Literature Review and Synthesis of the Effectiveness of Cover Crops for Water Quality Management in the Upper Mississippi River Basin

Abstract

This work was funded by the Walton Family Foundation and synthesizes the ‘state of the science’ regarding the use of cover crops as agricultural best management practices for water quality management. This work summarizes the effects of grasses, legumes, non-leguminous broadleaves, mixes, and living mulches on water quality, specifically nutrients, through the examination of several factors, including soil characteristics, health, and crop yield. The effect of cover crops is quite variable on site-specific field conditions, but the literature suggests a positive trend in the overall environmental benefits. The goal of this work is to identify the knowledge gaps for these cover crops in the Midwestern United States to guide future research.

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Terminology/Acronym List

Acronym	Meaning
BMP	Best management practice
C	Carbon
CAST	Chesapeake Assessment Scenario Tool
CBPWM	Chesapeake Bay Program Watershed Model
DAP	Diammonium phosphate
INRS	Iowa Nutrient Reduction Strategy
MARB	Mississippi/Atchafalaya River Basin
N	Nitrogen
N_2	Atmospheric nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
P	Phosphorus
PFI	Practical Farmers of Iowa
SOM	Soil organic matter
UMRB	Upper Mississippi River Basin
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency

Conversion Factors

Original (O)	Desired (D)	Multiplication Factor
Kilogram (kg)	Pound (lb)	× 2.204262
Pound (lb)	Kilogram (kg)	× 0.452592
Hectare (ha)	Acre (ac)	× 2.471054
Acre (ac)	Hectare (ha)	× 0.404686

** To convert from original (O) units to desired (D) units, multiply O by the multiplication factor.*

Executive Summary

Funded by the Walton Family Foundation, this work is intended to broaden the accepted or acknowledged water quality benefits of lesser studied cover crops. Hypoxia in the Gulf of Mexico has led to the formation of a committee called the Hypoxia Task Force (the Task Force)—a coalition of Federal, State, and Tribal governing authorities—to develop strategies to reduce the size of the hypoxic zone. As a result of the Task Force's initiatives, each state in the Mississippi/Atchafalaya River Basin (MARB) is developing a state-wide strategy to reduce its nutrient export (nitrogen, N, and phosphorus, P). The Task Force has recommended continued improvement of the accuracy, variation, and reproducibility of various strategies and conservation practices states are using to attain nutrient reductions. The intent of this work is to compare nutrient reduction efficiencies of cover crops along with other impacts on agricultural systems to inform states in the MARB in their decision to accept or consider reporting water quality benefits of these alternative management activities. Though primarily focused on the Upper Mississippi River Basin (UMRB), the information contained in this literature review can be extended to the entire MARB for inclusion in each state's nutrient reduction strategies.

This report evaluates the effects of leguminous cover crops, non-leguminous broadleaves, cover crop mixes, and living mulches in comparison to the traditional grass-based cover crop. It synthesizes the overall 'state of the science' to further understand the effects of these cover crops on soil health, crop yield, water quality, and understanding the water quality benefits of this management practice. Despite the extensive amount of research on cover crops, there remains a large degree of variability on their environmental effects. It is therefore challenging to provide conclusive statements on the direct water quality benefits; however, a preliminary illustration of these benefits on crop yield, nutrient reductions, and cost is shown in Table 1.

Table 1. Synthesis of the effects of each type of cover crop on various factors based on literature reviewed. Ancillary benefits are intended to highlight when other production goals should be considered, including soil health, cash crop yield, pest reductions, or any other benefit beyond water quality.

<table>
<tr><td></td><td colspan="4">Effect (++, +, − −, −, +/−)</td><td></td></tr>
<tr><td>Cover Crop</td><td>Crop Yield</td><td>N Immobilization</td><td>P Leaching/Runoff Reduction</td><td>Cost*</td><td>Ancillary Benefits</td></tr>
<tr><td>Grasses</td><td>+/−</td><td>++</td><td rowspan="5">Not enough direct research</td><td>$9-25/ac</td><td>N/A</td></tr>
<tr><td>Legumes</td><td>+</td><td>+/−</td><td>$14-36/ac</td><td>+</td></tr>
<tr><td>Non-Leguminous Broadleaves</td><td>+/−</td><td>++</td><td>$12-20/ac</td><td>++</td></tr>
<tr><td>Mixes</td><td>+</td><td>++</td><td>Depends on mixture composition</td><td>+</td></tr>
<tr><td>Living Mulches</td><td>−</td><td>+</td><td>$40/ac</td><td>N/A</td></tr>
</table>

*Effects are reported using the following symbology: "++" consistently positive effect; "+" generally positive effect; "− −" consistently negative effect; "−" generally negative effect; "+/−" mixed results. * Costs are an approximation of reported values from an interpretive summary by Kaspar et al. (2008) and a southeastern Missouri cover crop factsheet by the USDA (2014).*

The effect of cover crops on soil health is a primary area of research with effects on soil and groundwater quality of particular interest. A potentially counterintuitive relationship exists in the soil quality to water quality interaction—changes in soil characteristics that are often considered beneficial for soil and plants may be detrimental to groundwater quality due to increased infiltration and soluble nutrients leaching into shallow groundwater. As such, soil health effects can be used as a proxy for estimating the water quality benefits of cover crops. Grass-based cover crops produce the largest quantity of biomass, so they are favorable when increasing the soil organic matter (SOM) content of the system is of concern. Like most vegetation, they can also help prevent erosion. Legumes are the most effective cover crops to produce mixed quality residues, which improve soil quality; additionally, they improve the habitat quality for beneficial insects. Similarly, brassicas are typically considered competitive crops with soil quality benefits, namely regarding erosion, leaching, and soil structure. Mixes and living mulches have comparable effects on soil health characteristics, as they each provide varied benefits dependent on their vegetative composition. Ultimately, the continued use of cover crops increases SOM along with other beneficial soil characteristics, including improved soil fertility, increased base N mineralization, and enhanced soil structure.

The impacts of these five cover crops on crop yield are varied. The use of grass-based cover crops, namely cereal rye, has traditionally been associated with negative impacts on subsequent crop yield, particularly in corn systems. Brassicas have similar effects on corn and soybean yields to grass-based cover crops; however, brassicas also have a range of ancillary benefits like reducing pest populations, minimizing soil-borne disease incidence, and preventing weed growth, which can further benefit cash crop production. Similarly, even when fertilizer additions are limited, the use of leguminous cover crops often results in increases in crop yields due to their biological accumulation of N, assuming sufficient biomass production. Typically, cover crop mixes with a high proportion of legumes lead to increases in cash crop yield, while those with a high proportion of grass-based plants lead to decreases in cash crop yield. Living mulches typically have a negative impact on crop yield. Since, by definition, they are grown concurrently with the cash crop, there is increased resource competition which can lead to decreased yield of the primary crop. While cover crops have traditionally been associated with negative impacts on crop yield, more diverse cover crop options like legumes, non-leguminous broadleaves, and mixes can improve yield.

Cover crops are often associated with benefits to water quality, as their biomass can take up N from the soil and prevent leaching. Although research on the direct impact of grasses on water quality is limited, there is evidence to suggest that planting grass-based cover crops markedly improves water quality relative to fallow land. Brassicas have similar water quality benefits to grass-based cover crops, but the reported water quality benefits of leguminous cover crops are substantially varied. While research on the direct link between legumes and levels of NO_3^- leachate does not show substantial evidence supporting a mitigating capacity, legumes affect the N budget and the need for fertilization in agricultural systems. Mixes are typically associated with benefits in water quality; however, if they have a high composition of legumes, those benefits can be minimized. Living mulches minimally improve water quality since they are only implemented on land where crops are already growing, which means they do not prevent fallow land in non-growing seasons. While all cover crops improve water quality to some degree by taking up excess N from the soil, some types of cover crops are more effective than others.

Due to growing interest in agricultural sustainability, there is an increasing body of research leading to a better understanding of trends and patterns regarding the effects of cover crop usage. For example, cover crops tend to provide some water quality benefit, corn yield reductions can occur with late termination of cereal rye, cover crop mix efficacy is sensitive to planting and termination timing, and legumes provide some N fixation while grasses and small grains do not. However, most of these trends are general. Often, studies produce ranges of benefits or other effects that vary widely–sometimes by orders of magnitude–so the conclusions in this review are therefore tempered by substantial uncertainty and have been generalized accordingly.

1 Introduction

Hypoxia in the Gulf of Mexico has led to the formation of a committee called the Hypoxia Task Force (the Task Force)—a coalition of Federal, State, and Tribal governing authorities—to develop strategies to reduce the size of the hypoxic zone. Established in 1997 and co-chaired by the United States Environmental Protection Agency (USEPA) and the United States Department of Agriculture (USDA) (USEPA, 2016), the Task Force has developed a basin-wide Action Plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008), which highlights 11 "Actions to Accelerate the Reduction of Nitrogen and Phosphorus," for 12 states. Thus, each state in the Mississippi/Atchafalaya River Basin (MARB) is developing a state-wide strategy to reduce its nutrient export (nitrogen, N, and phosphorus, P). The Task Force has also recommended continued improvement of the accuracy, variation, and reproducibility of various strategies and conservation practices states are using to attain nutrient reductions. For reference, the Upper Mississippi River Basin (UMRB), which includes Illinois, Indiana, Iowa, southern Minnesota, and Ohio yields anywhere from 1,500 to over 3,100 kilograms of N per square kilometer annually, which is several times that of other basins that drain to the Gulf of Mexico (Goolsby et al., 2001; Figure 1).

