Spring 2015

Are cover crops worth it? It depends

Joshua S. Leirer
Purdue University

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Joshua S. Leirer

Entitled
Are Cover Crops Worth It? It Depends.

For the degree of Master of Science

Is approved by the final examining committee:

Wallace E. Tyner
Chair

James K. Binkley

Juan P. Sesmero

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): Wallace E. Tyner

Approved by: Ken Foster 4/21/2015

Head of the Departmental Graduate Program Date

ARE COVER CROPS WORTH IT? IT DEPENDS.

A Thesis

Submitted to the Faculty

of

Purdue University

by

Joshua S Leirer

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2015

Purdue University

West Lafayette, Indiana

ACKNOWLEDGEMENTS

Thank you Dr. Tyner for actually reading my drafts and meeting with me regularly. I was unaware of how rare these actions are for a major professor until I talked to my classmates.

Thank you Dr. Binkley for your econometric advice and taking the time to decipher what I was trying to do.

Finally I would like to thank and apologize to Dr. Tyner, Dr. Binkley, Dr. Sesmero and whoever else shows up for my defense for having to sit through a long winded presentation of the indefensible.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

ABSTRACT

Leirer, Joshua S. M.S., Purdue University, May 2015. Are Cover Crops Worth It? It Depends. Major Professor: Wallace E. Tyner.

Society is becoming increasingly more aware of the environmental consequences of agricultural production. Farmers today are under increasing pressure to adopt more sustainable farm management practices. One method to improve the sustainability of crop production is the use of cover crops. Cover crops are planted “off-season” to provide agronomic and environmental benefits. The objective of this research is to quantify the impacts of cover crops and determine where and under which management practices cover crops provide the greatest benefit. Management practices include different crop rotations, tillage practices and residue removal rates. This paper will focus on soil erosion, nitrate leaching and soil organic carbon.

To quantify the impact of cover crops, a dummy variable model was used to estimate the amount of soil erosion, nitrate leaching and soil organic carbon change for a combination of different management practices on soils with different land capability class ratings. Once the environmental outcomes have been determined, the benefits of cover crops can be quantified. Data for the environmental outcomes are simulated by the Landscape Environmental Assessment Framework (LEAF). To determine if cover crops are worth the cost, estimates for the price of soil erosion, nitrate leaching and soil organic carbon are combined with the environmental outcomes.

From this analysis we find that: (1) cover crops improve environmental outcomes (2) reduced till benefits more from cover crops than no till (3) continuous corn rotations benefits more from cover crops than corn soybean rotations (4) soils with higher land

capability class ratings benefit the most from cover crops (5) cover crops are needed to maintain positive soil organic carbon for medium residue harvest and high residue harvest (6) considering only the nutrient benefits of reduced soil erosion, reduced nitrate leaching and increased soil organic carbon rarely justifies the cost of cover crops (7) for high residue harvest, the social benefits of cover crops always exceed the cost.

CHAPTER 1: INTRODUCTION

Society is becoming increasingly more aware of the environmental consequences of agricultural production. This is evident from the increasing interest in environmental sustainability. Farmers today are under increasing pressure to adopt more sustainable farm management practices. One method to improve the sustainability of crop production is the use of cover crops. Cover crops are planted “off-season’ to provide agronomic and environmental benefits. The objective of this research is to quantify the impacts of cover crops and determine where and under which management practices cover crops provide the greatest benefits. Management practices include different crop rotations, tillage practices and residue removal rates

1.1 Cover Crops

Cover crops do not refer to any species of plant, but to a plant planted as an alternative to winter fallowing. Examples of commonly used cover crops include winter rye, radishes, crimson clover and hairy vetch. Benefits of cover crops include reduced soil erosion, reduced nitrate leaching, increased soil organic carbon, reduced soil compaction, increased soil moisture retention and providing food for pollinators. The magnitude of the benefits of cover crops depend on the cover crop, location, and management practice. Disadvantages of cover crops include cost of establishment, increased herbicide use difficulties in termination, and increased management skill required to succeed with a cover crop system.

1.2 Objective

Cover crops have costs that have been quantified by several researchers, but research is needed to quantify the benefits of cover crops. From this information producers could decide if the benefits of cover crops are worth the cost. This research shows that cover crops provide a variety of benefits. However, the magnitude of these benefits are dependent upon the site and the management practice cover crops are used with.

Even though cover crops improve environmental outcomes, cover crop usage remains low. This study seeks to quantify the impact of cover crops for different locations in Indiana and for different management practices. Once the environmental benefits of cover crops has been established, we will explore how the benefits vary with crop rotation, tillage regime, soil type, residue removal rates, and combinations of these factors. After the environmental impacts of cover crops have been quantified, these impacts will be assigned values to determine if the benefits of cover crops are greater than or less than the cost.

CHAPTER 2: LITERATURE REVIEW

This literature seeks to provide a summary of current research relating to this project as well as provide a brief overview of the many different subjects so that this thesis may be understood in the context of established research. Topics covered include cover crops, soil erosion, soil organic carbon, nitrate leaching and LEAF, the modeling system employed in this research. One purpose of this literature review is to define the necessary links among topics so that an economic analysis may be conducted.

2.1 Cover Crops

Generally speaking cover crops are crops grown "off-season" for their agronomic benefits. Reeves (1994) defines cover crops as "crops grown specifically for covering the ground to protect the soil from erosion and loss of plant nutrients through leaching and runoff." Cover crops are planted before the winter and are normally terminated by the winter weather (winter killing) or chemically with herbicide before planting in the spring. Mechanical termination of cover crops exists, but most studies focus on chemical termination (Creamer and Dabney, 2002). Commonly used cover crops include winter cereal grains, brassicas, legumes and annual grasses (CTIC).

