlation was observed in 2018. Principle Component Analysis (PCA) was conducted to observe the relationship between indices of fiber quality in 2019 (Figure 2.9). From this, it was observed that Cellulose, Lignin, ADF, and C:N ratio were all positively correlated to rye biomass and inversely correlated to N and S concentrations. Additionally, the 22 kg ha^{-1} treatment was observed to be much more influenced by measures of rye N and S while the 90 kg ha^{-1} treatment was affected to a greater degree by the fibrous components of rye in 2019.

As expected, plant accumulation of carbon, hemicellulose, cellulose, and lignin was affected by seeding rate as greater plant biomass and fibrous components in 2019 at the 90 kg ha^{-1} treatment resulted in higher levels of these fibers on a kg ha^{-1} basis

(Figure 2.10). In relation to the lack of difference observed in biomass between 22-67 kg ha^{-1}, there was no difference in fiber accumulation between these treatments. As a result, rye supplied low levels of C back to the soil in 2018. However, what was supplied was of very high quality. In 2019, rye supplied 4.7 times higher amounts of C of lower quality back to the soil.

2.4.4 N and S content of rye biomass

Rye uptake of nitrogen and sulfur was greater at 90 kg ha^{-1} in 2018 and 2019 although it was only deemed significantly different in 2018 for both N and S (Table 2.5). Plant concentrations of N and S were not significantly different in 2018; however, 2019 showed a trend towards decreasing N and S as seeding rate increased for both N and S. This suggests that as rye biomass increases in N limited soils, N becomes a limiting factor in the plant reducing further plant growth and uptake of nutrients resulting in lower concentrations of plant N and S.

2.4.5 Crop residues remaining

At the time of rye termination, increasing rye seeding rates significantly reduced the amount of corn residues remaining on the soil surface in both 2018 and 2019 with the 90 kg ha^{-1} seeding rate being significantly lower than the other treatments (Figure 2.11). By the R3 soybean growth stage we did not observe any statistical difference in residue remaining as early season gains in decomposition at higher seeding rates were offset by higher amounts of residue being returned to the soil. In 2019, much higher rye biomass production in the 90 kg ha $^{-1}$ treatment added significant amounts of rye residue to the soil surface and resulted in a significantly higher levels of residue. There was no statistical difference between the 22-67 kg ha^{-1} treatments which mirrors the lack of difference observed in rye biomass production. By the R6 soybean growth stage, there was a trend towards less residue remaining on the soil surface with higher seeding rates in 2018 most certainly reflecting the quick decomposition of high-quality rye material. However, in 2019 we observed the opposite trend in which elevated amounts of crop residues were found on the soil surface at higher rye seeding rates reflecting the greater amount of biomass of lower quality that was returned to the soil in 2019. The exception to this was the no rye treatment which did not benefit from early season decomposition with the rye treatments. A percent change in crop residue biomass between rye termination and the R6 soybean growth stage was calculated to account for differences in initial corn residue amounts at the time of termination due to effects of living rye on corn residues. While no significant difference in the percent changes in crop residue biomass were noted in 2018 due to high levels of variability, the amount of residues lost showed a clear increasing trend as seeding rate increased. Therefore, it appears that rye is aiding in the decomposition of corn residues from actively reducing the early season corn residue amounts and possibly from stimulating the decomposition of corn residue from more nutrient rich rye residue on top of it. In 2019, this trend reversed due to the higher levels of biomass and lower residue quality. Here, the percent change in residues remaining between rye termination and the R6 growth stage decreased as seeding rate increased showing significantly less of a decrease in residues at 90 kg ha^{-1} matching the trend observed in rye residue production (Figure 2.12). Furthermore, by standardizing residue decomposition of all rye treatments to the decomposition rate of the no-rye control treatment, a prediction of how much residue would be remaining on the soil surface if no rye was present could be made in order to make inferences about whether rye was influencing the decomposition of corn residues. By measuring the difference between the predicted values vs the observed values at the soybean R6 growth stage, it was noted that rye treatments resulted in an increase of decomposition of corn residues in 2018 as the amount of observed residue remaining was lower than the predicted amount of crop residues had no rye been present for all treatments. There was a trend for a greater decrease from the predicted value as seeding rate increased although it was not deemed to be significant. While all rye treatments exceeded the prediction value if no rye had been present in 2019, the 22-67 kg ha^{-1} showed less residue remaining at the end of the season than total rye production at the time of termination. This suggests quick turnover of residue material and nutrients was occurring. However, at the 90 kg ha^{-1} seeding rate, the difference between the predicted and observed values exceeded the total amount of rye production suggesting immobilization of nutrients in residue materials slowing down the decomposition rates (Figure 2.13). While these results show trends towards the ability of rye of higher quality to promote decomposition of corn residues, it must be interpreted with caution due to the indirect measurement of corn residues and the high variability present in the calculations.

2.4.6 Crop Residue Fiber Quality

Little difference was noted between fiber composition of crop residues at different seeding rates at the time of rye termination (Table 2.7). In 2018, NDF and hemicellulose values were significantly lower where no cover crop was planted. There were trends toward increasing concentrations of cellulose, lignin, and C:N ratios where a rye cover crop was present vs the control treatment; however, none of these were deemed to be significantly different. In 2019, lignin concentrations at 90 kg ha^{-1} was significantly higher than all other treatments. Additionally, CF was seen to increase as seeding rates increased. However, no other measures of fiber quality were significant. While residue fiber concentration does not provide strong evidence of decomposition dynamics due to the lack of difference in the majority of the parameters in the present study, the general trend where significance is observed is that higher concentrations of fibrous materials are present in the rye treatments vs the no-rye control. This agrees with the evidence seen in the crop residue biomass that greater decomposition is occurring in rye plots. Higher concentrations of fibrous materials suggest that the easily degraded materials have been broken down leaving a larger concentrations of the more recalcitrant, fibrous materials. No differences between crop residue fibrous materials were observed at the soybean R3 or R6 growth stage (Appendix A Table A.2.1, A.2.2).

On a kg ha^{-1} basis, trends towards lower total amounts of fibrous components in the agroecosystem were observed at higher seeding rates in 2018 at both rye termination and the R6 soybean growth stage. In 2019, an initial decrease in total fibrous components as seeding rates increased reflected the residue biomass amounts. This trend was then flipped by the R6 stage as higher amounts of residue were returned to the soil (Figure 2.14, Figure 2.15).

2.4.7 N and S concentrations of crop residues

Across both years, N and S remaining in crop residues trended towards decreasing as rye seeding rates increased at the time of rye termination (Figure 2.16, Figure 2.17). This reflects the trends observed in residue decomposition as treatments with higher planting densities lost more mass and released higher amounts of nutrients. In 2018, at the soybean R6 growth stage, no significant differences were observed between the rye treatments; however, the presence of rye promoted a statistically lower amount of nutrients remaining in crop residues as compared to the no-rye control suggesting that due to the high residue quality of rye, nutrient cycling occurred quickly (Figure 2.16). In 2019, at the 22 and 45 kg ha^{-1} treatments, the N contained in the residues offset any early season increases in N cycling; however, it did not result in a net immobilization of N in crop residues until 67 and 90 kg ha^{-1} (Figure 2.17, Figure 2.18). No statistical difference between the no-rye control and the 22-45 kg ha^{-1} treatments occurred suggesting that no more N was tied up in crop residues in the 22 kg ha^{-1} and 45 kg ha^{-1} treatments as the no-rye control. While rye biomass did not differ between 22-67 kg ha^{-1}, the increase in N remaining in residues is likely a result of higher C:N ratios and fibrous components in the 67 kg ha^{-1} treatment slowing down the cycling of N. During the 2018 growing season, there was a trend towards decreasing S remaining in crop residues as higher seeding rates enhanced decomposition across the growing season. Similarly, to the N trends in 2019, S did not statistically differ between the 0 and 45 kg ha^{-1} treatments resulting in a net mineralization of S throughout the growing season. The 67 and 90 kg ha^{-1} treatments had significantly higher amounts of S remaining tied up in crop residues by the soybean R6 growth stage (Figure 2.17). Sulfur was seen to mineralize out of crop residues between the time of rye termination and the soybean R6 growth stage for all treatments except 90 kg ha^{-1} which resulted in a replacement of S from what was tied up in crop residues at termination (Figure 2.18). While no significant differences between rye treatments were recorded in the percent loss of S between termination and the R6 stage, the no-rye control lost significantly more S lower the other rye treatments.

2.4.8 Soybean Production

Soybean production, nutrient status, and yield were unaffected by rye seeding rate treatment across both years. No effect on whole plant N concentrations were observed either year reflecting the ability of soybeans to regulate N uptake through biological fixation (Table 3.8, Table 3.9). In 2018 at the R3 growth stage, soybean S concentration in the no-rye control treatment was significantly lower than the treatments with a rye cover crop likely as a result of quick decomposition and rapid cycling of nutrients in cover crop materials observed in 2018 (Table 3.8). However, S was not seen to be different by the R6 growth stage (Table 3.9). In 2019, there was a trend towards decreasing S concentrations in soybean plants as seeding rates increased at both the R3 and R6 growth stages. However, it was not deemed to be significantly different at either sampling point. However, when data was combined across growth stages, S concentration declined as seeding rate increased and the 90 kg ha^{-1} was seen to be significantly lower ($p = 0.02$) than the no-rye treatment. These trends towards lower S concentrations, translated into significant differences in S uptake at the R3 growth stage with a 22% reduction in soybean S between the no-rye control and the 90 kg ha^{-1} treatment. This trend in higher S uptake where no rye was present remained at the R6 growth stage; however, it was not statistically significant.

With data pooled across 2018-2019, no difference in soybean yield was observed (Table 3.10). In 2018, 0 kg ha^{-1} and 90 kg ha^{-1} treatments outperformed the other treatments; however, no difference was observed in 2019. Test weight, moisture, plant stand, and 100 seed weight also showed no differences between treatments. However, when pooled across years, test weight trended downwards as seeding rate increased and was significantly lower (p=0.06) at the 90 kg ha^{-1} treatment.

A biplot examining the relationship between rye biomass, nutrients, and fibrous components with crop residue fiber concentrations with soybean N, S, and grain yield was performed to examine the relationship between different components in the system and their effect on the cycling of nutrients and soybean yield (Figure 3.19). In 2018, rye biomass and soybean S at the R6 growth stage were most strongly related to soybean yield suggesting the role of high-quality materials in quickly cycling and supplying nutrients to improve soybean production. In 2019, soybean N and S were related to yield and negatively related to fiber concentrations of crop residues at both the time of rye termination and the soybean R6 growth stage. Yield was positively related to the soybeans ability to accumulate N and S and negatively related to fiber concentrations at the R6 growth stage. Therefore, it appears that anything that raises fibrous components of crop residues will tend to inhibit N and S uptake which in turn effects crop yield. However, none of the parameters related to rye production directly correlated with soybean grain yield. However, as neither yield, soybean N or S concentrations, nor crop residue fiber concentrations were significant by treatments, it appears unlikely that rye treatments were affecting the relationship between soybean yield of the other parameters.

2.5 Discussion

2.5.1 Rye biomass production

Rye biomass production in this study averaged across year and treatment was lower than reported in other studies (Ruffo and Bollero, 2003a; Boyd et al., 2009; Brennan. and Boyd, 2012a) and other years at the Southeast Research farm (Sexton et al., 2017) which is likely due to later fall seeding dates and abnormally wet spring weather which may have suppressed rye production. Other studies have noted no differences in dry matter production at different seeding rates when terminated at anthesis (Whaley et al., 2000; Boyd et al., 2009; Brennan et al., 2013). Boyd et al. 2009 attributed this to an observed increase in tillering at lower seeding rates which seemed to compensate growth. Another study suggested that a lack of increase in rye biomass by increasing seeding rates was a result of nutrient and not seed limitations (Ryan et al., 2011). Those results were attributed to higher levels of tillering compensating for growth in lower seeding rates. While tillering was not measured in this study, differences in plant heights follow the results seen in other studies that show increases in plant heights as seeding rates increase. Boyd et al. (2009) showed that as seeding rate increased, plant tillering decreased and plant height increased linearly. However, the increase in biomass observed at 90 kg ha^{-1} in the present study is surprising given the lack of difference observed at the lower seeding rates. While the reason for this is unclear, it is possible that rye was limited in growth by wet growing conditions and that increased plant densities utilized more of this soil moisture and overcame growth limitations as waterlogged soil conditions can alter rye growth habits (Pedo et al., 2015).

2.5.2 Rye nutrient concentrations and residue quality

Factors that are important in predicting N concentration and consequently C:N ratio include planting density, total biomass production, growth stage, and soil N supply (Martinez-Feria et al., 2016). Averaged across treatments, N concentrations were 34.0 and 17.9 g kg^{-1} in 2018 and 2019 respectively. These differences can be due to fewer accumulated growing degree days at termination and nearly twice as high of an initial soil N reading in 2018 vs 2019 (Table 2.2). Brennan et al. (2013) observed rye N concentration decrease by seeding rate and hypothesized that it was a result of increased soil N competition. Therefore, in 2018 when rye biomass levels were low, sufficient soil fertility resulted in greater N and S uptake and higher plant concentrations without showing differences by treatment in plant concentration of these nutrients. Conversely, in 2019, rye N and S showed differences by treatment likely reflecting a higher level of competition for soil resources and suggests that at higher seeding rates, rye was simply meeting its basic N requirements. Greater biomass production limited soil N and resulted in lower concentrations of plant N and S which resulted in no significant differences in plant uptake of these nutrients while differences in plant concentrations were noted.

High N concentrations in plants has been shown to reduce the expression of genes involved in the biosynthesis of cellulose and lignin which leads to reduced structural integrity of plants (Ogden et al., 2018). Therefore, due to adequate plant N concentrations in 2018 and no differences in plant N concentration, it is not a surprise that no differences in fibrous components were noted. However, in 2019 where N became limiting, differences in cellulose and lignin were noted and seen to correlate with rye nitrogen concentrations (Figure 2.8).

Due to reduced growth in 2018, rye C:N ratios remained much lower than anticipated with a range between 10.8-13.5. This low C:N ratio likely drove rapid decomposition of the rye biomass and quicker nutrient cycling. With no differences in fiber composition by treatment observed, it appears that differences observed in decomposition were primarily influenced by C:N ratio. In 2019, C:N ratios ranged from 20.4-27.7 being nearly twice as high as the values observed in 2018. All fiber quality parameters with the exception of lignin were significantly higher in 2018 than 2019. This increase in C:N ratio and fibrous components coupled with greater amounts of biomass being returned to the soil changed the decomposition dynamics between the two growing seasons. Residue quality components all trended towards lower residue quality in 2019 as seeding rates increased with higher seeding rates being much closer related to the fibrous components while lower seeding rates were more influenced by plant nutrient concentrations.

Other studies have estimated that the critical N concentration of plant tissues for immobilization of N occurs between 14-18 g kg^{-1} N (Odhiambo and Bomke, 2000;

Brennan et al., 2013). Furthermore, Martinez-Fería (2016) showed that rye tissues are not likely to immobilize N unless allowed to grow beyond 1.57 Mg ha^{-1} which corresponds to a C:N ratio of around 25. In the present study, only the 90 kg ha^{-1} treatment in 2019 exceeded all three of these estimations of immobilization requirements. Using these estimations, mineralization of plant N would likely occur quite rapidly in 2018 while immobilization is more likely to occur in 2019 especially at 90 kg ha^{-1}.

2.5.3 Crop residue biomass

It appears that in this study, higher seeding rates of rye can promote decomposition of corn residues. The literature on the effects of living roots on residue decomposition has produced mixed results. Results of the present study are in line with others who have noted that the presence of living roots can positively influence crop residue decomposition through a microbial priming effect from root exudates that alter the biochemical conditions of the rhizosphere (Paré et al., 2000; Varela et al., 2014). In contrast, reductions in residue decomposition in the presence of growing plants could be attributed towards plants competing for nutrients or low soil water reducing microbial activity (Jannoura et al., 2012). Given that this environment was not limited in water or nutrients, a positive result on residue decomposition could be expected. Effects on decomposition in the present study are likely a combination of physical and biochemical factors. When winter rye was seeded in the fall, the drill aided in chopping up crop residues and promoting greater soil surface contact of the residues. This likely resulted in a decomposition disadvantage to the no-rye control and helps explain why crop residues remaining with the no-rye control treatment were in line with rye treatments at the R6 growth stage in 2019 and higher than the rye treatments in 2018. Yet, given that in a no-till production system, no field operations effecting crop residues would be made until soybean planting, the comparison between the no-rye treatment and rye treatments remains valid. However, it is interesting to note the trend in this study suggesting that higher planting densities are encouraging more rapid breakdown of corn residues likely due to higher root biomass at greater planting densities creating a stronger rhizosphere community. With residue management being identified as a barrier to cover crop production (Bergtold et al., 2019), this shows that there is little difference by the end of the season between rye and no-rye plots as long as biomass production is kept low and residue quality remains high.

2.5.4 Soybean production

Across growth stage, soybean S was seen to be lower at higher seeding rates; however, this did not affect soybean yield or soybean grain S concentrations and is rather a likely case of luxury consumption (Sexton et al., 1998; Hitsuda et al., 2004; Salvagiotti et al., 2012; Kaiser and Kim, 2013). Previous research has helped identify thresholds for S sufficiency. Hitsuda et al. (2004) indicated that grain S concentrations greater than 2.3 g kg^{-1} is adequate. Furthermore, in season measurements of leaf tissue S concentrations at the R2 growth stage between 2.0 and 3.1 g kg^{-1} were sufficient. Salvagiotti et al. (2012) suggests that N:S ratios <22:1 would not show deficiency. Furthermore, Kaiser and Kim (2013) did not find any benefit to soybean yield from S additions with SOM greater than 20 g kg^{-1}. While crop response to S varies widely based on soil, climatic, and nutritional conditions at each location, these thresholds can help guide assessment of S deficiency or sufficiency in the present study. Data from this trial met or exceeded all of these previously described criteria for S sufficiency with the exception of the soybean grain N:S ratio in 2019 (Tables A.3.7, A.3.1, 2.13). Additionally, from the lack of difference in yield and soybean grain S concentrations, it appears that S was not a limiting nutrient in this study (Table 2.11). However, while S dynamics did not impact yield in either year of this study, interesting trends in S cycling was observed in the 2019 growing season. It is important to note the difference in S uptake between no-rye control plots and plots where rye was present in 2019 (Tables 2.8, 2.9). Sulfur tied up in crop residues was higher as seeding rates increased at the R6 growth stage (Figure 2.17) which represents a pool of S inaccessible to the developing soybean crop. This S pool cycled slower at increased seeding rates (Figure 2.18) due to the lower residue quality of the rye material (Figures 2.4, 2.10). As a result, soybean S concentrations were significantly lower across the R3 and R6 growth stages ($p=0.02$) at the 90 kg ha^{-1} seeding rate. Therefore, where rye was present, S uptake by soybeans during the seed set through seed filling stages was lower. Sufficient soybean S concentrations in this study buffered against any negative effects on soybean yield. However, in lower fertility soils where S is limiting, the inability to access pools of S tied up in low quality crop residues may be enough to push soybeans into a S deficient and thereby yield limiting condition.

2.6 Management Implications

Management of biomass is a critical factor in determining success in achieving cover cropping goals. The difference between the two years of this study suggest that planting date and climatic factors appear to play the largest role in determining rye biomass production and residue quality ultimately impacting its ability to quickly cycle nutrients in the system. However, changes in seeding rate were able to achieve significantly different biomass production potential and residue quality at 90 kg ha^{-1} showing that seeding rate can be used to effect biomass production and quality with all other factors being equal.

When considering implementing a cover crop into a cropping system it is essential, to understand the main goal of the cover crop in order to effectively manage the biomass. Ruis et al. believe that cover crop biomass in excess of 2 Mg ha^{-1} is likely necessary to induce any changes in soil properties (Ruis et al., 2020). Therefore, when managing a cover crop to increase soil OM with the intent of realizing changes in soil properties such as increased porosity, aggregate stability, water infiltration and reduced bulk density, it may be necessary to utilize higher seeding rates of rye at or in excess of 90 kg ha^{-1}. Additionally, if weed suppression is the primary goal of the cover crop, higher planting densities or rye at or in excess of 90 kg ha^{-1} will likely result in greater ground cover and improved weed control. In terms of quickly cycling nutrients in a system, this study suggests that lower seeding rates of rye will enhance nutrient turnover from limited differences in biomass production and significantly higher residue quality in comparison to higher seeding rates.

2.6 Conclusions

The ability of cereal rye to cycle nutrients is strongly predicted by its biomass production which varied greatly between the two growing seasons. However, across both years, no differences were observed between the 22-67 kg ha^{-1} treatments in terms of biomass and nutrient uptake. Greater planting densities of rye appeared to stimulate early season corn residue decomposition resulting in lower amounts of residues and a greater release of these nutrients back to the system at the time of rye termination. However, when rye biomass is greater and of lower quality, these benefits in early season decomposition are offset by larger returns of rye residues and slower decomposition of the materials resulting in a slower cycling of nutrients. In these trials soybean nutrient concentrations and yield were unaffected by rye treatment; yet under S limiting conditions, the presence of higher seeding rates of rye may result in reduced soybean S concentrations leading to decreases in grain yield. The results of this study suggest that when rye is terminated late in the season, lower seeding rates of rye may provide the same benefits in nutrient cycling as higher seeding rates up until 90 kg ha^{-1}.

2.7 References

Agriculture, U. S. D. o., and S. A. R. a. Education. 1992. Managing cover crops profitably, Third editionWashington, DC: Sustainable Agriculture Research and Education Program of CSRS, U.S. Dept. of Agriculture

Emmaus, PA: Sustainable Agriculture Research and Education Program of CSRS, U.S. Dept. of Agriculture.

Appelgate, S. R., A. W. Lenssen, M. H. Wiedenhoeft, and T. C. Kaspar. 2017. Cover Crop Options and Mixes for Upper Midwest Corn–Soybean Systems. Agron. J. 109. doi:10.2134/agronj2016.08.0453.

Barel, J. M., T. W. Kuyper, J. Paul, W. Boer, J. H. C. Cornelissen, and G. B. De Deyn. 2019. Winter cover crop legacy effects on litter decomposition act through litter quality and microbial community changes. Journal of Applied Ecology 56:132-143. doi:10.1111/1365-2664.13261.

Bergtold, J., S. Ramsey, and J. Williams. 2019. A review of economic considerations for cover crops as a conservation practice. Renewable Agriculture and Food Systems 34:62-76. doi:10.1017/S1742170517000278.

Boyd, N., E. Brennan, R. Smith, and R. Yokota. 2009. Effect of Seeding Rate and Planting Arrangement on Rye Cover Crop and Weed Growth. Agron. J. 101:47-51. doi:10.2134/agronj2008.0059.

Bradford, M. A., B. Berg, D. S. Maynard, W. R. Wieder, and S. A. Wood. 2016. Understanding the dominant controls on litter decomposition. Journal of Ecology 104:229-238. doi:10.1111/1365-2745.12507.

Bremner, J. M. 1996. Nitrogen-Total. p. 1085-1121. *In* D. L. Sparks (ed.) Methods of soil analysis. Part 3. Madison, WI: Soil Sci. Soc. Am., Inc.

Brennan, E., and N. Boyd. 2012a. Winter Cover Crop Seeding Rate and Variety Affects during Eight Years of Organic Vegetables: I. Cover Crop Biomass Production. Agronomy Journal 104:684-698. doi:10.2134/agronj2011.0330.

Brennan, E., N. Boyd, and R. Smith. 2013. Winter Cover Crop Seeding Rate and Variety Effects during Eight Years of Organic Vegetables: III. Cover Crop Residue Quality and Nitrogen Mineralization. Agron. J. 105:171-182. doi:10.2134/agronj2012.0258.

Brockmueller, B., C. Bolkema, M. Buiter, A. Huizenga, B. Rops, G. Williamson, et al. 2016. Rye cover crop grown ahead of soybeans--2016 season--A first look at impacts on soybean nutrient uptake. Southeast South Dakota Exp. Farm Annual Progress Report 2016:34-39.

Caravetta, G. J., J. H. Cherney, and K. D. Johnson. 1990. Within-Row Spacing Influences on Diverse Sorghum Genotypes: II. Dry Matter Yield and Forage Quality. Agron. J. 82:210-215. doi:https://doi.org/10.2134/agronj1990.00021962008200020008x.

Casey, P. A. 2012. Plant guide for cereal rye (*Secale cereale*). USDA-Natural Resources Conservation Service, Plant Materials Center, Elsberry, MO.

Chatterjee, A., and U. Acharya. 2020. Controls of carbon and nitrogen releases during crops' residue decomposition in the Red River Valley, USA. Archives of Agronomy and Soil Science 66:614-624. doi:10.1080/03650340.2019.1630732.

De Bruin, J., P. Porter, and N. Jordan. 2005. Use of a Rye Cover Crop following Corn in Rotation with Soybean in the Upper Midwest. Agron. J. 97:587-598. doi:10.2134/agronj2005.0587.

Duval, M. E., J. A. Galantini, J. E. Capurro, and J. M. Martinez. 2016. Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. Soil and Tillage Research 161:95-105. doi:10.1016/j.still.2016.04.006.

Farsad, A., T. O. Randhir, S. J. Herbert, and M. Hashemi. 2011. Spatial Modeling of Critical Planting Date for Winter Rye Cover Crop to Enhance Nutrient Recovery. Agronomy Journal 103:1252-1257. doi:10.2134/agronj2010.0433.

Felipe de Mendiburu. 2017. agricolae: Statistical procedures for agricultural research. https://CRAN.R-project.org/package=agricolae

Finney, D. M., C. M. White, and J. P. Kaye. 2016. Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. Agron. J. 108:39-52. doi:10.2134/agronj15.0182.

Fustec, J., F. Lesuffleur, S. Mahieu, and J.-B. Cliquet. 2010. Nitrogen rhizodeposition of legumes. A review. Agron. Sustain. Dev. 30:57-66. doi:10.1051/agro/2009003.

Goode, K., and K. Rey. 2019. ggResidpanel: Panels and Interactive Versions of Diagnostic Plots using 'ggplot2'. R package version 0.3.0. https://CRAN.R-project.org/package=ggResidpanel

Hitsuda, K., G. Sfredo, and D. Klepker. 2004. Diagnosis of Sulfur Deficiency in Soybean using Seeds. Soil Science Society of America Journal 68:1445-1451. doi:10.2136/sssaj2004.1445.

Hunter, M. C., M. E. Schipanski, M. H. Burgess, J. C. Lachance, B. A. Bradley, M. E. Barbercheck, et al. 2019. Cover Crop Mixture Effects on Maize, Soybean, and Wheat Yield in Rotation. Agricultural & Environmental Letters 4:1-5. doi:10.2134/ael2018.10.0051.

Jannoura, R., B. Kleikamp, J. Dyckmans, and R. Joergensen. 2012. Impact of pea growth and arbuscular mycorrhizal fungi on the decomposition of 15 N-labeled maize residues. Biol Fertil Soils 48:547-560. doi:10.1007/s00374-011-0647-0.

Kaiser, D. E., and K. I. Kim. 2013. Soybean Response to Sulfur Fertilizer Applied as a Broadcast or Starter Using Replicated Strip Trials. Agronomy Journal 105:1189-1198. doi:10.2134/agronj2013.0023.

Kantar, M., and P. Porter. 2014. Relationship between planting date: growing degree days and the winter rye (Secale cereale L.) variety Rymin in Minnesota. Crop Manage. 13:1-9.

Karki, D. 2019. Cereal Rye Cover Crop Between Corn and Soybeans. South Dakota State University Extension. Retrieved from https://extension.sdstate.edu/cereal-rye-cover-crop-between-corn-and-soybean. (5 May, 2020).

Liu, J., N. Wu, H. Wang, J. Sun, B. Peng, P. Jiang, et al. 2016. Nitrogen addition affects chemical compositions of plant tissues, litter and soil organic matter. Ecology 97:1796-1806. doi:10.1890/15-1683.1.

Manjula, N., and R. Gelderman. 2015. Recommended Chemical Soil Test Procedures for the North Central RegionNorth Central Regional Research Publ. 221. Revised, Missouri Agric. Exp. Stn., Columbia, MO.

Marcillo, G., and F. Miguez. 2017. Corn yield response to winter cover crops: An updated meta-analysis. Journal of Soil and Water Conservation 72:226-239. doi:10.2489/jswc.72.3.226.

Martinez-Feria, R. A., R. Dietzel, M. Liebman, M. J. Helmers, and S. V. Archontoulis. 2016. Rye cover crop effects on maize: A system-level analysis. Field Crops Res. 196:145-159. doi:10.1016/j.fcr.2016.06.016.

Mirsky, S. B., W. S. Curran, D. A. Mortensen, M. R. Ryan, and D. L. Shumway. 2009. Control of Cereal Rye with a Roller/Crimper as Influenced by Cover Crop Phenology. Agronomy Journal 101:1589-1596. doi:10.2134/agronj2009.0130.

Odhiambo, J., and A. Bomke. 2000. Short term nitrogen availability following overwinter cereal/grass and legume cover crop monocultures and mixtures in south coastal British Columbia. Journal of Soil and Water Conservation 55:347-354.

Ogden, M., R. Hoefgen, U. Roessner, and S. Persson. 2018. Feeding the Walls: How Does Nutrient Availability Regulate Cell Wall Composition? International Journal of Molecular Sciences 19. doi:10.3390/ijms19092691.

Otte, B., S. Mirsky, H. Schomberg, B. Davis, and K. Tully. 2019. Effect of Cover Crop Termination Timing on Pools and Fluxes of Inorganic Nitrogen in No-Till Corn. Agron. J. doi:10.2134/agronj2018.10.0699.

Pantoja, J. L., K. P. Woli, J. E. Sawyer, and D. W. Barker. 2016. Winter Rye Cover Crop Biomass Production, Degradation, and Nitrogen Recycling. Agron. J. 108:841-853. doi:10.2134/agronj2015.0336.

Paré, T., E. G. Gregorich, and S. Nelson. 2000. Mineralization of nitrogen from crop residues and N recovery by maize inoculated with vesicular-arbuscular mycorrhizal fungi. Plant and Soil 218:11-20. doi:10.1023/A:1014958321933.

Pedo, T., E. Martinazzo, T. Aumonde, and F. A. Villela. 2015. Plant growth analysis and seed vigor expression: effects of soil waterlogging during rye plant development. Acta Bot. Bras. 29:1-7. doi:10.1590/0102-33062014abb3574.

Power, A. G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. Lond. B 365:2959-2971. doi:10.1098/rstb.2010.0143.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Reddy, B. V. S., P. Sanjana Reddy, F. Bidinger, and M. Blümmel. 2003. Crop management factors influencing yield and quality of crop residues. Field Crops Research 84:57-77. doi:10.1016/S0378-4290(03)00141-2.

Ruffo, M., and G. Bollero. 2003a. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal 95:900. doi:10.2134/agronj2003.0900.

Ruffo, M., D. Bullock, and G. Bollero. 2004. Soybean Yield as Affected by Biomass and Nitrogen Uptake of Cereal Rye in Winter Cover Crop Rotations. Agron. J. 96:800-805. doi:10.2134/agronj2004.0800.

Ruis, S. J., H. Blanco-Canqui, R. W. Elmore, C. Proctor, K. Koehler-Cole, R. B. Ferguson, et al. 2020. Impacts of cover crop planting dates on soils after four years. Agronomy Journal 112:1649-1665. doi:10.1002/agj2.20143.

Ryan, M., W. Curran, A. Grantham, L. Hunsberger, S. Mirsky, D. Mortensen, et al. 2011. Effects of Seeding Rate and Poultry Litter on Weed Suppression from a Rolled Cereal Rye Cover Crop. Weed Science 59:438-444. doi:10.1614/WS-D-10-00180.1.

Salvagiotti, F., G. Ferraris, A. Quiroga, M. Barraco, H. Vivas, P. Prystupa, et al. 2012. Identifying sulfur deficient fields by using sulfur content

N:S ratio and nutrient stoichiometric relationships in soybean seeds. Field Crops Research 135:107-115. doi:10.1016/j.fcr.2012.07.011.

Schipanski, M. E., M. Barbercheck, M. R. Douglas, D. M. Finney, K. Haider, J. P. Kaye, et al. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125:12-22. doi:10.1016/j.agsy.2013.11.004.

Sexton, P., D. Auch, and B. Rops. 2017. Burndown timing for a rye cover crop raised ahead of corn--A preliminary study. Southeast South Dakota Exp. Farm Annual Progress Report 2017:19-21.

Sexton, P. J., N. C. Paek, and R. Shibles. 1998. Soybean Sulfur and Nitrogen Balance under Varying Levels of Available Sulfur. Crop Science 38:975-982. doi:10.2135/cropsci1998.0011183X003800040016x.

Singer, J. W., and S. M. Nusser. 2007. Are cover crops being used in the US corn belt? J. Soil Water Conserv. 62:353-358.

Thompson, N. M., S. D. Armstrong, R. T. Roth, M. D. Ruffatti, and C. J. Reeling. 2020. Short-run net returns to a cereal rye cover crop mix in a midwest corn–soybean rotation. Agronomy Journal 112:1068-1083. doi:10.1002/agj2.20132.

United States Department of Agriculture-Natural Resource Conservation Service. 2020. Soil Map, Clay County, South Dakota (SD027). Retrieved from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. (accessed 26 February 2020).

Van Soest, P. J. 1963. Use of detergents in the analysis of fibrous feeds. 2. A rapid method for the determination of fiber and lignin. Journal of the Association of Official Agricultural Chemists 46:829-835.

Varela, M. F., C. M. Scianca, M. A. Taboada, and G. Rubio. 2014. Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina. Soil & Tillage Research 143:59-66. doi:10.1016/j.still.2014.05.005.

Vincent, Q. V. 2011. ggbiplot: A ggplot2 based biplot. R package version 0.55. http://github.com/vqv/ggbiplot

Waring, E. R., A. Lagzdins, C. Pederson, and M. J. Helmers. 2020. Influence of no-till and a winter rye cover crop on nitrate losses from tile-drained row-crop agriculture in Iowa. Journal of Environmental Quality 49:292-303. doi:10.1002/jeq2.20056.

Whaley, J. M., D. L. Sparkes, M. J. Foulkes, J. H. Spink, T. Semere, and R. K. Scott. 2000. The physiological response of winter wheat to reductions in plant density. Annals of Applied Biology 137:165-177. doi:10.1111/j.1744-7348.2000.tb00048.x.