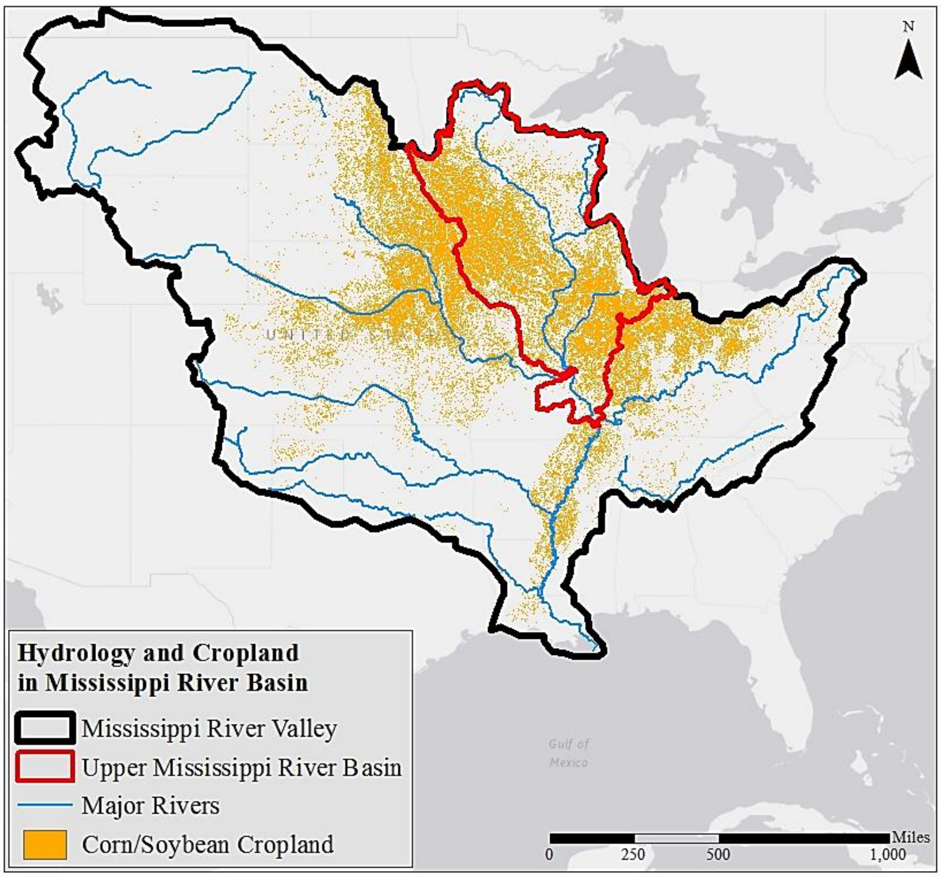

Figure 1. Major streams draining to the Gulf of Mexico in the Mississippi River Valley with associated corn/soybean cropland cover.

An extensive review of the effects of cover crops on water quality was recently completed by the U.S. EPA Chesapeake Bay Program through its Expert Panel process. The Chesapeake Bay Watershed, which has been under a Total Maximum Daily Load (TMDL) since 2010, used a suite of experts (the Panel) to provide insight regarding the addition of various cover crop species to the Chesapeake Bay Program Watershed Model (CBPWM) and to evaluate their associated nutrient and sediment reduction efficiencies. The Phase 5.3.2 version of the CBPWM added annual ryegrass, annual legumes, brassicas, forage radish, triticale, oats, and various legume-grass mixes as agricultural best management practices (BMPs) in the Chesapeake Bay Watershed (Clark et al., 2013). The latest version of the model to be released in 2018, Phase 6.0, will provide updates for the nutrient removal efficiencies of the cover crop types and expand the traditional cover crop BMP to include cropland with fall-applied manure following summer harvest (Staver et al., 2017). The results from this Panel may have applications that can be extended to the MARB, including estimated nutrient reduction efficiencies for the proposed cover crops (Appendix A).

The need for further MARB-based information is supported by Kaspar et al. (2008), who found 70% to 80% of the dominant corn-soybean cropping systems could benefit from using a cover crop. The general understanding of the effects of cover crops on water quality, soil health, and crop yield is evolving with available studies reporting a wide range of effectiveness. There is currently no single, comprehensive report documenting their effect, partially due to the challenges of understanding the effects of their complex nutrient removal process. Some variables include the evolving practice of planting cover crops, the physiological differences between types of vegetation, and the combined effects of climate, soils, and other factors across the expanse of the entire MARB.

This review is intended to highlight water quality benefits for cover crops other than the traditional grass-based cover crop (i.e. cereal rye) included in water quality studies. Historically, grass-based cover crops have been primarily used because they tend to over-winter well compared to other types of crops. However, due to advances in management, new breeding, genetic modification, and on-farm automation, the use of a more diverse set of cover crops is becoming increasingly practical. New cover crop mixes may be regionally tailored to provide maximum biomass growth, thereby increasing the potential for additional nutrient-loss reductions. Consequently, adapting to shifting growing regions by considering options that maximize cover crop growth and associated water quality benefits is critical. Although this document focuses on alternative cover crops, information on grass-based cover crops has also been included as a comparison since their impacts on water quality have been more established. This review also evaluates several other effects, including soil health impacts and implications for crop quality and yield. Accordingly, water quality benefits are perceptible regardless of the primary goal of cover crop selection, which could be enhancing soil health, increasing soil organic matter (SOM), controlling pests, or all of these objectives. The result of this review may facilitate the inclusion of more diverse or non-traditional cover crops by providing an acknowledged “credit” for producers while expanding management options.

This review focuses on a synthesis of the ‘state of the science’ and understanding the water quality benefits for five types of cover crops: grasses, legumes, non-leguminous broadleaves, mixes, and living mulches. It is intended to broaden the accepted or acknowledged water quality benefits of lesser studied cover crops. The intent is to compare nutrient reduction efficiencies along with other impacts on agricultural systems to inform states in the MARB in their decision to accept or consider reporting water quality benefits of these alternative management activities. Though primarily focused on the UMRB, the information contained in this literature review can be extended to the entire MARB for inclusion in each state’s nutrient reduction strategies.

2 Background

The primary purpose of this literature review is to summarize the water quality effects of cover crops with additional information regarding impacts on soil health, water storage, crop yield, and cost. Throughout the review, water quality effects are defined as reduction in sediment and nutrients from runoff or leachate to shallow groundwater or tile-drainage systems, as there is limited research on the water quality benefits at the 'edge of field' (Kasper et al., 2007; Qi et al., 2011).

A primary motivation for conducting this review was to identify regional differences in cover crop performance. An interpretive summary from Kaspar et al. (2008) noted that rye cover crops grown in colder climates had smaller N reduction benefits compared to those grown in warmer climates due to limited growth and frozen soils limiting water movement. The range of nitrate (NO_3^-) load reductions was reported between 13% and 95% moving from Minnesota to Kentucky, respectively; greater removal efficiency is associated with the more southern states. Reductions in phosphorus (P), on the other hand, were shown to be relatively high (54% to 94%) regardless of location. Further, the presence of artificial subsurface (i.e. tile) drainage contributes another nutrient loss pathway in addition to surface runoff. Distinguishing this pathway is particularly important in the Upper Mississippi states of Illinois, Iowa, and Minnesota, which have reported tile drainage areas of 48%, 32%, and 14% of cropland area, respectively (Sugg, 2007). In addition to climatic variations, differences in reported cover crop performance could also be attributed to these present and measured pathways.

Cover crops have great potential to significantly affect water quality based on how nutrient loss occurs in agricultural systems. Most commonly, the nutrient content assimilated in the plants during its growth is harvested and removed from the system. Additionally, N can be transformed from its inorganic form back into atmospheric N_2, which allows the natural cycle to continue. While nutrients naturally leach from the soil reserves into groundwater at very low concentrations, the leaching of supplemental nutrients (added during fertilization or manure application) increase the effect of this loss pathway on water quality. When it rains, the soil can only absorb and store a certain amount of water in its pores. The remaining water can become surface runoff, or it can flush into the groundwater. Since the organic forms of N and P are stored in soil reserves, this excess water can carry those nutrients along with it, ultimately reaching either surface bodies of water or groundwater. However, with the appropriate timing of cover crops this excess nutrient content may be taken up by the plant lessening the potential for eutrophication in downstream waterways.

2.2 Cover Crops and Soil Health

The continued use of cover crops has been linked to increases in soil organic matter (SOM) along with other beneficial soil characteristics, including improved soil fertility, increased bioavailable N, and enhanced soil structure (Abdollahi & Munkholm, 2013; Ding et al., 2006; MCCC, 2014; White et al., 2016; Dabney et al., 2001). The increase in SOM is beneficial to agricultural systems as the continued use of agricultural land depletes the soil's C pools. The impact on soil hydraulic characteristics due to changing SOM fractions is also well-established with the United States Department of Agriculture (USDA) Soil Water Characteristics Program (Saxton & Rawls, 2006); as SOM increases, saturated hydraulic conductivity (an indicator of infiltration), field capacity, and available water increase across all soil types. The link between cover crops (grass-based) and soil water content is highlighted by work done by Basche et al. (2016), which showed an increase of approximately 10% in the soil water content at field capacity and an increase of approximately 20% in plant-available water content when a cover-cropped field was compared to the standard corn-soybean control.

Although Basche et al. (2016) identified increased soil water content, the study did not find any significant impact on crop growth, leaf area, or N uptake when comparing cover crop and no cover crop treatment. This result implies that soil health needs to be measured directly, as these other factors may not be a reliable surrogate for soil health. Water quality improvements may result from changes in SOM, but cover crops can also reduce N through other processes, such as scavenging or taking up residual N into plant biomass, using excess water in the soil profile, and protecting the soil surface from wind and water erosion. Cover crops uptake inorganic forms of N from the soil and store that N in its organic form, which prevents it from leaching below the root zone; following decomposition of the cover crop, the organic N is released back into the soil for use by the subsequent cash crop (Dinnes et al., 2002).

Soil health is a primary factor affecting the overall agricultural production of crops. Soils provide the structure and nutrient content for health plant growth, yet the continued use of agricultural fields for crop production have negative effects on soil health. Consequently, the effect of cover crops on soil health is a primary area of research with effects on soil and groundwater quality. A potentially counterintuitive relationship exists in the soil quality to water quality interaction—changes in soil characteristics that are often considered beneficial for soil and plants may be detrimental to groundwater quality due to increased infiltration and soluble nutrients leaching into shallow groundwater.