Cover crops are believed to provide many desirable agronomic benefits to the farmer. Some of these benefits include reduced soil erosion, increased soil organic matter (SOM), increased soil water holding capacity, increased aeration, reduced tillage, reduced nitrate leaching and decreased soil compaction (Snapp, et al., 2005, Weil, et al., 2009). In a study on the effects of vetch and wheat cover crops, Mutchler and McDowell (1990) find that in conventional tillage systems, using cover crops reduced annual soil loss by 73%. Even with these agronomic benefits, adoption of cover crops is relatively low with an estimated 18% of farmers having ever used cover crops in the US Corn Belt (Singer, et al., 2007).

Moore, et al. (2014) evaluated cereal rye (*Secale cereal L.*) in corn silage-corn soybean rotations in a study lasting longer than 9 years. The authors compared the results of cereal rye when used after corn silage only, corn soybean only and both corn silage and corn soybean by comparing soil organic matter (SOM), particulate organic matter (POM) and potentially mineralizable N (PMN). Cereal rye when used after both crops or after corn silage provided a 15% increase in SOM, a 44% increase in POM and a 38% increase in PMN relative to not using cover crops (Moore, et al., 2014). When cereal rye was used after soybeans, the authors did not find a positive effect on soil quality indicators (Moore, et al., 2014). This is attributed to cereal rye not adding enough residue to the soil to cause measurable changes in SOM, POM or PMN (Moore, et al., 2014).

Snapp, et al. (2005) conducted a literature review of the costs and benefits of cover crops for four USDA growing zones. The benefits of cover crops include soil-amelioration and promotion of healthy crops (S. S. Snapp, 2005) . The cost of cover crop usage are divided into direct and indirect costs. Direct costs include cost of seed, equipment and establishment; Indirect costs are management problems and opportunity costs associated with delayed cash crop planting (S. S. Snapp, 2005). The authors find that (1) there are benefits of cover crops within irrigated cropping system since cover crops do not compete with cash crops for water (2) the benefits of cover crops are not always observed in the short term due to long term impacts of cover crops on soil health, cash crop yields, and pests. One shortcoming of the work by Snapp, et al. (2005) is that the work is more qualitative and lacks quantitative results. Labarta, et al. (2002) provided four economic methods that could be used to evaluate cover crops in potato-based crop systems. The methods cover include 1) evaluating comparative average profitability 2) integrating environmental impacts into profitability analysis 3) evaluating efficiency trade-offs between profitability and environmental impacts 4) variability of returns across systems. While the authors provide a framework to evaluate cover crops, no analysis of actual data is performed. Pratt, et al. (2013) found that annual ryegrass, cereal rye, crimson clover oats, oilseed radish, 60% annual ryegrass/ 40% oilseed radish and 60% crimson clover/40% annual ryegrass had positive net benefits per acre per year when the agronomic benefits of cover crops and the synergies between cover crops and corn stover harvest were included.

Cover crops have the potential to be important for sustainable corn stover harvest. Wilhelm, et al. (2010) determined that the agronomic factors of sustainable corn stover harvest are (1) Maintaining soil organic carbon, (2) Controlling wind and water erosion, (3) Plant nutrient balance, (4) Soil water and temperature dynamics, (5) Soil compaction and (6) Off-site environmental impacts. Many of these agronomic factors are improved by cover crop usage.

2.2 Soil Erosion

Soil erosion refers to the removal and transportation of soil from one site to another. The two primary sources of soil erosion are wind and water. There are both on-site and off-site costs of soil erosion. The on-site damages of soil erosion are potential reductions in soil productivity. There are numerous off-site damages that soil erosion causes, but one of the largest is related to effects of soil entering water sources.

Soil erosion can decrease soil productivity, thus soil erosion can negatively impact the farmer. Decreases in soil productivity from erosion include lower soil water retention capacity, plant nutrient loses, degradation of soil structure, and creation of non-uniform fields (Williams, et al., 1980).

Damages to water sources from soil erosion include but are not limited to, negative biological impacts such as the destruction of marine habitat, increased sedimentation in water storage facilities and increased maintenance costs of water ways from sediment buildup (Clark, 1985). Other damages from soil erosion include the health risks associated with increased levels of dust (Hotta, 2004).

Cover crops can reduce soil erosion. In a study on the effects of vetch and wheat cover crops Mutchler finds that in conventional till systems, using cover crops reduced annual soil loss by 73%.

The two most used methods of estimating on-site soil erosion damage are the change in productivity approach and nutrient replacement approach. The change in productivity approach estimates damages from soil erosion as the difference in crop yields with and without soil erosion multiplied by the price of the crop. The nutrient replacement approach measures how much soil erosion occurs and assigns a value based on the market value of the nutrients in the eroded soil. Barbier (1996) argues that both of these approaches overestimate the on-site damages of soil erosion. He argues that the best alternative approach to measuring the on-site damage of soil erosion is difference in Net Present Value (NPV) of farm income with erosion and without erosion.

Hansen and Ribaudo (2008) of USDA created estimates for willingness to pay of reductions in soil erosion for 14 different types of environmental benefits using travel costs, damage function, replacement costs and averting expenditures models. The benefits are estimated on the county level and on the Hydrologic Unit Code (HUC). Table 1 provides a summary of erosion damages.