White, C. M., S. T. DuPont, M. Hautau, D. Hartman, D. M. Finney, B. Bradley, et al. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agriculture, Ecosystems & Environment 237:121-133. doi:10.1016/j.agee.2016.12.016.

Wichern, F., J. Mayer, R. G. Joergensen, and T. Müller. 2007. Rhizodeposition of C and N in peas and oats after 13C– 15N double labelling under field conditions. Soil Biology and Biochemistry 39:2527-2537. doi:10.1016/j.soilbio.2007.04.022.

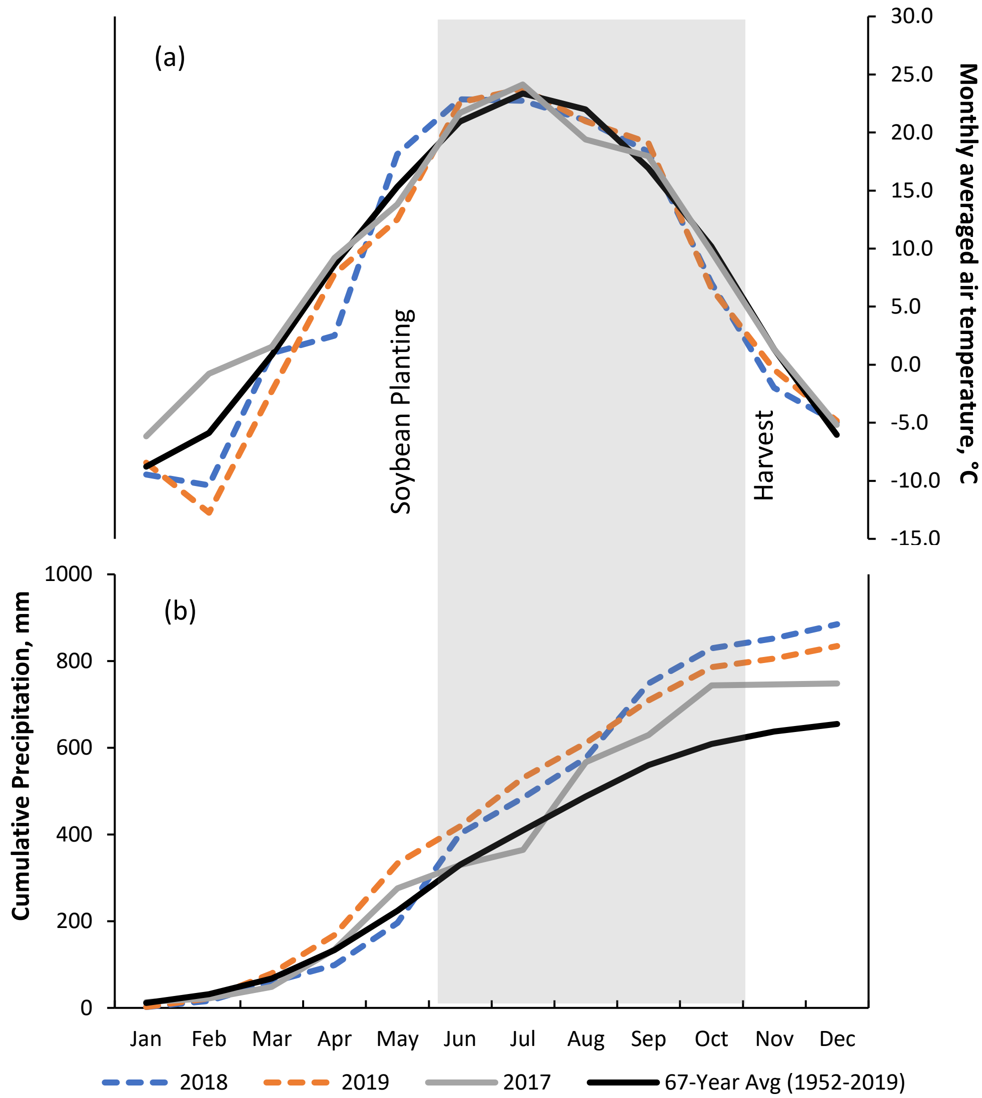


Figure 2.1. (a) Monthly average air temperatures (°C) (b) cumulative precipitation (mm) and 67-year averages (1956-2019) at the Southeast Research Farm in Beresford, SD, 2017-2019. Gray area indicates active soybean growing season. Weather data for monthly average air temperature and cumulative precipitation and 67-yr average data were obtained from the Southeast Research Farm weather station.

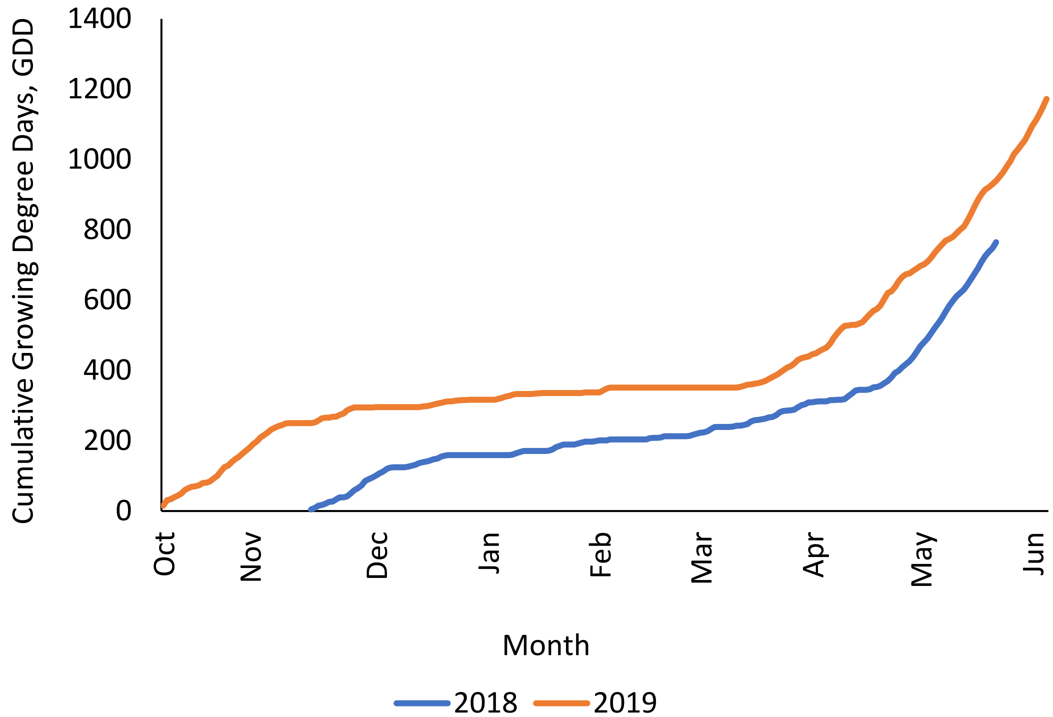


Figure 2.2. Cumulative rye GDD at the Southeast Research Farm near Beresford, SD, 2018-2019. GDD calculations were done using the equation $((T_{max} + T_{min}) / 2) - T_{Base}$ where $T_{Base} = (0°C)$

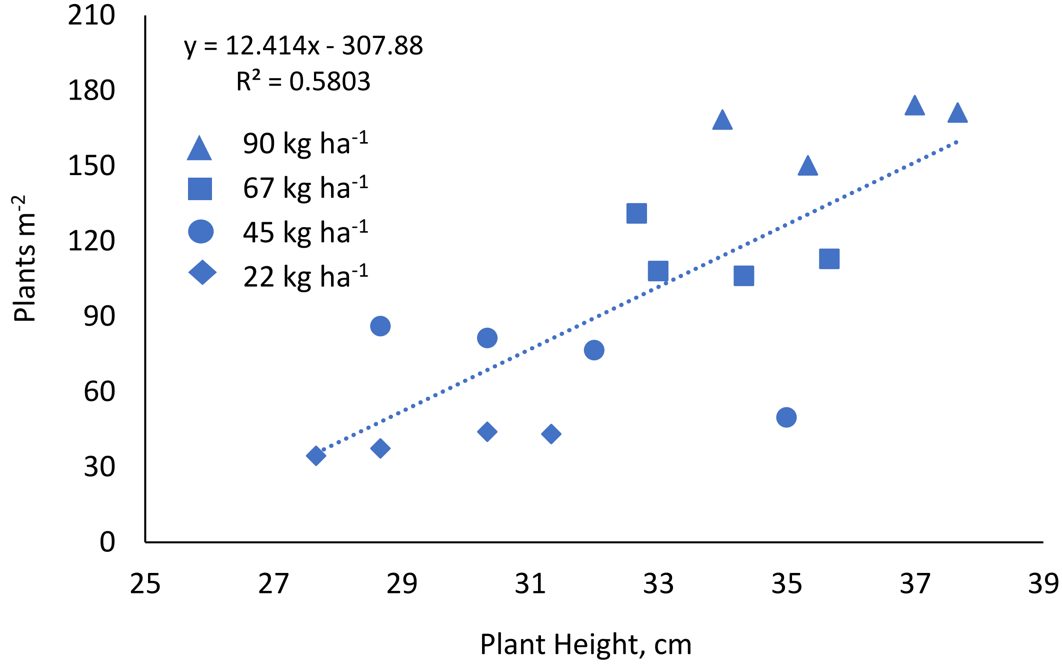


Figure 2.3. Relationship between spring rye stand counts and plant height at rye termination between 4 different rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2019. *Significant at p=0.05

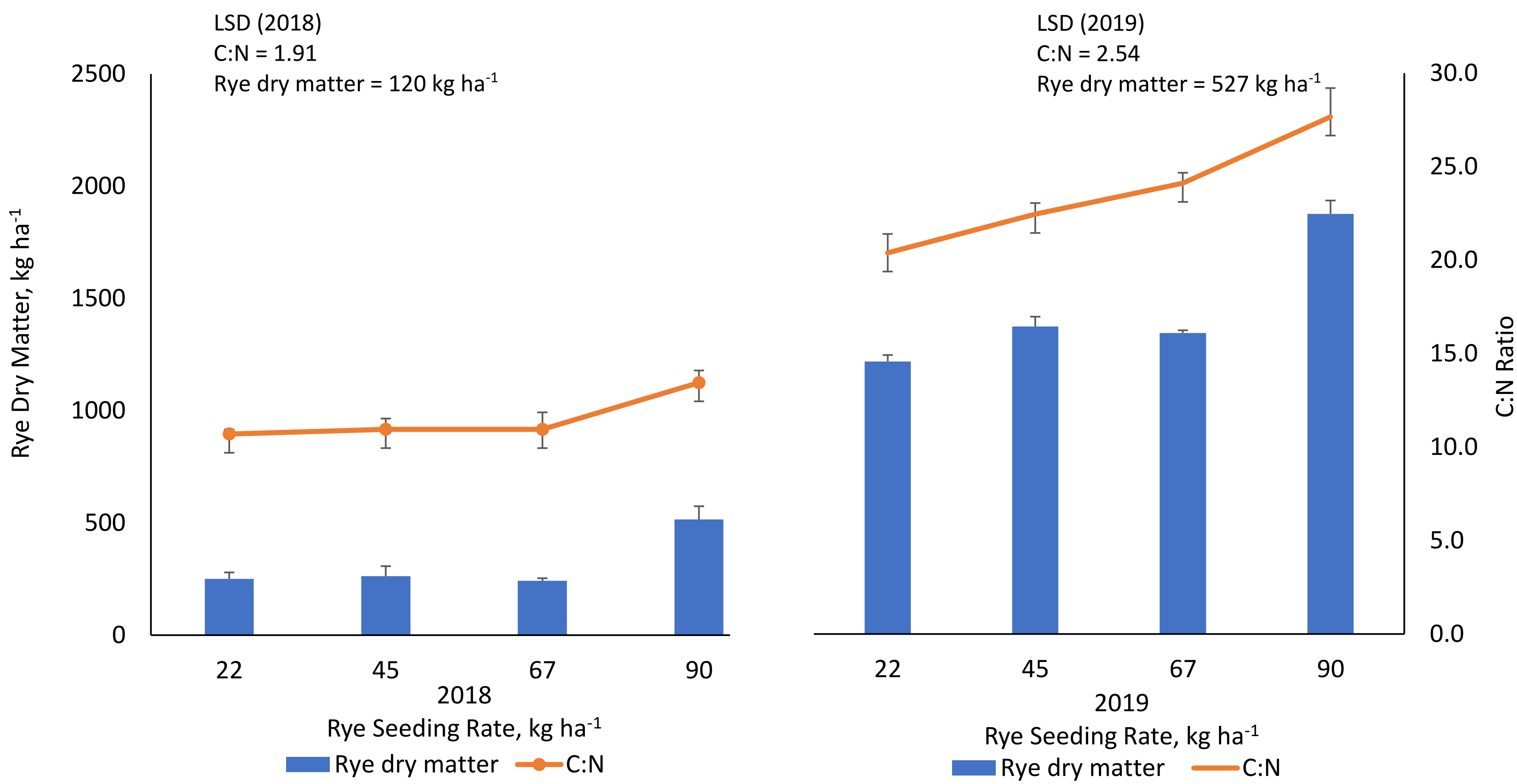


Figure 2.4. Rye dry matter production and C:N ratio measured at rye termination located at the Southeast Research Farm near Beresford, SD, 2018-2019.

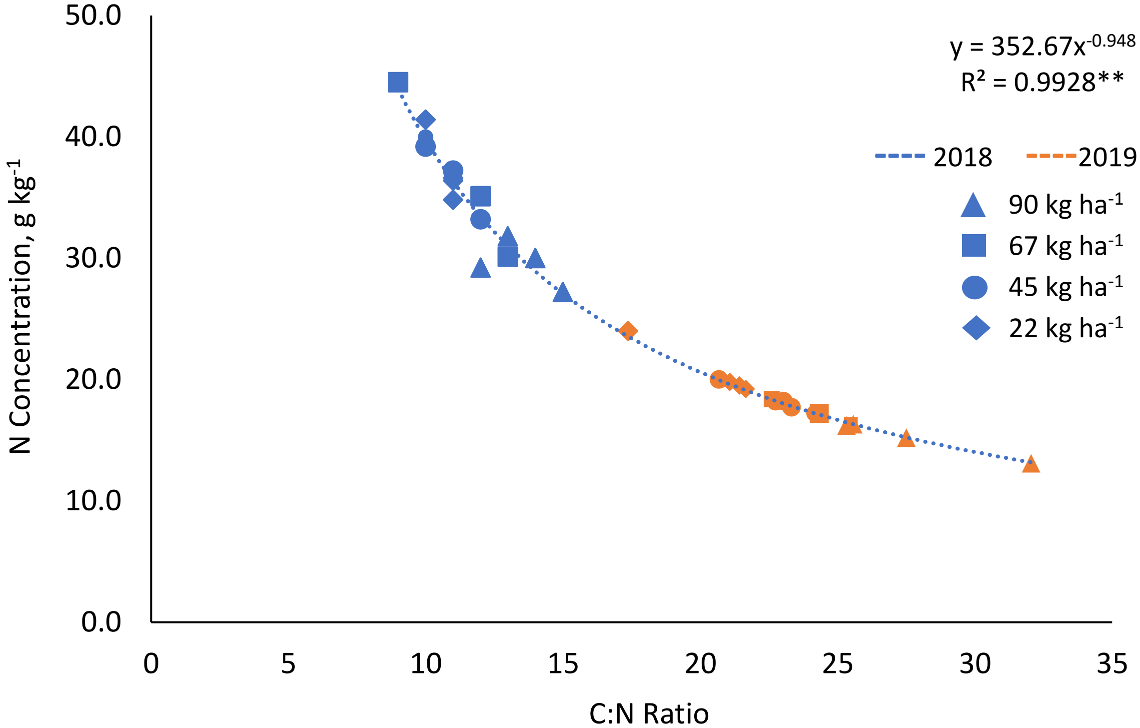


Figure 2.5. Relationship between N concentration and C:N ratio of 4 rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2018-2019. * Significant at p=0.05

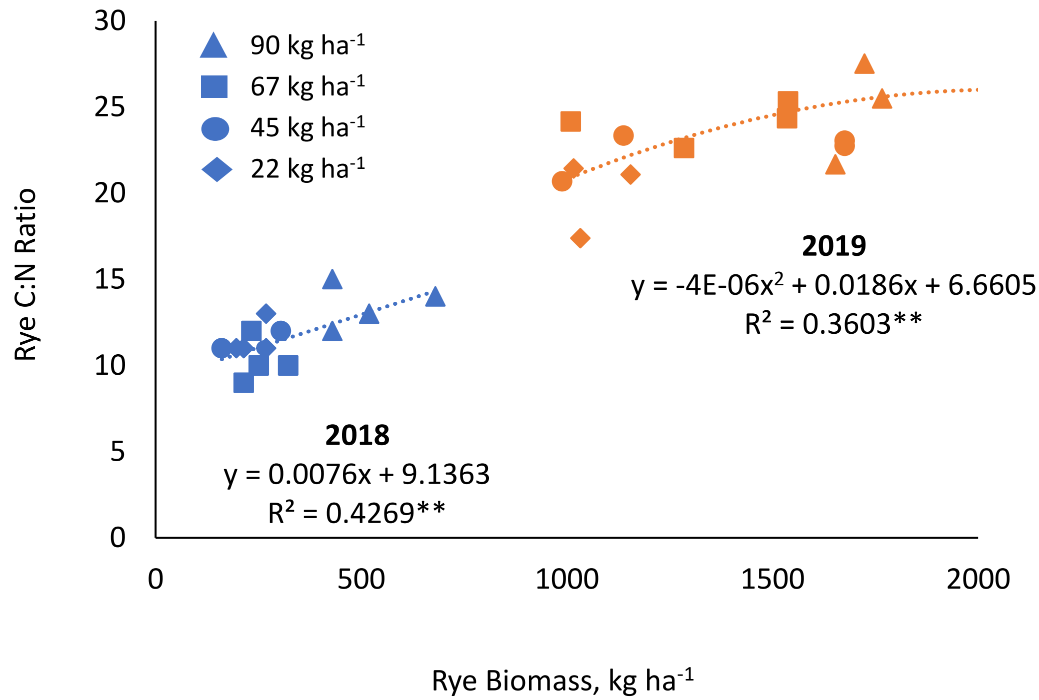


Figure 2.6. Relationship between rye biomass and rye C:N ratio measured at the time of rye termination between 4 different rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2018-2019. * Significant at p=0.05.

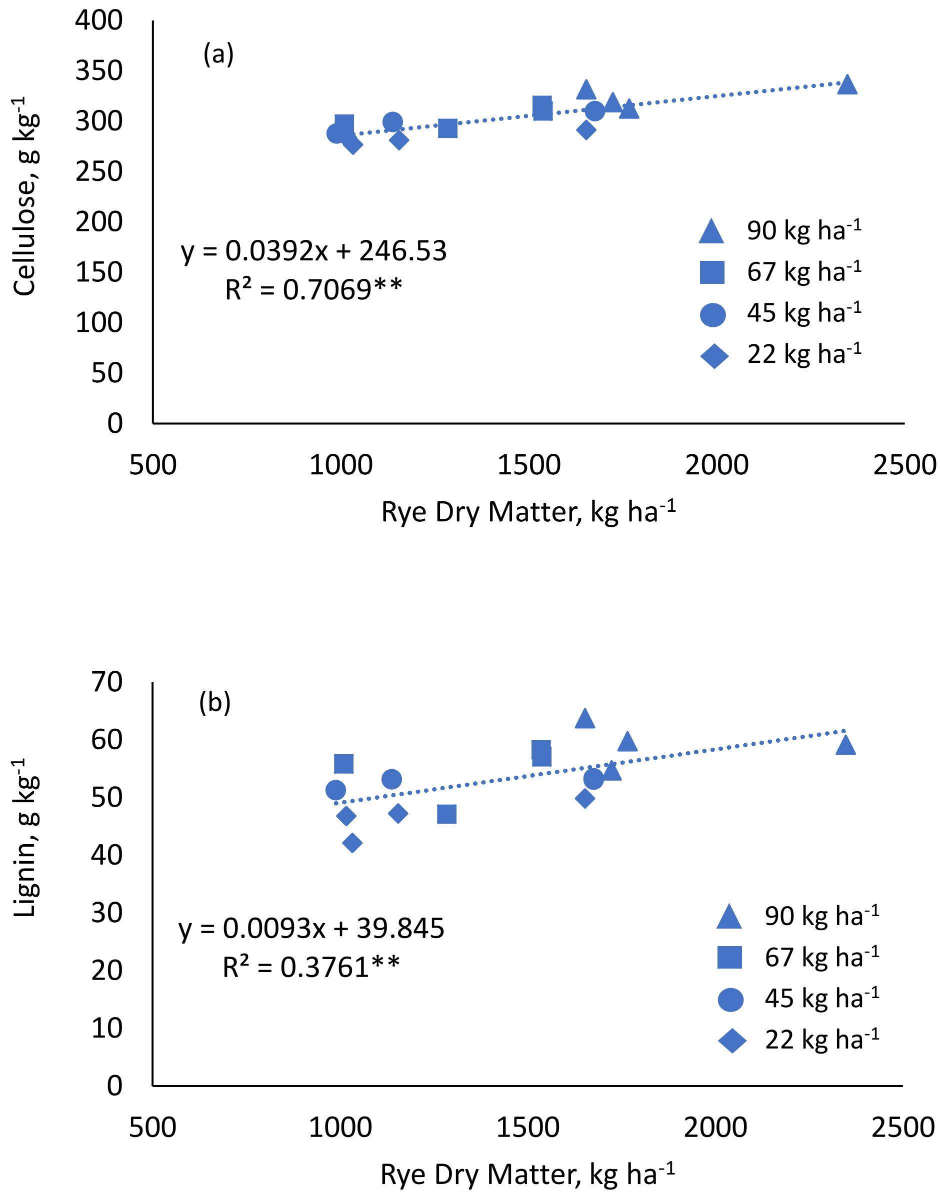


Figure 2.7. Relationship between (a) rye cellulose concentration (g kg^{-1}) and (b) rye lignin concentration (g kg^{-1}) with total rye dry matter (kg ha^{-1}) measured at rye termination across 4 seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2019. **Significant at p=0.05

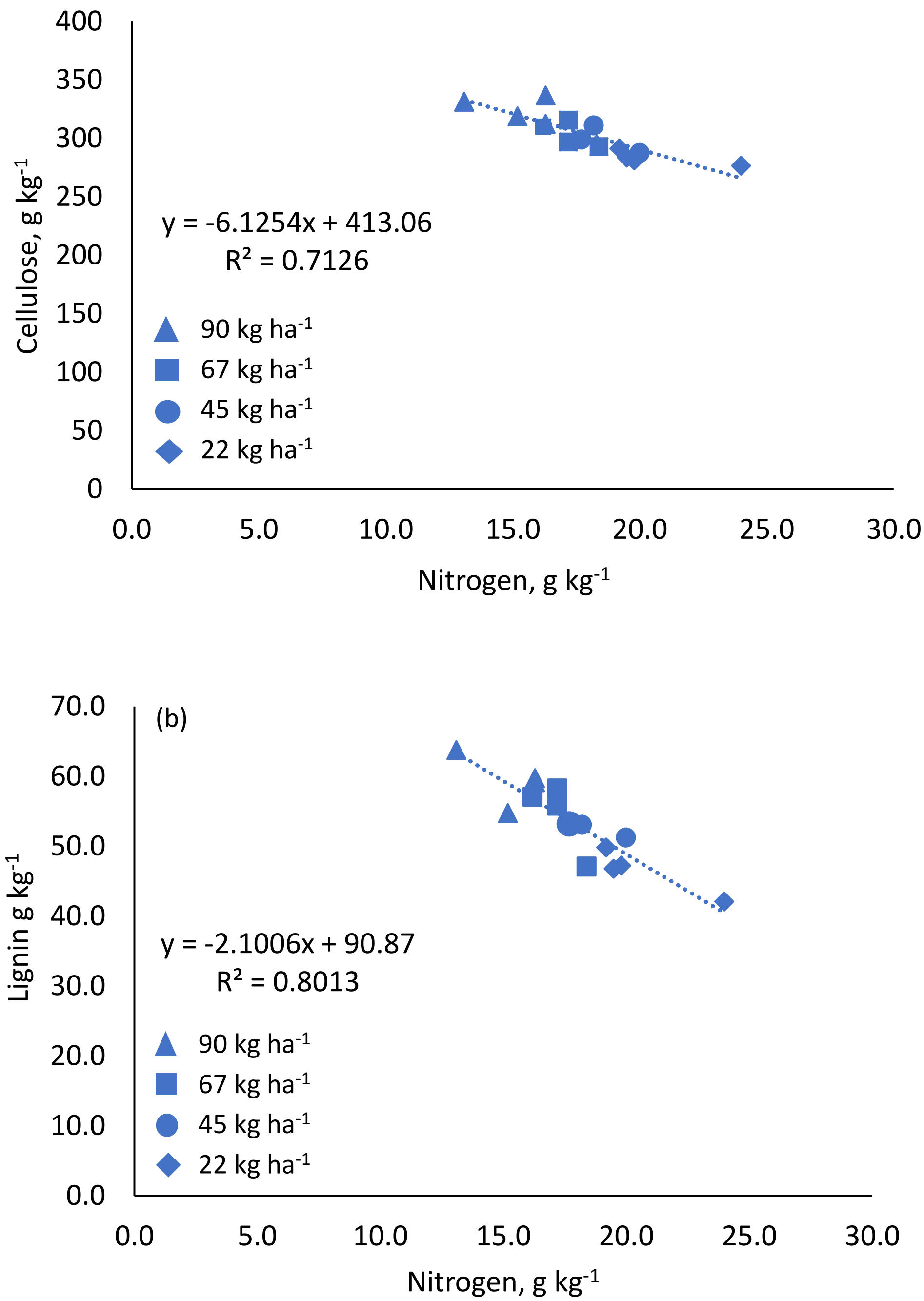


Figure 2.8. Relationship between (a) rye cellulose concentration (g kg^{-1}) and (b) rye lignin concentration (g kg^{-1}) with rye nitrogen concentration (g kg^{-1}) measured at rye termination across 4 seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2019. **Significant at p=0.05

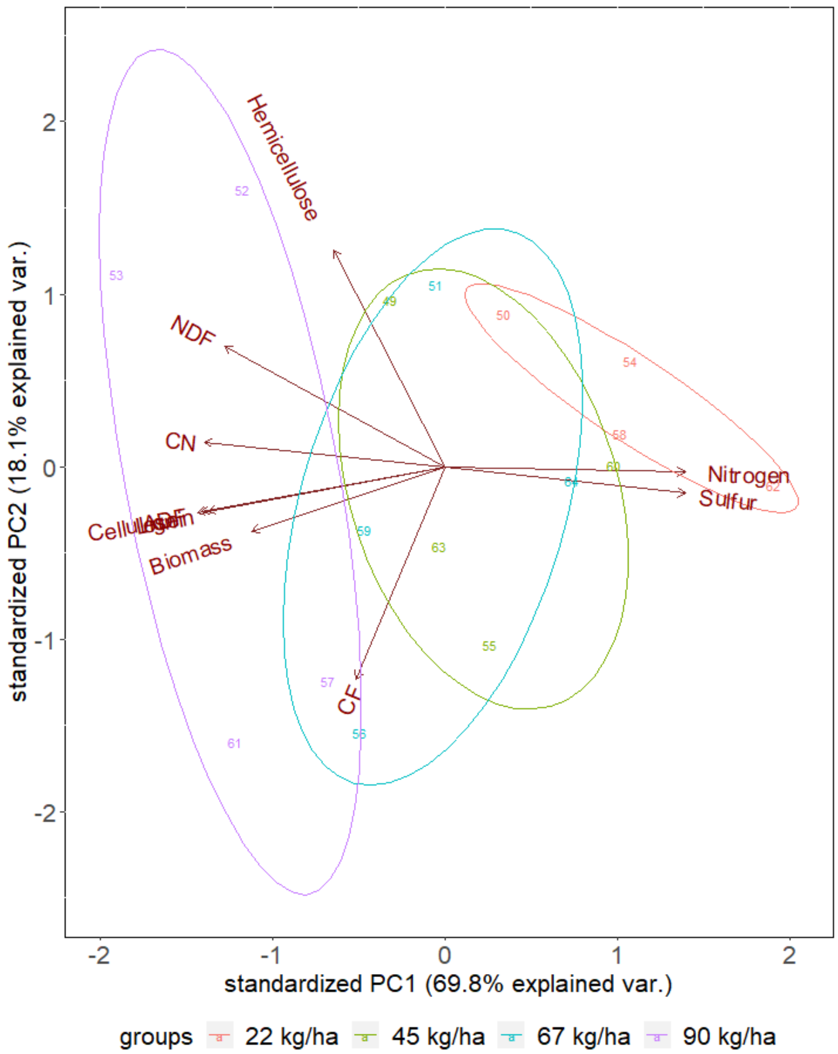


Fig 2.9. Biplot produced using the first and second components from principle component analysis containing rye parameters including biomass, cellulose, hemicellulose, lignin, Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), Crude Fiber (CF), C:N ratio, nitrogen concentration, and sulfur concentration for 4 rye seeding rate treatments measured at the Southeast Research Farm near Beresford, SD, 2019.

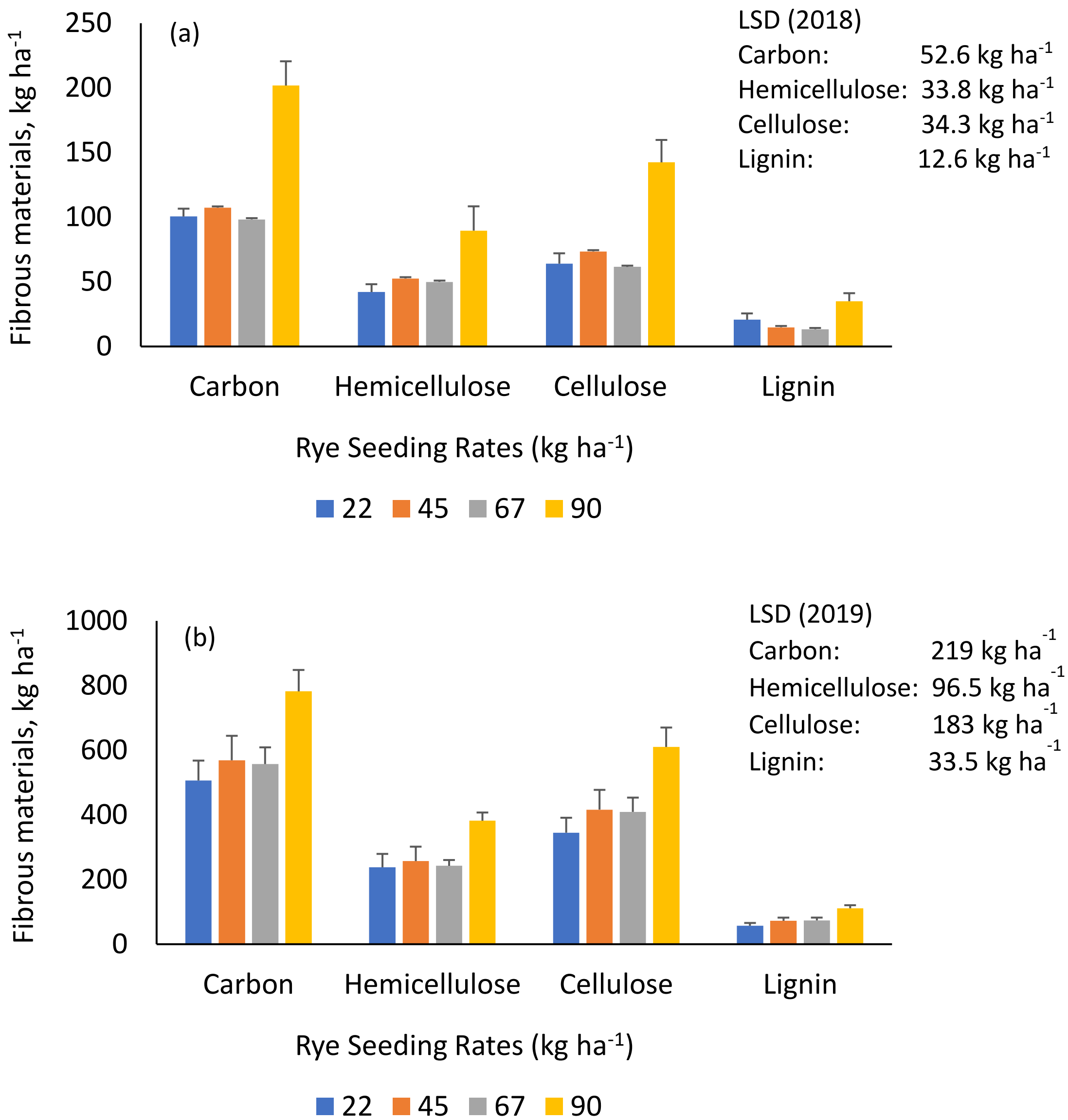
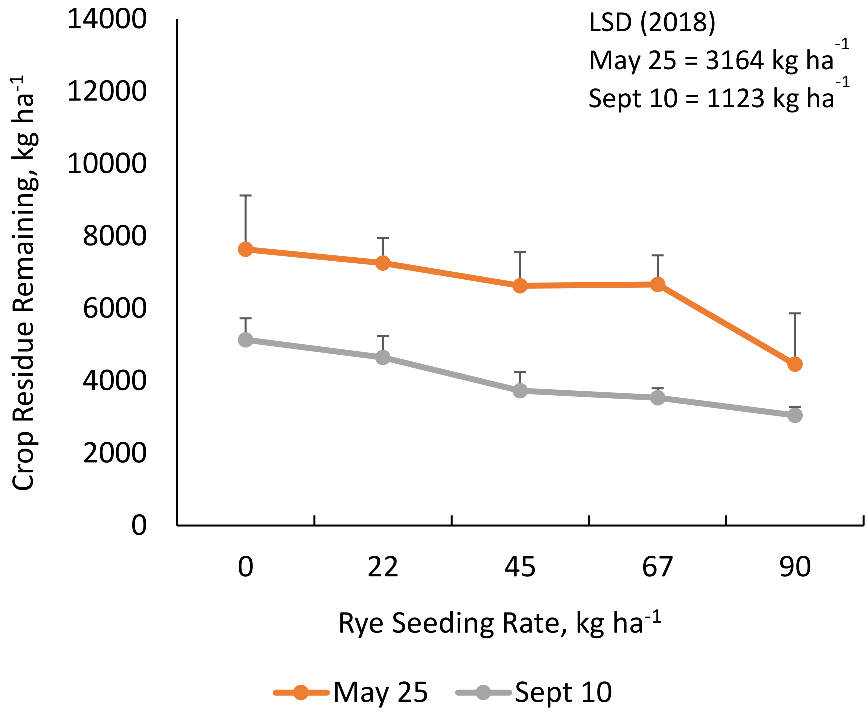


Figure 2.10. Carbon, hemicellulose, cellulose, and lignin concentration by rye at 5 rye seeding rate treatments measured at rye termination located at the Southeast Research Farm near Beresford, SD, (a) 2018 and (b) 2019.