A study by Soti, Rugg, & Racelis (2016) in Texas, looked at the impact of different cover crops (namely lablab, sunn hemp, pearl millet, and sudangrass) on mycorrhizal diversity, density, and structure. Their results indicated that cover crop type did not affect mycorrhizal diversity, but it did influence their density and structure. Additionally, sunn hemp, known to be a good sheep and goat forage (MCCC, 2014), resulted in the highest NO_3^- and P concentrations in soils available for crop production. Tonitto, David, & Drinkwater (2006) note 40% to 60% of an inorganically fertilized crops' N needs may come from reserves in the SOM, highlighting the importance of different N pools in the soil.

The loss of P is largely affected by subsurface soil characteristics. For example, higher saturated hydraulic conductivity may result in P loss due to greater rates of infiltration into the soil and subsequent tile drainage (Ojha et al., 2017). Similarly, in a tile-drained landscape, one point of consideration with increased infiltration often associated with cover crops and increased SOM is the potential for increased tile flow and associated NO_3^- and dissolved P loss due to increased soil porosity and decreased compaction (Abdollahi et al., 2013). However, it is important to note that surface runoff is often reduced when tile-drainage is present (Christianson et al., 2016), so total nutrient loss may be reduced as a result.

Overall, the majority of studies across most cover crop types show positive changes to soil health. Though minimal water quality data has been generated, changes in soil properties could, potentially, be used to infer water quality benefits. Multiple nutrient removal pathways make benefit separation difficult, highlighting the need for studies that directly compare the quality benefits of diverse cover crops. Due to the large number of inherently complex variables—soil characteristics (including cation exchange rate, macroporosity, mean aggregate size, and carbon content), temperature, plant type, atmospheric moisture, immediate local and regional groundwater conditions, and the antecedent conditions of the aforementioned variables—it can be difficult to parse the effects of any one factor with reasonable confidence.

3 Cover Crops

In the UMRB, corn production is expected to increase by approximately 14.4% due to the region's economic viability (Secchi et al., 2011). This agricultural intensification would result in a 5.4% and 4.1% increase in total N and P loads, respectively, delivered to the outlet of the UMRB in Grafton, Illinois (Secchi et al., 2011). As such, the study and implementation of agricultural conservation practices should be a primary focus for both food producers and the scientific community.

Due to growing interest in agricultural sustainability, there is an increasing body of research leading to a better understanding of trends and patterns regarding the effects of cover crop usage. For example, cover crops tend to provide some water quality benefit, corn yield reductions can occur with late termination of cereal rye, cover crop mix efficacy is sensitive to planting and termination timing, and legumes provide some N fixation while grasses and small grains do not. However, most of these trends are general. Often, studies produce ranges of benefits or other effects that vary widely–sometimes by orders of magnitude–and conclusions are therefore tempered by substantial uncertainty and must be generalized accordingly. Still, approximately 30% of producers are currently seeding cover crops prior to harvest (CTIC, SARE, & ASTA, 2016).

3.1 Grasses


http://practicalfarmers.org/app/uploads/2014/03/rye-elbon-8.jpg

In the 2015-2016 production year, cereals and grasses were found to be the primary cover crop used by American producers according a survey by the CTIC, SARE, & ASTA (2016). Cereal rye is especially common (MCCC, 2014), largely due to its rapid growth, substantial biomass production, and efficiency at scavenging inorganic N residing in the soil (Meisinger et al., 1991; Shipley et al., 1992). In addition, cereal cover crops produce the largest quantity of biomass, so they are favorable when increasing SOM content of the system is of concern (Snapp et al., 2005). Like most vegetation, cereal rye can help prevent erosion (Alliaume et al., 2014; De Baets et al., 2011), and it has multiple additional benefits within agricultural systems. In addition to cereal rye, annual ryegrass is a commonly used cover crop. It is important to note the distinction between these two grass-based cover crops, as they favor different growing conditions. However, like all conservation techniques, there are drawbacks to the use of grass-based cover crops; in this case, such drawbacks include a relatively little amount of N release for the cash crop during subsequent growing seasons and N immobilization in some cases (Snapp et al., 2005; Thorup-Kristensen et al., 2003). This section will outline the various impacts of grass-based cover crops on corn-soybean systems and water quality.

Most research regarding grass-based cover crops relates to impacts on crop yields. The use of grass-based cover crops, namely cereal rye, has traditionally been associated with negative impacts on subsequent crop yield, particularly in corn systems (Kaspar et al., 2007; Sawyer, Pantoja, & Barker, 2011; Vyn et al., 1999; Finney et al., 2016; Sawyer et al., 2010). Kaspar et al. (2007) observed a 9.7% and 6.7% reduction in corn and soybean yield, respectively, following the implementation of a rye cover crop. In one study, a 6% reduction in corn yield following rye cover crop growth was observed on four farms in Iowa (Sawyer, Pantoja, & Barker, 2011). In Pennsylvania, Finney et al. (2016) observed nearly a 45% reduction in corn yield following cereal rye growth, and in Ontario, Vyn et al. (1999) observed a 25.6 kg per hectare decrease in corn biomass following annual ryegrass. The apparent allelopathic relationship between rye and corn can be attributed to a multitude of factors, including soil water availability, insect and pest populations, and the influence of compounds from decomposition on plant growth and on the health of soil biota (Kaspar et al., 2008; Clark, 2008).

Similarly, Pantoja et al. (2015) observed a 6% reduction in corn yield and no effect on soybean yield following a rye cover crop. Sawyer et al. (2010) also report a decrease in corn yield following rye, but there was no statistically significant impact on soybean yield. This study reported an especially cold and wet season in addition to a heavy pest pressure during the rye treatment prior to corn planting, which likely amplified the observed reduction in corn yield and explains the null effect on soybean yield (Sawyer et al., 2010).

Additional studies in central Iowa and southern Minnesota have shown no statistically significant impact on corn or soybean yield following grass-based cover crop growth (Basche et al., 2016; Strock, Porter, & Russelle, 2004). Practical Farmers of Iowa (PFI) observed a corn yield reduction in three of ten sites from 2009 to 2010; however, PFI subsequently observed no statistically significant effect on corn or soybean yield following winter cereal rye cover cropping from 2011 to 2016 (PFI, 2016).

In contrast, the CTIC, SARE, & ASTA (2016) report a statistically significant increase in both corn and soybean yield following the growth of a cover crop. This is likely because the negative impacts of grass-based cover cropping on corn yield can be mitigated by effective planning and controlling of the cover crop's lifecycle. According to a study by Kaspar et al. (2008), over-wintering, grass-based cover crops should be terminated at least 10-14 days prior to planting corn for an optimal influence on corn yield. Evidence of the significance of lifecycle management and grass-based cover crop choice can be seen in the results of a model-based estimation by Lee et al. (2016); this study showed that early-planted cereal rye had the best performance in terms of NO_3^- reduction, while late-planted wheat had the worst. In addition to lifecycle control, the consideration of other factors that influence grass-based cover crop efficiency has the potential to mitigate adverse effects.

Although research on the direct impact of grasses on water quality is limited, there is evidence to suggest that planting grass-based cover crops markedly improves water quality relative to fallow land (Dabney et al., 2001; Snapp et al., 2005). However, there are several confounding variables that have the capacity to impact the overall efficiency of grass-based cover crops. Because of their unique physiology, grasses can scavenge N from the soil without producing N like legumes (Snapp et al., 2005). Additionally, the amount of biomass produced by a cover crop influences its ability to uptake nutrients. Ultimately, the higher the dry matter production of the grass, the more NO_3^- will be immobilized by the plant (Meisinger et al., 1991). Dry matter content is composed of above- and below-ground elements of vegetation; in other words, both the leaves and the root systems of a cover crop contribute to the crop's ability to prevent NO_3^- leaching (Friedrich et al., 1979). As such, the more biomass, the more water and nutrients the cover crop is likely to hold (Kaspar et al., 2008). Prabhakara, Hively, & McCarthy (2015) note a link between increases in cover crop biomass growth and water quality enhancements, which is a logical connection considering the potential for increased nutrient accumulation and water use. Similarly, Kuo & Sainju (1998) found a significant correlation both between rye biomass and residual N and rye biomass and N uptake. In addition to direct plant uptake, an Iowa study by Al-Kaisi et al. (2005) found that the biomass from perennial grass cover crops effectively increased the C and N sequestration capacity of Midwestern soils, which may further prevent nutrient leaching. High dry matter production of rye cover crops has also been associated with minimized weed growth (Boyd et al., 2009); this result is one that can make the growing conditions for subsequent cash crops more favorable, which may make seeding rye more appealing to farmers.

The growth curve of all plants, cover crops included, offers diminishing returns over time, with fastest growth rates in the middle of their growth cycles (Mirsky et al., 2009). When trying to increase the number of days per year with actively growing biomass, leaving the cover crop on the landscape as long as possible before planting the primary crop (e.g. terminate 10-14 days prior to planting corn, generally) would, intuitively, have additional water quality benefits. This has the potential to influence BMPs considering the broader goals of increased water quality and increased money-making crop yield. Feyereisen et al. (2006) assert that when planted in mid-September and terminated in mid-May, a winter rye cover crop has the potential to reduce NO_3^- losses by an average of 7.4 kg per hectare. However, this reduction was substantially lowered (down to 0.7 kg N per hectare) when the rye was sowed later and/or terminated earlier in the growing season (Feyereisen et al., 2006). Similarly, a study done by PFI (2016) indicated that increased seeding rate, earlier planting date, and later termination date increased biomass production during the 2015-2016 winter cereal rye cover crop year, further indicating the degree to which life cycle management impacts cover crop effectiveness.