Table 1: Summary of Erosion Damages from Hansen and Ribaudo (2008)

Source	Damage ($/ton of erosion)
Reservoir Services	0 to 1.38
Navigation Industry	0 to 5.00
Water-Based Recreation	0 to 8.81
Marine Recreational Fishing	0 to 1.57
Marine Commercial Fisheries	0 to 0.94
Freshwater Commercial Fisheries	0 to 0.12
Steam-Electric Power Plants	0.04 to 1.05
Municipal and Industrial Water Use	0.07 to 1.44
Flood Damages	0.10 to 0.77
Irrigation Ditches and Canals	0.01 to 1.02
Soil Productivity	0.26 to 1.27
Road Drainage Ditches	0.20
Municipal Water Treatment	0.05 to 1.16
Dust Cleaning	0 to 1.14

Source: Hansen and Ribaudo (2008)

The impact of soil erosion is dependent on location and soil type. To address this, soil loss tolerance values have been established. These estimates called T-values, are "the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely (Wischmeier and Smith, 1978)." T-values are measured in tons/acre/year. Conservation plans must have estimated soil erosion less than the T-value (Foster, 2001). However, there is a great deal of controversy surrounding these T-values. Two major complaints are that T-values do not include the impacts of erosion on water quality and that T-values exceed the natural rate of soil formation (Mann, et al., 2002). If T-values included both of these factors, then the tolerable soil loss would be lower.

2.3 Nitrate Leaching

Nitrate leaching refers to the loss of nitrate from the soil by water. Excess nitrates in water can have disastrous consequences for biological organisms. For humans, nitrates in well water have been attributed to cases of cyanosis in infants (Comly, 1945). Hypoxia in water refers to the depletion in oxygen to a level where aquatic organisms can no longer survive. Water pollution is a common cause of hypoxia. Nitrate leaching in the Midwest is attributed to hypoxia in the Gulf of Mexico.

Hypoxia can severely reduce the population of aquatic organisms. However, measuring the economic impact of hypoxia has proven challenging. Diaz and Solow (1999) created a conceptual model to measure how hypoxia affects both seafood demand and supply. Unfortunately, the economic assessment based on fisheries data failed to detect effects attributable to hypoxia. This is partially attributed to fish being able to move to non-hypoxic zones.

There are ways to reduce nitrate leaching other than applying less fertilizer. Some of these methods include using wetlands, denitrifying bioreactors and cover crops. Wetlands are ecosystems that are constantly saturated with water. When nitrate rich runoff enters the wetlands, aquatic organisms use the nitrate to grow. The nitrate is removed from the water through a process called denitrification, where nitrate is converted to dinitrogen and released into the atmosphere. Wetlands are expensive to build because of the opportunity cost of taking cropland out of production and the upfront cost of wetland construction. Christianson, et al. (2013) found the discounted cost of wetland construction in Iowa to range from \$267.48 $acre^{-1}$ to \$374.70 $acre^{-1}$.

Another way to reduce nitrate leaching is through denitrifying bioreactors. Denitrifying bioreactors are essentially well placed holes in the ground that are filled with wood chips. Denitrifying bacteria then use the wood chips as a source of energy to engage in denitrification, removing the nitrate from the water. In a study on the comparative cost effectiveness of nitrate reduction methods, Christianson, et al. (2013) found the average cost effectiveness of bioreactors to be \$2.10 ±\$0.90 kg N^{-1} yr^{-1}.

Cover crops are beneficial in reducing nitrate leaching. In a 15 year drainage study, Kladivko, et al. (2004) found that overall nitrate concentrations in subsurface water decreased. This decrease in Nitrate N concentrations was attributed to reduced fertilizer N rate and the addition of winter cover crops. Using a randomized complete-block split plot design, Brandi-Dohrn, et al. (1997) compared winter nitrate leaching losses under winter cereal rye and under winter fallow over 3 years in fields that were planted in a sweet corn/broccoli rotation. The authors find that using winter cereal rye reduced nitrate leaching between 16 kg N ha^{-1} and 34 kg N ha^{-1}.

2.4 Soil Organic Carbon

Soil organic carbon (SOC) refers to carbon within soil. SOC comes from the decomposition of organic matter, including crop residue and soil microorganisms. SOC acts as the main source of energy for soil microorganisms (Hoorman and Islam 2012). These microorganisms mineralize nutrients, allowing the nutrients to be availability to plants. SOC also changes the physical properties of the soil. Rawls, et al. (2003) used the U.S National Soil Characterization database along with regression trees and group method of data handling to explore water retention by taxonomic order. The authors found that at high organic carbon values, all soils showed an increase in water retention (Rawls, et al., 2003).

SOC and soil organic matter (SOM) are often used interchangeably. However, SOC is only a large component of soil organic matter (SOM). Two of the most common estimates for the percentage of SOC in SOM are 50% and 58%. SOM is reported as a percentage of total top soil mass.

SOM is extremely important to soil health. Loss of soil organic matter negatively affects the biological, chemical and physical functions of the soil (Wilhelm, et al., 2010). In general, the more SOM the better. Shukla, et al. (2006) performed a factor analysis of 5 treatments on soils in Ohio and found that soil organic carbon was the most dominant measured soil attribute as a soil quality indicator for the 0-10 cm and 10-20 cm depths.

The authors conclude that if only one soil attribute was to be used as a measure of changes in soil quality every 3-5 years, it should be soil organic carbon.