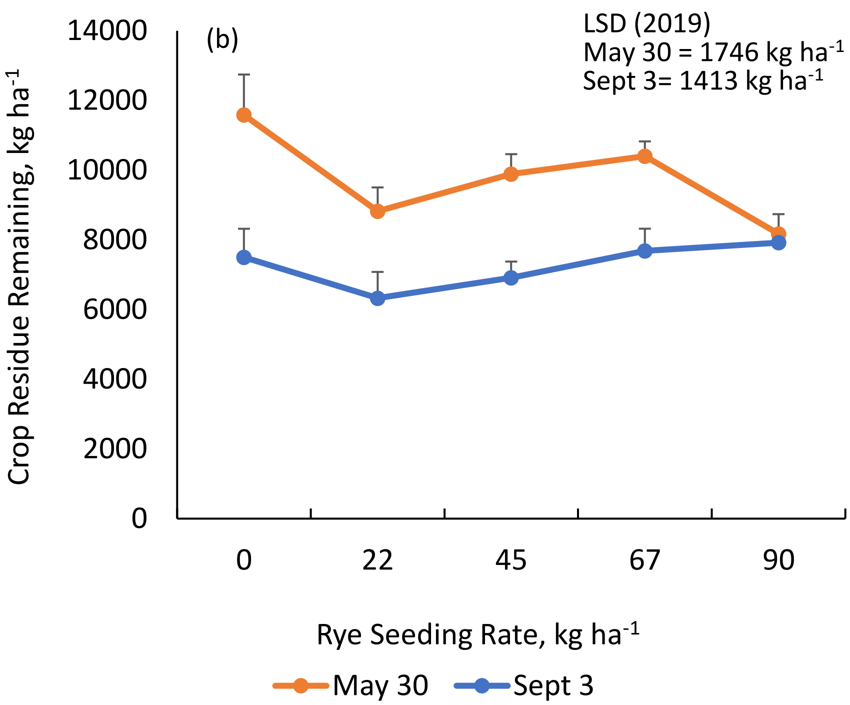


Figure 2.11. Crop residues remaining by 5 rye seeding rate treatments measured at rye termination and the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, (a) 2018 and (b) 2019.

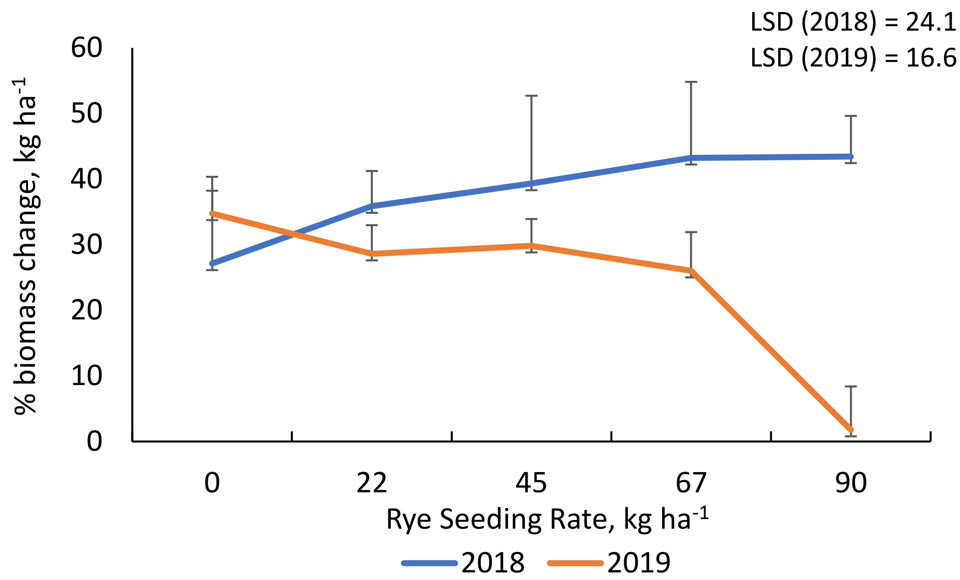


Figure 2.12. Change in amount of crop residue biomass between rye termination and the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

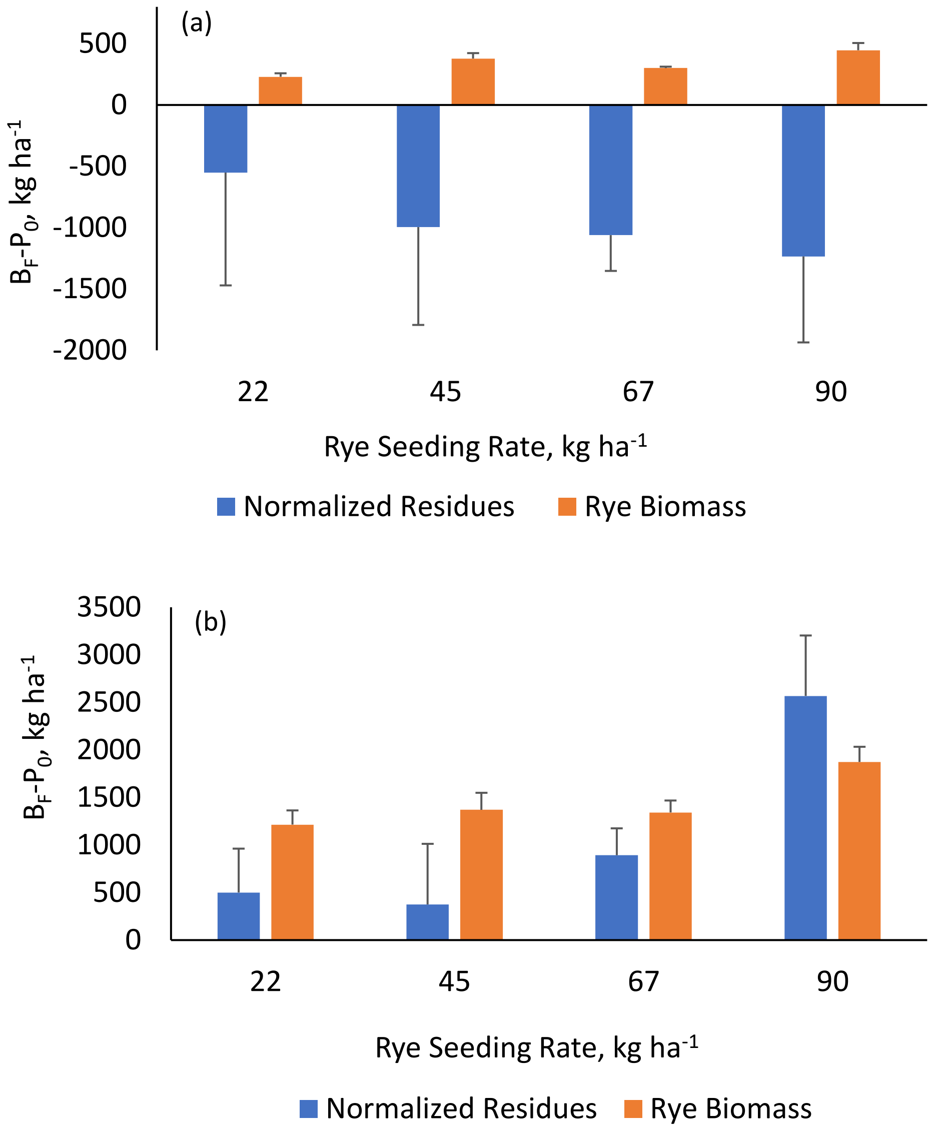


Figure 2.13. Differences in crop residues remaining normalized to the 0 kg ha^{-1} treatment measured at the soybean R6 growth stage and the corresponding rye dry matter production at the time of rye termination for 4 rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, (a) 2018 and (b) 2019. Normalized residues were calculated using the following equation where % RR= residue biomass remaining, W_I = residue biomass at rye termination for 0 kg ha^{-1} treatment, W_x = residue biomass at rye termination for x treatment, P_o = Predicted residue biomass at soybean R6 growth stage assuming 0 kg ha^{-1} of rye, B_x = Observed residue biomass at soybean R6 growth stage for x treatment: 1) % RR = $1-(W_I-W_x)/W_I * 100$. 2) $P_o = W_I * \%$ RR. 3) Normalized differences in residue=$B_x - P_o$.

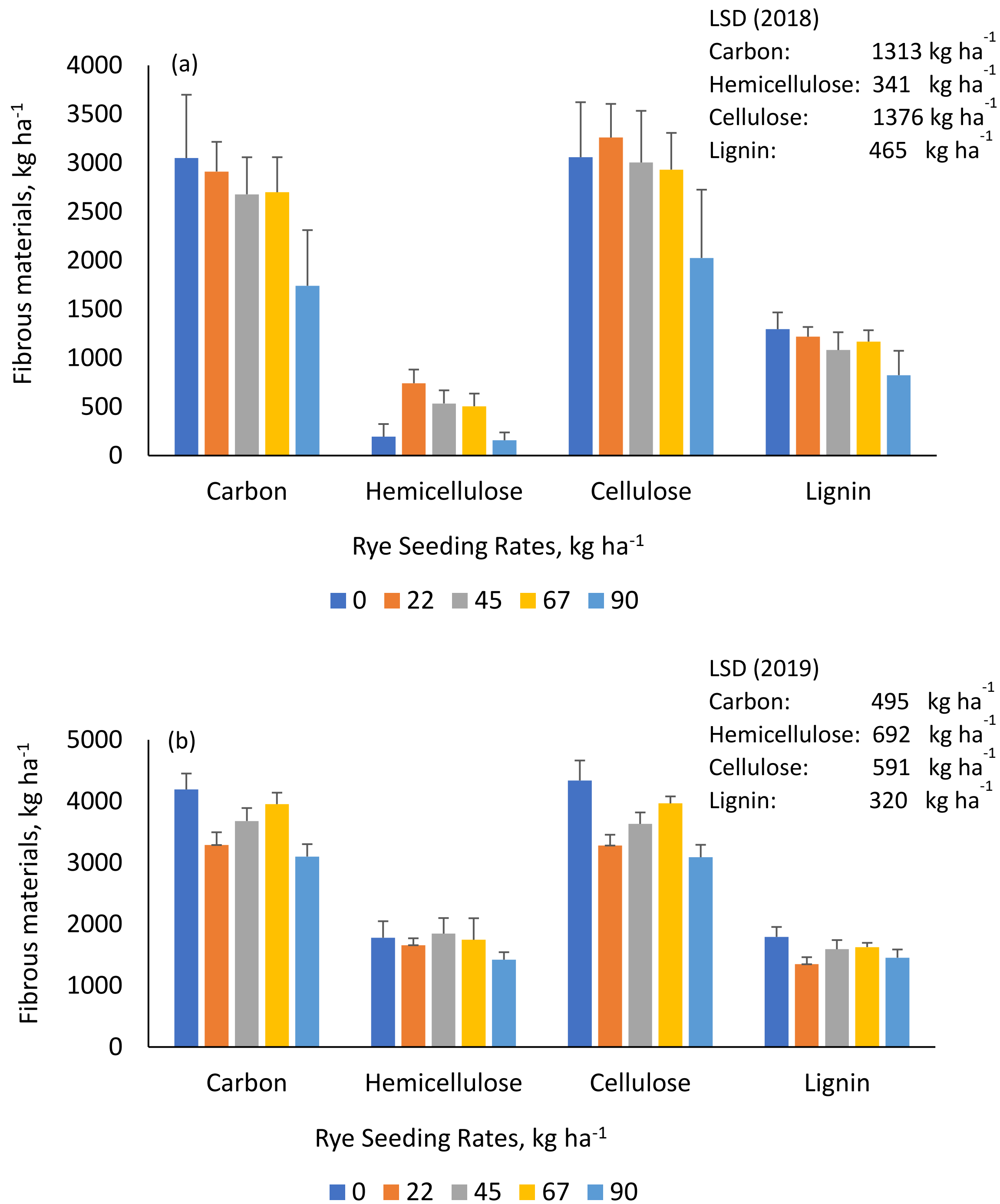


Figure 2.14. Total carbon, hemicellulose, cellulose, and lignin content of crop residues at 5 rye seeding rate treatments measured at rye termination located at the Southeast Research Farm near Beresford, SD, (a) 2018 and (b) 2019.

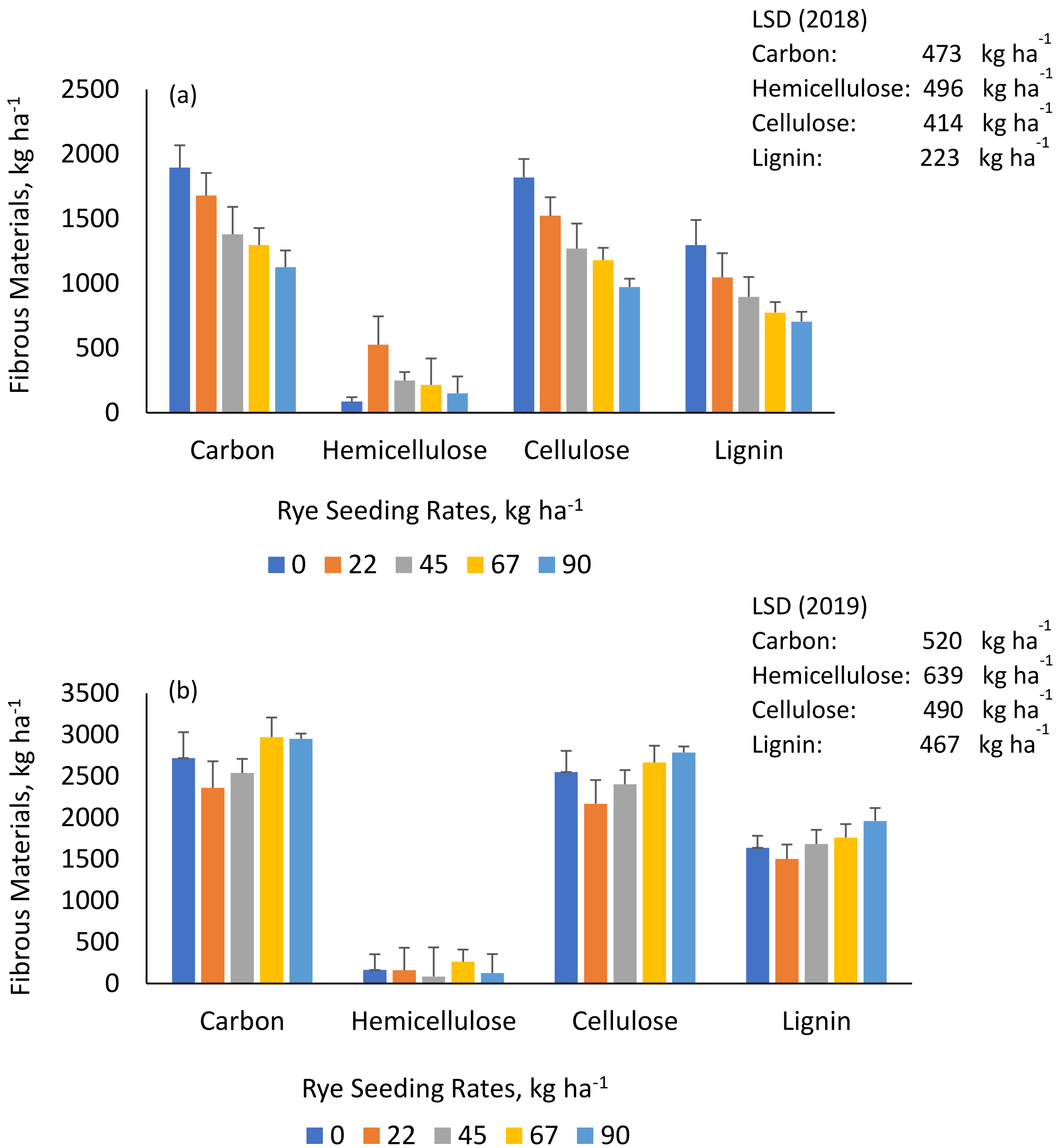
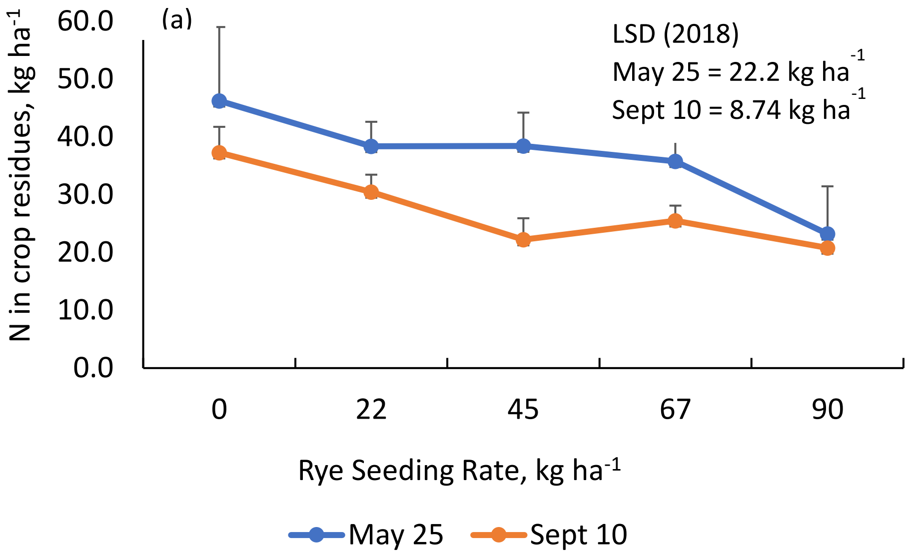


Figure 2.15. Total carbon, hemicellulose, cellulose, and lignin content of crop residues at 5 rye seeding rate treatments measured at the R6 soybean growth stage located at the Southeast Research Farm near Beresford, SD, (a) 2018 and (b) 2019.



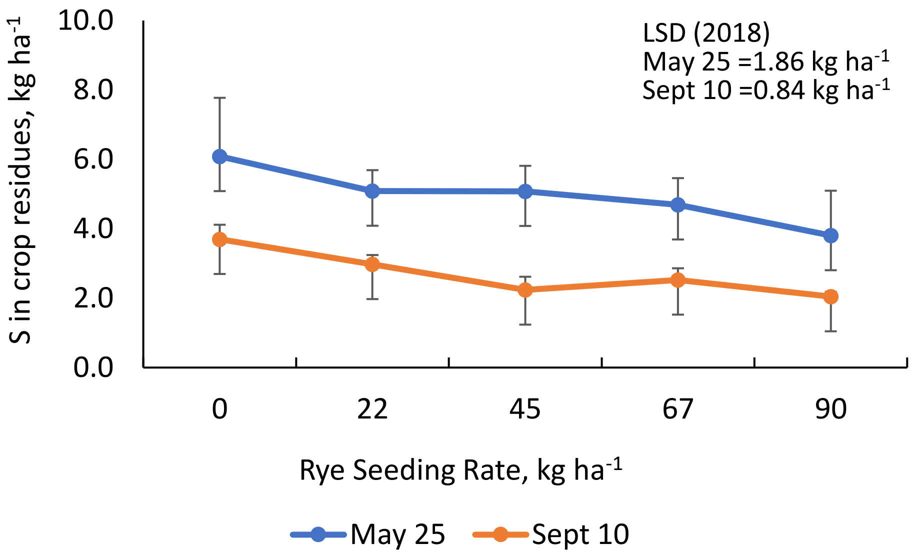


Figure 2.16. (a) N (kg ha^{-1}) and (b) S (kg ha^{-1}) remaining in crop residues by 5 rye seeding rate treatments measured at rye termination and at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018.

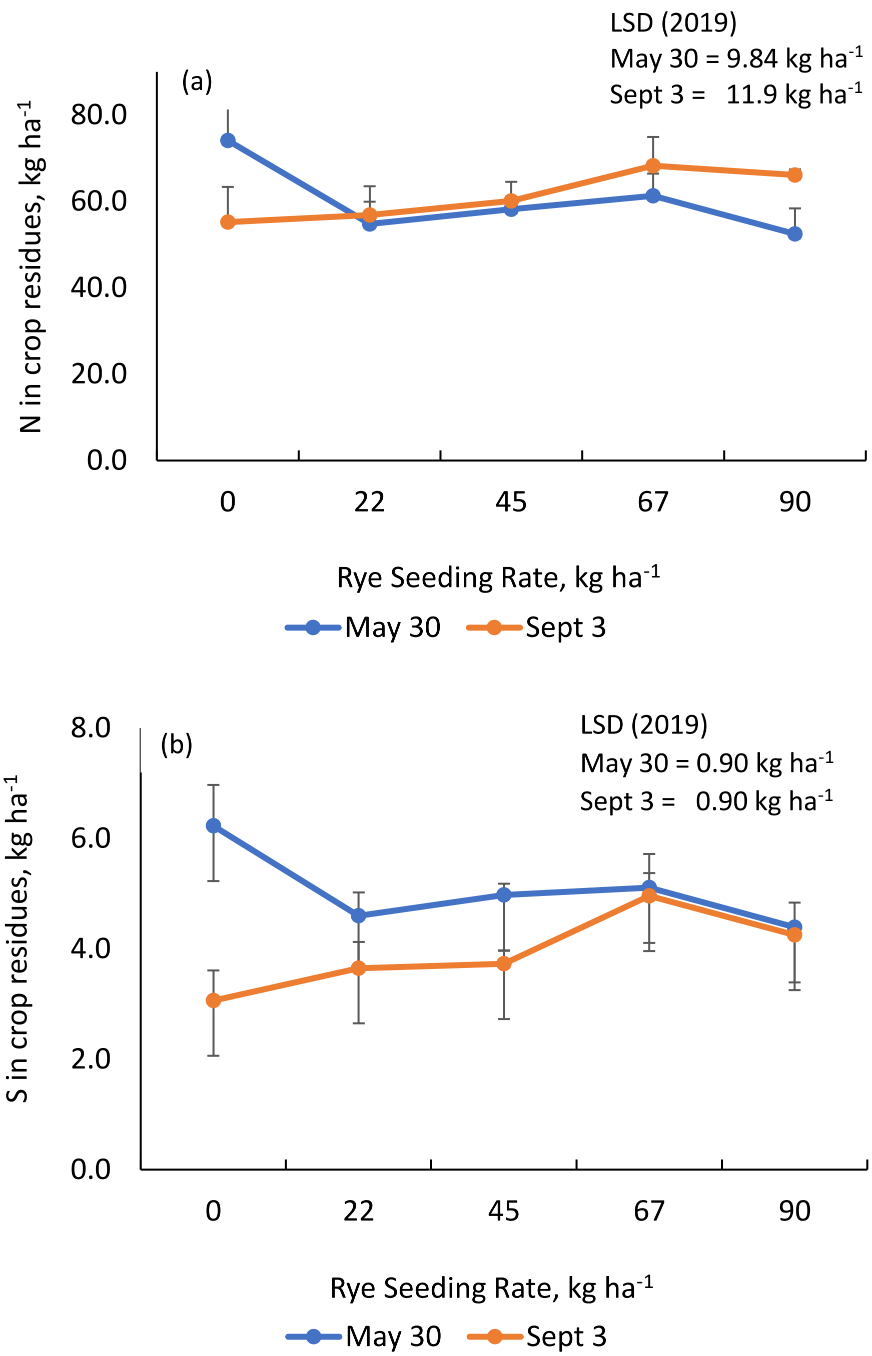
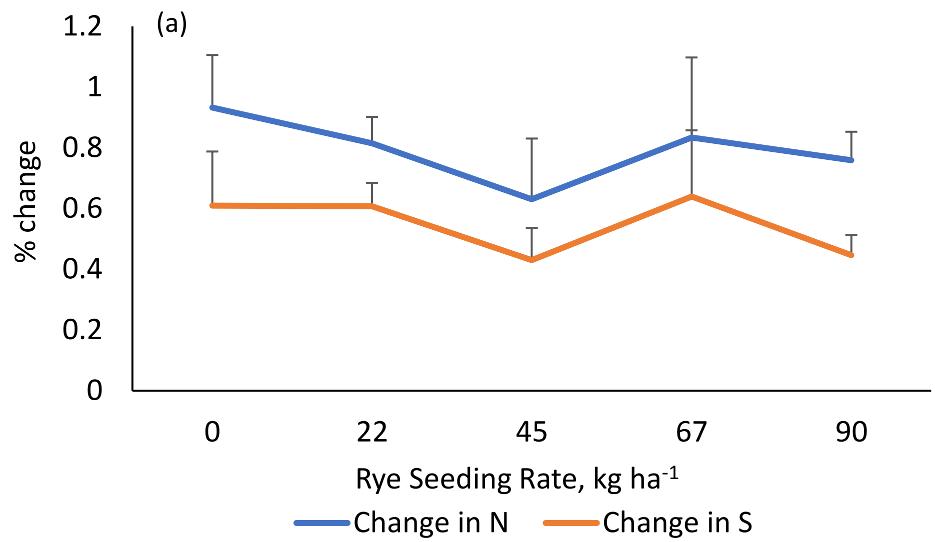


Figure 2.17. (a) N (kg ha^{-1}) and (b) S (kg ha^{-1}) remaining in crop residues by 5 rye seeding rate treatments measured at rye termination and at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.



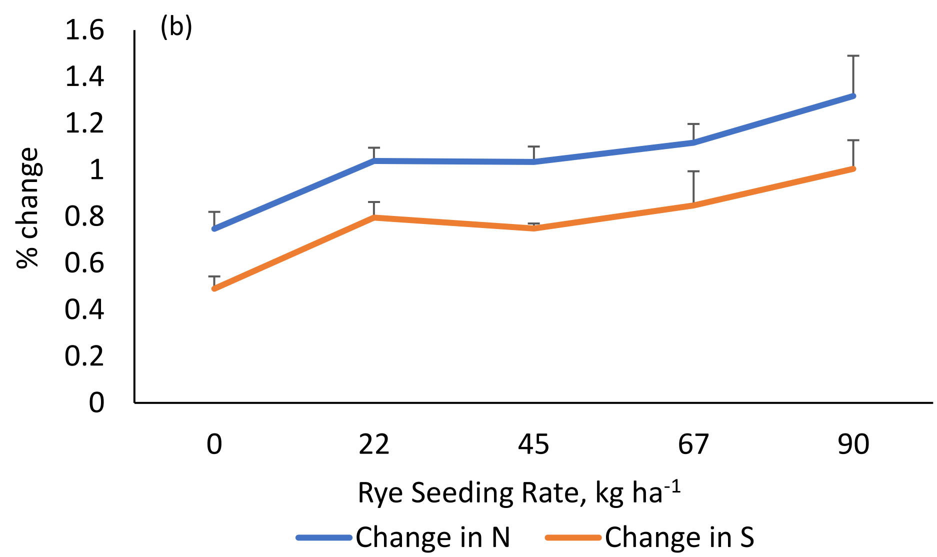


Figure 2.18. Change in kg ha^{-1} of N and S in crop residues between rye termination and the soybean R6 growth stage in (a) 2018 and (b) 2019 located at the Southeast Research Farm near Beresford, SD. Values less than 1 indicate net mineralization from residues while values that exceed 1 represent a net immobilization of nutrients in crop residues.

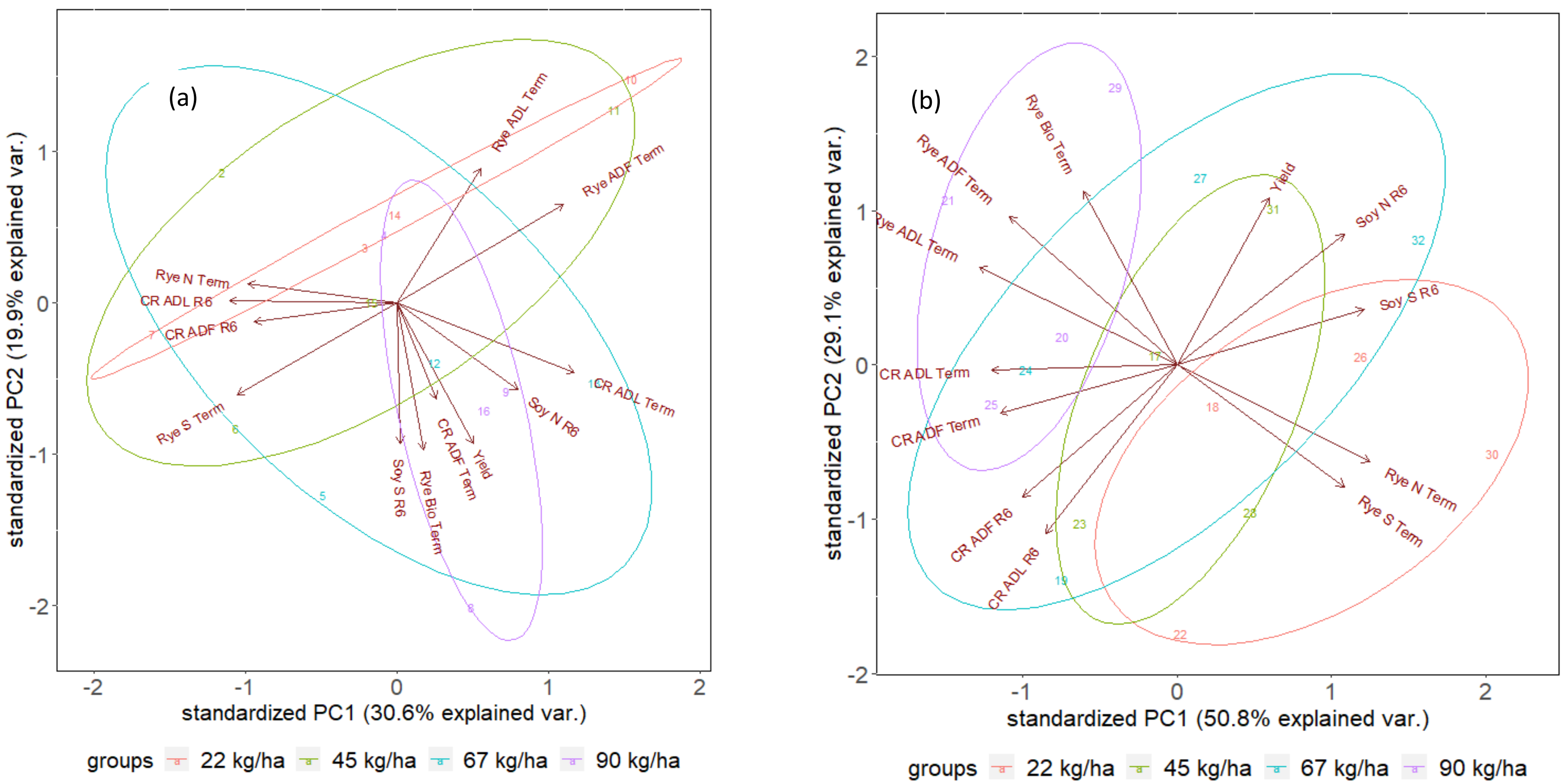


Fig 2.19. Biplots produced using the first and second components from principle component analysis containing rye biomass, N concentration, and S concentration measured at rye termination; crop residue ADF and ADL measured at rye termination and the soybean R6 growth stage, soybean N and S measured at the R6 growth stage; and soybean grain yield measured at harvest for 5 rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, (a) 2018 - (b) 2019. Abbreviations: CR=Crop residues, Term=measured at rye termination, R6=measured at soybean growth stage R6.

Table 2.1. Field management activities including rye cover crop planting and termination dates, 4 sampling dates, herbicide application, soybean planting and harvest dates during the growing season at the Southeast Research Farm near Beresford, SD, 2017-2019.

Growing Season Activity	**2018**	**2019**
Winter rye planting	November 13, 2017	October 3, 2018
1st Sampling	May 18, 2018	May 2, 2019
2nd Sampling	May 24, 2018	May 30, 2019
Rye Termination	May 22, 2018	June 5, 2019
Soybean planting	May 23, 2018	June 5, 2019
Herbicide application	July 6, 2018	July 13, 2019
3rd sampling	July 30, 2018	August 1, 2019
4th sampling	September 10, 2018	September 3, 2019
Soybean harvest	October 18, 2018	October 18, 2019

Table 2.2. Initial soil characteristics and soil classification at the Southeast Research Farm near, Beresford, SD, 2017-2019.

Growing Season	Soil Texture†	Soil Classification†	NO_3-N[a] (0-15 cm)	NO_3-N[a] (15-61 cm)	P[b]	K	Zn[c]	S[d] (0-15 cm)	S[d] (15-61 cm)	pH[e]
			----------------------	----------------------	------	mg kg^{-1}	------	----------------------	----------------------	
2017–2018	Silty Clay Loam	Fine-silty, mixed, mesic Udic Haplustolls	10.0	8.0	4.0	215	0.96	38.2	54.1	5.9
2018–2019	Silty Clay Loam	Fine-silty, mixed, mesic Udic Haplustolls	5.8	4.2	24	339	1.26	4.8	3.7	6.1

† (USDA-NRCS, 2020)

[a] soil nitrate (NO_3-N): using Nitrate Electrode method

[b] soil phosphorus: using Olsen P method

[c] soil zinc: DTPA extraction

[d] soil sulfur: Monocalcium phosphate extraction procedure

[e] soil pH: 1:1 extraction method

Table 2.3. Winter rye stand counts, number of plants lost, and mortality rate between fall and spring located at the Southeast Research Farm near Beresford, SD, 2019. Fall stands were recorded 26 days after planting on Oct. 29 while spring stand counts were measured on Apr. 8.