The effectiveness of cover crops may be evaluated by examining the relationship between biomass and cover crop nutrient reduction efficiency. While this is not a direct measure of water quality improvement, biomass can be indicative of a crop's ability to uptake nutrients and prevent leaching. Without direct water quality measurements, Hively et al. (2009) considered the impact of dry matter composition and used biomass multiplied by average N content to calculate N uptake as a proxy for N reductions in the system. Hively et al. (2009) determined that the N content in rye biomass (1.5%) was lower than that of barley (1.8%) or wheat (2.2%) in crop samples from December. This trend, although at a slightly higher scale, was echoed in their March samples as well (2.3% in rye, 2.9% in barley, and 3.1% in wheat); however, wheat was found to produce the lowest amount of biomass. Further, Hively et al. (2009) noted a N uptake of 3 kg to 18 kg per hectare in December and 9 kg to 29 kg per hectare in March. In both seasons, Hively et al. (2009) observed a negative correlation between the biomass and soil NO_3^- levels of the plots, which may indicate the N mobility in soil. Staver & Brinsfield (1998) observed a much higher biomass production using a rye cover crop in Maryland (1,793 kg to 4,048 kg per hectare) coupled with an average 80% reduction in NO_3^- leaching to groundwater compared to fallow land. These results were paralleled in a Pennsylvania study by Finney et al. (2016) that reported a biomass of 8,500 kg per hectare and an average NO_3^- leaching potential reduction of approximately 90% following a rye cover crop. Based on this research, grass-based cover crops that grow to produce the most biomass may have more dry matter, which may result in an increased capacity for the immobilization of NO_3^-; this may, in turn, increase the crop's water quality benefit.

In addition to crop-level distinctions, system-level factors, like the drainage of the landscape, also affect the ability of cover crops to reduce nutrient leaching. In order to assess the impact of drainage, it is essential to consider the nutrient loss pathways from the system. For example, surface runoff, which causes erosion, tends to be more important when considering P loss from a system, while tile-drainage tends to be more important when considering N loss, namely as water-soluble NO_3^- from a system (Christianson et al., 2016). Undrained systems, namely in freeze-thaw climates, have also been shown to have an increased amount of P loss with cover crops as compared to well-drained systems (Bechmann et al., 2005). Drainage distinctions can also affect the lag time of nutrient concentration reductions in local groundwater. In systems where N leaches into groundwater, a lag time of several years for N concentration reductions has been observed (Staver & Brinsfield, 1998), whereas the lag time for a tile-drained system can be essentially non-existent or up to a year (Kaspar et al., 2003).

Tile-drainage, in particular, has been shown to decrease the amount of NO_3^- lost from systems that utilize grass-based cover crops. A pair of Maryland-focused studies (Lee et al., 2016; Yeo et al., 2014)—using the Soil and Water Assessment Tool (SWAT) model and data from 1999 to 2008 on rye, barley, and wheat—found that early-planted winter cover crops outperformed late-planted winter cover crops in reducing NO_3^- load up to 67%, with rye being the most efficient. This is attributed to the fact that rye has an early and rapid growth stage. The studies showed that winter cover crops were more efficient at N removal in well-drained soils due to the soils' increased N leaching relative to poorly-drained soils. Poorly-drained soils (that have subsequently been drained with ditches or tile drainage) are found with less N in the soils due to existing ditches that effectively transport soluble N and anaerobic conditions that lead to denitrification, a permanent removal process of NO_3^-. The studies also found that there is increased N uptake in cover crops when following soybean rather than corn due to the availability of soil mineral N by mineralization of soybean residue. Following the institution of a rye cover crop on a tile-drained, corn-soybean rotation field in Iowa, there was a 59% reduction in NO_3^- loss from the system (Kaspar et al., 2007). Also under tile-drained conditions, Strock et al. (2004) observed a 13% reduction in NO_3^- loss over three years in southern Minnesota, while Helmers & Crumpton (2015) observed a 25% reduction in NO_3^- loss from a corn-soybean system after a cereal rye cover crop. Research has shown variation between NO_3^- loss after a rye cover crop in separate corn and soybean fields. Qi et al. (2011) found no significant reduction in NO_3^- concentration after a rye cover crop in a tile-drained, corn-only system; however, they observed an 11% reduction after that same cover crop in a soybean-only system. Similarly, Pederson et al. (2014) reports a larger reduction of NO_3^- in tile-drained, soybean-only systems

(45%) than in corn-only systems (22%) following a rye cover crop, indicating the influence of the primary crop on the efficacy of the cover crop. Non-tile-drained systems tend to benefit more from grass-based cover crops than do tile-drained systems, which emphasizes the significance of tile-drainage as a nutrient loss pathway. A non-tile-drained system with nearly zero runoff in Washington state showed a 73% to 84% reduction in NO_3^- leachate concentration, depending on the fertilization rate, when using a cereal rye cover crop in a corn-only system (Kuo, Huang, & Bembenek, 2001).

The general consensus among the scientific community is that grass-based cover crops are effective at preventing nutrient leaching due to their relatively high biomass production (Snapp et al., 2005; Dinnes et al., 2002). However, developing novel genotypes and implementation strategies is essential to preventing damaged corn yields following grass-based cover crop termination, as subsequent cash crop yield is a major determinant in farmers' willingness to implement new water quality improvement strategies (Thorup-Kristensen et al., 2003). Additionally, it is essential to acknowledge the economic constraints of cover crop implementation. Management practices, like seed selection, planting methods, and termination methods, can affect the cost of cover crops. As a baseline, Kaspar et al. (2008) note an establishment cost of approximately $25/acre, which can be extrapolated to a reduction cost of $1.25 to $3.12 per kilogram of N reduced in Iowa. However, work on the Iowa Nutrient Reduction Strategy (INRS), which considered potential yield loss, reported an annualized cost of $49/acre (for seed, planting, termination and yield loss), which equates to approximately $132 per kilogram of P reduction and $13.20 per kilogram of N reduction (IDALS, IDNR, & ISU, 2016).

Even though most cover crop research has focused on grasses and cereals, there is still limited direct measurement of their water quality benefits. This shortage of direct research is likely due to the difficulty of effectively regulated experimental setups, as controlling in-situ variables can be complicated. Laboratory-based experiments have the potential to offer the best ability to control the influence of variables that may affect the performance of cover crops. On the other hand, controlled experiments may limit the authenticity of the results as they inherently decrease the natural variation that influences the real-life application of such practices. By characterizing the impacts of individual variables on cover crop efficiency using heavily-controlled, laboratory-based experiments, researchers will eventually accumulate a sufficient baseline of documented data that will allow them to apply the results of such experiments to actual, in situ occurrences.

- Grasses produce high amounts of dry matter/biomass, which may result in:
    - Increased soil organic matter
    - Reduced soil compaction
    - Reduced erosion
    - Variable effects on corn and soybean yields
    - Increased amounts of immobilized NO_3^-
    - Reduced nutrient leaching into groundwater

3.2 Legumes

The most popular leguminous cover crops in the United States are crimson clover (*Trifolium incarnatum*), winter pea (*Pisum sativum*), and hairy vetch (*Vicia villosa*) based on a survey by the CTIC, SARE, & ASTA (2016). Legumes can fix atmospheric N, which decreases the need for N inputs for subsequent non-leguminous crops (Helmers et al., 2009; Dabney et al., 2001). As a result, legumes have the potential to decrease NO_3^- leaching from agricultural fields (Delgado, 2002; Delgado & Gantzer, 2015). Further, legumes are the most effective cover crops to produce mixed quality residues, which improve soil quality; additionally, they improve the habitat quality for beneficial insects (Snapp et al., 2005). However, legumes have a slow growth cycle, which makes their establishment more expensive (Snapp et al., 2005). According to a southeastern Missouri cover crop factsheet by the USDA (2014), leguminous cover crops can cost between $14 and $36 per acre. The various impacts of leguminous cover crops on corn-soybean systems and water quality are outlined in this section.

The use of leguminous cover crops often results in increases in primary crop yields due to their biological accumulation of N even when inorganic fertilizer additions are limited, assuming sufficient biomass production (Tonitto, David, & Drinkwater, 2006; White et al., 2016). This is attributed to the ability of leguminous plants to convert atmospheric N to forms of N suitable for use by a subsequent cash crop. The results of a study by Vyn et al. (1999) support this relationship; Vyn et al. (1999) observed a 40.4 kg per hectare increase in corn biomass following the implementation of a red clover cover crop. This relationship was also shown in a study by Kuo et al. (2001), in which increases in available soil N when using a hairy vetch cover crop were observed, which led to increased corn yields.

The reported water quality benefits of leguminous cover crops are substantially varied. Prior to a 14-year study in Michigan, Gentry et al. (2013) hypothesized the improvement of long-term soil health due to the incorporation of leguminous winter cover crops, namely red clover (*Trifolium pratense*). However, the resulting data showed no long-term soil or water quality improvements. Gentry et al. (2013) suggest this null relationship was a result of poor timing between the NO_3^- releases from the leguminous cover crops and the NO_3^- uptake by the cash crops. In other words, the NO_3^- immobilized by the legumes leached out of the soil due to rainfall and drainage before it could be used by the subsequent cash crop. This relationship is paralleled in other leguminous cover crops as well. Kuo et al. (2001) observed that the NO_3^- levels leaching from the root zone of hairy vetch tend to be higher than a control, which is postulated to be a result of the increased mineralization from the legumes. However, the results of comparable studies are highly varied. Kanwar et al. (2005) investigated alternative cropping systems in Iowa and their impact on NO_3^--N losses to shallow groundwater. The results indicated that alfalfa (*Medicago sativa L.*), specifically in strip intercropping systems, had the potential to significantly decrease NO_3^- leaching to subsurface drainage waters in an Iowa corn-soybean system when compared to a traditionally grown corn-soybean system. It is essential, however, to conduct more direct water quality research in response to leguminous cover crops to establish more predictable N reduction efficiencies.