There is no market price for SOC. However SOC is extremely valuable to soil productivity. Lal (2014) estimates the societal value of SOC to be .060 $/lb. His estimates are based on the cost of nutrients and dried crop residues needed to convert biomass C into SOC and the agronomic benefits of increased crop yields due to increased SOC. The yield benefits are a 5% increase in yields due to soil moisture conservation for a total gain of 9.31 bushels of grain per acre. The author uses a per bushel grain price of $5 for a total gain of $46.55 per acre. If this value was adjusted for per bushel grain price of $3.50 the total benefit would be $32.59 per acre. Using the estimates from Himes (1998) on the sequestration of biomass C as SOC, Lal (2014)estimates part of the value of SOC as the cost of converting biomass into SOC. To create 10,000 kg of SOC, 62,000 kg of dried crop residues are needed in addition to 833kg Nitrogen, 200kg Phosphorous and 143kg Sulfur. Note that these values are the mass of elements needed. The author estimates the price of each element by how much of each element is in each fertilizer (except for sulfur where the price of elemental sulfur is used instead). The author uses prices of crop residue .039 $/kg (35.45 $/ton), nitrogen .67 $/kg (.30 $/lb), phosphorous 1.94 $/kg (.88 $/lb), and sulfur .57 $/kg (.26 $/lb). If only the cost of N,P,S are considered then the value of SOC is .045 $/lb (Lal, 2014).

Soil carbon dynamics are extremely complicated. While there is carbon in both the roots of the plant and the above ground plant material, there are studies that suggest that source of carbon from subsurface plant material contributes greater to SOC that above surface residue. This is important because one of the cited limitations of corn stover harvest is maintaining SOC levels. However, there are studies that suggest that the root derived carbon, which is not harvested, may contribute to the majority of carbon inputs in soil. In a study on the short-term dynamics of root- and shoot-derived carbon from a leguminous green manure, Puget and Drinkwater (2001) monitored Hairy Vetch (a leguminous crop) *in situ* and discovered the differences in the retention of root (below ground) vs. shoot (above ground) C inputs. The authors find that litter origin (shoots or roots) played a critical role in determining the fate of C inputs. When the soil was tested at the end of the growing season, the authors found that nearly one-half of the root-derived C was still present in the soil, while only 13% of the shoot-derived C remained (Puget and Drinkwater, 2001). However, the authors urge caution about the long term implication of these results and only hypothesize that greater retention of root-derived C will result in greater longevity of root derived C as SOM (Puget and Drinkwater, 2001).

Tillage practices impact SOC. Tillage practices are often categorized by how much of the crop residue is disturbed. Havlin, et al. (1990) in a study on tillage and crop rotation impacts on eastern Kansas soils found that the tillage practice and crop rotations with the greatest increases in organic carbon and nitrogen were those that produced and left the greatest amount of residue on the soil surface. Conservation tillage tends to increase SOC because decomposition rates are slower from less mixing of the soil and lower soil temperatures compared to other tillage practices (Kern and Johnson, 1993). Lower soil temperatures slow the rate of decomposition of organic material allowing for more material to be converted into organic matter.

West and Post (2002) reviewed studies greater than 5 years in length that recorded SOC responses to changes in crop rotation and tillage practices. After calculating the 75% quantile of mean annual changes of carbon sequestration rates, the authors apply a nonlinear regression algorithm. The results of the regression suggest that the approximately 85% of the carbon sequestered when changing from conventional tillage to no till occurs in the top 7 cm (West and Post, 2002). The authors also find that there were statically significantly higher SOC levels under no till compared to reduce till and conventional tillage.

Baker, et al. (2007) challenge the widely held belief that soil disturbance from tillage was the primary cause of historical loss of SOC in North America. The authors claim the studies that estimate soil carbon changes through soil sampling may be biased from the sampling protocol used. Baker, et al. (2007) noticed in the work of West and Post (2002) that none of the studies reviewed tested soil samples below 30 cm. Some work has been done on distribution of SOC below 30cm. The authors suggest that the claims that tillage causes loss of SOC are from confusing correlation with causation. A potential alternative explanation is that increased tillage is historically correlated with changes in crop rotation (perennial vegetation to annual cropping) and land use (wetland to drained farm land) (Baker, et al., 2007).

Tillage practices also impact the ecology of the microorganisms in the soil. It is the microorganisms in the soil that are responsible for the decay of organic matter. Bacteria in the soil is more capable of surviving the impacts of tillage than mycorrhizal fungi, however mycorrhizal fungi are more efficient in carbon recycling (Hoorman and Islam 2012). More decomposition from mycorrhizal fungi results in increased SOC due to greater recalcitrant decomposition products compared to bacterial decomposition (Kern and Johnson 1993, Holland and Coleman 1987).

2.5 LEAF

The Landscape Environmental Assessment Framework (LEAF), formerly referred to as an integrated model, was developed by Muth and Bryden in 2013. It is the model that is used to generate data for this study. Using existing soil, crop and climate data, LEAF seamlessly ties together the Revised Universal Soil Loss Equation Version 2 (RUSLE2), Wind Erosion Prediction System (WEPS) and the Soil Conditioning Index (SCI) to "create a single integrated residue removal modeling system (Muth and Bryden 2013)." RUSLE2, WEPS, and SCI are all part of the USDA conservation management planning process, allowing for LEAF to be relevant to bioenergy decision makers (Muth and Bryden 2013). Prior to LEAF, the individual models needed manual data transfer to interact with each other, making residue availability assessments infeasible across large spatial domains and/or including many management practices (Muth and Bryden 2013). LEAF has been extended to include the DNDC model to quantify the biogeochemical interactions from residue removal.

Validation of LEAF comes from Muth and Bryden (2013). Muth and Bryden (2013) validate the LEAF framework by performing a set of verification runs to ensure that the results from LEAF matched the NRCS field office versions of RUSLE2 and

WEPS. Differences between LEAF results and NRCS field office results were attributed to significant digit rounding differences (Muth and Bryden, 2013).