Seeding Rate	Fall Stand	Spring Stand	Plants Lost	Mortality Rate
kg ha^{-1}	------------------------	plants m$^{2\ -1}$	----------------------	%
22	70 d	39.7 d	30.6^{NS}	41.6 a*
45	110 c	73.4 c	36.1	31.5 ab
67	152 b	115 b	37.6	22.1 ab
90	189 a	166 a	23.5	11.7 b
Mean	130	98.4	31.9	26.7
CV	14.2	9.36	64.3	51.2

^{NS} Not significant at P = 0.05

* significant at p = 0.1

Table 2.4. Initial rye biomass, macronutrient concentration and uptake measured on May 18, 2018 and May 2, 2019 located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	Biomass	N	P	K	S	N	P	K	S
2018	kg ha^{-1}	kg ha^{-1}	------------------------g kg^{-1}----------------------				----------------------kg ha^{-1}-------------------			
	22	230 b	41.1 a	5.45^{NS}	42.0 a	3.63^{NS}	9.31^{NS}	1.24^{NS}	9.54^{NS}	0.83^{NS}
	45	378 ab	40.2 a	5.60	41.0 a	3.65	15.3	2.14	15.5	1.37
	67	301 ab	38.0 ab	5.65	41.0 a	3.63	11.2	1.69	12.3	1.10
	90	446 a	35.0 b	5.20	39.0 b	3.38	16.0	2.33	17.4	1.51
	Mean	339	39	5.48	40.7	3.57	12.9	1.85	13.7	1.20
	CV	39.8	8.08	5.39	2.64	5.12	40.6	42.9	40.4	42.2
2019	22	42.3 b	50.6 a	6.29 a	37.8 a	3.66 a	2.80^{NS}	0.35^{NS}	2.11^{NS}	0.20^{NS}
	45	143 ab	44.3 b	5.31 b	33.7 b	3.16 b	6.32	0.77	4.88	0.45
	67	184 a	42.2 b	5.20 b	33.9 b	3.12 b	7.78	1.01	6.19	0.57
	90	198 a	41.9 b	6.18 a	34.8 ab	3.10 b	8.12	1.23	6.79	0.59
	Mean	142	30.7	5.71	34.9	3.22	6.48	0.87	5.18	0.47
	CV	61.2	49.8	8.76	5.29	7.59	56.4	63.9	59.2	54.8

^{NS} Not significant at P = 0.05

Table 2.5. Analysis of Variance and treatment means for rye N, P, K, and S concentration and uptake measured at rye termination located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	N	P	K	S	N	P	K	S
2018	kg ha^{-1}	----------g kg^{-1}----------				----------kg ha^{-1}----------			
	22	37.5 ^{NS}	5.38 ab	34.3^{NS}	3.30^{NS}	9.51 b†	1.38 b	8.87 b	0.85 b
	45	31.5	5.87 a	33.5	3.18	8.54 b	1.38 b	8.80 b	0.87 b
	67	37.5	5.73 ab	34.9	3.40	8.98 b	1.38 b	8.35 b	0.82 b
	90	29.5	5.18 b	33.9	3.10	15.3 a	2.68 a	17.8 a	1.61 a
	Mean	34.0	5.51	34.1	3.24	10.7	1.72	11.1	1.05
	CV	16.6	5.38	9.62	11.61	29.5	29.6	30.3	25.1
2019	22	20.6 a	4.02^{NS}	27.6 a	1.65 a	24.8^{NS}	4.85^{NS}	33.4^{NS}	1.98^{NS}
	45	18.5 b	3.78	27.2 a	1.52 ab	25.2	5.16	36.8	2.05
	67	17.3 b	3.55	26.2 ab	1.44 bc	23.1	4.80	35.1	1.93
	90	15.2 c	3.57	24.4 b	1.32 c	28.7	6.70	45.6	2.49
	Mean	17.9	3.7	26.33	1.48	25.5	5.38	37.7	2.11
	CV	6.6	8.12	4.7	6.2	21.0	27.3	22.1	20.6

Source					Pr>f			
SR (Seeding Rate)	0.03	NS	NS	NS	0.09	0.02	0.01	0.01
Year	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SR*Year	NS	NS	NS	NS	NS	NS	NS	NS

^{NS} Not significant at p = 0.05
† p = 0.1

Table 2.6. Components of rye residue quality including C, NDF, ADF, CF, hemicellulose, cellulose, and lignin measured at the time of rye termination at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	C	NDF	ADF	CF	Hemicellulose	Cellulose	Lignin
2018	kg ha^{-1}	--------------------------%--------------------------				------------------g kg^{-1}---------------------		
	22	39.9^{NS}	51.0^{NS}	34.1^{NS}	25.3^{NS}	170^{NS}	256^{NS}	86^{NS}
	45	41.1	50.8	34.1	27.3	198	285	56
	67	40.7	51.4	30.8	26.9	205	253	56
	90	38.9	51.8	34.7	29.0	171	276	72
	Mean	40.1	51.3	33.4	27.1	185	267	67.3
	CV	4.20	1.82	11.1	15.9	19.1	9.62	42.6
2019	22	41.7^{NS}	52.3 b	33.0 c	35.6^{NS}	193^{NS}	283 c	46.5 c
	45	41.5	54.0 b	35.5 b	38.8	185	302 b	52.5 b
	67	41.5	54.1 b	35.9 b	37.1	183	304 b	54.5 ab
	90	41.8	59.1 a	38.4 a	41.1	207	325 a	59.5 a
	Mean	41.6	54.9	35.7	38.15	192	303	53.3
	CV	0.64	4.00	3.89	9.08	7.92	3.65	6.24

* Abbreviations: C, Carbon; NDF, Neutral Detergent Fiber; ADF, Acid Detergent Fiber; CF, Crude Fiber

^{NS} Not significant at p = 0.05

Table 2.7. Biomass, C:N ratio and fibrous composition of crop residue materials at 5 rye seeding rate treatments during the 2018-2019 growing season measured at rye termination located at the SDSU Southeast Research Farm near Beresford, SD.

Sample Date	Seeding Rate	Biomass	C:N	NDF*	ADF	CF	HEM	CEL	L
	kg ha^{-1}			--------------------------------g kg^{-1}	-------------------------------				
2018	0	7635 a	69.3 ^{NS}	605 b	613 ^{NS}	387 ^{NS}	22.8 c	403 ^{NS}	164 ^{NS}
	22	7258 ab	76.1	719 a	617	399	101 a	448	169
	45	6626 ab	70.2	688 a	609	395	78.8 ab	448	161
	67	6662 ab	77.3	691 a	619	423	71.8 ab	440	179
	90	4457 b	77.4	677 a	631	403	46.3 bc	449	182
	mean	6528	74.1	676	618	401	64.2	438	172
	CV	31.5	7.99	5.82	3.83	14.3	45.9	6.50	8.95
	0	11583 a	57.9 ^{NS}	713 ^{NS}	533 ^{NS}	306† b	158 ^{NS}	378 ^{NS}	155 b
2019	22	8821 bc	60.9	720	528	357 a	192	374	153 b
	45	9885 abc	63.1	714	529	327 ab	185	368	152 b
	67	10406 ab	65.6	705	540	362 ab	166	382	158 b
	90	8174 c	60.3	732	556	370 a	177	378	177 a
	mean	9774	61.6	710	537	344	176	376	159
	CV	11.6	8.92	5.45	4.85	9.58	20.0	5.39	6.92

* Abbreviations: NDF, Neutral Detergent Fiber; ADF, Acid Detergent Fiber; CF, Crude Fiber; HEM, Hemicellulose; CEL, Cellulose; L, Lignin

^{NS} = Not significant at P = 0.05

† = Significant at P = 0.1

Table 2.8. Primary nutrient concentration and uptake of soybeans at 5 rye seeding rate treatments measured at the R3 soybean growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	Biomass	N	P	K	S	N	P	K	S
2018	kg ha^{-1}	kg ha^{-1}	----------g kg^{-1}----------				----------kg ha^{-1}----------			
	0	8368 ^{NS}	32.9 ^{NS}	2.69 ^{NS}	28.1 ^{NS}	2.03† b	272 ^{NS}	22.4 ^{NS}	234 ^{NS}	18.7 ^{NS}
	22	7758	33.2	2.81	28.7	2.14 ab	257	22.0	225	16.6
	45	8594	32.1	2.67	29.3	2.19 a	276	22.8	248	18.7
	67	9088	32.4	2.77	28.9	2.28 a	295	25.1	265	20.8
	90	8644	32.1	2.72	27.4	2.15 ab	274	23.3	233	18.5
	Mean	8490	32.5	2.73	28.5	2.16	275	23.1	241	18.6
	CV	17.2	7.55	10.2	5.88	4.37	16.8	13.9	14.6	17.0
2019	0	6208 ^{NS}	32.0 ^{NS}	3.32 ^{NS}	29.0 ^{NS}	1.70 ^{NS}	201 ^{NS}	24.2 a	203 ^{NS}	12.4 a
	22	6662	32.5	3.21	30.3	1.61	217	21.7 b	201	10.8 ab
	45	6062	30.4	3.00	29.9	1.67	185	18.0 c	180	9.58 b
	67	6360	32.0	3.04	29.7	1.61	204	19.3 bc	189	10.3 b
	90	6290	31.5	3.07	29.9	1.54	198	18.7 bc	183	9.57 b
	Mean	6316	31.7	3.1	29.7	1.6	201	20.1	190	10.4
	CV	11.5	5.65	13.1	9.67	7.51	12.5	8.02	8.89	8.93

^{NS} = Not significant at P = 0.05
† = Significant at P=0.1

Table 2.9. Primary nutrient concentration and uptake of soybeans at 5 rye seeding rate treatments measured at the R6 soybean growth stage located at the SDSU Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	Biomass	N	P	K	S	N	P	K	S
2018	kg ha^{-1}	kg ha^{-1}	---------------------g kg^{-1}-------------------				----------------------kg ha^{-1}------------------			
	0	11079† ab	34.2 NS	2.79† b	20.8 NS	2.17 NS	380 bc	31.1 bc	231 b	24.1 NS
	22	11967 ab	34.4	2.90 ab	21.3	2.19	412 ab	34.8 ab	256 ab	26.2
	45	12486 a	34.4	2.91 ab	21.1	2.16	429 a	36.5 a	265 a	27.1
	67	11104 ab	35.0	2.76 b	20.3	2.23	389 abc	30.5 c	225 b	24.8
	90	10496 b	34.8	2.98 a	21.5	2.16	365 c	31.3 bc	226 b	22.7
	Mean	11426	34.6	2.87	21.0	2.18	395	32.9	241	63.3
	CV	8.68	2.56	3.72	3.59	5.45	7.32	7.90	8.31	5.08
2019	0	15691 NS	30.7 NS	3.01 NS	20.1 NS	1.35 NS	482 NS	47.4 NS	314 NS	21.3 NS
	22	13787	31.1	2.86	20.7	1.34	427	39.7	287	18.5
	45	14982	30.1	2.53	19.6	1.25	451	37.5	293	18.8
	67	15304	31.1	2.77	19.8	1.26	480	42.7	303	19.6
	90	15607	30.0	2.74	19.6	1.22	468	42.6	306	19.0
	Mean	15074	30.6	2.78	20.0	1.28	462	42.0	301	19.5
	CV	11.1	3.45	14.0	6.96	8.17	12.1	22.0	14.0	15.2

NS = Not significant at P = 0.05
† = Significant at P=0.1

Table 2.10. Analysis of Variance and treatment means of soybean grain yield, test weight, moisture, plant stand, and 100 seed weight by 5 rye seeding rate treatments located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Yield	Test Weight	Moisture	Plant Stand	100 seed weight
	kg ha^{-1}	Mg ha^{-1}	Kg m^{-3}	%	plants ha^{-1}	g
2018	0	4.65 ab	621 ^{NS}	11.9 ^{NS}	374424 ^{NS}	14.9
	22	4.46 c	632	11.9	292654	16.1
	45	4.50 bc	591	11.4	305565	15.0
	67	4.49 c	610	11.5	292654	14.7
	90	4.66 a	572	11.3	301261	14.6
	mean	4.55	605	11.6	313312	15.1
	CV	2.19	6.30	3.54	23.3	1.61
2019	0	3.70 ^{NS}	697 ^{NS}	9.86 ^{NS}	238140 ^{NS}	15.8 ^{NS}
	22	3.77	694	9.55	255355	15.8
	45	3.76	690	9.84	241009	15.9
	67	3.72	684	9.63	301261	16.2
	90	3.81	612	8.67	229532	16.1
	mean	3.75	675	9.51	253059	16.0
	CV	4.26	10.7	9.71	11.5	3.08

Source			Pr>f		
Treatment (Trt)	NS	0.06	NS	NS	NS
Year	<0.001	<0.001	<0.001	0.001	0.005
Trt*Year	NS	NS	NS	NS	NS

^{NS} = Not significant at P = 0.05

Table 2.11. Soil NO_3^-, P, K, Zn, and S measured to a 15 cm depth and NO_3^- and S measured from a 15-61 cm depth on September 10 corresponding with the R6 soybean growth stage located at the Southeast Research Farm, 2018.

Sample Date	Seeding Rate	NO_3-	P	K	Zn	S	NO_3-	S
		--------------------------0-15 cm-----------------------					-----15-61 cm-----	
	kg ha $^{-1}$	--mg kg^{-1}------------------------------------						
Sept 10, 2018	0	3.15 ^{NS}	6.50 ^{NS}	157 ab	0.68 ^{NS}	8.18 ^{NS}	1.35 ^{NS}	14.7† ab
	22	3.10	5.50	145 bc	0.59	9.95	2.00	6.73 b
	45	3.05	6.67	164 a	0.94	6.65	1.70	10.9 b
	67	2.85	5.50	140 c	0.71	11.0	1.60	29.3 a
	90	3.80	7.50	153 abc	0.71	6.53	1.35	10.5 b
	Mean	3.19	6.32	152	0.73	8.47	1.60	14.8
	CV	28.5	29.7	6.79	31.1	38.5	22.2	72.4

^{NS} = Not significant at P = 0.05

† = Significant at P=0.1

Table 2.12. Soil NO_3^-, P, K, Zn, and S measured to a 15 cm depth and NO_3^- and S measured from a 15-61 cm depth measured on May 30 at rye termination, August 1 at the soybean R3 growth stage, September 3 corresponding with the R6 soybean growth stage located at the Southeast Research Farm, 2018.

Sample Date	Seeding Rate	OM	NO_3-	P	K	Zn	S	NO_3-	S
		--------------------------------0-15 cm--------------------------------						-----15-61 cm----	
	kg ha $^{-1}$								
May 30	0	4.53 ^{NS}	2.90 ^{NS}	22.8 ^{NS}	376 ^{NS}	3.47 ^{NS}	4.73 ^{NS}	4.13 ^{NS}	4.45 ^{NS}
	22	4.43	2.15	16.0	305	2.21	3.85	2.20	4.15
	45	4.45	1.93	13.5	297	2.44	3.68	2.10	3.35
	67	4.30	2.00	12.5	307	2.69	3.93	1.95	3.60
	90	4.53	2.25	9.50	308	2.19	4.45	2.10	3.20
	Mean	4.45	2.26	14.85	319	2.60	4.40	2.43	3.75
	CV	3.74	8.54	50.5	14.8	31.7	41.5	17.1	32.0
August 1	0	4.35 ^{NS}	2.50 † a	11.3 ^{NS}	203 ^{NS}	3.88 ^{NS}	9.65 ^{NS}	2.05 ^{NS}	8.50 ab
	22	4.45	2.35 a	10.5	268	3.23	9.13	2.00	10.1 a
	45	4.43	2.50 a	7.50	179	3.08	10.0	1.80	10.2 a
	67	4.38	2.10 ab	8.50	216	3.29	9.33	1.80	9.38 a
	90	4.45	2.00 b	10.5	270	3.34	9.68	1.67	6.63 b
	Mean	4.41	2.29	9.58	227	3.36	9.56	1.87	8.95
	CV	3.28	12.1	25.2	23.5	24.3	17.9	10.7	17.6
September 3	0	4.03 ^{NS}	0.90 ^{NS}	11.8 ^{NS}	251 ^{NS}	5.83 ^{NS}	5.58 ^{NS}	0.90 ^{NS}	4.60 ^{NS}
	22	4.05	1.60	9.25	256	3.88	4.70	0.90	4.13
	45	4.05	1.25	7.00	227	3.39	4.33	0.90	4.30
	67	4.03	1.25	7.50	248	4.21	5.20	0.75	4.85
	90	3.93	1.25	9.50	268	4.31	4.33	0.87	3.60
	Mean	4.02	1.25	9.00	249.9	4.32	4.83	0.86	4.30
	CV	1.83	44.9	35.6	9.07	30.0	25.6	11.5	21.6

† = Significant at P=0.1

^{NS} = Not significant at P = 0.05

Chapter 3: Winter rye cover crop termination timing effects on nutrient cycling and soybean production in southeast South Dakota

3.1 Abstract

Balancing winter rye (*Secale cereale* L.) cover crop biomass production with quality is important to maximize soil health benefits while minimizing risk to subsequent soybean production. Management of rye through five termination timing treatments was explored in a study at the Southeast Research Farm near Beresford, SD with the purpose of gaining insights on: 1) termination timing effects on biomass production and quality; 2) crop residue decomposition and nutrient release; 3) soybean nutrient balance and yield potential. Plant, residue, and soil samples were collected and analyzed for nutrient and fiber concentrations to observe changes in nutrient dynamics in the agroecosystem. Rye biomass and quality changes were most dramatic between the May 13th and May 31st termination treatments. Residue amounts by the end of the growing season were not different between April 19th and May 13th with the majority of biomass loss occurring by the R3 growth stage resulting in higher soybean N concentration. However, by the R6 growth stage no difference in N was observed. Soybean S concentration trended downward as termination was delayed but was not seen to be limiting to soybean yield. Furthermore, later terminated rye slowed soybean development which may have contributed to significantly higher soybean yields at the May 31st termination date. These results suggest delaying rye termination could increase soybean yields under high fertility soils where moisture is not limiting.

3.2 Introduction

Cover cropping has increasingly become more of a staple practice in annual cropping systems across the United States as a result of the diverse set of ecosystem services obtained which have the potential to lead to improved soil functioning, lessened environmental externalities, and decreased yield variability over time (Roth et al., 2018; Bergtold et al., 2019). However, even with the well-established benefits of cover crops on improving soil quality, limiting ground and surface water contamination, and cycling of nutrients, adoption rates across the Midwest remain low with South Dakota having the 3rd lowest proportion of annual cropland planted to cover crops in the United States (Hamilton et al., 2017). Currently, only 1.4% of cropland in South Dakota incorporates cover crops in their systems (USDA-NASS, 2019). Winter rye is the most common cover crop planted (CTIC, 2017) due to its relatively low cost, strong winterhardiness, and robust ability to cycle nutrients and add organic matter to soils through strong biomass production (Lacey et al., 2020). Hesitations to adopt cover crops such as rye as part of a conservation-based system arise from concerns over the profitability of incorporating cover crops due to the cost of establishment and perceived risk to cash crop yields (Singer and Nusser, 2007; Bergtold et al., 2019). These risks stem from concerns over water use, N dynamics, residues interfering with establishment, and short growing seasons not resulting in adequate time for cover crop establishment (Hamilton et al., 2017; Thompson et al., 2020). Research is promoting the role of winter rye cover crops as part of an ecosystem-based, conservation approach which through the addition and maintenance of organic materials in the soil system and the stimulation of soil microbiological activity, there is the potential to increase yields and reduce yield variability over time (Drinkwater and Snapp, 2007; Lal, 2015). This has encouraged interest in cover cropping from farmers looking to implement these practices as well as policy makers seeking to incentivize cover crops to increase adoption as part of an integrated conservation system. However, many gaps in knowledge remain on how to best manage winter rye under the diversity in geography and environments across the United States. A meta-analysis by Thompson et al. (2020) showed inconsistency in cash crop yield response to rye, but generally net returns were negative in short term studies. Therefore, further research is necessary to adequately address producers' concerns regarding winter rye cover crops and further guidance and support from universities and policy makers to ensure that cover crop benefits can be maximized while economical risks are minimized.

The balance that needs to be struck in properly managing winter rye is the interface between biomass and quality. Many of the ecosystem services obtained from cover crops are dependent on biomass production (Finney et al., 2016; Ogilvie et al., 2019; Ruis et al., 2019; Ruis et al., 2020). Ruis et al. (2020) found from a review of the literature that increases in rye biomass led to improvements in SOC and aggregate stability over time. However, as biomass is accumulated, there becomes a greater short term risk to cash crop yields through uptake of soil resources including both water and nutrients (Krueger et al., 2011). Therefore, further research is necessary to improve the understanding of managing the complex interrelationship between cover crop biomass with economic and environmental tradeoffs. Key management approaches to control biomass of winter rye include 1) planting date (Kantar and Porter, 2014), 2) termination timing (Otte et al., 2019), 3) and seeding rates (Brennan et al., 2013). In Midwest corn-soybean rotations, winter rye planting date is often variable due to the timing of cash crop harvest which is highly dependent on yearly weather trends. Seeding rates have shown varied success in altering total rye biomass production due to the compensatory nature of tillering under lower planting densities (Boyd et al., 2009; Ryan et al., 2011; Brennan. and Boyd, 2012a). Therefore, altering rye termination timing may be the most direct and effective method for producers to alter biomass production as well as counteract the negative implications of water use and nutrient sequestration.

Delaying termination of rye results in higher biomass and a greater uptake of soil nutrients which can be directly related to reductions in nutrient losses (Ruffo et al., 2004). However, delayed termination decreases the quality of rye as the plant invests more resources in the production of fibrous materials (Alonso-Ayuso et al., 2014; Otte et al., 2019). Nutrient release is effected by the plant composition of hemicellulose, cellulose, and lignin as nutrients become bound up in strongly recalcitrant materials which decompose slower than soluble compounds (Dabney et al., 2001; Ruffo and Bollero, 2003b). In contrast, earlier terminated rye takes up fewer nutrients and cycles them faster, so they are more likely to become available before cash crop uptake.

Generally, it is encouraged to terminate rye approximately two weeks ahead of planting to reduce risk to the following cash crop (Duiker and Curran, 2005; Acharya et al., 2017; Reed et al., 2019). Planting rye ahead of corn carries a greater risk to cash crops through reduction of yield from allelopathic effects, N immobilization, and disease risk and therefore requires a stricter adherence to earlier termination (Acharya et al., 2017). However, soybeans tolerate later terminations due to lessened concerns over N uptake by rye (Wells et al., 2013). Reed et al. (2019) noted no negative effects on soybean yield when planted at the time of rye termination. However, previous research in Southeast South Dakota has shown indications that S, a nutrient commonly in association with N, may be sequestered by rye and limiting to soybean production (Brockmueller et al., 2016; Sexton et al., 2017). Therefore, where soil S availability is deficient or marginal, later termination dates could negatively affect soybean yield if sequestered S is not synchronized with plant S demand leaving soybeans in an S deficient state.

Therefore, the objectives of this study were: 1) Examine the biomass production of a winter rye cover crop in relation to timing of its termination in order to observe the effects on nutrient uptake and residue quality and gain insights on the extent of nutrient sequestration and the potential for release back into the soil; 2) Observe how rye biomass related to crop residue amounts, decomposition, and nutrient immobilization throughout the growing season; 3) Measure the effects of termination treatments on soybean development, nutrient concentration, and yield to better understand potential tradeoffs between rye biomass production and soybean production.

3.3 Materials and Methods

3.3.1 Site Description

A rye burndown study was implemented at the Southeast Research Farm near Beresford, SD (43°03'N, 96°53'W) in the spring of 2018. Monthly averaged temperature and cumulative precipitation are shown in Figure 2.1. The field was located on an Egan-Clarno-Trent complex soil with 1-6% slopes (Fine-silty, mixed, mesic Udic Haplustolls) and an Egan-Trent silty clay loam soil (Fine-silty, mixed, mesic Udic Haplustolls) with 0-2% slopes (USDA-NRCS, 2020). Initial soil classifications and nutrient data are presented in Table 3.2. This trial was fit into a corn-soybean-small grain rotation under no-till management with the previous corn crop being harvested as corn sileage. Fertilizers were last applied to corn in the previous growing season with 103 kg ha^{-1} of N and 11 kg ha^{-1} of S being applied preplant and 24 kg ha^{-1} of N side dressed. Initial soil samples were collected on Nov 21, 2018 by collecting a composite sample using a hand probe with a diameter measuring 12.7 mm. Soils were air dried and ground to pass through a 2mm sieve and analyzed according to the procedures described by Manjula and Gelderman (2015). Soil NO_3- was analyzed using the Nitrate Electrode method, P was measured by the Olsen method, K was extracted with 1 *M* of NH_4OAc, pH and EC were measured using a 1:1 extraction, Zn determined through the diethylenetriaminepentaacetic acid (DTPA) extraction, and S was measured by the Monocalcium Phosphate Extraction procedure.

3.3.2 Experimental Design

The field trial was set up using a Latin Square design with five burndown treatments and five replications. Burndown treatment dates were scheduled for every 10 days beginning April 19; however, actual burndown dates varied slightly depending on weather conditions. Actual burndown dates were April 19, April 29, May 13, May 23, and May 31st. Plot sizes were 8 m by 14 m with a 3 m alley between each replication to avoid areas of increased corn residues left behind from sileage harvest.

3.3.3 Crop Management

Agronomic activities can be found in Table 3.1. In the fall of 2018, winter rye (VNS) was planted at a rate of 50 kg ha^{-1} on row spacing of 19 cm drilled into corn sileage residue. It was terminated according to the treatment structure using 2.34 L ha^{-1} of glyphosate for the initial three burndown dates. The chemical mixture was made stronger as the growing season progressed to achieve adequate burndown as the rye matured. The May 13 burndown used 2.34 L ha^{-1} of glyphosate, 0.73 L of Saflufenacil, and 1% v/v methylated seed oil surfactant (MSO). The May 23 burndown used a mix of 2.05 L ha^{-1} of glyphosate, 1.56 L ha^{-1} of metolachlor, 0.07 L ha^{-1} of Saflufenacil, and 0.24 L ha^{-1} of metribuzin. On May 31st, 2.34 L ha^{-1} of glyphosate and 1.17 L ha^{-1} of metolachlor were applied. In addition to the May 31st treatment plots, all other plots with the exception of the May 23rd treatments received 2.34 L ha^{-1} of glyphosate and 1.17 L ha^{-1} of metolachlor on May 31st to provide preemergence weed control. A stronger preemergence application was previously applied to the May 23rd treatments at the time of termination and was therefore excluded from receiving an additional herbicide application on May 31st. Soybean variety AG24X7 (Asgrow Seed Co LLC, Creve Coeur, MO) were no-till drilled at a rate of 429,000 seeds ha^{-1} with a row spacing of 19 cm. A post emergence herbicide was applied during the growing season that mixed 2.34 L ha^{-1} of glyphosate, 0.02 L ha^{-1} of cloransulam-methyl, 2.5% v/v urea ammonium nitrate (UAN), and 1% v/v crop oil concentrate (COC).

3.3.4 Cover crop, plants, and residue sampling

Throughout the growing season, each plot was sampled by hand on three different dates using two cuts from a crop cut frame measuring 0.22 m^2. Initial samples were taken only on the termination date for each specific treatment. Rye and crop residue biomass were collected at the initial sampling. During the soybean growing season, samples were taken at the soybean R3 and R6 growth stage to collect soybean and crop residue samples. Plant heights and stand counts were recorded while weed pressure was monitored using a 1-10 scale. Senesced leaves from the soybeans were collected and analyzed separately from the crop residues. Soybean samples were subsampled at the R3 sampling by collecting 10 representative plants from the crop cut frame. At the R6 growth stage, all collected soybean plants were processed. Additionally, soybean leaf tissue samples were collected at the R3 stage by randomly selecting 7 trifoliate from the first fully mature node from the top of the plant. Upon completion of sampling, samples were oven dried at 60°C to a constant weight and dry weight was measured and converted to kg ha^{-1}. Once dried, all samples were ground first through a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a 2-mm sieve. Subsamples of the ground tissues were taken and passed through a UDY mill (UDY Corporation, Fort Collins, CO) with a sieve of <1-mm.

3.3.5 Soil Sampling

Soil samples were taken at the time of each sampling using a soil probe with a diameter of 12.7 mm. Samples were subdivided between 0-15 cm and 15-61 cm to be analyzed separately. At the initial sampling, two soil cores were collected from each plot and composited across five replications to provide a baseline measurement for each treatment. During the soybean growing season all plots were sampled at the R3 and R6 growth stages by collecting six soil cores to a 15 cm depth and four cores to a 61 cm depth for each plot . Soil samples were air dried and ground to pass through a sieve size of 2-mm.

3.3.6 Soybean Harvest

At harvest, plant heights and stand counts were recorded. Plots were harvested using a Zürn small plot combine (150, Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany). The harvested area was 1.5 m by 12.2 m for each plot and occurred on the opposite half of the plot from where biomass samples were collected. Grain test weight and moisture were measured using an onboard unit in the Zürn combine. A subsample of soybean grain was collected and ground through a KnifeTec to prepare for further analysis (Tecator, Höganäs, Sweden).

3.3.7 Laboratory Analysis

All plant, residue, leaf tissue, senesced leaves, and grain samples were measured for nutrient concentrations using an ICP at Ward Labs in Kearney, NE. Total C and N were measured using a dry combustion analyzer (LECO TruSpec CN 628, LECO Corp, St. Joseph, MI) for all samples excluding the grain (Bremner, 1996). A fiber analysis procedure was performed for all rye and residue tissues on an Ankom 200 Fiber Analyzer (ANKOM Technology, Macedon, NY) to measure ADF, NDF, ADL, and CF using the Van Soest method (Van Soest, 1963). Hemicellulose fractions were calculated by subtracting the ADF from NDF while cellulose concentrations was determined by subtracting ADL from ADF.

Soil samples were analyzed for NO_3-N, Olsen P, Potassium, Zinc, and Sulfur. All nutrients were analyzed to the 0-15 cm depth while NO_3-N and Sulfur were also analyzed to a depth of 61 cm. Additionally, organic matter, pH, and electrical conductivity were measured for all samples.

3.3.8 Statistical Analysis

Statistical analysis was done using RStudio statistical software version 3.5.1 (R Core Team, 2018). A two-way ANOVA using a linear model was used to test all independent variables. All effects were considered to be fixed effects. Model assumptions and potential outliers were tested using the Shapiro-Wilk normality test, examining residuals plots using the ggResidpanel package (Goode and Rey, 2019) and calculating the standardized residuals. Fishers Protected LSD (Felipe de Mendiburu, 2017) at a $p < 0.05$ level was used for mean separation. Further data analysis was conducted using correlations while principle component analysis was conducted using the ggbiplot package in RStudio (Vincent, 2011).

3.4 Results and Discussion

3.4.1 Weather

This research site averages 655 mm of precipitation annually across a 67-year history. In 2019, precipitation finished well above average measuring 835 mm for a 27% increase from the historical average. During the rye growing season, frequent large precipitation events occurred with May recording 75 mm of rainfall more than the 67-

year average (Figure 2.1). Spring temperatures were within the average temperature range with April and May measuring 0.8 and 2.8 degrees below average respectively. Between the first 2 termination dates, rye accumulated an average of 10.8 GDD per day which increased to 15.3 daily accumulated GDD between the final 2 termination dates (Figure 3.1). The soybean growing season saw normal temperature ranges and above average precipitation (Figure 2.1).

3.4.2 Rye Production

Rye biomass production increased slowly between the April 19th and April 29th termination dates with no significant difference in dry matter noted between the two treatments. However, as temperature and day length increased in May, rye dry matter begin to accumulate rapidly (Figure 3.2). Rye added 929 kg ha^{-1} of biomass between the April 19th and May 13th treatments over a time period of 24 days. However, between the May 13th to May 23rd and the May 23rd to May 31st treatments rye added 957 and 949 kg ha^{-1} of additional biomass respectively. This rapid increase in biomass production between the middle part to the end of May signifies that these two weeks are the most critical in terms of determining the influence a cover crop will have on the soil environment and the following cash crop. Total biomass production at the final termination date was 2835 kg ha^{-1} which is in line with previous observations at the Southeast Research Farm (Sexton et al., 2017).

3.4.3 Rye N and S

As the growing season progressed, the N and S concentration in rye tissues declined as observed by other studies (Alonso-Ayuso et al., 2014; Lawson et al., 2015)

(Table 3.3). However, even with declining concentrations, the large increase in biomass as rye matured resulted in a significantly greater uptake of N and S into rye tissues.

3.4.4 Rye Quality

As anticipated, rye quality steadily decreased as termination was delayed. High rye N concentrations at the initial sampling date resulted in a low C:N ratio. As the growing season progressed, reductions in N concentration as rye accumulated biomass led to steady increases in C:N ratio which led to a tight correlation between rye biomass and C:N ratio (R^2 = 0.95) (Figure 3.3). The range of C:N ratios observed in this study from vegetative stages up through the boot stage corresponded with those observed in other studies (Wagger, 1989; Lawson et al., 2015; Pantoja et al., 2016; Otte et al., 2019). Fibrous composition of rye materials increased as the growing season progressed as observed in other studies (Wagger, 1989; Alonso-Ayuso et al., 2014). NDF, ADF, and CF increased throughout the rye growing season (Figure 3.4). Cellulose concentration was significantly higher at each subsequent termination date (Figure 3.5a). Hemicellulose trended upward but was only significantly lower at the April 29th treatment with no differences noted amount the other treatments. In contrast lignin was significantly higher at the April 29th treatment, but was not different at later termination dates. Rye biomass best predicted cellulose concentration as a tight correlation (R^2=0.90) existed between the two. Hemicellulose was weakly correlated (R^2=0.32) while lignin was not seen to correlate with biomass. While trends in lignin concentration through delayed termination differed from similar studies, it agreed with conclusions that only slight differences in lignin concentrations occur over time as rye is not as sensitive to changes in lignin by termination time (Wagger, 1989; Alonso-Ayuso et al., 2014).

Working as a function of increased biomass and higher fibrous components, accumulation of carbon, hemicellulose, cellulose, and lignin increased as rye growth was extended (Figure 3.5b). While higher inputs of carbon from delayed termination have direct impacts on the improvement of soil properties, greater levels of fibrous materials will slow decomposition and nutrient release. Ruis (2020) found that changes in soil properties may be limited unless rye reaches at least 2 Mg ha^{-1} of biomass production. In the present study, this threshold was only reached by allowing rye to persist until boot stage on May 31st.

Principle component analysis aided in understanding the relationships between parameters of rye quality. Positive relationships were observed between rye biomass, C:N ratio, and cellulose concentrations while negative relationships between N and S existed with biomass reflecting the decrease in quality as biomass accumulates (Figure 3.6). Lignin and Hemicellulose were seen to be negatively related to each other (R^2 = 0.51); however, interestingly neither were seen to correlate with plant biomass. This negative correlation between lignin and hemicellulose has been observed in other studies and described that lignin replaces hemicellulose within the cell (Allison et al., 2012; Liu et al., 2016). Furthermore, later termination dates were more strongly related to measures of plant fiber whereas earlier termination dates corresponded to plant N and S concentrations.