While research on the direct link between legumes and levels of NO_3^- leachate does not show substantial evidence supporting a mitigating capacity, legumes affect the N budget and the need for fertilization in agricultural systems. Fortuna et al. (2008) found that legumes—namely hairy vetch—reduced the N fertilizer requirement of the subsequent corn crop, increased the total C and N content of the soil, and increased the amount of plant-available N. Drinkwater et al. (1998) found that the implementation of a diverse leguminous cover crop significantly increases both the C and N retention capability of an agricultural soil, which in turn decreases nutrient losses from the system. A meta-analysis by Tonitto, David, & Drinkwater (2006) showed potential for a well-defined, long-term N budget when using legumes to supply large quantities of NO_3^- required by a cash crop. In contrast to the 40% to 60% of N coming from SOM in systems receiving inorganic N, up to 80% of required N was reported to be pulled from SOM in systems managed for N production using legumes (Tonitto, David, & Drinkwater, 2006). Similarly, McVay et al. (1989) assessed the capacity of leguminous cover crops to substitute the fertilizer-N requirements of a no-till corn system in Georgia. The incorporation of a leguminous cover crop effectively replaced from 99 to 123 kilograms per hectare of the fertilizer-N requirements of the corn system (McVay et al., 1989). McVay et al. (1989) also observed a reduced P availability to plants following a winter legume cover crop; they assert that this effect was a result of a lowered soil pH from the NH_4^+ produced by the legumes. As such, it is economically logical to implement winter legume cover crops considering the relative price of fertilizer-N.

The beneficial effects of N-fixation from leguminous cover covers and consequential increases in cash crop yield and physical soil stabilization are well recorded (Ranells & Wagger, 1996; Tonitto, David, & Drinkwater, 2006). However, there are additional benefits of leguminous cover crop usage. Below-ground impacts, such as those on soil quality and soil biota, are examples of lesser-studied benefits. Zgadzaj et al. (2016) showed how root nodule symbiosis affects the performance of the legume *Lotus japonicas*. Zgadzaj et al. (2016) outline key symbiotic genes that establish the bacterial community in the root and rhizosphere, which contributes to legume growth. If these genes are found in certain cover crops, it may explain some of the benefits and performance, which may allow for improved selection of appropriate cover crops for specific conservation goals. Further, Debosz et al. (1999) found that soil microbial biomass can increase up to 60% following multiple years of a leguminous cover crop. Similarly, Galvez et al. (1995) found that a single season with a hairy vetch cover crop increased the initial presence of vesicular-arbuscular mycorrhizal (VAM) fungi, which enhances the symbiotic relationship beneficial for the growth of many subsequent crops (Galvez et al., 1995). This relationship between legumes and soil health is, intuitively, an important one, as soil health impacts plant health, and plant health impacts nutrient uptake, which affects water quality.

In addition to affecting grass-based cover crops, lifecycle management practices also significantly affect the biomass production of legumes (Lawson et al., 2013). As such, further research on the specific impacts of planting and termination dates is required. While legume cover crops contribute N to subsequent crops and can thereby potentially increase cash crop yields, grasses and brassicas are better at removing residual N before leaching can occur. The latter tend to be N-limited, so mixing grass and legumes can increase total carbon input into the soil through biomass production and decrease N leaching (Finney et al., 2016). Though based on limited data, a meta-analysis by Tonitto, David, & Drinkwater (2006) showed that overall, legume cover crops (neglecting any ancillary benefits) may provide 55% to 60% of the N water quality benefits compared to those provided by grass-based systems. Work by Meisinger et al. (1991) suggests that legume cover crops prevent NO_3^- leaching two to three times less effectively than brassicas or grasses. However, work in the Chesapeake Bay, as summarized by the Chesapeake Assessment Scenario Tool (CAST, 2017) documentation, shows that legumes, relative to grasses, provide just over 20% of the water quality benefits for N (Figure 3) and approximately 50% of the water quality benefits for P (Figure 4).

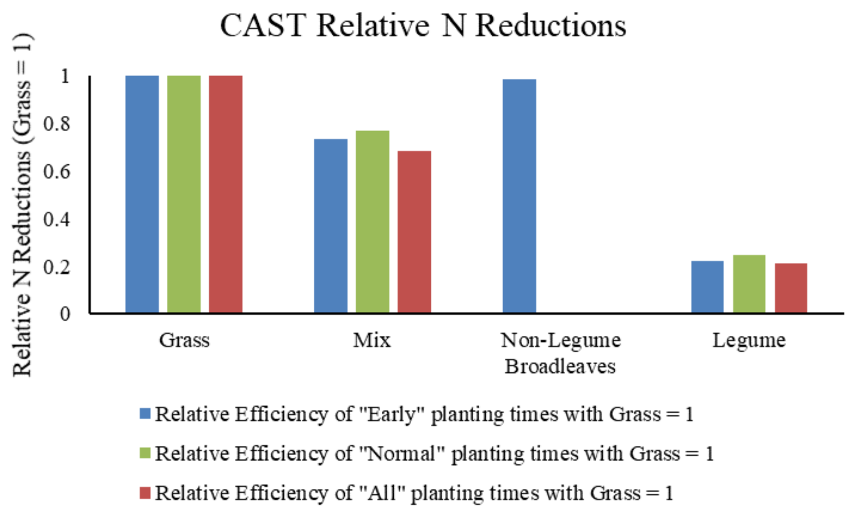

Figure 2. Relative nitrogen water quality benefits of broad cover crop categories. Data have been aggregated based on CAST documentation (CAST, 2017).

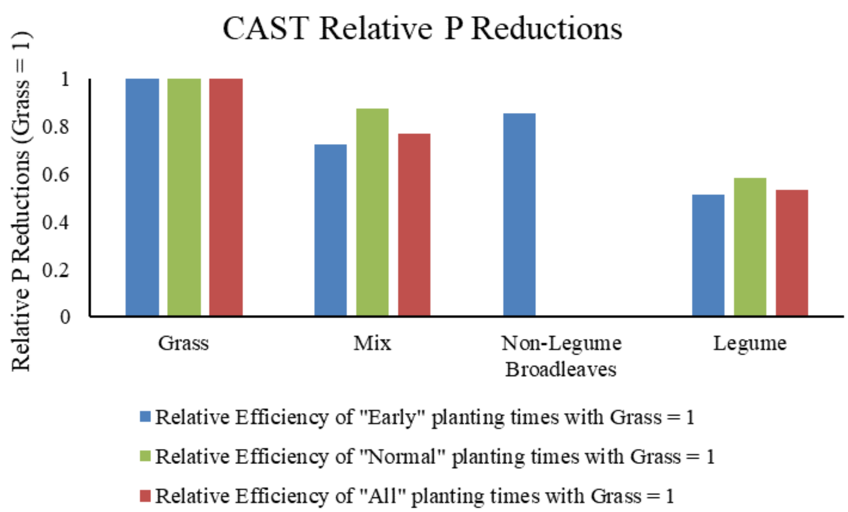

Figure 3. Relative phosphorus water quality benefits of broad cover crop categories. Data have been aggregated based on CAST documentation (CAST, 2017).

There is still little conclusive work relating water quality benefits to the use of leguminous cover crops with quantitative metrics. However, the available research indicates that when using legumes to supply N for a subsequent cash crop, management and timing are essential in eliciting both N benefits to subsequent cash crops and water quality benefits.

- Legumes fix N, which may result in:
  - Increased N available in the soil
  - Increased cash crop yields
  - Reduced fertilizer-N requirements
  - Potential increased N loss in artificial drainage

3.3 Non-Leguminous Broadleaves

Some of the most widely used non-legume, broadleaf cover crops are brassicas—like canola, turnip, brussels sprout, and mustard—along with plants like buckwheat and oilseed radish (MCCC, 2014), as these plants have been shown to have soil quality benefits. The most prevalent cover crop among brassicas is radish, followed by rapeseed and turnip (CTIC, SARE, & ASTA, 2016). Brassicas are typically considered competitive crops with soil quality benefits, namely regarding erosion, leaching, and soil structure (White et al., 2016). Brassicas are also beneficial when the control of soil pests is a primary concern (Snapp et al., 2005). Further, mustards have been found to be quick-growing and well suited for growth in early spring in the western Corn Belt of the United States (Wortman, Francis, & Lindquist, 2012). This section will outline the impacts of such non-leguminous broadleaf cover crops on corn-soybean systems and water quality.

While it is important to attempt to quantify the benefits of agricultural practices in other ways, the cost-benefit analysis is equally important, especially for lesser-studied cover crops like brassicas. The typical establishment cost of non-leguminous broadleaves in the UMRB is approximately $12 to $20 per acre (USDA, 2014). Weil & Kremen (2007) conducted a preliminary study that outlined benefits of non-leguminous broadleaves that could lead to savings. Brassicas can capture and return N, which would decrease the amount of fertilizer used (Weil & Kremen, 2007). Additionally, these cover crops were found to decrease soil compaction, which can reduce the need for deep subsoil tillage, in turn reducing erosion and associated P losses (Weil & Kremen, 2007). It is important to note, however, that these same benefits are observed with grass and cereal cover crop usage, though to varying degrees (Clark, 2008).

There are characteristics unique to brassicas that are not observed in other types of cover crops. Brassicas contain glucosinolates that form bio-toxic secondary products when broken down, which have the potential to control weeds, soil-borne diseases, insects, and nematodes (Weil & Kremen, 2007; Snapp et al., 2005; Potter et al., 1998). The relationship between glucosinolates from brassicas and the limited success of weed species is well-documented (Weil & Kremen, 2007; Smith et al., 2016; Brown & Morra, 1995). Smith et al. (2016) observed both direct and indirect effects of glucosinolates from brassicas on the growth and success of parasitic dodder vines (*Cuscuta gronovii*). Additionally, Brown & Morra (1995) found that the glucosinolates in brassicas produce compounds that inhibit the germination of weed seeds. As such, there is often a reduction in weeds on plots planted with brassicas, which could lead to minimized herbicide use (Weil & Kremen, 2007). Brassica-derived glucosinolates have also been shown to impact both macro- and micro-fauna and flora affecting crop yields. In a study by Potter et al. (1998), soils treated with tissue from a variety of brassica species were shown to kill approximately 56% to 95% of exposed root lesion nematodes (*Pratylenchus neglectus*), and such exposure significantly suppressed nematode abundance, which could reduce plant stress. Similarly, Lazzeri & Manici (2001) found that brassica-containing green manure suppresses the growth and success of fungi (namely *Pythium* species) detrimental to crop yields, while also increasing the total microbial activity of the treated soil. Cumulatively, these effects have the potential to make the growing conditions for subsequent cash crops more favorable, ultimately increasing crop yield.