LEAF was used by Bonner, et al. (2014) to determine the amount of sustainable removable biomass under different definitions of sustainability for Indiana, Illinois, Iowa, Minnesota and Nebraska. The authors found that while using the NRCS sustainability criteria, having total erosion less than the T-value and maintaining soil organic carbon (SCI>0), the amount of available stover ranged from 96.2 million Mg to 194.2 million Mg annually depending on which management practices were used. Using another stricter sustainability criteria where total erosion is less than one half the T-value and having the SCI-organic matter (OM) sub factor to be greater than zero, the authors found that the amount of a sustainably removable corn stover ranged between 36.5 million Mg and 148.1 million Mg annually depending on the management practices used.

LEAF was used by Abodeely, et al. (2012) to analyze the long term impact of interval residue removal practices on soil organic matter. In an interval removal practice, crop residue is removed bi-annually or tri-annually instead of yearly. An interval removal system reconciles the negative impact of residue harvest on soil with the removal rates that are economically viable (Abodeely, et al., 2012). The authors find that over 20 years the bi-annual and tri-annual result in higher soil organic carbon levels than annual removal and emphasize the potential importance of interval removal on at risk land.

Bonner, et al. (2014) used LEAF in a case study for Hardin County, Iowa to show how subfield decision making can be used to target areas for conversion to energy crop production. Motivation for the strategy come from the author’s observation that at .20 $ kg^{-1} (\$5 $bushel^{-1}$) 85% of the corn producing field in Hardin County are modeled to have some areas operating at a negative net cost, creating an opportunity for another crop to be planted in these unprofitable areas. The results suggest that implementing switchgrass where corn grain models return a net economic loss can increase sustainable biomass production from 48% to 99% and increase the field level profitability.

LEAF has also been used in applied economics research. In a benefit cost analysis of cover crops, Pratt, et al. (2013) used LEAF to estimate the amount of removable biomass with and without cover crops while holding soil erosion constant. The results suggest that when including agronomic factors and corn stover harvest, cover crops usually have a positive NPV. English, et al. (2013) used a dynamic optimization framework to determine profit maximizing management practice combinations and used LEAF to estimate the amount of soil erosion and amount of removable biomass under each combination of management practices. The results suggest that if soil erosion damages are internalized and there is a market for corn stover, then profit maximizing behavior will result in adoption of cover crops and no till for most areas of Indiana.

CHAPTER 3: METHODOLOGY AND DATA

The goal of this thesis is to identify under which management practices cover crops provide the greatest benefits. This chapter will provide the methodology and data used to achieve this goal. A dummy variable model will be used to quantify the environmental impacts of cover crops under different management practices and land capability classes. The management practices examined will be cover crops, residue harvest, tillage practice and crop rotation. The environmental impacts of cover crops for this analysis will be soil erosion, nitrate leaching and soil organic carbon (SOC) change. Data for the environmental impacts of the management practices will come from the Landscape Environmental Assessment Framework (LEAF).

Once the environmental impact of cover crops has been quantified, an economic interpretation of the impacts will be provided. Since there is no market price for soil erosion, nitrate leaching and SOC change, it will be necessary to estimate values for these environmental impacts. Since cover crops provide value to the farmer and society, estimates will be created for the nutrient benefit of cover crops and social benefit of cover crops. Separating the results into nutrient and social benefits will provide insight on who gains the most from cover crop usage. The results of the economic interpretation will provide information about where and under which management practices cover crops provide the greatest benefits.

3.1 Environmental Factors and LEAF

The Landscape Environmental Assessment Framework (LEAF) is a toolset that utilizes national, regional and subfield scales to assess the impact of different management practices on environmental factors. The implementation of LEAF used for this paper uses the Revised Universal Soil Loss Equation (RUSLE2), the Wind Erosion Prediction System (WEPS), the Soil Conditioning Index (SCI), and the bio geochemical Denitrification and Decomposition (DNDC) model. LEAF quantifies the simulated outcome of different management practices for different environmental factors. The LEAF outputs used for this paper are:

1) Annual wind and water erosion (tons $acre^{-1}$ $year^{-1}$)

2) Annual change in soil organic carbon (lbs $acre^{-1}$ $year^{-1}$)

3) Annual loss of nitrate in first 30cm of soil (lbs $acre^{-1}$ $year^{-1}$)

The entire state of Indiana was simulated at the SSURGO soil type level for a variety of management practices. This version of LEAF provides all the permutations for each soil type of two tillage practices, six crop rotations, four cover crop choices, four residue harvest amounts, two strip barrier choices and four yield drags for a total of 720 outcomes for each site. LEAF provides outputs for 1,688 SSURGO soil types resulting in a total of 1,215,360 simulated observations for Indiana. Note that only SSURGO soil types with over 1,000 acres were used.

The Land Capability Classification (LCC) is a rating system that was developed by the Soil Conservation Service as a planning tool for laying out conservation measures and practices for farms to avoid serious deterioration of the land (Helms, 1992). There are eight classes of land, labeled 1 through 8, in the LCC. The first four classes (1 through 4) are considered suitable for cropland; the last four (5 through 8) are considered not suitable for cropland (Helms, 1992). The assignment of an area to a class is based on landscape location, slope of field, depth, texture and reaction of the soil (Helms, 1992). Soil types in LEAF have LCC ratings ranging from 1 through 6.