3.4.5 Crop residue biomass

Initially, little difference was observed in the decomposition of corn residues at the earliest sampling dates. By May 23rd corn residues begin to decrease with May 31st having significantly lower amounts of remaining residues than May 23rd (Figure 3.7). At the R3 soybean growth stage on August 6th, clear differentiation was observed in residue amounts by termination dates reflecting the correlation between rye biomass and residue amounts at the R3 growth stage (R^2 = 0.83). However, little additional decomposition occurred for the April 19th to May 13th termination treatments between the R3 growth stage and the R6 growth stage (Figure 3.7). Several other studies have shown that initial C:N ratios are well correlated with decomposition rates (Ibewiro et al., 2000; Lupwayi et al., 2004; Sievers and Cook, 2018) while fibrous components are shown to further slow decomposition (J.G Cobo, 2002; Harre et al., 2014). Therefore, the majority of residue biomass is lost in the first four weeks after desiccation for materials with high residue quality while low quality materials have a slower but steady release over the initial 16 weeks (Wagger, 1989; Ruffo and Bollero, 2003a; Lupwayi et al., 2004). By the R6 growth stage, there was no difference in residue amounts on the soil surface between the earliest three termination treatments. This suggests rapid decomposition occurred where biomass was low and residue quality was high.

3.4.6 Chemical composition of crop residues

While little differences were observed in crop residue fibrous components, NDF had a significant trend towards decreasing as termination was delayed (Table 3.4). This likely reflects the breakdown of the hemicellulose component of NDF. By the soybean

R3 and R6 growth stage, the N concentration of residues increased at later termination treatments showing the greater amount of N containing residues that were still present on the surface (Table 3.5). Where greater decomposition had occurred at earlier terminations, more N had been liberated from crop residues and mineralized back into the soil. This same trend was also seen with the fibrous composition of rye. At later termination dates, NDF values were significantly higher when examining R3 and R6 values suggesting that more lignocellulosic materials remained in larger amounts of biomass present from rye (Table 3.4). Lignin being the most recalcitrant fiber tended to have higher values although not significantly at the R3 stage. At the R6 stage, May 31st had the lowest concentration of lignin in crop residues.

Nitrogen concentration of crop residues decreased between May 13th and May 31st of the initial sampling reflecting the greater decomposition that was seen in residue biomass (Table 3.5). At both the R3 and the R6 growth stage, N concentration was highest for the May 23rd and May 31st treatments. S concentrations were significantly higher at the May 23rd and May 31st treatments at the R3 growth stage and trended towards higher at the R6 growth stage, but it was not seen to be significant (p=0.11).

As termination date was delayed, N and S uptake increased significantly resulting in much higher amounts of nutrients being immobilized into crop residues by the R3 growth stage (Table 3.5). Nitrogen held in rye tissues at the R3 stage was significantly higher at each subsequent termination date with the exception of the first two termination dates as a result of minimal change in biomass production between these two termination treatments. Sulfur uptake trended upwards but was not seen as being significantly different between the May 13th and May 31st termination dates. By the R6 growth stage N and S retained in crop residues remained significantly higher at the May 31st termination date and was numerically, but not significantly, higher for May 23rd as compared to May 13th. Rye treatments terminated between April 19th and May 13th saw crop residues lose 55%, 50%, and 51% of their mass respectively between the initial sampling and the R6 growth stage while the May 23rd treatment lost 25% of its crop residue biomass (Figure 3.8a). However, a rapid decline was observed for the May 31st treatment which saw a net increase in total crop residue biomass by 65%, N in biomass by 184%, and S in biomass by 128%. All other treatments saw net decreases in crop residue biomass, N, and S with the exception of N in residue biomass for the May 23rd treatment which increased by 23%. This gives evidence that delaying rye termination could result in a net immobilization of N and S by the end of the growing season. This effect was lessened by terminating rye two weeks before planting and no significant differences were noted in amounts of N or S mineralized out of crop residues between the April 19th and May 13th treatments.

Between the R3 and R6 growth stages, no additional N or S appeared to be released between the April 19th and April 29th termination dates (Figure 3.8b). May 13 saw slight increases in release as residues lost 14% and 11% of N and S respectively between the R3 and R6 growth stages. May 23rd lost 24% more N and 32% more S while the May 31st treatment saw losses of 23% N and 24% S. These results suggest that most N and S mineralization is occurring between the initial samplings and the soybean R3 growth stage for the earliest two termination dates. However, between the R3 and R6 growth stage, more N and S is mineralized at the two later termination timings. These results are supported by Sievers et al. (2018) who demonstrated that low C:N ratio materials lose more than 80% of their N in the first four weeks following termination. The remaining N is bound in highly recalcitrant materials leading to little additional N release during the remainder of the growing season. In contrast high C:N ratio materials continually released low amounts of N throughout the growing season.

3.4.7 Soybean Production

Soybean biomass was observed to be significantly higher for earlier termination dates at the R3 growth stage (Table 3.6). Nitrogen concentrations of whole plant soybeans were seen to be significantly higher for the April 19th termination treatment at the R3 growth stage. This data is supported by 3rd leaf tissue samples that were taken at the same stage showing N concentration was significantly lower at the May 31st treatment (Table 3.7). Sulfur concentrations on a whole plant basis trended downwards as termination was delayed although these differences were not deemed to be significant (p=0.28). Due to the combined effects of lower biomass and nutrient concentrations at later termination dates, N and S uptake were significantly the lowest at the May 31st termination and increased as rye was terminated earlier. At the R6 growth stage, soybean biomass was not significantly different but continued to trend towards lower biomass at later terminations. Furthermore, N was not seen to be significantly different at the R6 growth stage. Sulfur concentration was numerically the highest at the earliest termination date and lowest and the latest termination date; however, these results were not significant (p=0.12). However, when S data was combined across growth stage significant differences were observed (p=0.05) with the May 31st treatment showing the lowest S concentration.

Soybean development was accelerated by earlier terminated rye. These treatments senesced leaves at a quicker rate than later terminated treatments (Figure 3.9). This effect was observed at both the R3 and R6 growth stage with the May 31st treatment having significantly lower amounts of senesced leaves than earlier terminated treatments. Discussion on the effect of rye termination on soybean development in the literature is limited; however, other studies have produced similar results (Bauer, 1991; Westgate et al., 2005). Westgate et al. (2005) attributed delayed termination of soybeans to allelopathic effects from rye which could reduce the germination and vigor of soybean plants. In the present study, soybean stand counts were measured at the R3, R6 (data not presented), and harvest growth stages (Table 3.8). At each of these stages, plant stands trended downward as termination was delayed; however, it was not seen to be significantly different. When stand counts were analyzed combining all 3 growth stages, the May 31st treatment had a significantly lower stand (p=0.10) than the April 19 treatment (Figure 3.10). However, no correlation was observed between senesced leaves and plant stand (R^2 <0.001). Bauer (1989) believed delayed development of soybeans came as a result of increased water usage of rye as termination was pushed further towards rye maturity. Yet, given that precipitation amounts in the present study were well above average throughout the growing season, this explanation is unlikely for this current situation. Soybean phenology is influenced by a combination of temperature and photoperiod with nutritional and moisture status acting as additional determinants on soybean development and maturity. Higher temperatures have been observed to increase the speed of development of soybeans resulting in earlier flowering and lower yields as the crop spends less time in the vegetative state. (George et al., 1990; Setiyono et al., 2007). Given that a stronger correlation exists between crop development and soil temperature instead of air temperature (Sabri et al., 2018) it is possible that the higher level of ground cover from later termination dates resulted in a soil temperature buffer which slowed crop development.

Significant differences were observed in soybean grain yield ($p=0.1$) and test weight ($p=0.04$) with the May 31st treatment recording both the highest yield and test weight (Table 3.8). Nitrogen grain concentration was significantly highest for the May 31st treatment and trended downwards as termination became earlier. While S concentration was not seen to be significant, similar numeric trends of decreasing S concentration at earlier terminations was observed. Other studies have noted delayed termination has resulted in either neutral (Rosario-Lebron et al., 2019) or negative (Rex et al., 1992; Westgate et al., 2005) yields in soybeans. Lower yields were generally attributed to water usage of rye or allelopathic effects lowering planting density. Moisture was above average during this growing season and likely was not a limiting yield factor. While it appeared that later terminated rye reduced soybean stands it is unlikely that it resulted in a yield deficit as soybeans are adept at compensating for lower stands while maintaining maximum yield potential by increases in plant branching and pods per plant (Epler and Staggenborg, 2008; Cox et al., 2010). The positive yield effect observed in this study may be attributed to later termination dates spending longer time in vegetative states due to the delayed soybean development that was observed (George et al., 1990).

3.4.8 Soil nutrient concentration

Soil nutrient analysis produced limited differences in N and S concentration throughout the growing season (Table 3.9). Initial samples at the time of termination were compiled across replication. N in the top 15 cm was seen to be higher at the earliest termination date. Yet, by the R3 and R6 growth stages no differences in N were observed. S trended downwards as termination was delayed in the initial sampling reflecting rye uptake. At the R3 growth stage, the May 23rd treatment was significantly lower than April 29th and May 13th. However, no differences were recorded between other treatments. Additionally, no difference was seen in soil S concentration by the soybean R6 growth stage.

3.5 Management Implications

Cover crop management is dependent on a variety of factors including producers' goals, climatic conditions, and cropping sequence considerations. Biomass management of rye is the overarching variable that influences all of these considerations in determining how to best manage cover crops. From this study, it is apparent that rye growth increases rapidly in the second part of May indicating timely rye control is necessary to achieve the desired cover crop outcome. When trying to maximize benefits to soil properties, it appears that allowing rye to reach boot stage is beneficial in order to build sufficient levels of biomass to catalyze these changes in soil quality as described by Ruis et al. (2020) who suggested a minimum of 2 Mg ha^{-1} of biomass to initiate changes on high fertility soils. However, if nutrient uptake or residue management is a concern, this study shows that there is no difference in an April 19th or April 29th termination in terms of N or S release by the end of the growing season. A slight decrease in N and S mineralization from residues is noted at May 13th before more significant decreases in nutrient release from residues occurs at the May 23rd and May 31st termination dates. Therefore, if nutrient immobilization is a concern among producers, this study demonstrates that allowing rye to persist until mid-May may not subject the subsequent crop to deficiencies. While delaying termination appeared to initially lower soil nutrient concentrations, biomass, and stand, this did not have a negative effect on yield. Development of soybeans was delayed as rye termination date was delayed which resulted in higher yields. Results from a single year study show that under sufficient nutrient and moisture conditions, delaying rye termination may allow for maximizing soybean yield and the potential for soil health benefits.

3.6 Conclusions

Rye biomass increased slowly between April 19-May 13 and then dramatically between May 13-May 31st resulting in greater nutrient uptake as termination was delayed and lower quality of residues. This differentiation in biomass and quality impacted the breakdown of crop residues and cycling of nutrients throughout the growing season. No difference was noted by the end of the growing season in residues remaining between the earliest three termination dates suggesting that quick decomposition occurred with higher quality residues. Soybean N concentration and biomass was significantly lower at the R3 growth stage; yet by the R6 growth stage these differences had been bridged which may have been aided by a greater flux of N release from later terminated rye of lower quality. Sulfur was not seen to be significantly different although trends indicated lower concentrations were present in later terminated rye. Soybean development was delayed as termination was pushed later into May which may have been the driving factor behind higher soybean grain yields for the May 31st termination treatment.

3.7 References

Acharya, J., M. G. Bakker, T. Moorman, T. C. Kaspar, A. Lenssen, and A. E. Robertson. 2017. Time Interval Between Cover Crop Termination and Planting Influences Corn Seedling Disease, Plant Growth, and Yield. PLANT DIS. 101:591-600. doi:10.1094/PDIS-07-16-0975-RE.

Agriculture, U. S. D. o., and S. A. R. a. Education. 1992. Managing cover crops profitably, Third editionWashington, DC: Sustainable Agriculture Research and Education Program of CSRS, U.S. Dept. of Agriculture

Emmaus, PA: Sustainable Agriculture Research and Education Program of CSRS, U.S. Dept. of Agriculture.

Allison, G. G., C. Morris, S. J. Lister, T. Barraclough, N. Yates, I. Shield, et al. 2012. Effect of nitrogen fertiliser application on cell wall composition in switchgrass and reed canary grass. Biomass and Bioenergy 40:19-26. doi:10.1016/j.biombioe.2012.01.034.

Alonso-Ayuso, M., J. L. Gabriel, M. Quemada, and A. Shrestha. 2014. The Kill Date as a Management Tool for Cover Cropping Success. PLoS ONE 9. doi:10.1371/journal.pone.0109587.

Appelgate, S. R., A. W. Lenssen, M. H. Wiedenhoeft, and T. C. Kaspar. 2017. Cover Crop Options and Mixes for Upper Midwest Corn–Soybean Systems. Agron. J. 109. doi:10.2134/agronj2016.08.0453.

Barel, J. M., T. W. Kuyper, J. Paul, W. Boer, J. H. C. Cornelissen, and G. B. De Deyn. 2019. Winter cover crop legacy effects on litter decomposition act through litter quality and microbial community changes. Journal of Applied Ecology 56:132-143. doi:10.1111/1365-2664.13261.

Basche, A. D., T. C. Kaspar, S. V. 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. Agricultural Water Management 172:40-50. doi:10.1016/j.agwat.2016.04.006.

Bauer, T. L. 1991. Use of the allelopathic and mulch properties of rye as a method of weed control in soybean. M.S. Thesis. Univ. of Wisconsin, Madison.

Bergtold, J., S. Ramsey, and J. Williams. 2019. A review of economic considerations for cover crops as a conservation practice. Renewable Agriculture and Food Systems 34:62-76. doi:10.1017/S1742170517000278.

Boyd, N., E. Brennan, R. Smith, and R. Yokota. 2009. Effect of Seeding Rate and Planting Arrangement on Rye Cover Crop and Weed Growth. Agron. J. 101:47-51. doi:10.2134/agronj2008.0059.

Bradford, M. A., B. Berg, D. S. Maynard, W. R. Wieder, and S. A. Wood. 2016. Understanding the dominant controls on litter decomposition. Journal of Ecology 104:229-238. doi:10.1111/1365-2745.12507.

Bremner, J. M. 1996. Nitrogen-Total. p. 1085-1121. *In* D. L. Sparks (ed.) Methods of soil analysis. Part 3. Madison, WI: Soil Sci. Soc. Am., Inc.

Brennan, N. Boyd, and R. Smith. 2013. Winter Cover Crop Seeding Rate and Variety Effects during Eight Years of Organic Vegetables: III. Cover Crop Residue Quality and Nitrogen Mineralization. Agron. J. 105:171-182. doi:10.2134/agronj2012.0258.

Brennan., and N. Boyd. 2012a. Winter Cover Crop Seeding Rate and Variety Affects during Eight Years of Organic Vegetables: I. Cover Crop Biomass Production. Agronomy Journal 104:684-698. doi:10.2134/agronj2011.0330.

Brockmueller, B., C. Bolkema, M. Buiter, A. Huizenga, B. Rops, G. Williamson, et al. 2016. Rye cover crop grown ahead of soybeans--2016 season--A first look at impacts on soybean nutrient uptake. Southeast South Dakota Exp. Farm Annual Progress Report 2016:34-39.

Burger, M., and L. E. Jackson. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biol. Biochem. 35:29-36. doi:10.1016/S0038-0717(02)00233-X.

Caravetta, G. J., J. H. Cherney, and K. D. Johnson. 1990. Within-Row Spacing Influences on Diverse Sorghum Genotypes: II. Dry Matter Yield and Forage Quality. Agron. J. 82:210-215. doi:https://doi.org/10.2134/agronj1990.00021962008200020008x.

Casey, P. A. 2012. Plant guide for cereal rye (*Secale cereale*). USDA-Natural Resources Conservation Service, Plant Materials Center, Elsberry, MO.

Cassman, K. G. 2002. Agroecosystems, Nitrogen-Use Efficiency, and Nitrogen Management. Ambio 31:132-140.

Chatterjee, A., and U. Acharya. 2020. Controls of carbon and nitrogen releases during crops' residue decomposition in the Red River Valley, USA. Archives of Agronomy and Soil Science 66:614-624. doi:10.1080/03650340.2019.1630732.

Cox, W. J., J. H. Cherney, and E. Shields. 2010. Soybeans Compensate at Low Seeding Rates but not at High Thinning Rates. Agronomy Journal 102:1238-1243. doi:10.2134/agronj2010.0047.

Crandall, S. M., M. L. Ruffo, and G. A. Bollero. 2005. Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn. Plant Soil 268:209-219. doi:10.1007/s11104-004-0272-x.

CTIC. 2013. 2012-2013 Cover Crop Survey. June 2013 Survey Analysis. Joint Publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program. Retrieved from https://www.sare.org/Learning-Center/Topic-Rooms/Cover-Crops/Cover-Crop-Surveys. (accessed 28 February 2020).

CTIC. 2017. Report of the 2016-17 national cover crop survey. Joint Publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. Retrieved from https://www.sare.org/Learning-Center/Topic-Rooms/Cover-Crops/Cover-Crop-Surveys. (accessed 28 February 2020).

Dabney, S. M., J. A. Delgado, and D. W. Reeves. 2001. USING WINTER COVER CROPS TO IMPROVE SOIL AND WATER QUALITY. Communications in Soil Science and Plant Analysis 32:1221-1250. doi:10.1081/CSS-100104110.

De Bruin, J., P. Porter, and N. Jordan. 2005. Use of a Rye Cover Crop following Corn in Rotation with Soybean in the Upper Midwest. Agron. J. 97:587-598. doi:10.2134/agronj2005.0587.

Drinkwater, L. E., and S. S. Snapp. 2007. Nutrients in Agroecosystems: Rethinking the Management Paradigm. p. 163-186. *In* D. L. Sparks (ed.) Advances in Agronomy. Academic Press

Duiker, S., and W. Curran. 2005. Rye Cover Crop Management for Corn Production in the Northern Mid-Atlantic Region. Agronomy Journal:1413-1418.

Duval, M. E., J. A. Galantini, J. E. Capurro, and J. M. Martinez. 2016. Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. Soil and Tillage Research 161:95-105. doi:10.1016/j.still.2016.04.006.

Ellis, E. C., J. O. Kaplan, D. Q. Fuller, S. Vavrus, K. Klein Goldewijk, and P. H. Verburg. 2013. Used planet: a global history. Proc Natl Acad Sci U S A 110:7978-7985. doi:10.1073/pnas.1217241110.

Epler, M., and S. Staggenborg. 2008. Soybean Yield and Yield Component Response to Plant Density in Narrow Row Systems. cm 7. doi:10.1094/CM-2008-0925-01-RS.

Farsad, A., T. O. Randhir, S. J. Herbert, and M. Hashemi. 2011. Spatial Modeling of Critical Planting Date for Winter Rye Cover Crop to Enhance Nutrient Recovery. Agronomy Journal 103:1252-1257. doi:10.2134/agronj2010.0433.

Felipe de Mendiburu. 2017. agricolae: Statistical procedures for agricultural research. https://CRAN.R-project.org/package=agricolae

Finney, D. M., C. M. White, and J. P. Kaye. 2016. Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. Agron. J. 108:39-52. doi:10.2134/agronj15.0182.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, et al. 2011. Solutions for a cultivated planet. Nature 478:337-342. doi:10.1038/nature10452.

Fustec, J., F. Lesuffleur, S. Mahieu, and J.-B. Cliquet. 2010. Nitrogen rhizodeposition of legumes. A review. Agron. Sustain. Dev. 30:57-66. doi:10.1051/agro/2009003.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, et al. 2003. The Nitrogen Cascade. BioScience 53:341-356. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO2.

George, T., D. P. Bartholomew, and P. W. Singleton. 1990. EFFECT OF TEMPERATURE AND MATURITY GROUP ON PHENOLOGY OF FIELD GROWN NODULATING AND NONNODULATING SOYBEAN ISOLINES.

Goode, K., and K. Rey. 2019. ggResidpanel: Panels and Interactive Versions of Diagnostic Plots using 'ggplot2'. R package version 0.3.0. https://CRAN.R-project.org/package=ggResidpanel

Hamilton, A. V., D. A. Mortensen, and M. K. Allen. 2017. The state of the cover crop nation and how to set realistic future goals for the popular conservation practice. Journal of Soil and Water Conservation 72:111A-115A. doi:10.2489/jswc.72.5.111A.

Harre, N., J. Schoonover, and B. Young. 2014. Decay and Nutrient Release Patterns of Weeds Following Post-Emergent Glyphosate Control. Weed Science 62:588-596. doi:10.1614/WS-D-14-00058.1.

Hitsuda, K., G. Sfredo, and D. Klepker. 2004. Diagnosis of Sulfur Deficiency in Soybean using Seeds. Soil Science Society of America Journal 68:1445-1451. doi:10.2136/sssaj2004.1445.

Hunter, M. C., M. E. Schipanski, M. H. Burgess, J. C. Lachance, B. A. Bradley, M. E. Barbercheck, et al. 2019. Cover Crop Mixture Effects on Maize, Soybean, and Wheat Yield in Rotation. Agricultural & Environmental Letters 4:1-5. doi:10.2134/ael2018.10.0051.

Ibewiro, B., N. Sanginga, B. Vanlauwe, and R. Merckx. 2000. Nitrogen contributions from decomposing cover crop residues to maize in a tropical derived savanna. Nutrient Cycling in Agroecosystems 57:131-140. doi:10.1023/A:1009846203062.

J.G Cobo, E. B., D.C.L. Kass, R.J. Thomas. 2002. Decomposition and Nutrient Release by Green Manures in a Tropical Hillside Agroecosystem. Plant Soil 240:331-342.

Jannoura, R., B. Kleikamp, J. Dyckmans, and R. Joergensen. 2012. Impact of pea growth and arbuscular mycorrhizal fungi on the decomposition of 15 N-labeled maize residues. Biol Fertil Soils 48:547-560. doi:10.1007/s00374-011-0647-0.

Justes, E., B. Mary, and B. Nicolardot. 2009. Quantifying and modelling C and N mineralization kinetics of catch crop residues in soil: parameterization of the residue decomposition module of STICS model for mature and non mature residues. Plant Soil 325:171-185. doi:10.1007/s11104-009-9966-4.

Kaiser, D. E., and K. I. Kim. 2013. Soybean Response to Sulfur Fertilizer Applied as a Broadcast or Starter Using Replicated Strip Trials. Agronomy Journal 105:1189-1198. doi:10.2134/agronj2013.0023.

Kantar, M., and P. Porter. 2014. Relationship between planting date: growing degree days and the winter rye (Secale cereale L.) variety Rymin in Minnesota. Crop Manage. 13:1-9.

Karki, D. 2019. Cereal Rye Cover Crop Between Corn and Soybeans. South Dakota State University Extension. Retrieved from https://extension.sdstate.edu/cereal-rye-cover-crop-between-corn-and-soybean. (5 May, 2020).

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO3 concentration and load in tile drainage. J. Environ. Qual. 36:1503-1511. doi:10.2134/jeq2006.0468.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye Cover Crop and Gamagrass Strip Effects on NO3 Concentration and Load in Tile Drainage. J. Environ. Qual. 36:1503-1511. doi:10.2134/jeq2006.0468.

Kessavalou, A., and D. T. Walters. 1999. Winter Rye Cover Crop Following Soybean Under Conservation Tillage: Residual Soil Nitrate. Agron. J. 91:643-649. doi:10.2134/agronj1999.914643x.

Krueger, E., T. Ochsner, P. Porter, and J. Baker. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agron. J. 103:316-323. doi:10.2134/agronj2010.0327.

Kuo, S., and E. Jellum. 2000. Long-term winter cover cropping effects on corn (Zea mays L.) production and soil nitrogen availability. Biol. Fertil. Soils 31:470-477.

Lacey, C., C. Nevins, J. Camberato, E. Kladivko, A. Sadeghpour, and S. Armstrong. 2020. Carbon and nitrogen release from cover crop residues and implications for cropping systems management. Journal of Soil and Water Conservation:jswc.2020.00102. doi:10.2489/jswc.2020.00102.

Lal, R. 2015. Sequestering carbon and increasing productivity

by conservation agriculture. Journal of Soil and Water Conservation 70:55-62. doi:10.2489/jswc.70.3.55A.

Lawson, A., C. Cogger, A. Bary, A.-M. Fortuna, and A. Shrestha. 2015. Influence of Seeding Ratio, Planting Date, and Termination Date on Rye-Hairy Vetch Cover Crop Mixture Performance under Organic Management. PLoS ONE 10. doi:10.1371/journal.pone.0129597.

Lindsey, L., K. Steinke, D. Warncke, and W. Everman. 2013. Nitrogen Release from Weed Residue. Weed Sci. 61:334-340. doi:10.1614/WS-D-12-00090.1.

Liu, J., N. Wu, H. Wang, J. Sun, B. Peng, P. Jiang, et al. 2016. Nitrogen addition affects chemical compositions of plant tissues, litter and soil organic matter. Ecology 97:1796-1806. doi:10.1890/15-1683.1.

Lupwayi, N., G. Clayton, J. O'Donovan, K. Harker, T. Turkington, and W. Rice. 2004. Decomposition of crop residues under conventional and zero tillage. Can. J. Soil Sci. 84:403-410.

Manjula, N., and R. Gelderman. 2015. Recommended Chemical Soil Test Procedures for the North Central RegionNorth Central Regional Research Publ. 221. Revised, Missouri Agric. Exp. Stn., Columbia, MO.

Marcillo, G., and F. Miguez. 2017. Corn yield response to winter cover crops: An updated meta-analysis. Journal of Soil and Water Conservation 72:226-239. doi:10.2489/jswc.72.3.226.

Martinez-Feria, R. A., R. Dietzel, M. Liebman, M. J. Helmers, and S. V. Archontoulis. 2016. Rye cover crop effects on maize: A system-level analysis. Field Crops Res. 196:145-159. doi:10.1016/j.fcr.2016.06.016.

McDaniel, M. D., L. K. Tiemann, and A. S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24:560-570. doi:10.1890/13-0616.1.

McSwiney, C. P., S. S. Snapp, and L. E. Gentry. 2010. Use of N immobilization to tighten the N cycle in conventional agroecosystems. Ecol. Appl. 20:648-662. doi:10.1890/09-0077.1.

Mirsky, S. B., W. S. Curran, D. A. Mortensen, M. R. Ryan, and D. L. Shumway. 2009. Control of Cereal Rye with a Roller/Crimper as Influenced by Cover Crop Phenology. Agronomy Journal 101:1589-1596. doi:10.2134/agronj2009.0130.

Mirsky, S. B., M. R. Ryan, J. R. Teasdale, W. S. Curran, C. S. Reberg-Horton, J. T. Spargo, et al. 2013. Overcoming Weed Management Challenges in Cover Crop—Based Organic Rotational No-Till Soybean Production in the Eastern United States. Weed Technol. 27:193-203. doi:10.1614/WT-D-12-00078.1.

Moore, E. B., M. H. Wiedenhoeft, T. C. Kaspar, and C. A. Cambardella. 2014. Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage–Soybean Cropping Systems. Soil Sci. Soc. Am. J. 78:968-976. doi:10.2136/sssaj2013.09.0401.

Morton, L. W., and L. J. Abendroth. 2017. Crops, climate, culture, and change. J. Soil Water Cons. 72:47A-52A. doi:10.2489/jswc.72.3.47A.

National Agricultural Statistic Services (USDA-NASS). 2019. Census of Agriculture, United States Summary and State Data. Volume 1. Geographic Area Series. Part 51. AC-17-A-51. U.S. Department of Agriculture-National Agricultural Statistics Service, Washington, DC.

Odhiambo, J., and A. Bomke. 2000. Short term nitrogen availability following overwinter cereal/grass and legume cover crop monocultures and mixtures in south coastal British Columbia. Journal of Soil and Water Conservation 55:347-354.

Ogden, M., R. Hoefgen, U. Roessner, and S. Persson. 2018. Feeding the Walls: How Does Nutrient Availability Regulate Cell Wall Composition? International Journal of Molecular Sciences 19. doi:10.3390/ijms19092691.

Ogilvie, C. M., W. Deen, and R. C. Martin. 2019. Service crop management to maximize crop water supply and improve agroecosystem resilience: A review. Journal of Soil and Water Conservation 74:389. doi:http://dx.doi.org/10.2489/jswc.74.4.389.

Otte, B., S. Mirsky, H. Schomberg, B. Davis, and K. Tully. 2019. Effect of Cover Crop Termination Timing on Pools and Fluxes of Inorganic Nitrogen in No-Till Corn. Agron. J. doi:10.2134/agronj2018.10.0699.

Pantoja, J. L., K. P. Woli, J. E. Sawyer, and D. W. Barker. 2015. Corn Nitrogen Fertilization Requirement and Corn–Soybean Productivity with a Rye Cover Crop. Soil Sci. Soc. Am. J. 79:1482-1495. doi:10.2136/sssaj2015.02.0084.

Pantoja, J. L., K. P. Woli, J. E. Sawyer, and D. W. Barker. 2016. Winter Rye Cover Crop Biomass Production, Degradation, and Nitrogen Recycling. Agron. J. 108:841-853. doi:10.2134/agronj2015.0336.

Paré, T., E. G. Gregorich, and S. Nelson. 2000. Mineralization of nitrogen from crop residues and N recovery by maize inoculated with vesicular-arbuscular mycorrhizal fungi. Plant and Soil 218:11-20. doi:10.1023/A:1014958321933.

Pedo, T., E. Martinazzo, T. Aumonde, and F. A. Villela. 2015. Plant growth analysis and seed vigor expression: effects of soil waterlogging during rye plant development. Acta Bot. Bras. 29:1-7. doi:10.1590/0102-33062014abb3574.

Poffenbarger, H. J., S. B. Mirsky, R. R. Weil, J. E. Maul, M. Kramer, J. T. Spargo, et al. 2015. Biomass and Nitrogen Content of Hairy Vetch–Cereal Rye Cover Crop Mixtures as Influenced by Species Proportions. Agron. J. 107. doi:10.2134/agronj14.0462.

Power, A. G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. Lond. B 365:2959-2971. doi:10.1098/rstb.2010.0143.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ranells, N. N., and M. G. Wagger. 1996. Nitrogen Release from Grass and Legume Cover Crop Monocultures and Bicultures. Agron. J. 88:777-882. doi:10.2134/agronj1996.00021962008800050015x.

Reddy, B. V. S., P. Sanjana Reddy, F. Bidinger, and M. Blümmel. 2003. Crop management factors influencing yield and quality of crop residues. Field Crops Research 84:57-77. doi:10.1016/S0378-4290(03)00141-2.

Reed, H. K., H. D. Karsten, W. S. Curran, J. F. Tooker, and S. W. Duiker. 2019. Planting Green Effects on Corn and Soybean Production. Agronomy Journal 111:2314-2325. doi:10.2134/agronj2018.11.0711.

Rex, L., F. W. Simmons, M. W. Loyd, and W. S. Edward. 1992. Effect of Rye (Secale cereale) Mulch on Weed Control and Soil Moisture in Soybean (Glycine max). Weed Technology 6:838-846. doi:10.1017/S0890037X00036356.

Rorick, J. D., and E. J. Kladivko. 2017. Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. J. Soil Water Conserv. 72:260.

Rosario-Lebron, A., A. W. Leslie, V. L. Yurchak, G. Chen, and C. R. R. Hooks. 2019. Can winter cover crop termination practices impact weed suppression, soil moisture, and yield in no-till soybean [Glycine max (L.) Merr.]? Crop Protection 116:132-141. doi:10.1016/j.cropro.2018.10.020.

Roth, R. T., M. D. Ruffatti, P. D. O'Rourke, and S. D. Armstrong. 2018. A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central Illinois on farm case study. Agricultural Systems 159:69-77. doi:10.1016/j.agsy.2017.10.007.

Ruffo, M., and G. Bollero. 2003a. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agronomy Journal 95:900. doi:10.2134/agronj2003.0900.

Ruffo, M., and G. Bollero. 2003b. Residue decomposition and prediction of carbon and nitrogen release rates based on biochemical fractions using principal-component regression. Agronomy Journal 95:1034. doi:10.2134/agronj2003.1034.

Ruffo, M., D. Bullock, and G. Bollero. 2004. Soybean Yield as Affected by Biomass and Nitrogen Uptake of Cereal Rye in Winter Cover Crop Rotations. Agron. J. 96:800-805. doi:10.2134/agronj2004.0800.

Ruis, S. J., H. Blanco-Canqui, C. F. Creech, K. Koehler-Cole, R. W. Elmore, and C. A. Francis. 2019. Cover Crop Biomass Production in Temperate Agroecozones. Agronomy Journal 111:1535-1551. doi:10.2134/agronj2018.08.0535.

Ruis, S. J., H. Blanco-Canqui, R. W. Elmore, C. Proctor, K. Koehler-Cole, R. B. Ferguson, et al. 2020. Impacts of cover crop planting dates on soils after four years. Agronomy Journal 112:1649-1665. doi:10.1002/agj2.20143.

Ryan, M., W. Curran, A. Grantham, L. Hunsberger, S. Mirsky, D. Mortensen, et al. 2011. Effects of Seeding Rate and Poultry Litter on Weed Suppression from a Rolled Cereal Rye Cover Crop. Weed Science 59:438-444. doi:10.1614/WS-D-10-00180.1.

Sabri, N. S. A., Z. Zakaria, S. E. Mohamad, A. B. Jaafar, and H. Hara. 2018. Importance of Soil Temperature for the Growth of Temperate Crops under a Tropical Climate and Functional Role of Soil Microbial Diversity. Microbes and Environments 33:144-150. doi:10.1264/jsme2.ME17181.

Salvagiotti, F., G. Ferraris, A. Quiroga, M. Barraco, H. Vivas, P. Prystupa, et al. 2012. Identifying sulfur deficient fields by using sulfur content

N:S ratio and nutrient stoichiometric relationships in soybean seeds. Field Crops Research 135:107-115. doi:10.1016/j.fcr.2012.07.011.

Sarrantonio, M., and E. Gallandt. 2008. The Role of Cover Crops in North American Cropping Systems. J. Crop Prod. 8:53-74. doi:10.1300/J144v08n01_04.

Schipanski, M. E., M. Barbercheck, M. R. Douglas, D. M. Finney, K. Haider, J. P. Kaye, et al. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125:12-22. doi:10.1016/j.agsy.2013.11.004.