The biomass production of non-leguminous broadleaves, as with other types of cover crops, substantially affects their nutrient removal efficiency. Finney et al. (2016) found large biomass production (7,500 kg per hectare) using canola in Pennsylvania in an oat-corn rotation. Based on this study, potentially leachable NO_3^- was reduced by approximately 90% using canola, as compared to a control with no cover crop. Further, White et al. (2016) noted canola reduced soil NO_3^- levels to below 1 mg per kg, which was similar to their results for cereal rye. In a study by Justes et al. (1999), a radish cover crop substantially reduced the mineral N content of the surrounding agricultural soil. This finding is supported by oilseed radish being reported as an effective N scavenger (MCCC, 2014). In a study by Cooper et al. (2017), the implementation of an oilseed radish cover crop lowered the riverine NO_3^- concentration below the drinking water standard, which is impressive considering water downstream of the fallow control was above the standard for 88% of the sampled year. As such, non-leguminous broadleaves have the capacity to reduce NO_3^- leachate that may reach streams.

The life cycle management of non-legume broadleaf cover crops is especially important in their ability to reduce nutrients. Martinez-Ferian, Kaspar, & Wiedenhoeft (2016) conducted a study on the Baldur cultivar of winter canola (*Brassica napus L. Baldur*) used in a corn-soybean rotation on two farms in central Iowa in order to evaluate the winter survival likelihood. It was found that planting time is critical, and this cultivar of canola is most efficient when seeded in early September. Over the two observed seasons, the canola had considerable winter survival one year (2012-2013) when seeded early and established well; however, the 2013-2014 season saw total kill of all plants due to abnormally low temperatures and a lack of adequate snow cover to protect the crops from the extreme cold. Because of the early seeding requirement for successful canola and the general late harvest timing of soybeans, aerial seeding needs to be further examined for successful incorporation into corn-soybean rotations.

The timing of planting leguminous cover crops affects N uptake and retention. Thomsen & Hansen (2014) examined cruciferous cover crops (oil radish and white mustard) that were sown pre-harvest by broadcasting into winter wheat in July and grew until September and late autumn. When harvested in September, the cruciferous cover crop uptake was at a maximum of 24 kg N per hectare. When harvested in late autumn, the pre-harvest oil radish uptake was at a maximum of 66 kg N per hectare. These results imply that harvesting in late autumn is preferable in terms of N uptake when compared to a September harvest. In spring, Weil & Kremen (2007) found that there was little N leaching in winter-killed forage radish in finer textured soils (silt loams with clay loam subsoils), but there was a flush of NO_3^- release in early spring after a rainy period. These results suggest that radish cover crops should be followed by an early planted cash crop or paired with grasses in sandy soils to minimize NO_3^- leaching. These results suggest the influence of climate patterns on N cycling and use of cover crops.

While N uptake is often a primary concern, P should also be considered. Radishes are one non-leguminous broadleaf cover crop that impacts P availability. White & Weil (2011) compared the P concentrations in bulk soil with the area surrounding the radish taproot. When a radish dies, it decomposes quickly and leaves a large hole. It was found that there is an increase in P around the taproots. This could be due to P moving from the bulk soils to the taproots and P getting released when the radish dies. It could also be due to exudates from the radish which may increase soil P availability. White & Weil (2011) suggest that planting radish may be an option for P deficient areas, as the radish taproots seem to increase the P concentration of adjacent soils.

Most of the research comparing non-legume broadleaves to other types of cover crops uses cereal rye as a frame of reference. In a study by Finney et al. (2016), a dimensionless metric called the N retention service is introduced. The N retention service is a measure of how well a cover crop can retain N and prevent it from leaching. Finney et al. (2016) note the maximum N retention service of canola occurs at a biomass production of approximately 7,000 kg per hectare; in other words, canola provided approximately the same N retention service as cereal rye but with less of a negative impact on corn yield (corn yield of approximately 7-8 megagrams per hectare using canola compared to a yield of 3-4 megagrams per hectare using cereal rye). Further, a study by Dean & Weil (2009) assessed the NO_3^- uptake and leaching effects of forage radish, oilseed radish, rapeseed, and rye. The N uptake of brassicas was greater than or equal to rye during the fall, while the rapeseed uptake was greater than rye during the spring. Dean & Weil (2009) also observed that the freeze-killed forage radish released N earlier than the still-growing rapeseed and rye in coarse-textured soils. Thus, forage radish may be beneficial for early spring planted summer crops, but rapeseed or rye would be better for late spring planting.

Meisinger et al. (1991) determined that brassicas and grasses are approximately equivalent in their ability to minimize NO_3^- leaching; in comparison, legumes were found to be approximately two to three times less effective than brassicas in the same respect. Similarly, the CAST documentation (CAST, 2017) asserts that non-leguminous broadleaves may be nearly as effective at reducing N as a grass-based cover crop if planted prior to harvest (Figure 3) and approximately 85% as effective at reducing P loss (Figure 4). However, planting after harvest or later results in no water quality benefits.

In part due to the allelopathic relationship between cereal rye and a following corn crop, interest in non-grass cover crops has been increasing. As with grasses, many of these non-leguminous broadleaf options are chosen for their short growing windows or their over-wintering capability. Even if these cover crops are winter-killed, some N loss reduction benefits may be achieved due to scavenging N from the soil and putting it back on the surface through biomass production, which makes their implementation favorable for both corn and soybean yield and water quality.

- Non-leguminous broadleaves produce adequate dry matter, which may result in:
    - Increased soil organic matter
    - Reduced soil compaction
    - Reduced erosion
    - Variable corn and soybean yields
    - Reduced NO_3^- leaching into groundwater
- Some non-leguminous broadleaves produce glucosinolates, which can result in:
    - Reduced incidence of soil-borne diseases
    - Reduced amount of weeds
    - Reduced nematode and predatory insect populations

3.4 Mixes

There is growing interest in more creative or customized cover crop mix options. Mixes include any set of cover crop species not dominated by any one species. This shift in practice may be attributed to the interactions between certain cover crops and target cash crops, desired soil characteristics, pest or disease concerns, and emerging organic and low- or no-till cultivation practices. According to a CTIC, SARE, & ASTA (2016) report, the use of cover crop mixes is growing with 51% of respondents reporting they started off using only one species but have since modified their cover crop management to include multiple species. The timing of benefits given certain environmental conditions has led to the use of mixes. For example, grasses reduce N in shallow groundwater and scavenge N from the soil, which has a water quality benefit (Kaspar et al., 2008; Prabhakara, Hively, & McCarthy, 2015), while legumes convert atmospheric N_2 to usable plant food for subsequent cash crops (Helmers et al., 2009). If both can be used and timed so that they work in concert, it is possible to control the amount of N in the system via cover crop management. Further, such a practice would minimize fertilizer usage without reducing crop yields, which would improve water quality. However, there are difficulties, including timing with weather, competing environmental needs, and potential costs. This section will outline the benefits and consequences of cover crop mixes with respect to corn-soybean systems and water quality concerns.

Largely due to the physiological differences among the types of cover crops included in many mixes, there is a wide variety of variables that influence the nutrient reduction effectiveness of cover crop mixes. Overall seeding rates may increase when working with mixes (Kuo et al., 2001). Work done in Washington State (Kuo et al., 2001) investigated the use of cereal rye, annual ryegrass, hairy vetch, and combinations of vetch with rye and ryegrass as cover crops for corn. The results indicated that a mix of cereal rye or annual ryegrass and hairy vetch produced the largest amount of biomass (2,200 and 2,500 kg per hectare, respectively). Additionally, the mixes tended to show beneficial traits of both plant types with increased available soil N, high biomass, and minimal NO_3^- leaching. Based on leaching NO_3^- concentrations, the cereal rye and hairy vetch combination was similar to a monoculture of cereal rye (Kuo et al., 2001). Reviewing reported concentrations, this was a 70% to 80% NO_3^- leachate concentration reduction when compared to the no cover crop control.

Similarly, a study by Deppe (2016) looked at the effects of cover crop mixes in combination with fall-applied N. Using a corn control, daikon radish, cereal rye, and a cereal rye/daikon radish mixture, varying rates of anhydrous ammonia (a N source) was added the fall prior to corn planting. The results indicate that regardless of the N application rate, the no cover crop corn control had a 3-6% lower yield relative to the cereal rye and the mixture. Cereal rye showed the best results for sequestering N from the soil. In contrast, the daikon radish may increase the risk of leaching as it dies off and can release inorganic N well before substantial growth of cereal rye can immobilize the excess N.

Lemus & White (2017) compared the biomass production and nutrient removal efficiency of four cover crop mixes in Starkville, Mississippi. A mix of 40% radish and 60% annual ryegrass produced the largest amount of biomass, approximately 2,720 kilograms of dry matter per acre. The mix with the lowest biomass production was composed of 85% cereal rye and 15% crimson clover, while the mix with the largest nutrient removal efficiency for N, P, potassium (K), and calcium (Ca) was composed of 75% cereal rye, 20% crimson clover, and 5% red clover.

In a study by Acuña & Villamil (2014), the short-term effects of a radish with rye, triticale, buckwheat, and hairy vetch mix in Illinois were investigated. The results of this study indicated that cover crops significantly lowered soil NO_3^-, compared to land with no cover crop. There were differences in soil NO_3^- levels among the cover crops, which was predicted to be a result of the different scavenging abilities and the length of that cover crop's growing season. For example, plants that overwintered showed lower soil NO_3^- levels. Further, cover crop treatments of radish/rye and radish/triticale significantly reduced soybean yield when compared to radish alone, radish/buckwheat, or radish/hairy vetch mixes.

Different mix ratios also have different rates of N release due to varying biomass content. As such, certain mixes may have more practical applications for nutrient uptake by subsequent cash crops. For example, Lawson et al. (2013) found that the N release rate from a rye-vetch mix was the most optimal for uptake by subsequently grown organic sweet corn. In Maryland, Poffenbarger et al. (2015) studied the biomass and N content of a comparable hairy vetch/cereal rye mix of varying proportions. The results indicated a hairy vetch/cereal rye seeding rate of 27:34 kg per hectare was most favorable when the goal was maximizing N content in cover crop biomass. However, more research should be done to effectively match specific crop systems with the most appropriate mix ratios.