While LEAF provides outputs for six crop rotations, only continuous corn (CG, CG, CG) and corn-soybean (CG,SB) rotations are examined. These two rotations are chosen because they are the most popular crop rotations in Indiana. No vegetative barrier (NVB) is used to allow the focus of analysis to be on cover crops. For continuous corn rotation, a yield drag of 4 bushels per acre (drag4) is used. This yield drag was chosen to give continuous corn a yield penalty, but is small enough to acknowledge that advances in GMO technology may be able to reduce the yield penalty close to zero. There is no yield penalty for corn-soybean rotation. There are 4 cover crops used in this version of LEAF: no cover crops, 100% rye, and two mixes of cover crops: 40% rye,60%clover and 60%rye,40%radish. This analysis will use only 100% rye because of uncertainty in LEAF results for SOC changes from using cover crop mixes. In this paper the residue harvest will be referred to as no residue harvest, low residue harvest, medium residue harvest and high residue harvest respectively. These correspond to removal rates of approximately, 0%, 35%, 52%, and 83% respectively. All residue harvest rates are used and residue is assumed to have moisture content of 15%

In addition to only looking a subset of management practices, only a subset of all the soil types are used. Only soils with a non-irrigated LCC rating 1 through 3 are used. This is justified in two ways. The first justification is that 1543 of the 1688 soil types (91.40%) used by LEAF are represented by non-irrigated Land Capability Classification rating 1 through 3. So the majority of Indiana is represented in this range of ratings. The second justification is that soils with NIRR Capability Class rating above 4 have severe limitations to agricultural production and do not reflect a large share of land being used for crops. While it is possible for LCC ratings of 5 and 6 to be used for cropland, focusing only on LCC rating 1 through 4 allows for a comprehensive story about Indiana agriculture can be told without excessive analysis. However, there are potential issues with the outcomes of soils with LCC rating 4 used in the DNDC model. The LEAF data showed unusual values for nitrate leaching values on soils with LCC rating 4. After consulting with the Gabe McNunn, the person responsible for implementation of DNDC in LEAF, he recommended tossing some of the bad soils out of the analysis. Rather than attempt to identify which soils within LCC rating 4 were well behaved, the entire group was removed. So only LCC ratings 1 through 3 are used.

The distribution of non-irrigated Land Capability Classification ratings in Indiana is heavily skewed. Figure 1 provides a visual distribution of LCC ratings for Indiana. Land Capability Classification rating 2 accounts for 68.25% (1152 of 1668) of the total soil types used by LEAF. Land Capability Classification 1 and 3 account for 100 and 291 soil types respectively. The white areas represent soils not included in LEAF. Notable white space includes the city of Indianapolis, Hoosier National Forest, Brown County State Park and other forest.

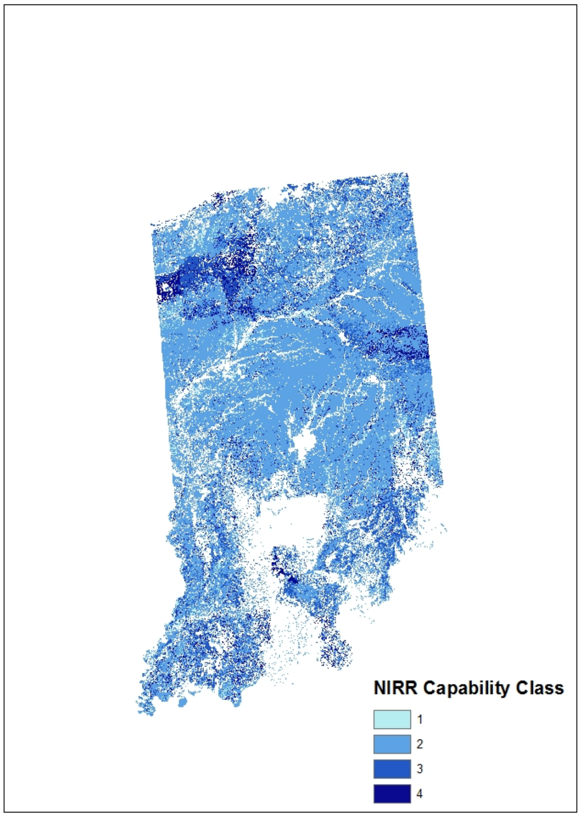

Figure 1: Distribution of NIRR Capability Classes in Indiana

3.2 Valuation of Environmental Factors

3.2.1 Soil Organic Carbon

Lal (2014) estimated the replacement cost of creating SOC by estimating the value of the biomass and the nutrients needed to convert biomass into SOC. For this analysis the value of SOC is estimated by the value of the nutrients only, the value of the biomass is ignored. Several studies have shown that carbon input from roots is a substantial part of the carbon in SOC (Wilhelm, et al., 2010). These below group carbon inputs are not harvested when corn stover is harvested. Therefore, the opportunity costs of below ground crop residue is zero. This does not say that the below ground carbon inputs have no use. It says that there is no alternative use for below ground carbon inputs other than for SOC. Rather than try to estimate what percentage of carbon inputs comes from above or below ground carbon sources, the replacement cost of SOC is valued at the cost of nutrients in fertilizer form. This estimate is a lower bound for the actual replacement cost of SOC.

Roughly 1832.6 lbs-N, 440 lbs-P, and 314.6 lbs-S are needed to convert 136,400 lbs of crop residue into 22,000 lbs-SOC. This corresponds to .08 lbs-N, .02 lbs-P and .01 lbs-S to create 1 lbs-SOC. These values are not the nutrient content of the biomass, but the amount of nutrients required to sequester carbon into the soil. Notice that 136,400 lbs of crop residue is required to make only 22,000 lbs-SOC. This is because under aerobic conditions only approximately 35% of the carbon in residue becomes sequestered in the hummus (dead part of SOM) and the amount of carbon in oven dried residue is approximately 45% of the mass of the residue (Himes, 1998). So only 15.75% of the crop residue mass becomes SOM mass.