Setiyono, T. D., A. Weiss, J. Specht, A. M. Bastidas, K. G. Cassman, and A. Dobermann. 2007. Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. Field Crops Research 100:257-271. doi:10.1016/j.fcr.2006.07.011.

Sexton, D. Auch, and B. Rops. 2017. Burndown timing for a rye cover crop raised ahead of corn--A preliminary study. Southeast South Dakota Exp. Farm Annual Progress Report 2017:19-21.

Sexton, N. C. Paek, and R. Shibles. 1998. Soybean Sulfur and Nitrogen Balance under Varying Levels of Available Sulfur. Crop Science 38:975-982. doi:10.2135/cropsci1998.0011183X003800040016x.

Sievers, T., and R. L. Cook. 2018. Aboveground and Root Decomposition of Cereal Rye and Hairy Vetch Cover Crops. Soil Sci. Soc. Am. J. 82. doi:10.2136/sssaj2017.05.0139.

Singer, J. W., and S. M. Nusser. 2007. Are cover crops being used in the US corn belt? J. Soil Water Conserv. 62:353-358.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. Global Biogeochem. Cycles 13:647-662. doi:10.1029/1999gb900015.

Snapp, S. S., S. M. Swinton, R. Labarta, D. Mutch, J. R. Black, R. Leep, et al. 2005. Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. Agron. J. 97:322-332. doi:10.2134/agronj2005.0322a.

Stute, J., K. Shelly, D. Mueller, and T. Wood. 2007. Planting winter rye after corn silage: Managing for forage. Retrieved from https://fyi.extension.wisc.edu/forage/planting-winter-rye-after-corn-silage-managing-for-forage/. (accessed 13 January 2020).

Thelen, K. D., and R. H. Leep. 2002. Integrating a Double-Cropped Winter Annual Forage into a Corn-Soybean Rotation. Crop Manage. 1. doi:10.1094/cm-2002-1218-01-rs.

Thompson, N. M., S. D. Armstrong, R. T. Roth, M. D. Ruffatti, and C. J. Reeling. 2020. Short-run net returns to a cereal rye cover crop mix in a midwest corn–soybean rotation. Agronomy Journal 112:1068-1083. doi:10.1002/agj2.20132.

United States Department of Agriculture-Natural Resource Conservation Service. 2020. Soil Map, Clay County, South Dakota (SD027). Retrieved from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. (accessed 26 February 2020).

USDA-ARS. 2012. Plant Hardiness Zone Map. Retrieved from https://planthardiness.ars.usda.gov/PHZMWeb/. (accessed 26 February, 2020).

Van Soest, P. J. 1963. Use of detergents in the analysis of fibrous feeds. 2. A rapid method for the determination of fiber and lignin. Journal of the Association of Official Agricultural Chemists 46:829-835.

Varela, M. F., C. M. Scianca, M. A. Taboada, and G. Rubio. 2014. Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina. Soil & Tillage Research 143:59-66. doi:10.1016/j.still.2014.05.005.

Vincent, Q. V. 2011. ggbiplot: A ggplot2 based biplot. R package version 0.55. http://github.com/vqv/ggbiplot

Wagger, M. G. 1989. Time of Desiccation Effects on Plant Composition and Subsequent Nitrogen Release from Several Winter Annual Cover Crops. Agron. J. 81:236-241. doi:10.2134/agronj1989.00021962008100020020x.

Wang, T. 2019. Cover Crop Usage in South Dakota is on the Rise. Retrieved from https://extension.sdstate.edu/cover-crop-usage-south-dakota-rise. (accessed February 19, 2020).

Waring, E. R., A. Lagzdins, C. Pederson, and M. J. Helmers. 2020. Influence of no-till and a winter rye cover crop on nitrate losses from tile-drained row-crop agriculture in Iowa. Journal of Environmental Quality 49:292-303. doi:10.1002/jeq2.20056.

Wells, M. S., S. C. Reberg-Horton, A. N. Smith, and J. M. Grossman. 2013. The Reduction of Plant-Available Nitrogen by Cover Crop Mulches and Subsequent Effects on Soybean Performance and Weed Interference. Agron. J. 105:539-545. doi:10.2134/agronj2012.0396.

Westgate, L., J. Singer, and K. Kohler. 2005. Method and Timing of Rye Control Affects Soybean Development and Resource Utilization. Agronomy Journal 97:806-816. doi:10.2134/agronj2004.0223.

Whaley, J. M., D. L. Sparkes, M. J. Foulkes, J. H. Spink, T. Semere, and R. K. Scott. 2000. The physiological response of winter wheat to reductions in plant density. Annals of Applied Biology 137:165-177. doi:10.1111/j.1744-7348.2000.tb00048.x.

White, C. M., S. T. DuPont, M. Hautau, D. Hartman, D. M. Finney, B. Bradley, et al. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agriculture, Ecosystems & Environment 237:121-133. doi:10.1016/j.agee.2016.12.016.

Wichern, F., J. Mayer, R. G. Joergensen, and T. Müller. 2007. Rhizodeposition of C and N in peas and oats after 13C– 15N double labelling under field conditions. Soil Biology and Biochemistry 39:2527-2537. doi:10.1016/j.soilbio.2007.04.022.

Yeo, I., S. Lee, A. Sadeghi, P. C. Beeson, W. Hively, G. McCarty, et al. 2014. Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model. Hydrol. Earth Syst. Sci. 18:5239-5253. doi:10.5194/hess-18-5239-2014.

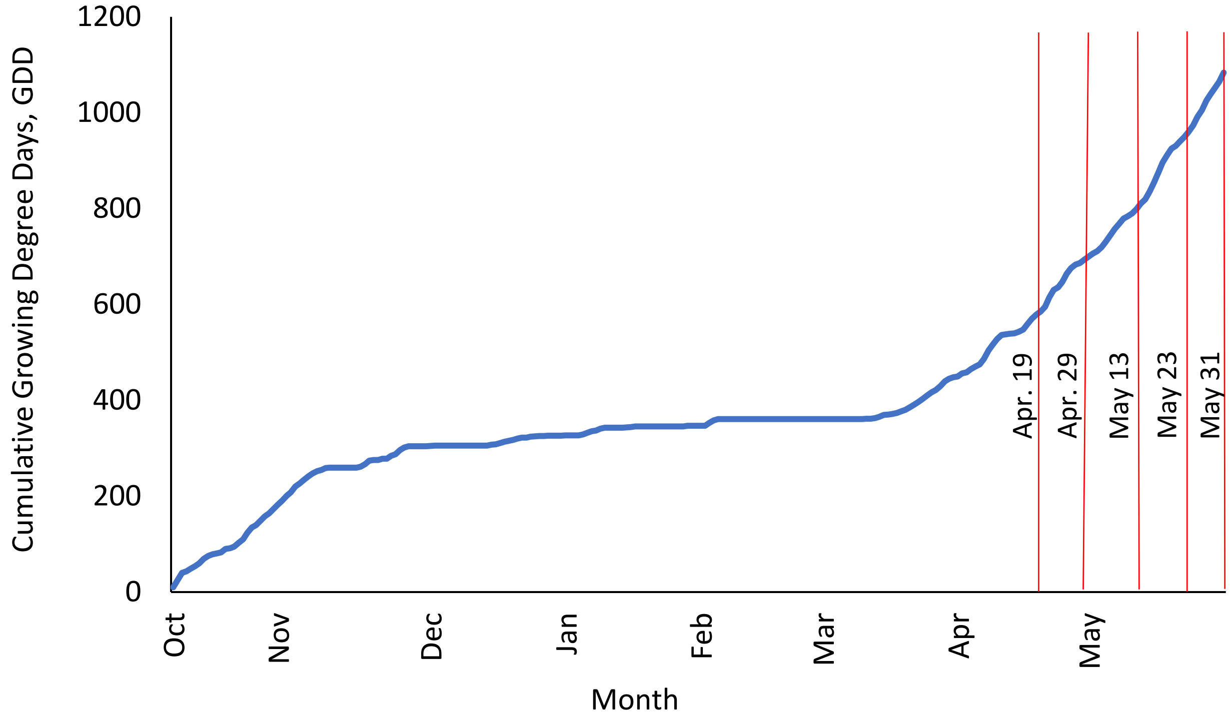


Figure 3.1. Cumulative GDD indicating termination dates for the 2019 growing season at the Southeast Research Farm near Beresford, SD. GDD calculations were done using the equation $((T_{max} + T_{min}) / 2) - T_{Base}$ where $T_{Base} = (0°C)$.

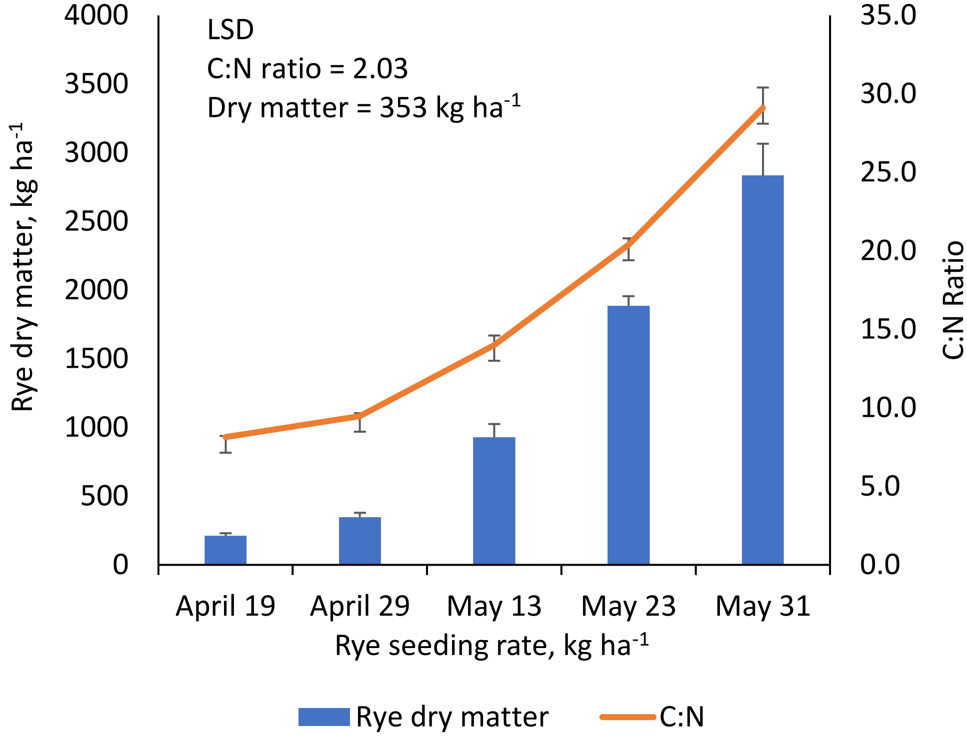


Fig 3.2. Rye dry matter production and C:N ratio of 5 rye termination dates measured at the time of rye termination located at the SDSU Southeast Research Farm near Beresford, SD, 2019.

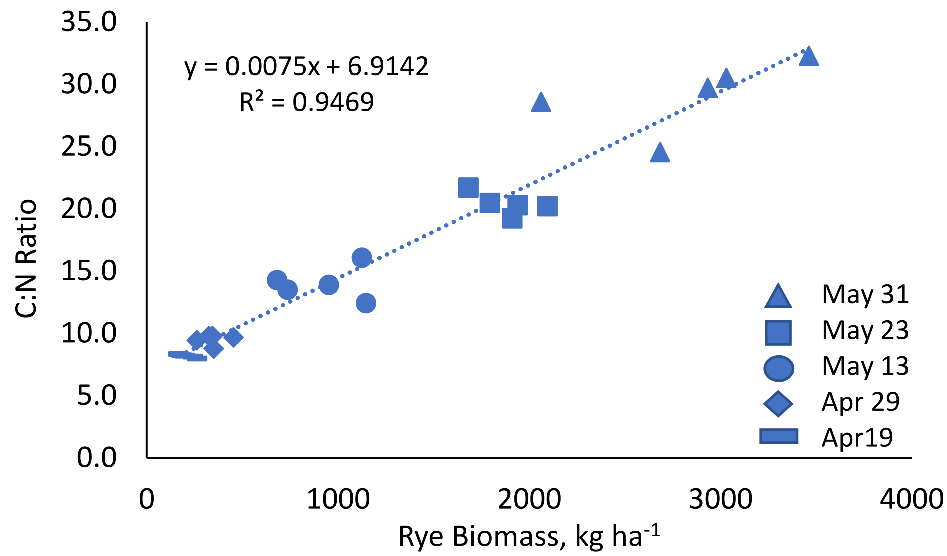


Figure 3.3. Relationship between rye biomass and C:N ratio measured at each rye termination date located at the Southeast Research Farm near Beresford, SD, 2019.

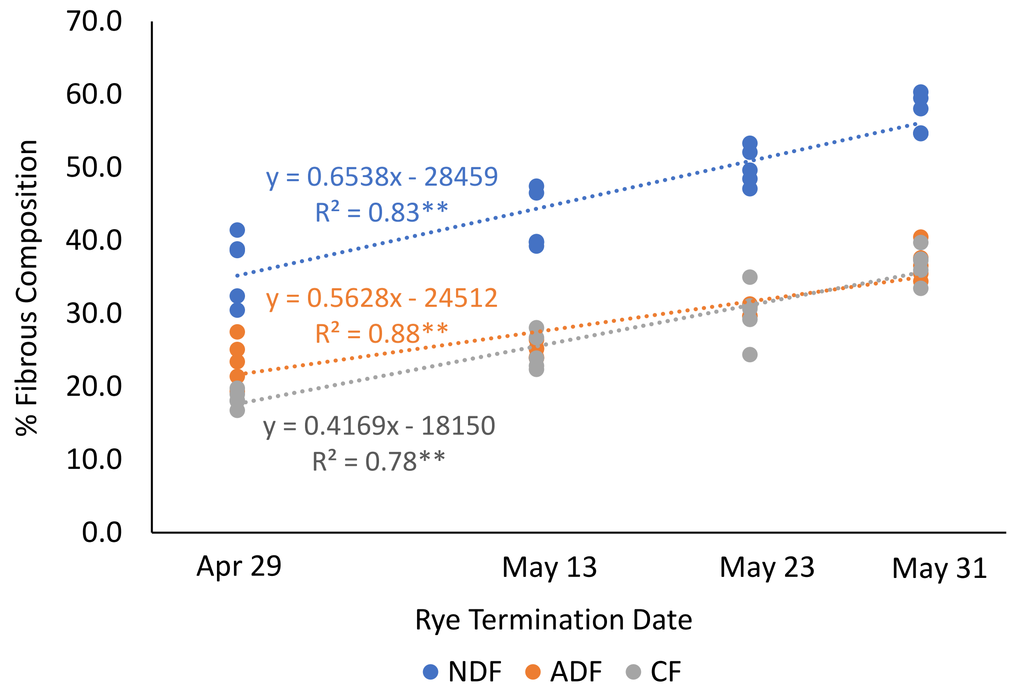


Figure 3.4. Percent composition of Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), and Crude Fiber at 4 rye termination treatments located at the Southeast Research Farm near Beresford, SD, 2019.

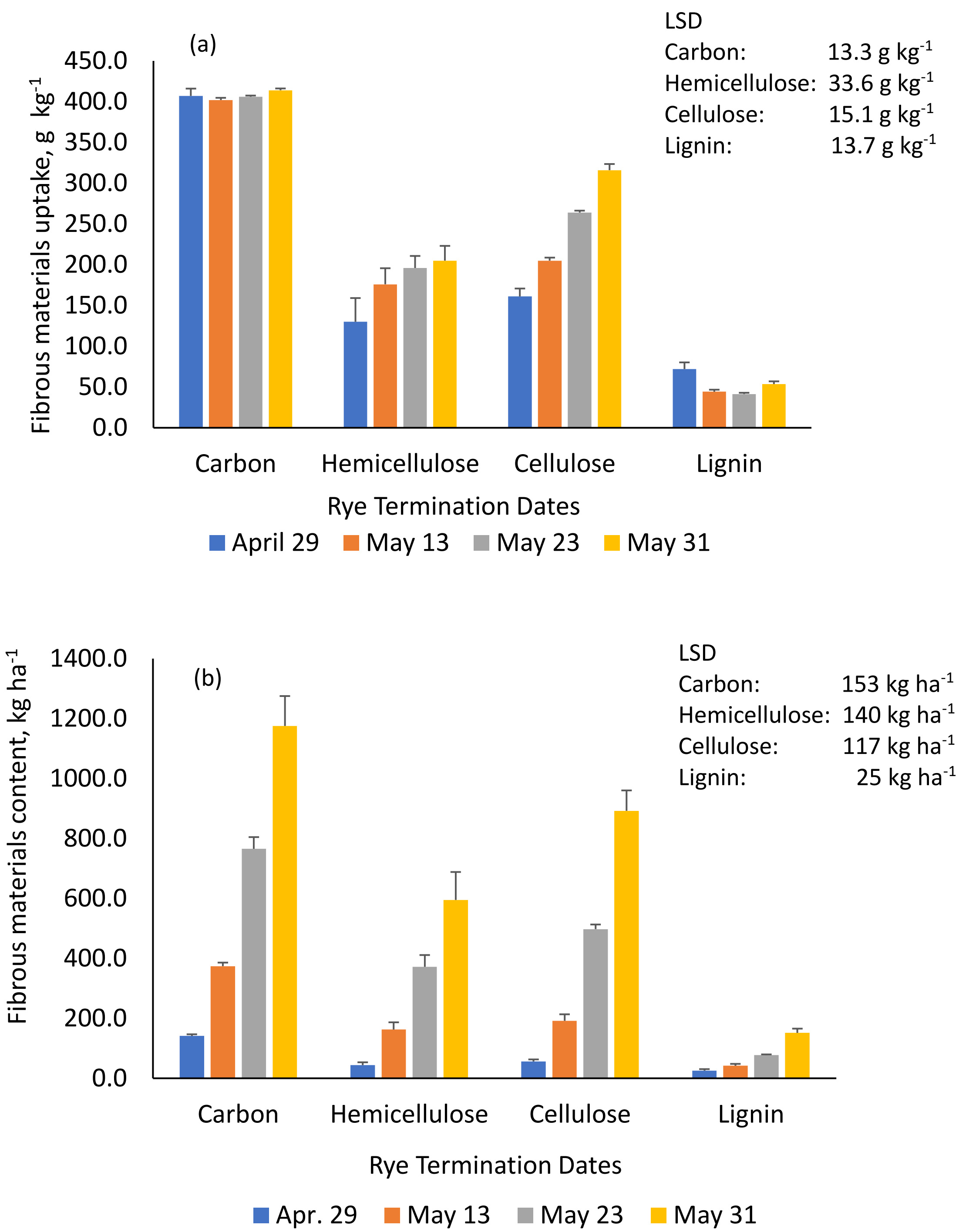


Figure 3.5. Carbon, hemicellulose, cellulose, and lignin concentrations and uptake of rye tissues measured at the time of rye termination for 4 rye termination date treatments located at the Southeast Research Farm near Beresford, SD, 2019.

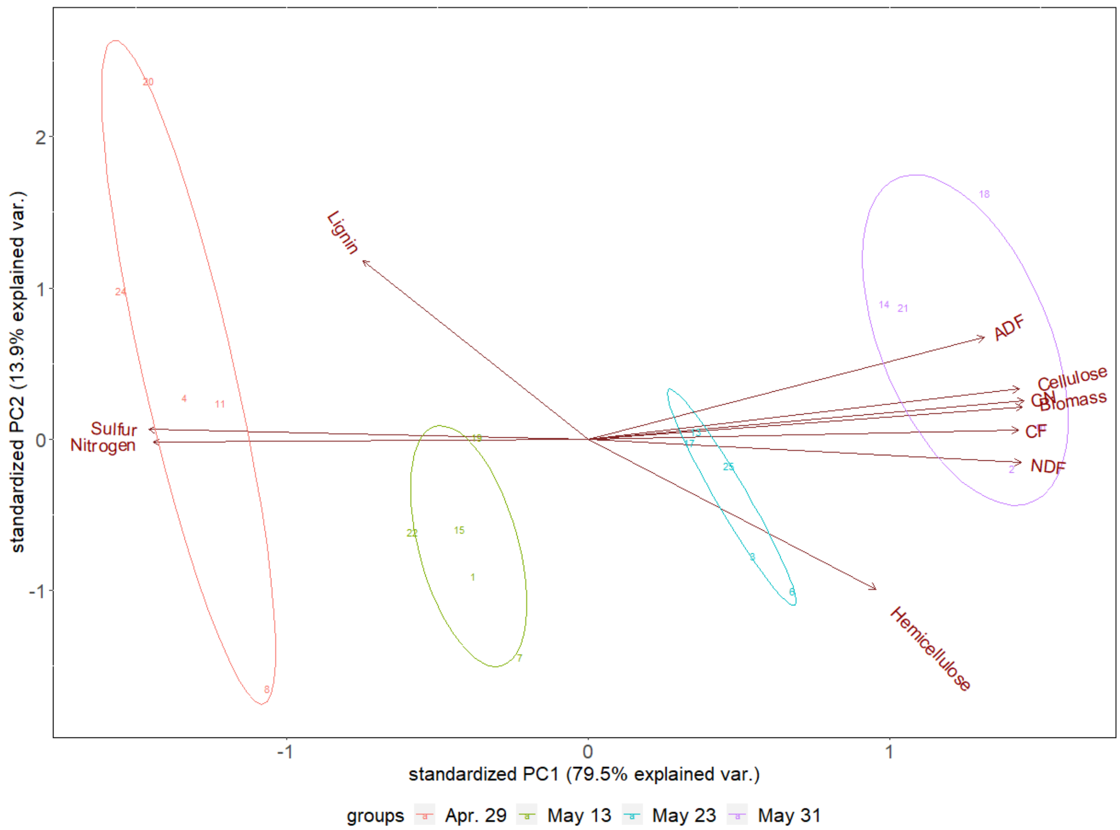


Figure 3.6. Biplot produced using the first and second components from principle component analysis containing rye biomass, cellulose, hemicellulose, lignin, Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), Crude Fiber (CF), C:N ratio, rye nitrogen concentration, and rye sulfur concentration for 4 rye termination date treatments measured at the Southeast Research Farm near Beresford, SD, 2019.

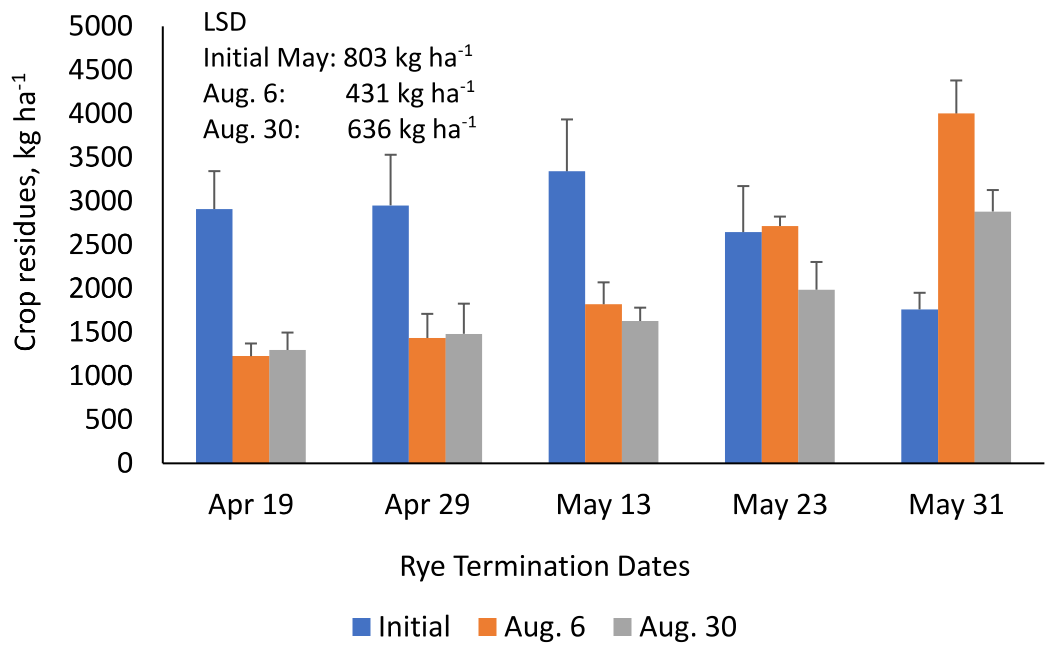


Figure 3.7. Crop residues remaining for 5 rye termination timing treatments measured initially at the time of rye termination, August 6 corresponding with the soybean R3 growth stage, and August 30 corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

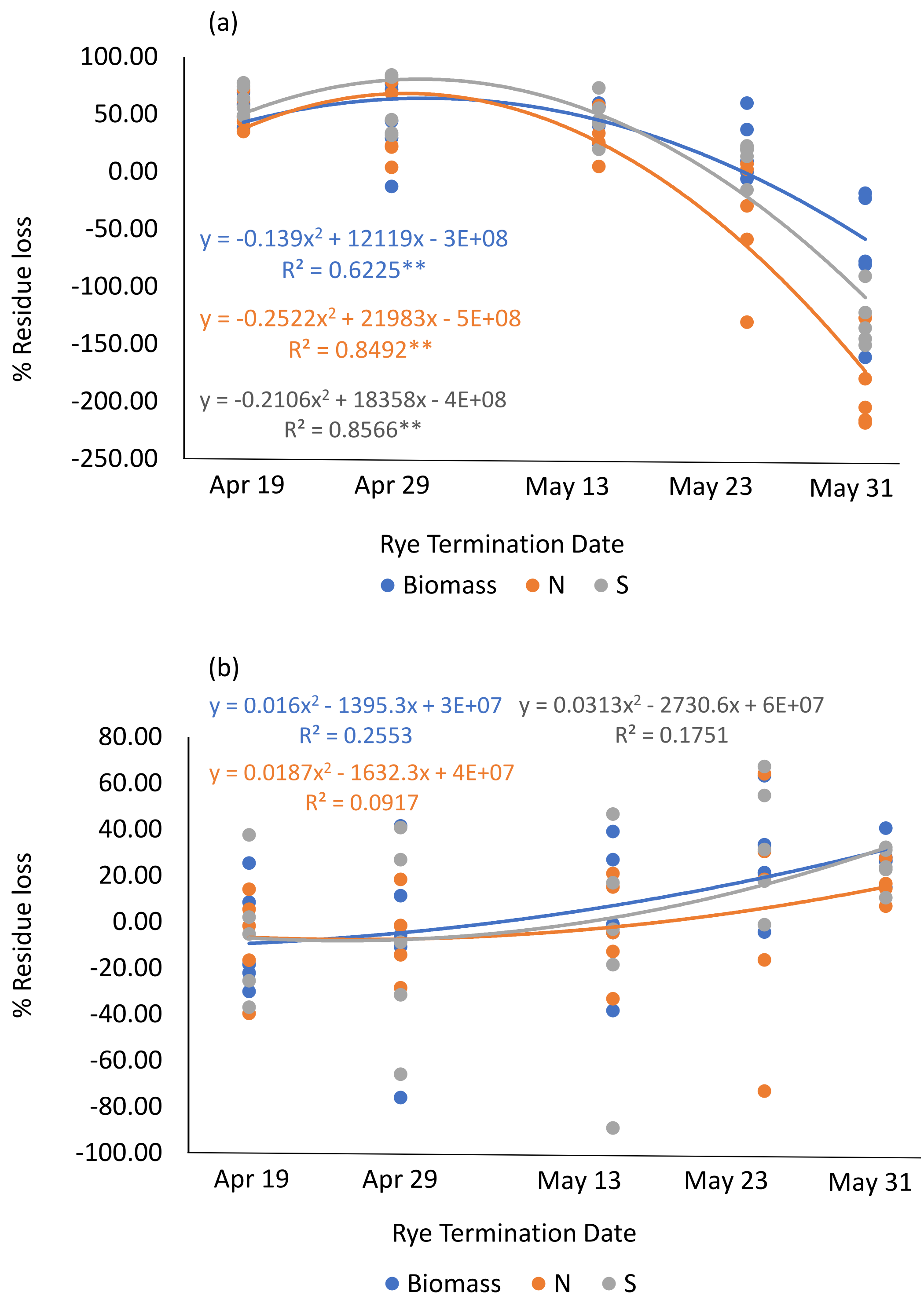


Figure 3.8. Percent loss of crop residue Biomass, N, and S between (a) the initial sampling and August 30 corresponding with the soybean R6 growth stage and (b) August 6 at the soybean R3 growth stage with the R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

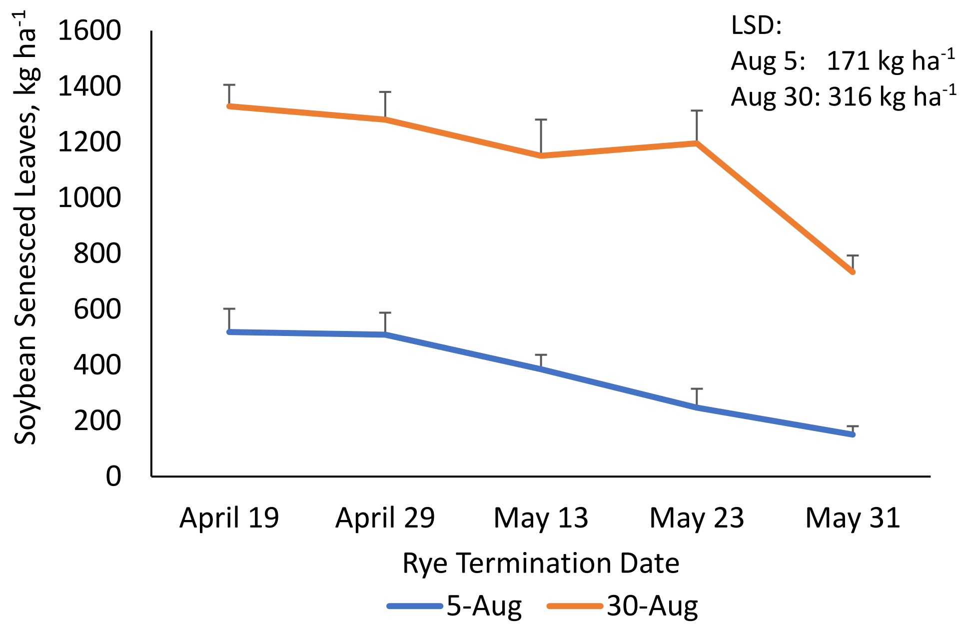


Figure 3.9. Soybean senesced leaves at 5 rye termination treatments measured on August 5 corresponding with the soybean R3 growth stage and August 30 at soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

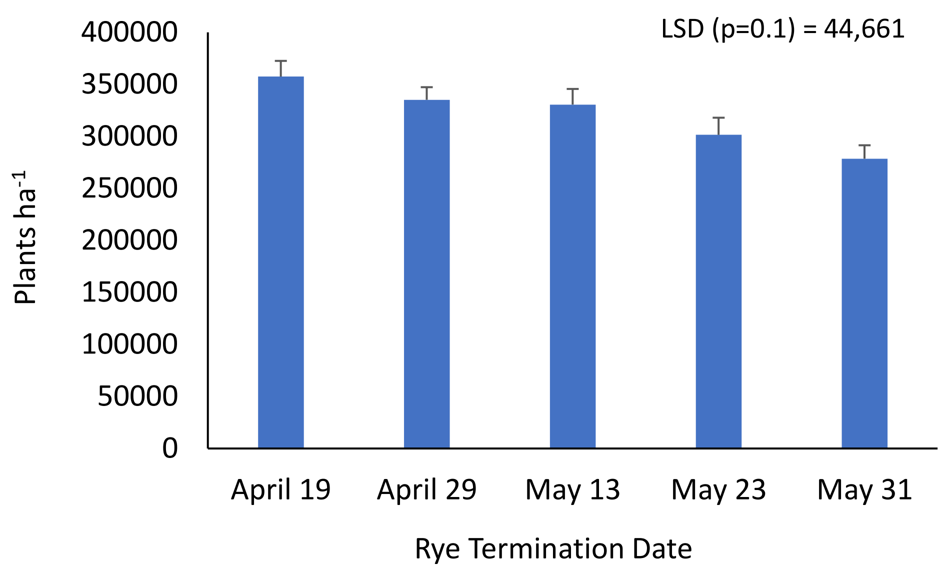


Figure 3.10. Soybean plant stand averaged across the R3, R6, and harvest growth stages for 5 rye termination timing treatments located at the Southeast Research Farm near Beresford, SD, 2019

Table 3.1. Field management operations including winter rye planting and burndown, sampling dates, herbicide applications, soybean planting, and harvest dates at the Southeast Research Farm near Beresford, SD, 2019.

Activity	**Year**
	2018-2019
Winter rye planting	October 2, 2018
1st burndown date and sampling	April 19, 2019
2nd burndown date and sampling	April 29, 2019
3rd burndown date and sampling	May 13, 2019
4th burndown date and sampling	May 23, 2019
5th burndown date and sampling	May 31, 2019
Soybean planting	June 4, 2019
Herbicide application	July 12, 2019
6th Sampling	August 5, 2019
7th Sampling	August 29, 2019
Soybean harvest	October 18, 2019

Table 3.2. Initial soil characteristics and classifications at the Southeast Research Farm Agricultural Exp. Station, Beresford, SD, 2019.

Growing Season	Soil Texture[†]	Soil Classification[†]	NO_3-N[a] (0-15 cm)	Olsen P[b]	K	Zn[c]	S[d] (0-15 cm)	pH[e]
			----------------------------	----------------------------	Mg kg^{-1}	----------------------	----------------------	
2018-2019	Silty Clay Loam	Fine-silty, mixed, mesic Udic Haplustolls	5.2	22.5	193	2.95	6.3	5.2

[†] (USDA-NRCS, 2020)
[a] soil nitrate (NO_3-N): using Nitrate Electrode method
[b] soil phosphorus: using Olsen P method
[c] soil zinc: DTPA extraction
[d] soil sulfur: Monocalcium phosphate extraction procedure
[e] soil pH: 1:1 extraction method

Table 3.3. Rye nutrient concentration and uptake of macronutrients at the time of rye termination for each of the 5 termination timing treatments measured at the Southeast Research Farm near Beresford, SD, 2019.