Finney et al. (2016) found a mix with forage radish, oats, canola, and cereal rye provided the highest potentially leachable NO_3^- reduction of approximately 95% with an approximate 32% corn yield decrease. The same study reported a mix with canola, cereal rye, barley and ryegrass had a slightly lower potentially leachable NO_3^- reduction of approximately 92%, a mix with sunn hemp, soybeans, canola, and cereal rye resulted in a NO_3^- reduction of 91%, and a mix of red clover, hairy vetch, canola, and cereal rye had a NO_3^- reduction of 89%. The only treatment with no adverse impacts on corn yield was the red clover, hairy vetch, canola, and cereal rye mix. Additionally, Finney et al. (2016) concluded that increasing the number and diversity of cover crop species increased biomass production and consequently N retention by the cover crop mix. With a possible 89% NO_3^- reduction and no adverse impact on yields, research on proper mix sequencing and timing has great potential for practical and profitable use.

Cover crops are used on no-till farms to help reduce compaction. In a study by Wells, Reberg-Horton, & Mirsky (2016) located in North Carolina, roller crimpers were used to lay cover crops down as a uniform surface mulch, and corn was drilled in a no-till management system, which used two cover crop mixtures: winter pea/cereal rye and hairy vetch/cereal rye. The study found that soil type and condition may play a key role in soil moisture, as more clay-saturated soils provide a firmer surface for planting, decreasing instances where the cover crop is pushed into the soil (thus reducing cash crop seed/soil contact) in the roller crimping process. The study found that the date of corn planting did not affect weed biomass or improve soil water content. Based on these results, Well, Reberg-Horton, & Mirsky (2016) assert that no-till planter innovations are needed to minimize disturbances to the cover crop mulch. Another study evaluating non-conventional farming practices (Brennan, Boyd, & Smith, 2013) looked at the effects of winter cover crops on an organic vegetable farm in California over eight years, specifically cover crop residue quality and N mineralization. Brennan, Boyd, & Smith (2013) examined rye, legume/rye, and mustard, and found that mustard and a legume/rye combination produce higher quality residue that decomposes quicker and decreases problems with subsequent tillage. However, during one of the study years, there was rainfall after the cover crop was incorporated, and reduced soil N was observed, suggesting leaching from the system.

Like legumes and non-leguminous broadleaves, CAST documentation (2017) indicates that mixes provide between 70% and 85% of the water quality benefits of grasses. As noted previously, the benefits of mixes are likely more due to the biomass production rather than specifics of the mix; however, the growth characteristics of the species selected will ultimately determine biomass production. Compared to single-plant cover crops, Hauggaard-Nielsen et al. (2008) found that a grain-legume cover crop mix increased the proportion of N derived from atmospheric N_2 fixation by approximately 10-15% on average. By increasing the amount of N made available to plants from the atmosphere, less N needs to be provided in the form of fertilizer, which would provide both water quality and economic benefits. Further, Ranells & Wagger (1996) found that grass-legume bicultures not only produced more dry matter than legume monocultures, but the mixes also reduced N leaching more than legume monocultures.

While limited research is available, the existing research suggests that cover crop mixes are among the most beneficial types of cover crops when it comes to managing N budgets without compromising subsequent cash crop yield. In addition to these benefits, intercropped mixtures have been shown to reduce the general incidence of disease by 20-40% (Hauggaard-Nielsen et al., 2008).

- Mixes combine the effects of various types of cover crops, which can result in:
  - Increased soil organic matter
  - Reduced soil compaction
  - Reduced erosion
  - Unaffected corn and soybean yields, if correct cover crop species are selected
  - Increased amounts of immobilized NO_3^-
  - Reduced nutrient leaching into groundwater
  - Reduced fertilizer-N requirements
  - Secondary benefits, like weed, pest, and disease control

3.5 Living Mulches

Living mulches are cover crops that are grown concurrently with a primary crop and a relatively new type of cover crop with only 3 publications since 2009 focusing on water quality. Perennial grasses and legumes are the most common types of cover crops used as living mulches, for the same reasons they are popular as traditional cover crops: overall soil quality improvement and N fixation, respectively (CTIC, SARE, & ASTA, 2016). Most of the existing research on living mulches has been done internationally on vegetable cropping systems (Masiunas, 2008). There is also research on living mulch usage in international apple orchards (Qian et al., 2015; Rusen et al., 2015; Licznar-Malanczuk, 2014), potato production systems (Boyd et al., 2012; Kolodziejczyk et al., 2017), and wheat production systems (Carof et al., 2007; Hiltbrunner et al., 2007). However, there is minimal research on the use of living mulches in corn-soybean systems, and there is even less information regarding these systems in the Midwestern United States.

The negative correlation between N management for water quality and N addition for improving crop yield necessitates that all agricultural conservation practices, including living mulches, are balanced such that crop yield is not impaired to a point of decreased profitability. According to Kaspar et al. (2008), the cost of living mulches is estimated to be $40.35 per acre annually, which equates to a cost of $2.18 to $4.99 per kilogram of N (in the form of NO_3^- leachate) reduced in Iowa. Finding a profitable balance can be difficult due to the various factors that affect crop yield following the implementation of an agricultural conservation practice like the usage of living mulches.

While the effects of the implementation of a living mulch depends on the type of crop inter-planted with the primary crop, living mulches generally result in decreased cash crop yields based on the existing research. In a study by Albrecht (2009), there was a 10% corn yield loss following the implementation of a kura clover (*Trifolium ambiguum*) living mulch in a continuous corn system. In a corn-soybean system with a kura clover living mulch, Qi et al. (2011) observed a 60% decrease in corn yields. These yield losses are largely a result of the competition for available resources like water and nutrients.

Due to living mulches making use of the available nutrients, the amount of N stored in the soil decreases. As such, in addition to decreasing corn yields, the implementation of a kura clover living mulch has also been shown to substantially reduce the amount of N leaching. Both Albrecht (2009) and Qi et al. (2011) note a 50% N reduction in water sampled below the root zone. However, reactive P appears to have a more complex pathway than NO_3^-. In a four-year study, Helmers et al. (2009) found that total reactive P concentration for a kura clover living mulch with corn was not significantly lower than that of a corn-soybean control. Although very little water quality data exists for systems using a living mulch, Kaspar et al. (2008) suggest this conservation practice is at least as effective as a traditional grass-based cover crop.

As with most conservation practices, as management evolves, performance will likely also increase. Zemenchik et al. (2000) noted complete termination of kura clover before planting corn showed higher corn yields than other types of suppression techniques. The importance of complete termination was highlighted by the fact even when fertilized, band killing, or simple suppression hampered resulting corn yields. Additionally, since it is difficult for many livnig mulches to survive under the canopy cover of annual grain crops due to minimized light conditions, more management strategies need to be developed prior to their widespread implementation (Kaspar et al., 2008). In a study by Pearson et al. (2014) in Fruita, Colorado, the implementation of a kura clover living mulch was shown to decrease crop yield in a corn-only system; however, Pearson et al. (2014) found that using strip tillage, furrow irrigation, and a N fertilization rate of 168 kilograms per hectare produced similar corn yields to those of conventional systems, which shows the influence of more informed management practices.

- Living mulches are grown concurrently with primary crops, which may result in:
  - Increased competition for resources
  - Reduced amount of nutrients available to the primary crop
  - Reduced corn and soybean yields
- Living mulches produce dry matter/biomass, which can result in:
  - Increased soil organic matter
  - Reduced soil compaction
  - Reduced erosion
  - Reduced NO_3^- leaching

4 Conclusion

There is an extensive amount of literature on the use of cover crops as a conservation practice; however, there is limited direct measurement and study of water quality benefits from their use. Consequently, proxies for the water quality benefits of cover crops, such as biomass and dry matter content, are most often used to characterize the potential for water quality impacts. To date, most of the water quality information has been generated on grass cover crops with little on the performance of leguminous and non-leguminous broadleaf cover crops and even less on mixes and living mulches. However, collectively the research shows an overall positive impact on water quality with the use of cover crops, despite the wide range in variability reported making conclusive statements on the direct water benefits challenging. Table 1 provides a summary of the research to date on the effect of cover crops on crop yield, nutrient leaching and cost to implement. The interpretation of these effects should be advisory in nature given the wide range of results found in the literature.

Table 2. Synthesis of the effects of each type of cover crop on various factors based on literature reviewed. Ancillary benefits are intended to highlight when other production goals should be considered, including soil health, cash crop yield, pest reductions, or any other benefit beyond water quality.

	Effect (++, +, − −, −, +/−)				
Cover Crop	Crop Yield	N Immobilization	P Leaching/Runoff Reduction	Cost*	Ancillary Benefits
Grasses	+/−	++	Not enough direct research	$9-25/ac	N/A
Legumes	+	+/−		$14-36/ac	+
Non-Leguminous Broadleaves	+/−	++		$12-20/ac	++
Mixes	+	++		Depends on mixture composition	+
Living Mulches	−	+		$40/ac	N/A

*Effects are reported using the following symbology: "++" consistently positive effect; "+" generally positive effect; "− −" consistently negative effect; "−" generally negative effect; "+/−" mixed results. * Costs are an approximation of reported values from an interpretive summary by Kaspar et al. (2008) and a southeastern Missouri cover crop factsheet by the USDA (2014).*

There is abundant research suggesting a connection between cover crop implementation and soil health, especially in terms of nutrient retention capacity, SOM content, and porosity (Abdollahi et al., 2013; Abdollahi & Munkholm, 2013; Ding et al., 2006; MCCC, 2014; White et al., 2016; Dabney et al., 2001); however, the relationship between cover crop implementation and water quality is more indirect. Nevertheless, analyzing the factors that indirectly influence a cover crop's water quality benefit has the potential to further illuminate this relationship.