When evaluating the price of nutrients it must be remembered that the amount of nutrients needed are reported in terms of pounds of their elemental form, and not of their fertilizer form. To find the price of the elemental form, the price of fertilizer must be adjusted for how much of each element is in the fertilizer. The only exception to this is sulfur. Elemental sulfur is added to soils to treat sulfur deficiency since it is approximately one third of the cost of sulfur from fertilizers (Lang, et al., 2007).

Fertilizers are a form of nutrients immediately available to the plants, as elemental forms must go through a mineralization process to become available for plant use. So, the tradeoff is that elemental sulfur is not available immediately to the plants (Lang, et al., 2007). The estimate for sulfur is a lower bound since local costs of Sulfur and application costs could not be found. Table 2 provides a summary of fertilizers and prices used to estimate the cost of creating SOC.

Table 2: Elements, Nutrients and Prices Needed to Create SOC

Nutrient	Fertilizer	Cost of Fertilizer ($/ton)	Cost of Nutrient ($/lb)	Source	Comments
Nitrogen	Urea (46% N)	482.50	.52	Iowa Production Cost Report (Bi-weekly)	Tuesday, Nov 18th, 2014: Bulk, FOB distributor
Phosphorous	Mono-ammonium phosphate (52% P)	601.50	.57	Iowa Production Cost Report (Bi-weekly)	Tuesday, Nov 18th, 2014: Bulk, FOB distributor
Sulfur	Elemental Sulfur	145.00	.072	Argus FMB Sulphur	US Gulf FOB Q3-2014

Source: Author's summary

Applying the methodology from Lal (2014) the benefit from SOC can be written as:

$$Value\ of\ SOC\ Change\ \left(\frac{\$}{acre}\right) = \left[N\ Needed\ (lbs) * Cost\ of\ N\ \left(\frac{\$}{lbs}\right) + P\ Needed\ (lbs) * Cost\ of\ P\ \left(\frac{\$}{lbs}\right) + S\ Needed * Cost\ of\ S\ \left(\frac{\$}{lbs}\right)\right] * \left(\frac{1}{1 lbs\ SOC}\right) * SOC\ Change\ \left(\frac{lbs\ SOC}{acre}\right)$$

Using the parameters from Lal (2014) and price data from Iowa Production Cost Report (Bi-weekly) and Argus FMB Sulphur, we arrive at the per pound price of SOC of \$.056. This value is then multiplied by the change in SOC to arrive at the value of SOC change. The estimate of \$.056 lb^{-1} is greater than 0.045 \$ lb^{-1}, the nutrient replacement cost for SOC given by Lal (2014).

3.2.2 Soil Erosion

One of the most comprehensive evaluations of soil erosion comes from Hansen and Ribaudo (2008) who estimated the willingness to pay for per ton reductions in soil erosion for 14 different types of benefits using travel costs, damage function, replacement costs and averting expenditures models. The benefits are estimated on the county level and on the Hydrologic Unit Code (HUC). A hydrological unit code is a sequence of symbols that identifies a hydrological feature.

The soil erosion damage estimates from Hansen and Ribaudo (2008) will be used to estimate the nutrient and social cost of soil erosion. The per ton damage to soil productivity is estimated at \$1.01 for Indiana. This damage to soil productivity will represent the nutrient cost of soil erosion. The per ton off-site soil erosion damage estimates for counties in Indiana range from \$4.70 to \$8.04. The social cost of soil erosion will be set at 4.96 \$/ton, which is the median of the off-site soil erosion damages for counties in Indiana provided by Hansen and Ribaudo (2008). The majority of counties in Indiana have per ton damages between $4.70 and $5.37. Figure 2 shows how soil erosion damages are distributed.

The reason the estimates from Hansen and Ribaudo (2008) were used is because this was the only paper found that address the damage from soil erosion in Indiana explicitly. Another reason is that other papers estimate total soil erosion damages for an entire region such as Appalachian or Corn Belt (Colacicco, et al., 1989). However, the damages from soil erosion can vary greatly within a state because erosion near water sources is more damaging than soil erosion away from water sources. This is addressed by Hansen and Ribaudo (2008). Because of these reasons I have more confidence in the estimates provided by Hansen and Ribaudo (2008) than other papers.