Rye Termination	N	P	K	S	N	P	K	S
	--------------------g kg^{-1}-------------------				---------------------kg ha^{-1}-------------------			
April 19	50.4 a	5.94 a	31.8 a	3.81 a	10.6 c	1.26 d	6.74 d	0.80 d
April 29	43.0 b	5.08 b	32.1 a	3.14 b	14.9 c	1.86 d	11.2 d	1.09 d
May 13	28.9 c	4.60 c	30.3 a	2.29 c	26.9 b	4.26 c	28.1 c	2.13 c
May 23	20.0 d	3.87 d	28.2 b	1.66 d	37.7 a	7.26 b	53.2 b	3.13 b
May 31	14.3 e	3.34 e	22.3 c	1.29 e	40.4 a	10.0 a	66.8 a	3.65 a
Mean	31.3	4.54	28.9	2.44	26.1	4.72	31.8	2.16
CV	5.69	3.49	4.81	6.31	17.4	9.35	12.2	16.9

Table 3.4. Crop residue fiber concentrations of 5 rye termination timing treatments measured initially at the time of termination, on August 5th corresponding with the soybean R3 growth stage, and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	NDF*	ADF	CF	CEL	L
		-----------------%----------------			--------g kg^{-1}-----	
April 19	April 19	60.0 a	58.4 ^{NS}	28.8 ^{NS}	32.7 a†	257 ^{NS}
April 29	April 29	47.9 b	59.9	26.0	32.8 a	273
May 13	May 13	45.8 c	58.6	25.8	27.7 b	298
May 23	May 23	42.3 bc	55.7	22.1	30.5 ab	251
May 31	May 31	40.0 bc	59.1	19.9	32.8 a	279
	mean	46.7	58.3	24.5	31.3	272
	CV	12.2	8.62	27.9	10.0	10.7
August 5	April 19	45.8 ab	63.7 ^{NS}	27.4 ^{NS}	33.7 ^{NS}	300 ^{NS}
	April 29	53.2 a	60.1	26.1	31.7	273
	May 13	38.4 b	57.2	20.8	28.2	290
	May 23	43.9 ab	58.4	25.6	30.6	278
	May 31	52.8 a	60.6	29.5	34.5	261
	mean	46.8	60.0	25.9	31.7	281
	CV	15.9	7.93	23.9	14.8	8.40
August 30	April 19	38.8 c	55.1 bc	21.4 bc	29.3 ab	258† ab
	April 29	48.4 ab	61.0 a	26.7 a	32.9 a	280 a
	May 13	50.7 b	58.9 ab	25.0 ab	29.6 ab	293 a
	May 23	42.3 bc	53.5 c	19.8 c	26.3 b	271 ab
	May 31	52.7 a	56.6 abc	29.2 a	32.6 a	239 b
	mean	46.8	57.0	24.4	30.2	269
	CV	15.9	5.76	13.2	10.6	10.5

* Abbreviations: NDF, Neutral Detergent Fiber; ADF, Acid Detergent Fiber; CF, Crude Fiber HEM, Hemicellulose;CEL, Cellulose; L, Lignin

^{NS} = Not significant at P = 0.05

† = Significant at P=0.1

Table 3.5. Crop residue nutrient concentration and uptake of macronutrients for 5 rye termination timing treatments measured initially at the time of termination, on August 5th corresponding with the soybean R3 growth stage, and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	N	P	K	S	N	P	K	S
		--------------------g ha $^{-1}$------------------				------------------kg ha $^{-1}$----------------			
Apr 19	Apr 19	8.92 a	0.89 ^{NS}	1.86 b	0.77 a	27.2 a	2.68 a	5.56 a	2.37 a
Apr 29	Apr 29	8.20 ab	0.87	1.94 ab	0.73 ab	25.7 a	2.74 a	5.94 a	2.30 a
May 13	May 13	8.38 ab	0.86	2.14 a	0.72 ab	27.8 a	2.91 a	7.13 a	2.39 a
May 23	May 23	7.48 bc	0.87	2.14 a	0.67 bc	21.0 a	2.35 a	5.63 a	1.82 ab
May 31	May 31	7.10 c	0.79	1.88 b	0.63 c	12.4 b	1.38 b	3.27 b	1.09 b
	Mean	8.02	0.86	1.99	0.70	22.8	2.41	5.51	1.99
	CV	9.04	8.63	8.07	9.80	25.5	27.3	26.8	28.6
Aug 5	Apr 19	9.40 bc	0.72 b	1.94 b	0.64 b	11.6 d	0.91 d	2.48 c	0.82 c
	Apr 29	8.60 c	0.65 b	1.56 b	0.54 b	12.9 d	0.91 d	2.07 c	0.74 c
	May 13	11.0 ab	0.80 b	2.04 b	0.59 b	20.2 c	1.69 c	3.91 c	1.28 c
	May 23	12.6 a	1.40 a	3.98 a	0.87 a	33.9 b	3.78 b	10.8 b	2.35 b
	May 31	11.4 a	1.44 a	4.80 a	0.82 a	45.8 a	5.70 a	19.1 a	3.27 a
	Mean	10.6	1.01	2.86	0.71	24.9	2.60	7.68	1.70
	CV	11.1	12.7	21.1	22.7	16.8	21.2	29.6	25.1
Aug 30	Apr 19	9.40 c	0.76 c	2.34 b	0.63 ^{NS}	12.9 c	1.06 c	3.25 c	0.89 c
	Apr 29	8.80 c	0.68 c	2.10 b	0.54	12.8 c	1.02 c	3.15 c	0.80 c
	May 13	10.6 bc	0.87 bc	2.48 b	0.71	17.3 bc	1.39 c	3.95 c	1.14 bc
	May 23	13.4 a	1.28 ab	4.02 a	0.83	25.9 b	2.44 b	7.61 b	1.60 b
	May 31	12.6 ab	1.38 a	4.86 a	0.88	35.2 a	3.92 a	13.8 a	2.49 a
	Mean	11.0	0.99	3.16	0.72	20.8	1.97	6.35	1.38
	CV	18.2	31.7	34.7	27.8	30.9	35.3	41.4	36.6

^{NS} = Not significant at P = 0.05

Table 3.6. Soybean nutrient concentration and uptake for 5 rye termination timing treatments measured on August 5th at the soybean R3 growth stage, and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Biomass	N	P	K	S	N	P	K	S
		kg ha^{-1}	------------------g kg^{-1}----------------				--------------------kg ha $^{-1}$------------------			
August 5	April 19	6207 a†	37.1 a	3.20 ^{NS}	22.5 ^{NS}	2.17 ^{NS}	223 a	19.8 a	139 a	13.5 a
	April 29	5987 ab	35.0 b	3.28	22.7	2.10	211 ab	19.6 a	136 ab	12.7 ab
	May 13	4920 bc	35.0 b	3.11	23.8	2.07	174 bc	15.6 b	118 abc	10.2 c
	May 23	5432 abc	34.7 b	3.22	22.6	2.10	189 abc	17.5 ab	123 bc	11.4 bc
	May 31	4795 c	33.8 b	3.34	23.3	2.01	163 c	16.1 b	112 c	9.69 c
	Mean	5491	35.0	3.23	23.0	2.09	195	17.8	126	11.5
	CV	15.2	3.63	5.81	8.97	5.13	18.2	11.8	11.0	12.7
August 30	April 19	9638 ^{NS}	34.5 ^{NS}	2.97 ^{NS}	17.9 ^{NS}	1.88 ^{NS}	332 ^{NS}	27.2 ^{NS}	170 ^{NS}	18.1 ^{NS}
	April 29	9617	34.7	2.72	16.1	1.76	333	25.6	151	16.9
	May 13	9275	34.7	2.71	17.8	1.83	322	25.3	167	17.1
	May 23	9142	35.4	2.79	18.6	1.85	323	25.5	170	17.0
	May 31	9136	34.9	2.73	17.3	1.69	319	25.0	158	15.4
	Mean	9361	34.9	2.77	17.5	1.80	326	25.7	163	16.9
	CV	22.1	2.03	6.27	10.6	6.43	22.2	21.5	19.2	21.2

^{NS} = Not significant at P = 0.05

† = Significant at P=0.1

Table 3.7. Soybean nutrient concentration of soybean 3rd leaf tissues of 5 rye termination timing treatments measured on August 5th corresponding with the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
		-----------------	-----------------	-----------------	g kg^{-1}	-----------------	-----------------	-----------------	-----------------	mg kg^{-1}	-----------------	-----------------
Aug 5	Apr 19	6.95 ab	0.61 ^{NS}	2.27 ^{NS}	0.26 ^{NS}	0.77 ^{NS}	0.37 ^{NS}	40.4 ^{NS}	88.0 ^{NS}	6.70 ^{NS}	42.9 ^{NS}	0.33 ^{NS}
	Apr 29	7.20 a	0.61	2.32	0.28	0.90	0.40	44.0	94.0	14.7	48.8	1.07
	May 13	6.62 bc	0.60	2.40	0.27	0.93	0.42	40.8	93.0	24.2	48.9	0.59
	May 23	6.74 bc	0.58	2.29	0.27	0.98	0.42	44.0	89.3	11.2	48.8	0.85
	May 31	6.45 c	0.60	2.33	0.26	0.88	0.39	41.0	88.4	7.88	44.0	0.33
	Mean	6.79	0.60	2.32	0.27	0.89	0.40	42.0	90.5	12.5	46.5	0.62
	CV	3.84	12.8	11.7	11.2	23.5	20.7	21.2	11.2	130	23.0	88.4

^{NS} = Not significant at P = 0.05

Table 3.8. Soybean yield, test weight, moisture, 100 seed weight, plant stand and grain nutrient concentrations for 5 rye termination timing treatments measured at harvest on October 18 located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Yield	Test Weight	Moisture	100 seed weight	Plant Stand	Plant Height	N	P	K	S
		Mg ha^{-1}	kg m^{-3}	%	g	plants ha^{-1}	cm	-----------------------g kg^{-1}	---	---	--------------------
Oct 18	Apr 19	4.77 ab†	758 b	11.6 NS	758 NS	289211 NS	85.3 a	63.2 c	5.00 b	17.1 b	2.92 NS
	Apr 29	4.50 b	757 b	11.6	757	321345	85.0 a	63.5 bc	5.10 b	17.2 b	2.96
	May 13	4.53 b	764 a	11.8	764	325936	85.2 a	63.6 abc	5.13 b	17.6 b	2.97
	May 23	4.53 b	761 ab	11.7	761	261667	82.7 ab	64.2 ab	5.22 b	17.9 ab	3.05
	May 31	4.91 a	765 a	11.7	765	243304	81.1 b	64.4 a	5.45 a	18.5 a	3.05
	Mean	4.65	761	11.7	761	288293	83.9	63.8	5.19	17.6783	2.99
	CV	5.58	0.56	1.97	0.56	29.1	2.81	0.91	3.14	3.01	4.03

NS = Not significant at P = 0.05

† = Significant at P=0.1

Table 3.9. Soil NO_3^-, P, K, Zn, and S measured to a 15 cm depth and NO_3^- and S measured from a 15-61 cm depth measured initially at the time of termination, August 5th corresponding with R3 soybean growth stage, and on August 30th at the R6 soybean growth stage located at the Southeast Research Farm near Beresford, SD, 2019. Initial samples taken at termination time were composited across replications.

Sample Date	Rye Termination	OM	NO_3-	P	K	Zn	S	NO_3-	S
		0-15 cm						15-61 cm	
						mg kg^{-1}			
Apr 19	Apr 19	4.50	4.40	28.0	156	4.25	8.86	5.80	5.26
Apr 29	Apr 29	4.70	2.20	21.0	149	5.70	7.08	5.20	5.55
May 13	May 13	4.90	2.00	24.0	160	5.65	6.79	3.20	7.70
May 23	May 23	4.80	2.00	21.0	144	6.05	6.37	2.80	5.06
May 31	May 31	4.90	2.00	19.0	130	6.55	5.49	2.00	4.89
Aug 5	Apr 19	4.53 ^{NS}	0.90 ^{NS}	15.3 ^{NS}	164 ^{NS}	4.53 ^{NS}	5.86 ab	1.40 ^{NS}	5.68 ^{NS}
	Apr 29	4.74	1.52	19.6	161	6.68	6.86 a	1.40	5.10
	May 13	4.46	1.64	17.0	172	5.36	6.52 a	1.20	6.39
	May 23	4.60	1.12	15.8	167	5.58	5.02 b	1.12	5.67
	May 31	4.38	1.30	16.5	164	4.76	6.03 ab	1.35	5.38
	Mean	4.55	1.31	16.9	166	5.45	6.07	1.29	5.65
	CV	7.19	35.8	30.0	5.13	31.1	13.2	13.8	20.2
Aug 30	Apr 19	4.06 ^{NS}	1.40 ^{NS}	14.0 ^{NS}	158 ^{NS}	3.72 b	7.45 ^{NS}	1.32 ^{NS}	5.42 ^{NS}
	Apr 29	4.36	1.56	15.8	160	4.96 a	6.16	1.36	5.02
	May 13	4.18	1.60	13.8	164	4.41 a	5.65	1.28	4.73
	May 23	4.16	1.32	14.4	158	4.84 a	5.73	1.40	5.18
	May 31	4.08	1.40	15.8	158	4.85 a	5.28	1.32	4.89
	Mean	4.17	1.46	14.8	160	4.56	6.05	1.34	5.05
	CV	3.37	16.4	17.7	2.63	9.93	24.3	11.3	22.2

^{NS} = Not significant at P = 0.05

CHAPTER 4: GENERAL CONCLUSIONS

Biomass management of a rye cover crop is important in realizing cover cropping goals. With concerns over reduced crop yields as a result of implementing a rye cover crop, this set of studies sought to examine how biomass and quality can be managed together through seeding rates and termination timings to impact the flow of nutrients within the agroecosystem and reduce the likelihood of observing decreases in soybean production and yield from an inability to access N and S immobilized in crop residues. In this study, biomass was seen to increase slowly initially as termination was delayed with 32.8% of biomass accumulation occurring between April 19th and May 13th. The remaining 67.2% of biomass production was rapidly accumulated between May 13th and May 31st. Rye seeding rates did not affect biomass production until 90 kg ha^{-1} was applied where biomass was seen to be significantly higher. Where significant increases in biomass were observed, there was also significantly greater rye uptake of N and S signifying that in these later termination treatments and the 90 kg ha^{-1} seeding rate, more N and S are being cycled. The speed at which they cycle and their ability to synchronize nutrient release with soybean uptake depends on residue quality. Increases in biomass were seen to correlate with lower residue quality as termination was delayed. During the 2018 season, only C:N ratios at the 90 kg ha^{-1} treatment were significantly higher as adequate N and low biomass reduced the potential for differences in residue quality. However, in 2019, C:N ratio increased as seeding rate increased while fibrous composition was only higher at 90 kg ha^{-1}. Therefore, the results of this study suggest that lower seeding rates of rye may provide the same benefits in nutrient cycling as higher seeding rates up until 90 kg ha^{-1}.

Crop residue decomposition occurred more rapidly where seeding rates were higher and resulted in an increase in decomposition over the growing season in 2018. However, in 2019 high levels of biomass replaced initial gains in decomposition and resulted in higher amounts of N and S remaining in crop residues by the end of the growing season. With delayed rye termination, greater residue biomass was observed on May 23rd and May 31st with no differences in biomass noted between April 19th and May 13th at the end of the growing season reflecting the ability of high quality residue to quickly decompose. N and S were primarily released by the R3 growth stage for the April 19th to May 13th treatments while a greater flux of nutrients was seen to be released for the May 23rd and May 31st treatments in comparison to the April 19th to May 13th treatments between the R3 and R6 growth stages.

Both studies resulted in significantly lower soybean S concentrations across growth stage and significant differences in soybean S uptake. The exception to this was increasing S trends as seeding rate increased in 2018 as a result of low biomass and high quality rye materials which quickly cycled and released nutrients. N concentrations or uptake of soybeans was generally not seen to be significant between treatments reflecting the ability of soybeans to regulate N uptake. Where residue sequestered more N and S at later terminations and at the 90 kg ha^{-1} seeding rates, lower levels of S were observed in the soybean plant.

In these trials yield was unaffected by rye seeding rate. Therefore, under high fertility soils and adequate moisture, a rye cover crop does not appear to suppress soybean yield although trends towards lower S were noted and could influence crop yield much more significantly in soils where S content is marginal. Later termination of rye produced higher yields at the May 31st termination date. Delayed soybean maturity where greater amounts of crop residues were found may have played a role in increasing yields by effecting soil temperature and moisture regimes. Results from this study suggest that in high fertility soils and adequate moisture, later termination dates will not negatively impact soybean yields and may in some cases result in yield advantages.

APPENDICES

APPENDIX A

Table A.1.1. Initial rye nutrient concentration of secondary nutrients measured on May 18, 2018 and May 2, 2019 located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
2018	kg ha^{-1}	---------g kg^{-1}--------		--------------------------mg kg^{-1}--------------------------				
	22	5.38 ^{NS}	2.38 a	27.8 ^{NS}	52.8 ^{NS}	11.1 ab	7.63 a	0.29 ^{NS}
	45	5.30	2.28 a	24.3	52.5	10.4 ab	6.45 ab	0.31
	67	4.95	2.18 ab	24.3	54.8	11.2 a	6.58 ab	0.27
	90	4.60	2.03 b	25.3	58.0	10.2 b	5.93 b	0.38
	Mean	5.06	2.21	25.4	54.5	10.7	6.64	0.32
	CV	11.5	7.03	16.2	15.7	5.55	11.3	49.5
2019	22	8.66 ^{NS}	2.73 ^{NS}	27.0 ^{NS}	88 ^{NS}	10.9 ^{NS}	3.47 ^{NS}	2.66 ^{NS}
	45	7.91	2.53	20.8	126.8	10.8	3.58	2.18
	67	7.79	2.54	30.3	99.3	10.7	3.30	1.77
	90	7.93	2.52	31.3	122.5	11.2	3.48	2.37
	Mean	8.03	2.57	27.3	110.5	10.9	3.45	2.22
	CV	5.6	8.1	35.7	25.0	16.3	14.36	32.1

^{NS} Not significant at P = 0.05

Table A.1.2. Initial rye nutrient uptake of secondary nutrients measured on May 18, 2018 and May 2, 2019 located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Year	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
2018	kg ha^{-1}	----------------	----------------	----------------	kg ha^{-1}	----------------	----------------	----------------
	22	1.18 ^{NS}	0.53 ^{NS}	0.008 ^{NS}	0.013 ^{NS}	0.0026 ^{NS}	0.0017 ^{NS}	0.00007 ^{NS}
	45	1.97	0.86	0.010	0.021	0.0039	0.0024	0.00012
	67	1.49	0.64	0.010	0.017	0.0034	0.0020	0.00009
	90	2.09	0.92	0.013	0.026	0.0045	0.0026	0.00017
	Mean	1.68	0.74	0.010	0.019	0.0036	0.0022	0.00011
	CV	42.7	40.7	57.7	47.5	38.2	41.6	64.8
2019	22	0.47 ^{NS}	0.15 ^{NS}	0.001 ^{NS}	0.005 ^{NS}	0.0006 ^{NS}	0.0002 ^{NS}	0.0001 ^{NS}
	45	1.11	0.35	0.003	0.019	0.0015	0.0005	0.0003
	67	1.39	0.45	0.005	0.020	0.0020	0.0006	0.0004
	90	1.58	0.51	0.006	0.022	0.0022	0.0007	0.0005
	Mean	1.18	0.38	0.004	0.017	0.0016	0.0005	0.0003
	CV	57.8	58.9	60.0	56.8	55.5	56.5	68.9

^{NS} = Not significant at P = 0.05

Table A.1.3. Nutrient concentration of rye secondary nutrients at 4 rye seeding rate treatments measured at rye termination located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	-----------------------------------			mg kg^{-1}		-----------------------------------	
2018	22	4.70^{NS}	2.29^{NS}	33.3^{NS}	105^{NS}	11.3^{NS}	6.45^{NS}	1.21^{NS}
	45	4.65	2.20	22.0	80.3	12.1	6.20	0.93
	67	4.53	2.26	28.0	86.8	11.2	6.25	0.96
	90	4.05	2.20	29.8	88.3	10.7	6.28	1.06
	Mean	4.48	2.24	28.3	90.1	11.3	6.30	1.04
	CV	10.3	14.2	21.1	20.2	15.6	9.54	60.1
2019	22	3.50^{NS}	1.27^{NS}	16.8^{NS}	62.0^{NS}	7.08 a	2.48^{NS}	1.31^{NS}
	45	3.57	1.30	18.5	66.3	6.45 a	2.68	1.35
	67	3.75	1.37	18.0	67.3	5.43 b	2.73	1.26
	90	3.41	1.24	13.5	63.5	5.15 b	2.55	1.07
	Mean	3.55	1.30	16.7	64.8	6.03	2.61	1.25
	CV	7.72	6.86	24.6	11.9	12.4	10.2	24.1

^{NS} = Not significant at P = 0.05

Table A.2.1. C:N ratio and fibrous concentrations of crop residue materials at 5 rye seeding rate treatments measured at the R3 soybean growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019

Sample Date	Seeding Rate	C:N	NDF*	ADF	CF	HEM	CEL	L
	kg ha^{-1}		-----------	-----------	-----g kg^{-1}-----	-----------	-----------	-----------
2018	0	60.8^{NS}	630^{NS}	555^{NS}	378^{NS}	75.3^{NS}	356^{NS}	199^{NS}
	22	61.0	682	589	379	92.8	366	223
	45	55.7	678	588	364	89.5	361	228
	67	56.2	688	568	409	120	368	200
	90	55.2	673	605	383	68.5	374	231
	mean	57.8	670	612	382	89.2	365	216
	CV	16.4	8.89	8.35	12.5	46.9	10.8	15.0
	0	50.8^{NS}	576^{NS}	580^{NS}	375^{NS}	0.0^{NS}	366^{NS}	214^{NS}
2019	22	49.1	634	567	405	66.8	371	196
	45	48.2	584	565	388	32.3	364	187
	67	45.5	611	570	398	40.3	360	210
	90	50.7	629	573	425	56.3	379	194
	mean	48.9	606	571	398	38.2	368	200
	CV	7.27	10.2	2.30	11.8	142	5.81	9.60

* Abbreviations: NDF, Neutral Detergent Fiber; ADF, Acid Detergent Fiber; CF, Crude Fiber; HEM, Hemicellulose; CEL, Cellulose; L, Lignin

^{NS} = Not significant at P = 0.05

Table A.2.2. C:N ratio and fibrous concentration of crop residue materials at 5 rye seeding rate treatments measured at the R6 soybean growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	C:N	NDF*	ADF	CF	HEM	CEL	L
	kg ha^{-1}		-----------------------------------g kg^{-1}-------------------------------					
2018	0	51.4 ^{NS}	625 ^{NS}	609 ^{NS}	403 ^{NS}	1.58 ^{NS}	35.9 ^{NS}	250 ^{NS}
	22	55.1	665	554	445	11.0	33.2	222
	45	53.3	647	577	394	7.03	33.9	238
	67	51.0	662	556	441	10.9	33.5	221
	90	52.8	613	573	412	4.05	33.0	243
	mean	52.7	641	574	419	6.71	33.9	235
	CV	11.2	6.37	6.06	10.1	80.4	7.95	8.65
2019	*0*	50.0 a	588 ^{NS}	563 ^{NS}	340 ^{NS}	25.0 ^{NS}	342 ^{NS}	220 ^{NS}
	22	41.6 b	609	580	341	29.3	342	238
	45	42.3 b	611	590	338	21.0	348	242
	67	43.7 b	619	579	388	34.5	347	231
	90	44.7 ab	617	599	328	17.5	352	247
	mean	44.5	608	582	345	25.5	346	236
	CV	7.79	7.74	3.82	8.93	241	3.69	10.8

* Abbreviations: NDF, Neutral Detergent Fiber; ADF, Acid Detergent Fiber; CF, Crude Fiber; HEM, Hemicellulose; CEL, Cellulose; L, Lignin

^{NS} = Not significant at P = 0.05

Table A.2.3. Initial nutrient concentration of crop residues at 5 rye seeding rate treatments measured on May 2 located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	$kg\ ha^{-1}$	---g kg^{-1}---						---mg kg^{-1}---				
2019	0	7.65 a	0.83 a	2.80^{NS}	0.63^{NS}	5.27 a	1.78^{NS}	27.3^{NS}	204^{NS}	9.68^{NS}	3.98^{NS}	2.00^{NS}
	22	6.48 bc	0.63 b	2.63	0.57	4.65 ab	1.57	17.5	170	7.90	3.38	1.37
	45	6.85 ab	0.61 b	2.35	0.56	4.70 ab	1.63	20.8	173	8.78	3.40	1.97
	67	6.13 bc	0.58 b	2.35	0.52	4.28 b	1.52	22.0	138	6.55	3.00	1.24
	90	5.80 c	0.61 b	2.03	0.51	4.52 b	1.47	19.0	179	8.33	3.20	1.63
	Mean	6.58	0.65	2.41	0.56	4.68	1.59	21.0	173	8.25	3.39	1.64
	CV	10.1	20.1	20.2	11.2	9.62	14.1	22.0	24.6	26.8	17.4	44.4

^{NS} = Not significant at P = 0.05

Table A.2.4. Nutrient concentration of crop residues at 5 rye seeding rate treatments measured at rye termination located at the SDSU Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	------g kg^{-1}------						------mg kg^{-1}------				
2018	0	5.83^{NS}	0.86 a	2.73^{NS}	0.95^{NS}	2.94 b	1.59^{NS}	28.8 a	141^{NS}	8.85^{NS}	5.20^{NS}	1.14^{NS}
	22	5.28	0.70 b	2.28	0.70	3.22 ab	1.52	21.5 ab	139	9.03	5.33	0.78
	45	5.80	0.80 a	2.35	0.77	3.21 ab	1.53	15.0 b	148	8.43	5.40	0.76
	67	5.30	0.69 b	2.55	0.71	3.17 ab	1.55	21.5 ab	152	9.60	5.23	1.20
	90	5.08	0.66 b	2.20	0.81	3.41 a	1.53	17.8 b	174	9.10	5.15	0.98
	Mean	5.46	0.74	2.42	0.79	3.20	1.54	20.9	151	9.00	5.26	0.97
	CV	9.89	7.94	13.8	17.6	5.97	6.68	28.5	16.4	17.3	5.98	28.6
2019	0	6.38^{NS}	0.66^{NS}	2.38^{NS}	0.54^{NS}	4.84^{NS}	1.74^{NS}	24.8 ab	274^{NS}	11.8 a	3.65 a	2.62^{NS}
	22	6.20	0.63	2.00	0.52	4.70	1.63	24.5 ab	248	9.70 bc	3.25 b	2.04
	45	5.90	0.60	2.10	0.51	4.56	1.69	28.0 a	259	9.75 bc	3.53 ab	2.51
	67	5.90	0.58	2.03	0.49	4.29	1.52	19.8 b	223	9.05 c	3.15 b	1.98
	90	6.38	0.65	1.90	0.54	4.65	1.56	24.5 ab	230	10.7 ab	3.30 ab	2.11
	Mean	6.15	0.62	2.08	0.52	4.60	1.63	24.1	247	10.1	3.38	2.25
	CV	8.53	11.5	13.51	7.46	6.47	9.07	14.7	16.2	9.81	7.42	31.0

^{NS} = Not significant at P = 0.05

Table A.2.5. Nutrient concentration of crop residues at 5 rye seeding rate treatments measured at the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	----------------------------------g kg^{-1}	---------------------------------					---------------------------mg kg^{-1}	-------------------------			
2018	0	6.35^{NS}	0.71^{NS}	2.05^{NS}	0.64^{NS}	3.43^{NS}	1.87^{NS}	24.5^{NS}	249^{NS}	11.4^{NS}	6.40^{NS}	1.66^{NS}
	22	6.13	0.65	1.70	0.60	3.65	1.75	25.5	238	10.6	6.35	1.50
	45	6.50	0.68	1.93	0.61	3.78	1.78	20.8	255	10.6	6.20	1.58
	67	6.93	0.72	1.70	0.65	3.83	1.66	31.0	204	9.88	6.13	1.65
	90	6.93	0.72	1.68	0.64	3.73	1.67	21.8	213	8.93	6.05	1.49
	Mean	6.57	0.69	1.81	0.62	3.70	1.74	24.7	231	10.3	6.23	1.58
	CV	12.5	12.2	14.3	7.95	6.90	6.34	33.9	24.0	16.7	8.37	33.5
2019	0	7.45† b	0.65^{NS}	2.13^{NS}	0.55^{NS}	3.94^{NS}	1.57^{NS}	30.5^{NS}	234^{NS}	5.33^{NS}	4.50^{NS}	2.21 a
	22	7.90 ab	0.75	2.38	0.50	3.83	1.37	27.5	224	7.45	4.15	2.05 a
	45	8.00 ab	0.85	2.88	0.54	4.01	1.50	31	233	8.00	4.40	2.24 a
	67	8.45 a	0.83	2.80	0.55	3.82	1.46	30.75	223	6.15	3.63	1.79 ab
	90	7.88 ab	0.77	2.63	0.51	3.45	1.27	25.75	172	8.40	3.65	1.22 b
	Mean	7.94	0.77	2.56	0.52	3.81	1.43	29.1	217	7.07	4.09	1.91
	CV	5.64	16.45	18.25	8.07	14.46	14.28	20.26	25.36	33.68	17.14	20.53

^{NS} = Not significant at P = 0.05

† = Significant at P= 0.1

Table A.2.6. Nutrient concentration of crop residues at 5 rye seeding rate treatments measured at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	------------------------------g kg^{-1}	------------------------------	------------------------------	------------------------------	------------------------------	------------------------------	-------------------------mg kg^{-1}	-------------------------	-------------------------	-------------------------	-------------------------
2018	0	7.25^{NS}	0.86 a	3.15^{NS}	0.72^{NS}	4.31^{NS}	2.22^{NS}	27.0^{NS}	256^{NS}	11.8^{NS}	8.40^{NS}	2.42^{NS}
	22	6.65	0.69 b	2.80	0.65	4.52	2.05	23.3	289	12.1	8.48	2.44
	45	6.47	0.69 b	2.73	0.65	4.45	2.04	24.5	274	11.1	8.63	2.38
	67	7.18	0.78 ab	3.00	0.71	4.72	2.20	28.8	291	11.5	8.55	2.34
	90	6.95	0.73 ab	2.90	0.66	4.60	2.02	27.3	288	11.4	8.65	2.59
	Mean	6.92	0.75	2.93	0.68	4.52	2.10	26.2	279	11.5	8.54	2.43
	CV	7.44	10.7	8.91	6.59	10.0	10.8	25.0	17.3	17.9	9.97	24.1
2019	0	7.30 b	0.548† b	1.83† b	0.403 b	4.07^{NS}	1.62^{NS}	27.3^{NS}	253^{NS}	6.15^{NS}	4.20^{NS}	2.10^{NS}
	22	9.05 a	0.795 a	2.60 a	0.575 a	4.34	1.70	31.0	248	2.38	4.75	2.09
	45	8.70 a	0.725 ab	2.63 a	0.543 a	4.46	1.68	31.3	264	3.50	4.63	2.16
	67	8.83 a	0.775 a	2.68 a	0.603 a	4.18	1.65	29.3	230	5.03	4.65	2.04
	90	8.35 a	0.763 a	2.60 a	0.538 a	4.53	1.69	33.8	250	5.20	4.75	2.06
	Mean	8.45	0.721	2.47	0.528	4.32	1.67	30.7	249	4.41	4.60	2.09
	CV	7.24	0.072	0.247	0.053	6.94	11.3	16.4	14.9	27.2	13.9	25.4

^{NS} = Not significant at P = 0.05

† = Significant at P= 0.1

Table A.2.7. Initial nutrient uptake of crop residues at 5 rye seeding rate treatments measured on May 2 located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
		---kg ha $^{-1}$---										
2019	0	91.8 a	7.93 ^{NS}	31.2 ^{NS}	7.51 a	63.3 a	21.7 a	0.29 ^{NS}	2.38 a	0.118† a	0.0480 a	0.024 ^{NS}
	22	62.2 b	5.95	25.1	5.36 b	44.6 b	15.1 b	0.17	1.65 b	0.075 b	0.032 b	0.013
	45	62.2 b	5.55	22.0	5.13 b	43.3 b	15.2 b	0.19	1.53 b	0.0825 ab	0.031 b	0.019
	67	54.4 b	5.23	21.4	4.65 b	37.9 b	13.7 b	0.21	1.23 b	0.0625 b	0.028 b	0.011
	90	54.2 b	5.68	19.0	4.78 b	42.2 b	13.8 b	0.17	1.68 b	0.078 b	0.030 b	0.015
	Mean	64.9	5.97	23.4	5.49	46.3	15.9	0.21	1.69	0.083	0.034	0.016
	CV	16.0	20.4	25.8	17.4	17.8	22.5	42.1	24.4	30.4	22.0	46.5

^{NS} = Not significant at P = 0.05

† = Significant at P= 0.1

Table A.2.8. Nutrient uptake of crop residues at 5 rye seeding rate treatments measured at rye termination located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	---------	---------	---------	---------	---------	kg ha $^{-1}$	---------	---------	---------	---------	---------
2018	0	46.3 ^{NS}	5.39† a	21.7 ^{NS}	6.08 ^{NS}	23.0 ^{NS}	12.8 ^{NS}	0.21 a	1.19 ^{NS}	0.066 ^{NS}	0.039 ^{NS}	0.009 ^{NS}
	22	38.4	5.03 a	16.6	5.09	23.1	11.0	0.15 ab	0.99	0.065	0.038	0.006
	45	38.4	5.19 a	15.3	5.08	21.0	10.1	0.10 bc	0.94	0.056	0.036	0.005
	67	35.8	4.60 ab	17.2	4.69	20.9	10.2	0.14 abc	0.98	0.062	0.034	0.008
	90	23.2	3.00 b	12.4	3.81	15.5	8.49	0.07 c	0.77	0.040	0.023	0.004
	Mean	36.4	4.60	16.9	4.89	20.6	10.5	0.13	0.98	0.058	0.034	0.006
	CV	39.6	24.3	24.5	24.4	29.6	23.5	37.0	35.3	32.4	31.0	44.5
2019	0	74.1 a	7.68 a	28.4 a	6.23 a	56.1 a	18.2 a	0.29 a	3.35† a	0.125 ^{NS}	0.043 a	0.032 ^{NS}
	22	54.8 b	5.58 b	17.9 b	4.60 b	41.6 bc	14.7 bc	0.22 b	2.25 b	0.090	0.029 b	0.018
	45	58.2 b	5.93 b	20.7 ab	4.97 b	44.9 b	16.7 ab	0.32 a	2.57 ab	0.098	0.035 ab	0.025
	67	61.3 b	5.95 b	21.1 ab	5.11 b	44.6 bc	15.8 ab	0.21 b	2.31 ab	0.093	0.033 b	0.021
	90	52.5 b	5.33 b	15.6 b	4.39 b	37.9 c	12.8 c	0.20 b	1.90 b	0.088	0.027 b	0.018
	Mean	60.2	6.09	20.7	5.06	45.0	15.5	0.25	2.47	0.099	0.033	0.023
	CV	10.6	15.9	24.1	11.6	9.9	12.1	16.6	27.7	23.1	18.3	42.5