Biomass production, and, by extension, dry matter content, are the most acknowledged beneficial characteristics of all types of cover crops (Kaspar et al., 2008; Kuo and Sainju, 1998; Friedrich et al., 1979; Prabhakara, Hively, & McCarthly, 2015). Since grasses have been shown to produce the largest amount of biomass (Meisinger et al., 1991; Snapp et al., 2005; White et al., 2016), they are the most efficient at reducing NO_3^- leaching (Hively et al., 2009; PFI, 2016; Staver & Brinsfield, 1998; Finney et al., 2016). Grasses also overwinter most reliably and are relatively inexpensive and easy to establish (Snapp et al., 2005; White et al., 2016). However, much of the available research indicates that grass-based cover crops have a negative impact on subsequent cash crop yields, especially when that subsequent crop is corn (Kaspar et al., 2007; Sawyer, Pantoja, & Barker, 2011; Vyn et al., 1999; Finney et al., 2016; Sawyer et al., 2010). Nevertheless, appropriate lifecycle management of grass-based cover crops can mitigate their negative impact on corn yield (Kaspar et al., 2008; Lee et al., 2016).

Legumes typically produce less biomass than grasses, but since they are already fixing atmospheric N_2, which can reduce fertilizer costs, they can be less effective in terms of nutrient removal (Meisinger et al., 1991; CAST, 2017; Tonitto, David, & Drinkwater, 2006). They are more expensive and slower to establish than grasses (Snapp et al., 2005; USDA, 2014). Because legumes increase the amount of quality residues in the surrounding soil (White et al., 2016; Tonitto, David, & Drinkwater, 2006), they can decrease the N input requirements of an agricultural system (Helmers et al., 2009; Fortuna et al., 2008; Drinkwater et al., 1998; McVay et al., 1989). Legumes also have been shown to increase the microbial biomass in surrounding soil (Zgadzaj et al., 2016; Debosz et al., 1999) along with increasing the amount of mycorrhizal fungi available for subsequent cash crops (Galvez et al., 1995). The combination of the N provided via atmospheric N_2 fixation and the beneficial impact on soil microbiota can result in increases in subsequent cash crop yield (Vyn et al., 1999; Kuo et al., 2001). Although they do not sequester as much N as grasses, legumes can produce comparable dry matter through proper lifecycle management practices (e.g., including a legume in an extended rotation), making them more effective in terms of nutrient removal (Lawson et al., 2013).

Non-leguminous broadleaves have been shown to have similar biomass production to grasses (Meisinger et al., 1991; Weil & Kremen, 2007). As a result, they are also as effective as grasses in terms of nutrient removal efficiency and the reduction of NO_3^- leaching (Cooper et al., 2017; Meisinger et al., 1991; CAST, 2017; Dean & Weil, 2009; Justes et al., 1999; White et al., 2016). Not only do they reduce nutrient leaching as effectively as grasses, but non-leguminous broadleaves have also been shown to decrease corn yield less so than do grasses (Finney et al., 2016). Arguable the most beneficial impact of non-leguminous broadleaves, however, is their ability to make growing conditions more favorable for subsequent cash crops. These cover crops produce glucosinolates, which have been linked to weed suppression (Weil & Kremen, 2007; Smith et al., 2016; Brown & Morra, 1995) and limited growth and success of parasitic fauna, including nematodes, microbiota, and insects (Potter et al., 1998; Lazzeri & Manici, 2001).

Because of the specialized benefits associated with each type of cover crop, mixes are becoming increasingly popular (CTIC, SARE, & ASTA, 2016). While mixes only yield 70% to 85% of the water quality benefits of grasses, they can decrease the amount of N input required by increasing the amount of atmospheric N_2 fixed and utilized (Hauggaard-Nielsen et al., 2008; Ranells & Wagger, 1996). Mixes also produce similar amounts of biomass to grasses, making them effective for reducing nutrient leaching (Deppe et al., 2016; Kuo et al., 2001; Lemus & White, 2017; Acuña & Villamil, 2014; Finney et al., 2016). To make cover crop mixes even more effective, however, more research is needed regarding the complex interactions between plants, such as the effects of competition on resource acquisition and the effects of allelopathic products on plant health.

Research to date finds that living mulches are typically associated with decreases in crop yield (Albrecht et al., 2009; Qi et al., 2011) due to resource competition between the living mulch and the cash crop. However, living mulches are also associated with reduced N leaching (Albrecht et al., 2009; Qi et al., 2011) and P leaching (Helmers et al., 2009), and they are considered at least as effective as the traditional grass-based cover crop (Kaspar et al., 2008).

Ultimately, the research regarding the water quality impacts of cover crop implementation, while not nearly complete, largely reports a correlation between cover crop usage and nutrient leachate reductions.

While biomass/dry matter production does serve as a relatively effective proxy for the water quality benefits of cover crops, research on novel methodology for the direct measurement of their water quality benefits should be pursued. Additional work is need to more explicitly investigate the direct effect of alternative cover crops on water quality improvement. Considering the substantial amounts of nutrients transported to the Gulf of Mexico from the Upper Mississippi River Basin—and even more so from the Mississippi/Atchafalaya River Basin as a whole—it is essential for the scientific community to more fully investigate preventative, mitigation techniques for the excessive nutrient transport that occurs from agricultural lands in the Midwestern United States.

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6 Appendices

Appendix A. Estimated relative nutrient reduction efficiency of cover crop species/mixes in Mesozoic Lowlands and Valley and Ridge Siliciclastic regions (for low-till and high-till land uses) as proposed by the Phase 6.0 update of the Chesapeake Bay Program Watershed Model.

		Low-Till Land Uses			High-Till Land Uses		
Cover Crop Type	**Planting Time & Type**	**TN**	**TP**	**TSS**	**TN**	**TP**	**TSS**
Traditional Rye	Early-planted Drilled	0.34	0	0	0.34	0.15	0.2
Traditional Rye	Early-planted Other	0.29	0	0	0.29	0.15	0.2
Traditional Rye	Early-planted Aerial	0.19	0	0	0.19	0.15	0.2
Traditional Rye	Normal-planted Drilled	0.31	0	0	0.31	0.07	0.1
Traditional Rye	Normal-planted Other	0.27	0	0	0.27	0.07	0.1
Traditional Rye	Late Drilled	0.15	0	0	0.15	0	0
Traditional Rye	Late-planted Other	0.12	0	0	0.12	0	0
Traditional Annual Ryegrass	Early-planted Drilled	0.22	0	0	0.22	0.1	0.15
Traditional Annual Ryegrass	Early-planted Other	0.19	0	0	0.19	0.1	0.15
Traditional Annual Ryegrass	Early-planted Aerial	0.125	0	0	0.125	0.1	0.15
Traditional Annual Ryegrass	Normal-planted Drilled	0.2	0	0	0.2	0.05	0.07
Traditional Annual Ryegrass	Normal-planted Other	0.18	0	0	0.18	0.05	0.07
Traditional Annual Legume	Early-planted Drilled	0.05	0	0	0.05	0.06	0.08
Traditional Annual Legume	Early-planted Other	0.05	0	0	0.05	0.06	0.08
Traditional Annual Legume	Early-planted Aerial	0.03	0	0	0.03	0.06	0.08
Traditional Annual Legume	Normal-planted Drilled	0.05	0	0	0.05	0.03	0.04
Traditional Annual Legume	Normal-planted Other	0.04	0	0	0.04	0.03	0.04

		Low-Till Land Uses			High-Till Land Uses		
Cover Crop Type	**Planting Time & Type**	**TN**	**TP**	**TSS**	**TN**	**TP**	**TSS**
Traditional Brassica	Early-planted Drilled	0.24	0	0	0.24	0.1	0.13
Traditional Brassica	Early-planted Other	0.2	0	0	0.2	0.1	0.13
Traditional Brassica	Early-planted Aerial	0.135	0	0	0.135	0.1	0.13
Traditional Forage Radish	Early-planted Drilled	0.2	0	0	0.2	0.06	0.09
Traditional Forage Radish	Early-planted Other	0.17	0	0	0.17	0.06	0.09
Traditional Forage Radish	Early-planted Aerial	0.11	0	0	0.11	0.06	0.09
Traditional Forage Radish	Plus Early-planted Drilled	0.22	0	0	0.22	0.08	0.12
Traditional Forage Radish	Plus Early-planted Other	0.19	0	0	0.19	0.08	0.12
Traditional Forage Radish	Plus Early-planted Aerial	0.12	0	0	0.12	0.08	0.1.2
Traditional Forage Radish	Plus Normal-planted Drilled	0.16	0	0	0.16	0.04	0.06
Traditional Forage Radish	Plus Normal-planted Other	0.14	0	0	0.14	0.04	0.06
Traditional 1:2 Legume/Grass Mix	Early-planted Drilled	0.15	0	0	0.15	0.1	0.15
Traditional 1:2 Legume/Grass Mix	Early-planted Other	0.13	0	0	0.13	0.1	0.15
Traditional 1:2 Legume/Grass Mix	Early-planted Aerial	0.08	0	0	0.08	0.1	0.15
Traditional 1:2 Legume/Grass Mix	Normal-planted Drilled	0.14	0	0	0.14	0.05	0.07
Traditional 1:2 Legume/Grass Mix	Normal-planted Other	0.12	0	0	0.12	0.05	0.07
Traditional 1:1 Legume/Grass Mix	Early-planted Drilled	0.2	0	0	0.2	0.1	0.15

		Low-Till Land Uses			High-Till Land Uses		
Cover Crop Type	**Planting Time & Type**	**TN**	**TP**	**TSS**	**TN**	**TP**	**TSS**
Traditional 1:1 Legume/Grass Mix	Early-planted Other	0.17	0	0	0.17	0.1	0.15
Traditional 1:1 Legume/Grass Mix	Early-planted Aerial	0.11	0	0	0.11	0.1	0.15
Traditional 1:1 Legume/Grass Mix	Normal-planted Drilled	0.19	0	0	0.19	0.05	0.07
Traditional 1:1 Legume/Grass Mix	Normal-planted Other	0.16	0	0	0.16	0.05	0.07