^{NS} = Not significant at P = 0.05

† = Significant at P= 0.1

Table A.2.9. Nutrient uptake of crop residues at 5 rye seeding rate treatments measured at the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	------------------------------					kg ha $^{-1}$	------------------------------				
2018	0	37.7 ^{NS}	4.26 ^{NS}	12.1 ^{NS}	3.86 ^{NS}	25.4 ^{NS}	11.2 ^{NS}	0.15 ^{NS}	1.42 ^{NS}	0.066 ^{NS}	0.038 ^{NS}	0.010 ^{NS}
	22	45.7	4.85	12.6	4.42	27.0	12.7	0.19	1.72	0.077	0.046	0.011
	45	49.9	5.22	14.0	4.70	29.2	13.3	0.15	1.81	0.080	0.047	0.011
	67	47.0	4.85	11.6	4.38	26.2	11.3	0.21	1.39	0.067	0.042	0.011
	90	43.4	4.49	10.5	3.96	23.3	10.4	0.14	1.33	0.055	0.038	0.009
	Mean	44.7	4.73	12.2	4.26	26.2	11.8	0.17	1.54	0.069	0.042	0.010
	CV	28.7	30.7	26.7	28.7	23.7	27.1	39.8	28.5	29.4	26.7	38.6
2019	0	69.7 ^{NS}	6.04 ^{NS}	19.7 ^{NS}	4.47 ^{NS}	36.6 ^{NS}	14.5 ^{NS}	0.284 ^{NS}	2.17 ^{NS}	0.050 ^{NS}	0.042 ^{NS}	0.021 ^{NS}
	22	70.3	6.62	21.2	4.43	33.9	12.1	0.242	1.97	0.065	0.036	0.018
	45	69.1	7.37	24.9	4.68	34.8	13.0	0.271	2.03	0.069	0.038	0.019
	67	72.9	7.20	24.3	4.79	33.0	12.7	0.272	1.91	0.056	0.029	0.019
	90	82.3	8.08	27.5	5.26	35.8	13.1	0.266	1.78	0.088	0.038	0.013
	Mean	72.8	7.06	23.5	4.73	34.8	13.1	0.267	1.97	0.066	0.037	0.018
	CV	11.3	20.0	23.3	14.5	14.1	13.5	20.0	21.8	35.0	16.1	26.1

^{NS} = Not significant at P = 0.05

Table A.2.10. Nutrient uptake of crop residues at 5 rye seeding rate treatments measured at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Fe	Mn	Cu	B	Mo
	kg ha $^{-1}$				kg ha $^{-1}$					kg ha $^{-1}$			
2018	0	37.3 a	4.28 a	16.1 a	3.70 a	21.9 a	11.4 a	0.14 ^{NS}	22.1 a	1.35 a	0.062 a	0.043 a	0.013† a
	22	30.5 ab	3.15 b	12.8 ab	2.97 ab	20.7 ab	9.48 ab	0.11	22.2 a	1.37 a	0.056 a	0.039 ab	0.012 ab
	45	22.2 bc	2.38 bc	9.25 b	2.24 bc	16.2 c	7.61 bc	0.09	15.8 b	0.99 b	0.041 b	0.032 bc	0.009 b
	67	25.5 bc	2.76 bc	10.7 b	2.52 bc	16.8 bc	7.79 bc	0.11	17.1 b	1.02 b	0.040 b	0.030 bc	0.008 b
	90	20.8 c	2.29 c	9.25 b	2.04 c	14.6 c	6.29 c	0.09	16.0 b	0.86 b	0.035 b	0.027 c	0.008 b
	Mean	27.9	3.06	11.9	2.77	18.2	8.63	0.11	18.7	1.15	0.048	0.035	0.010
	CV	19.9	14.8	17.7	18.5	13.9	14.5	30.4	16.2	17.3	16.4	16.0	24.8
2019	0	55.2 ^{NS}	4.18 ^{NS}	13.7† b	3.06 c	30.9 ^{NS}	12.4 ^{NS}	0.229 ^{NS}	32.5 ^{NS}	1.93 ^{NS}	0.045 ^{NS}	0.032 ^{NS}	0.015 ^{NS}
	22	56.9	4.92	16.1 a	3.65 bc	27.5	10.9	0.203	27.4	1.58	0.016	0.030	0.013
	45	60.2	4.99	18.0 a	3.73 bc	30.6	11.5	0.215	30.6	1.82	0.024	0.031	0.015
	67	68.3	6.04	20.8 a	4.96 a	34.5	13.0	0.236	29.1	1.82	0.040	0.037	0.016
	90	66.1	6.03	20.6 a	4.25 ab	35.9	13.4	0.267	34.2	1.98	0.041	0.038	0.016
	Mean	61.3	5.23	17.8	3.80	31.9	12.3	0.230	30.8	1.83	0.033	0.034	0.015
	CV	12.6	21.1	21.4	15.0	16.2	20.6	21.8	26.0	22.8	33.8	20.0	28.2

^{NS} = Not significant at P = 0.05
† = Significant at P= 0.1

Table A.3.1. Nutrient concentration of the soybean 3rd leaf at 5 rye seeding rate treatments measured at the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	----------g kg^{-1}----------						----------mg kg^{-1}----------				
2019	0	60.2 ^{NS}	5.21 ^{NS}	22.5 ^{NS}	2.48 ^{NS}	8.82 ^{NS}	3.18 ^{NS}	33.5 ^{NS}	56.3 ^{NS}	9.65 ^{NS}	44.6 ^{NS}	0.64 ^{NS}
	22	58.2	4.37	21.3	2.26	8.20	2.86	30.5	56.3	10.3	44.4	0.41
	45	60.6	5.20	24.2	2.45	9.46	3.32	35.5	64.3	10.5	47.7	0.46
	67	57.4	4.56	22.5	2.29	8.80	2.95	30.8	61.3	8.75	44.0	0.18
	90	59.4	5.14	23.9	2.37	9.13	3.16	34.5	64.5	9.85	44.5	0.48
	Mean	59.2	4.90	23.1	2.37	8.88	3.09	33.0	60.7	9.78	45.0	0.43
	CV	4.26	14.3	8.62	5.44	8.24	10.8	9.62	9.02	18.0	8.52	69.8

^{NS} = Not significant at P = 0.05

Table A.3.2. Secondary nutrient concentration of soybeans at 5 rye seeding rate treatments measured at the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	--------g kg^{-1}-------		---------------------------mg kg^{-1}---------------------------				
2018	0	9.86 ^{NS}	4.37 ^{NS}	16.3 ^{NS}	67.5 ^{NS}	9.70 ^{NS}	32.8 ^{NS}	0.13 ^{NS}
	22	9.83	4.30	18.5	64.5	9.03	32.2	0.12
	45	9.94	4.25	19.8	64.3	9.53	32.0	0.10
	67	10.3	4.35	20.3	65.5	9.45	31.8	0.22
	90	9.87	4.27	21.8	65.8	9.15	32.6	0.17
	Mean	9.97	4.31	19.3	65.5	9.37	32.3	0.15
	CV	7.24	5.94	18.6	11.9	12.2	7.56	42.8
2019	0	12.6 ^{NS}	4.26 ^{NS}	29.0 ^{NS}	54.8 ^{NS}	8.80 ^{NS}	37.8 ^{NS}	0.418 ^{NS}
	22	11.9	3.96	29.5	55.8	7.98	37.8	0.138
	45	12.2	4.47	29.8	57.5	9.03	36.0	0.323
	67	12.0	4.11	29.8	58.3	8.30	36.4	0.183
	90	11.5	3.86	28.5	50.8	8.33	34.4	0.105
	Mean	12.03	4.13	29.3	55.4	8.49	36.5	0.233
	CV	4.62	7.23	8.27	8.19	17.5	9.09	79.9

^{NS} = Not significant at P = 0.05

Table A.3.3. Secondary nutrient concentration of soybeans at 5 rye seeding rate treatments measured at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	-------g kg^{-1}------		----------------------------mg kg^{-1}--------------------------				
2018	0	8.44 ^{NS}	3.81 ^{NS}	20.3 ^{NS}	66.8* a	9.95 ^{NS}	31.1 ^{NS}	1.19 ^{NS}
	22	8.70	3.90	20.3	66.5 a	9.83	32.4	1.11
	45	8.41	3.85	16.3	64.0 ab	9.90	31.9	1.16
	67	8.34	3.73	17.8	58.8 b	9.98	30.0	0.89
	90	8.02	3.66	15.5	62.0 ab	9.23	31.4	1.40
	Mean	8.38	3.79	18.0	63.6	9.78	31.3	1.15
	CV	6.05	5.98	18.1	6.50	5.70	4.58	32.0
2019	0	11.0 ^{NS}	3.49 ^{NS}	19.8 ^{NS}	45.0 ^{NS}	5.08 ^{NS}	31.9 b	0.795 ^{NS}
	22	11.1	3.61	21.8	45.3	8.60	35.8 a	0.555
	45	10.7	3.45	20.8	44.0	6.23	34.3 ab	0.860
	67	10.6	3.23	20.5	43.3	4.90	35.7 a	0.510
	90	10.7	3.24	20.8	41.5	6.30	34.3 ab	0.613
	Mean	10.8	3.40	20.7	43.8	6.29	34.5	0.667
	CV	3.51	8.12	5.75	5.66	32.3	4.31	36.9

^{NS} = Not significant at P = 0.05

* = Significant at P= 0.1

Table A.3.4. Soybean nutrient uptake of secondary nutrients at 5 rye seeding rate treatments measured at the soybean R3 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	----------	----------	----------	kg ha $^{-1}$	----------	----------	----------
2018	0	222 [NS]	36.3 [NS]	0.13 [NS]	0.56 [NS]	0.08 [NS]	0.27 [NS]	0.0010 bc
	22	188	33.0	0.14	0.49	0.07	0.25	0.0009 bc
	45	206	36.9	0.17	0.56	0.08	0.28	0.0008 c
	67	231	39.3	0.18	0.59	0.09	0.29	0.0019 a
	90	209	37.0	0.19	0.56	0.08	0.28	0.0015 ab
	Mean	84.9	36.5	0.16	0.55	0.08	0.68	0.0012
	CV	17.0	18.2	24.1	13.8	18.4	13.9	35.7
2019	0	78.3 [NS]	26.9 [NS]	0.185 [NS]	0.349 [NS]	0.056 [NS]	0.241 [NS]	0.003 [NS]
	22	78.9	26.5	0.199	0.373	0.054	0.254	0.001
	45	74.4	27.5	0.183	0.352	0.055	0.219	0.002
	67	76.4	26.4	0.190	0.374	0.053	0.231	0.001
	90	71.1	24.5	0.181	0.315	0.052	0.215	0.001
	Mean	75.8	26.3	0.188	0.352	0.054	0.232	0.002
	CV	12.7	14.9	14.4	15.8	22.7	15.4	85.5

[NS] = Not significant at P = 0.05

Table A.3.5. Soybean nutrient uptake of secondary nutrients at 5 rye seeding rate treatments measured at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha $^{-1}$	-----	-----	-----	kg ha $^{-1}$	-----	-----	-----
2018	0	93.6* ab	42.0* ab	0.23 ^{NS}	0.74* ab	0.11 ab	0.34 bc	0.0138 ^{NS}
	22	104 a	46.2 a	0.24	0.79 a	0.12 a	0.39 ab	0.0139
	45	104 a	47.4 a	0.20	0.80 a	0.12 a	0.40 a	0.0151
	67	92.9 ab	41.6 ab	0.20	0.66 b	0.11 ab	0.33 c	0.0097
	90	83.9 b	38.0 b	0.17	0.65 b	0.10 b	0.33 c	0.0151
	Mean	95.6	43.1	0.21	0.73	0.11	0.36	0.0135
	CV	10.7	10.6	21.4	11.5	10.0	9.3	34.9
2019	0	172 ^{NS}	55.1 ^{NS}	0.31 ^{NS}	0.71 ^{NS}	0.08 ^{NS}	0.49 ^{NS}	0.013 ^{NS}
	22	154	49.3	0.28	0.63	0.12	0.49	0.008
	45	159	51.8	0.31	0.66	0.09	0.52	0.013
	67	157	49.8	0.32	0.68	0.08	0.55	0.008
	90	167	50.9	0.32	0.65	0.10	0.54	0.010
	Mean	162	51.4	0.310	0.666	0.093	0.516	0.010
	CV	14.1	12.7	9.24	13.7	35.0	12.9	34.2

^{NS} = Not significant at P = 0.05

* = Significant at P= 0.1

Table A.3.6. Nutrient concentration of soybean senesced leaves at 5 rye seeding rates measured at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	------------g kg^{-1}------------						------------mg kg^{-1}------------				
2018	0	18.1 ^{NS}	1.50 ^{NS}	18.3 ^{NS}	1.83 ^{NS}	25.1 ^{NS}	6.52 ^{NS}	30.8 ^{NS}	255 ^{NS}	10.2 ^{NS}	49.3 ^{NS}	1.29 ^{NS}
	22	17.6	1.40	16.3	1.78	24.9	6.62	33.8	293	13.1	48.7	2.49
	45	16.0	1.37	16.2	1.64	22.9	6.29	44.5	320	13.5	45.3	2.94
	67	16.8	1.45	17.6	1.82	24.9	6.28	35.0	315	12.3	46.5	2.75
	90	16.0	1.43	20.1	1.72	23.0	6.13	35.5	276	11.2	46.9	1.96
	Mean	16.89	1.43	17.7	1.76	24.2	6.37	35.9	292	12.0	47.3	2.29
	CV	11.0	11.6	15.7	10.4	10.4	7.80	25.9	19.7	17.0	13.5	39.6
2019	0	15.8 ^{NS}	1.22 ^{NS}	11.0 ^{NS}	1.20 ^{NS}	29.2 ^{NS}	6.67 a	61.0 ^{NS}	286 ^{NS}	286 ^{NS}	40.1 ^{NS}	1.89* a
	22	16.6	1.20	10.7	1.21	27.6	5.71 b	69.3	292	292	44.2	1.64 a
	45	15.0	1.01	12.2	1.10	28.7	5.83 b	64.8	256	256	44.1	1.35 ab
	67	16.4	1.14	11.8	1.18	29.3	5.47 b	65.0	255	255	45.2	0.95 ab
	90	16.1	1.17	11.9	1.16	30.2	5.26 b	72.0	237	237	47.8	0.65 b
	Mean	16.0	1.15	11.5	1.17	29.0	5.74	66.4	265	265	44.3	1.30
	CV	6.58	21.8	15.8	9.44	8.76	7.34	14.4	20.9	20.9	9.26	47.2

^{NS} = Not significant at P = 0.05

* = Significant at P= 0.1

Table A.3.7. Nutrient concentration (kg ha^{-1}) of soybean senesced leaves at 5 rye seeding rate treatments measured at the R6 soybean growth stage located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	----------	----------	----------	----------	----------	kg ha^{-1}	----------	----------	----------	----------	----------
2018	0	18.0 a	1.49 NS	18.2 NS	1.82 NS	24.9 NS	6.46 NS	0.031 NS	0.25 NS	0.010 NS	0.049 NS	0.0013 NS
	22	18.7 a	1.50	17.5	1.89	26.3	6.91	0.036	0.31	0.014	0.051	0.0026
	45	17.7 ab	1.52	17.9	1.80	24.9	6.74	0.048	0.37	0.015	0.049	0.0024
	67	17.5 ab	1.50	18.4	1.88	25.6	6.44	0.036	0.27	0.013	0.048	0.0028
	90	15.9 b	1.55	21.8	1.86	23.4	6.59	0.038	0.27	0.012	0.051	0.0021
	Mean	17.6	1.51	18.8	1.85	25.1	6.63	0.038	0.31	0.013	0.050	0.0022
	CV	6.43	10.5	13.5	8.99	5.42	5.61	22.7	29.6	23.9	12.2	35.8
2019	0	4.97 NS	0.221 NS	3.21 NS	0.386 NS	9.18 NS	2.67 a	0.020 NS	0.079 NS	0.00033 NS	0.012 NS	0.0004* a
	22	4.05	0.288	3.04	0.291	7.21	1.53 ab	0.018	0.067	0.00055	0.011	0.0003 abc
	45	3.99	0.277	3.65	0.299	7.99	1.68 ab	0.019	0.071	0.00067	0.012	0.0004 abc
	67	3.75	0.266	3.17	0.274	6.97	1.35 b	0.016	0.062	0.00033	0.010	0.0002 bc
	90	3.73	0.267	2.86	0.271	6.95	1.42 ab	0.018	0.060	0.00061	0.011	0.0002 c
	Mean	4.10	0.266	3.18	0.304	7.66	1.68	0.018	0.068	0.0005	0.011	0.0003
	CV	27.0	30.9	25.3	26.6	21.8	24.6	23.1	35.3	46.9	17.8	31.3

NS = Not significant at P = 0.05

* = Significant at P= 0.1

Table A.3.8. Nutrient concentration of soybean grain at 5 rye seeding rate treatments measured at soybean harvest located at the Southeast Research Farm near Beresford, SD, 2018-2019.

Sample Date	Seeding Rate	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
	kg ha^{-1}	----------	----------	----------	g kg^{-1}	----------	----------	----------	----------	mg kg^{-1}	----------	----------
2018	0	62.3 ^{NS}	5.59 ^{NS}	19.1 ^{NS}	3.44 ^{NS}	3.11 ^{NS}	2.63 ^{NS}	44.0 ^{NS}	29.5 ^{NS}	14.4 ^{NS}	32.4 ^{NS}	2.99 c
	22	62.4	5.62	18.9	3.34	3.08	2.63	43.3	29.3	14.6	32.1	2.62 c
	45	62.2	5.42	18.7	3.33	3.02	2.60	41.8	28.5	15.0	32.0	5.61 ab
	67	62.7	5.68	18.7	3.37	2.97	2.58	41.8	27.8	13.4	31.3	3.38 bc
	90	61.6	5.50	18.6	3.35	2.87	2.59	38.3	27.7	13.9	31.5	6.66 a
	Mean	62.2	5.56	18.8	3.39	3.01	2.60	41.8	28.6	14.3	31.9	4.25
	CV	0.99	4.96	1.81	4.50	4.13	2.22	18.9	4.30	5.91	3.16	34.1
2019	0	58.7 ^{NS}	5.73 ^{NS}	17.7 ^{NS}	2.43 ^{NS}	3.21 ^{NS}	2.46 ^{NS}	33.3 ^{NS}	27.0 ^{NS}	12.8 ^{NS}	31.8 ^{NS}	1.31 ^{NS}
	22	58.5	5.71	18.1	2.33	3.27	2.47	34.5	26.5	12.5	33.0	1.51
	45	59.3	5.53	17.6	2.36	3.17	2.44	34.8	26.5	12.6	32.1	1.63
	67	59.2	5.58	17.9	2.34	3.17	2.47	33.8	26.5	12.5	32.3	2.26
	90	58.9	5.75	17.8	2.34	3.27	2.43	33.3	27.8	13.7	33.0	1.68
	Mean	58.9	5.66	17.8	2.36	3.22	2.45	33.9	26.9	12.8	32.4	1.68
	CV	0.95	0.95	3.76	5.16	6.12	5.75	10.4	7.03	8.62	3.18	33.6

^{NS} = Not significant at P = 0.05

APPENDIX B

Table B.1.1. Crop residue nutrient concentration of micronutrients for 5 rye termination timing treatments measured initially at the time of termination, on August 5th corresponding with the soybean R3 growth stage, and on August 30th at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Ca	Mg	Zn	Mn	Cu	B	Mo
		---------g kg $^{-1}$-------		----------------------------mg kg $^{-1}$------------------------				
Apr 19	Apr 19	5.19 a†	2.04 ^{NS}	98.8 ^{NS}	658 ^{NS}	13.8 b†	4.80 ^{NS}	2.88 b
Apr 29	Apr 29	4.96 ab	2.25	114	798	14.6 b	4.72	3.14 b
May 13	May 13	4.78 ab	2.14	115	769	14.6 b	4.86	3.34 b
May 23	May 23	4.55 b	2.27	106	771	16.6 a	5.02	4.26 a
May 31	May 31	4.44 b	2.05	99.6	674	15.4 ab	4.62	2.92 b
	Mean	4.78	2.15	107	734	15.0	4.80	3.42
	CV	8.09	10.2	14.1	12.9	9.00	9.80	22.2
Aug 5	Apr 19	4.38 ^{NS}	1.70 ^{NS}	78.3 ^{NS}	540 ^{NS}	11.0 ^{NS}	4.28 ^{NS}	2.52 ^{NS}
	Apr 29	4.48	1.73	71.6	494	11.2	4.32	2.92
	May 13	4.54	1.68	76.6	540	11.2	4.20	2.80
	May 23	4.88	1.91	82.6	520	11.5	4.74	2.54
	May 31	4.18	1.78	71.2	434	11.8	4.80	3.38
	Mean	4.49	1.76	76.0	505	11.3	4.47	2.83
	CV	22.4	19.8	24.1	20.7	23.1	19.2	28.4
Aug 30	Apr 19	5.11 ^{NS}	2.10 ^{NS}	77.8 ^{NS}	615 a	13.2 ^{NS}	7.06 ^{NS}	3.12 ^{NS}
	Apr 29	4.66	1.84	76.0	536 abc	11.6	6.66	3.29
	May 13	5.30	2.06	88.2	601 ab	12.0	7.38	3.17
	May 23	4.60	2.06	80.2	524 bc	13.2	7.25	3.78
	May 31	5.49	2.26	67.6	463 c	12.2	7.78	3.70
	Mean	5.05	2.06	78.0	551	12.4	7.23	3.42
	CV	14.5	13.1	17.3	11.8	18.7	15.3	18.2

^{NS} = Not significant at P = 0.05

† = Significant at P=0.1

Table B.1.2. Crop residue nutrient uptake of micronutrients for 5 rye termination timing treatments measured initially at the time of termination, on August 5th corresponding with the soybean R3 growth stage, and on August 30th at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Ca	Mg	Zn	Mn	Cu	B	Mo
		----------	----------	----------	kg ha $^{-1}$	----------	----------	----------
Apr 19	Apr 19	15.4 a	6.0 a	0.26 ab	1.94 a	0.040 ab	0.014 a	0.008 bc
Apr 29	Apr 29	15.0 a	6.83 a	0.37 a	2.43 a	0.044 a	0.014 a	0.009 abc
May 13	May 13	15.9 a	7.14 a	0.39 a	2.46 a	0.048 a	0.016 a	0.011 a
May 23	May 23	12.2 ab	5.94 a	0.29 ab	2.01 a	0.044 a	0.013 a	0.011 ab
May 31	May 31	7.82 b	3.57 b	0.17 b	1.16 b	0.0268 b	0.008 b	0.006 c
	Mean	13.3	5.91	0.30	2.00	0.041	0.013	0.0090
	CV	26.1	26.5	32.7	24.6	23.8	26.4	24.4
Aug 5	Apr 19	5.55 d	2.11 c	2.11 c	0.67 b	0.014 c	0.005 c	0.003 c
	Apr 29	6.04 cd	2.32 c	2.32 c	0.70 b	0.015 c	0.006 c	0.004 c
	May 13	8.62 cd	3.18 c	3.18 c	1.02 b	0.018 c	0.008 c	0.005 bc
	May 23	13.2 b	5.19 b	5.19 b	1.42 a	0.031 b	0.013 b	0.007 b
	May 31	16.5 a	7.01 a	7.01 a	1.70 a	0.045 a	0.019 a	0.013 a
	Mean	9.98	3.96	3.96	1.10	0.025	0.010	0.006
	CV	19.9	21.1	21.1	24.2	19.3	22.6	30.1
Aug 30	Apr 19	7.02 b	2.88 c	0.14 ab	0.85 ^{NS}	0.018 bc	0.010 c	0.005 b
	Apr 29	7.10 b	2.70 c	0.11 b	0.76	0.017 c	0.010 c	0.005 b
	May 13	8.63 b	3.30 bc	0.14 ab	0.99	0.019 bc	0.012 bc	0.005 b
	May 23	10.4 b	4.48 b	0.16 ab	1.03	0.026 b	0.016 b	0.007 ab
	May 31	15.7 a	6.44 a	0.19 a	1.26	0.034 a	0.022 a	0.010 a
	Mean	9.76	3.96	0.15	0.98	0.023	0.014	0.006
	CV	29.1	27.3	38.0	30.3	27.3	29.2	36.0

^{NS} = Not significant at P = 0.05

Table B.2.1. Soybean nutrient concentration of micronutrients for 5 rye termination timing treatments measured on August 5th corresponding with the soybean R3 growth stage and on August 30th at the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Ca	Mg	Zn	Mn	Cu	B	Mo
		---------g kg^{-1}-------		------------------------mg kg^{-1}----------------------				
Aug 5	Apr 19	11.9 b	4.90 a†	30.2 NS	84.5 NS	8.22 NS	41.6 NS	0.22 NS
	Apr 29	11.7 b	4.83 a	31.0	84.8	9.36	40.8	0.24
	May 13	11.8 b	4.45 b	32.8	85.0	8.32	40.3	0.16
	May 23	12.2 b	4.72 ab	33.6	86.8	8.82	40.9	0.26
	May 31	13.5 a	4.96 a	35.0	95.6	7.26	42.7	0.24
	Mean	12.2	4.77	32.5	87.5	8.40	41.3	0.22
	CV	3.40	5.63	11.6	7.78	16.8	5.05	116.52
Aug 30	Apr 19	10.8 NS	4.65 NS	29.2 NS	78.8 NS	8.30 NS	35.9 NS	0.33 NS
	Apr 29	10.7	4.59	28.0	73.0	7.86	34.5	0.43
	May 13	10.9	4.53	29.4	76.8	7.98	35.1	0.28
	May 23	10.7	4.36	28.0	76.4	7.70	34.8	0.24
	May 31	11.1	4.44	28.2	71.6	7.46	35.0	0.22
	Mean	10.8	4.52	28.6	75.3	7.86	35.1	0.30
	CV	7.07	8.72	12.8	8.48	7.46	6.62	60.9

NS = Not significant at P = 0.05

† = Significant at P=0.1

Table B.2.2. Soybean nutrient uptake of micronutrients for 5 rye termination timing treatments measured on August 5th at the soybean R3 growth stage and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Ca	Mg	Zn	Fe	Mn	Cu	B	Mo
					kg ha $^{-1}$				
Aug 5	Apr 19	73.8 ^{NS}	30.4 a†	0.19 ^{NS}	0.78 ^{NS}	0.55 ^{NS}	0.05 a	0.26 a†	0.0014 ^{NS}
	Apr 29	69.9	29.0 ab	0.19	0.62	0.51	0.06 a	0.25 ab	0.0013
	May 13	58.5	25.5 c	0.17	0.70	0.43	0.04 bc	0.20 b	0.0007
	May 23	65.5	23.7 abc	0.18	0.61	0.47	0.05 abc	0.22 ab	0.0039
	May 31	65.0	21.6 bc	0.17	0.51	0.45	0.04 c	0.20 b	0.0011
	Mean	66.9	26.2	0.18	0.64	0.48	0.05	0.23	0.0017
	CV	15.4	18.0	11.7	30.0	14.4	21.0	14.1	164
Aug 30	Apr 19	105 ^{NS}	45.3 ^{NS}	0.29 ^{NS}	0.67 ^{NS}	0.75 ^{NS}	0.08 ^{NS}	0.35 ^{NS}	0.0038 ^{NS}
	Apr 29	102	43.9	0.26	0.67	0.69	0.08	0.33	0.0041
	May 13	101	42.4	0.28	0.76	0.79	0.07	0.33	0.0026
	May 23	97	39.9	0.26	0.64	0.69	0.07	0.32	0.0018
	May 31	102	40.6	0.26	0.75	0.65	0.07	0.32	0.0022
	Mean	102	42.4	0.27	0.69	0.72	0.07	0.33	0.0029
	CV	21.5	22.8	19.4	33.1	22.0	23.6	21.2	65.9

^{NS} = Not significant at P = 0.05

† = Significant at P=0.1

Table B.2.3. Nutrient concentration of soybean senesced leaves for 5 rye termination timing treatments measured on August 5th at the soybean R3 growth stage and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
		----g kg^{-1}----						----mg kg^{-1}----				
Aug 5	Apr 19	15.5 [NS]	1.13 c[†]	9.54 ab	1.57 [NS]	32.9 [NS]	10.3 [NS]	93.4 [NS]	463 [NS]	9.80 a	49.6 [NS]	1.83 [NS]
	Apr 29	14.7	1.15 bc	8.66 abc	1.50	31.9	9.55	93.0	433	10.4 a	48.5	1.94
	May 13	16.3	1.30 abc	10.3 a	1.67	31.7	9.63	110	448	10.3 a	48.1	1.96
	May 23	16.2	1.39 a	7.70 c	1.60	35.6	10.9	112	448	10.2 a	51.1	1.86
	May 31	16.7	1.38 ab	8.14 bc	1.59	34.5	10.4	100	418	8.46 b	51.2	1.42
	Mean	15.9	1.27	8.86	1.59	33.3	10.2	102	442	9.825	49.7	1.80
	CV	7.79	13.7	13.8	9.15	11.6	11.9	21.2	13.8	7.10	8.02	22.0
Aug 30	Apr 19	18.1 [NS]	1.36 b	10.3 ab[†]	1.33 [NS]	22.6 b[†]	6.46 [NS]	72.2 [NS]	408 [NS]	12.6 [NS]	46.3 b	2.62 [NS]
	Apr 29	17.6	1.31 bc	8.34 b	1.23	21.8 b	6.51	69.4	372	11.2	44.7 b	2.06
	May 13	17.1	1.24 c	10.0 ab	1.32	22.4 b	6.48	72.6	388	10.5	45.0 b	1.79
	May 23	17.8	1.50 a	11.1 a	1.41	23.6 ab	6.65	69.0	315	10.5	48.1 ab	1.91
	May 31	18.4	1.57 a	8.76 b	1.43	26.3 a	7.34	76.2	328	10.1	55.6 a	1.46
	Mean	17.8	1.40	9.70	1.34	23.3	6.69	71.9	362	11.0	47.9	1.97
	CV	4.89	5.79	16.3	9.30	10.3	12.7	11.7	21.0	15.8	12.1	35.9

[NS] = Not significant at P = 0.05

[†] = Significant at P=0.1

Table B.2.4. Nutrient uptake of soybean senesced leaves for 5 rye termination timing treatments measured on August 5th at the soybean R3 growth stage and on August 30th corresponding with the soybean R6 growth stage located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	N	P	K	S	Ca	Mg	Zn	Mn	Cu	B	Mo
		kg ha $^{-1}$										
Aug 5	Apr 19	8.10 a	0.57 a	5.30 a	0.82 a	16.6 a	5.15 a	0.05 a	0.24 a	0.005 a	0.025 a	0.0009 a
	Apr 29	7.43 a	0.57 a	4.57 a	0.78 a	16.0 a	4.89 a	0.05 a	0.24 a	0.005 a	0.024 a	0.0009 a
	May 13	6.18 b	0.49 a	3.91 a	0.62 b	12.3 b	3.74 b	0.04 a	0.17 b	0.004 ab	0.019 b	0.0007 ab
	May 23	3.92 c	0.32 b	1.86 b	0.38 c	8.52 c	2.72 c	0.03 b	0.11 c	0.002 bc	0.013 c	0.0003 bc
	May 31	2.48 d	0.21 b	1.28 b	0.24 d	5.17 d	1.56 d	0.02 b	0.06 d	0.001 c	0.008 d	0.0002 c
	Mean	5.55	0.43	3.38	0.56	11.5	3.56	0.04	0.16	0.00	0.02	1.80
	CV	14.2	22.6	29.9	17.0	17.4	20.4	25.4	14.9	33.3	18.9	22.0
Aug 30	Apr 19	23.9 a	1.79 a	13.3 a	1.75 a	29.9 a	8.60 a	0.10 a	0.55 a	0.017 a	0.061 a	0.0036 a†
	Apr 29	22.5 a	1.68 a	10.8 a	1.58 a	27.7 a	8.33 a	0.09 a	0.48 ab	0.014 a	0.057 ab	0.0026 ab
	May 13	19.7 a	1.46 ab	11.5 a	1.48 a	25.3 a	7.32 a	0.08 a	0.43 ab	0.013 ab	0.051 b	0.0020 ab
	May 23	21.4 a	1.81 a	13.6 a	1.68 a	27.8 a	7.84 a	0.08 a	0.37 bc	0.012 a	0.057 ab	0.0024 ab
	May 31	13.6 b	1.16 b	6.56 b	1.05 b	19.1 b	5.33 b	0.06 b	0.24 c	0.007 b	0.040 c	0.0011 b
	Mean	20.2	1.58	11.2	1.51	26.0	7.48	0.08	0.41	0.01	0.05	0.002
	CV	17.5	18.9	26.9	15.9	14.8	16.1	15.9	25.3	30.3	12.6	52.6

† = Significant at P=0.1

Table B.2.5. Secondary nutrient concentration of soybean grain for 5 rye termination timing treatments measured at harvest on October 18 located at the Southeast Research Farm near Beresford, SD, 2019.

Sample Date	Rye Termination	Ca	Mg	Zn	Mn	Cu	B	Mo
		---------g kg^{-1}-------		--------------------------mg kg^{-1}-----------------------				
October 18	April 19	2.87 b	2.21 b	35.8 NS	34.0 NS	12.0 NS	39.9 NS	2.22 NS
	April 29	2.77 b	2.15 b	34.8	34.5	11.6	38.7	1.87
	May 13	2.80 b	2.19 b	35.8	34.6	11.5	38.4	1.75
	May 23	2.84 b	2.20 b	36.8	34.6	12.2	38.0	3.26
	May 31	3.01 a	2.34 a	36.2	34.0	12.0	39.8	1.83
	Mean	2.86	2.22	35.9	34.3	11.9	38.1	2.20
	CV	2.47	2.95	4.92	2.84	4.14	3.49	82.1

NS = Not significant at P = 0.05