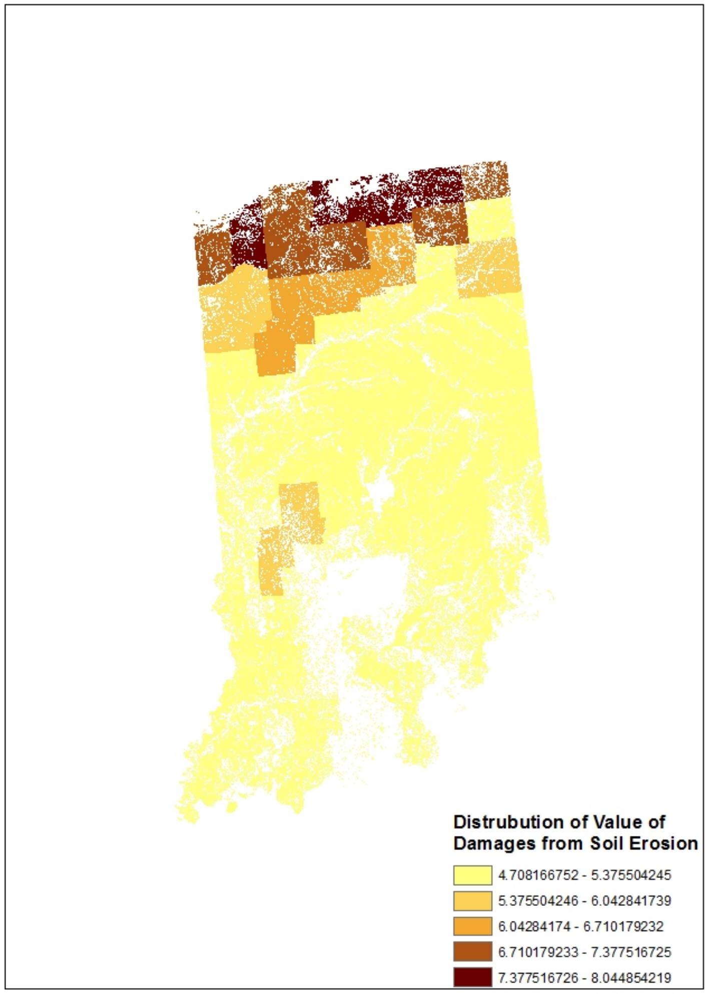

Figure 2: Distribution of Value of Damages from Soil Erosion
Source: Author Adaption of Data in (Hansen and Ribaudo, 2008)

3.2.3 Nitrate Leaching

Christianson, et al. (2013) calculated the comparative average cost effectiveness of nitrogen mitigation from denitrifying bioreactors to be \$2.10 ± \$.90 kg $N^{-1}yr^{-1}$ (\$.95 ± \$.41 lb-$N^{-1}yr^{-1}$). This price does not estimate the damage caused by nitrate leaching. There is a shortage of reliable estimated benefits for hypoxia (a situation caused by nitrate leaching) reduction (Diaz and Solow, 1999, Doering, et al., 1999). Rather than guessing at the damage from nitrate leaching, the benefit of nitrate leaching reduction used for this analysis represents the price at which a farmer would be indifferent to preventing nitrate leaching (by construction of a denitrifying bioreactor) versus paying a tax on the quantity of nitrate leached. One reason denitrifying bioreactors was used compared to other nitrogen removal efforts (wetlands) was because of the relatively small amount of surface area required by denitrifying bioreactors. Since denitrifying bioreactors are less than 0.5% of the drainage treatment area, the opportunity cost of the forgone production from the land is relatively small. Wetlands on the other hand require .5-2% of the treatment area for the wetland basin and 3.5% of the treatment area for a grass buffer (Christianson, et al., 2013). The amount of nitrate leaching comes from the LEAF field 'no3_leach.' One kg-N removed corresponds to 4.42 kg-NO_3^- removed. So the cost of removing pure nitrate is \$0.21/lb-NO_3^-.

3.3 Cover Crop Costs

Pratt, et al. (2013) estimated the cost of annual ryegrass to be \$34.43 $acre^{-1}$ by using data from the Midwest Cover Crop Council (MCCC) Decision Tool, interviews with farmers and the formula:

$$
\begin{aligned}
&Cost\ of\ Cover\ Crop\left(\frac{\$}{acre}\right) \\
&\quad = Establishment\ Cost\ \left(\frac{\$}{acre}\right) + Termination\ Cost\ \left(\frac{\$}{acre}\right) \\
&\quad + Unexpected\ Cost\ \left(\frac{\$}{acre}\right)
\end{aligned}
$$

3.4 Econometric Models

One of the goals of this model will be to quantify the impact of different combinations of management practices and LCC ratings on soil erosion, nitrate leaching and SOC change. To do this a dummy variable model is used that includes each of the individual management practices, LCC ratings and their interactions with each other. The results of this model will determine the mean impact of cover crops when used with different management practices and different LCC soil ratings.

All of the independent variables in the model are dummy variables that are equal to 1 when the management practice is used and 0 otherwise. Here *D* is used to signify the coefficient of a dummy variable. Robust regressions are run to address heteroskedasticity. Subscripts are abbreviations described in Table 3.

Soil Erosion model:

$$\text{Total Erosion} = \beta_0 + D_{CC} + D_{Low} + D_{Med} + D_{High} + D_{Ccorn} + D_{RT} + D_{LCC2} + D_{LCC3} + D_{interactions} + \varepsilon$$

Soil Carbon model:

$$\text{Soil Carbon} = \beta_0 + D_{CC} + D_{Low} + D_{Med} + D_{High} + D_{Ccorn} + D_{RT} + D_{LCC2} + D_{LCC3} + D_{interactions} + \varepsilon$$

Nitrate Leaching model:

$$\text{Nitrate Leaching} = \beta_0 + D_{CC} + D_{Low} + D_{Med} + D_{High} + D_{Ccorn} + D_{RT} + D_{LCC2} + D_{LCC3} + D_{interactions} + \varepsilon$$

Table 3: Abbreviations of Variables

Subscript	Name
CC	Cover Crop
Low	Low residue harvest
Med	Medium residue harvest
High	High Residue Harvest
Ccorn	Continuous Corn
Rt	Reduced Till
LCC2	LCC rating 2
LCC3	LCC rating 3

The results of these models are used to calculate mean outcome of soil erosion, nitrate leaching and SOC change from all the combination of management practices and LCC ratings. From these results we are interested in testing the following hypotheses:

1) There are no differences in nitrate leaching, soil erosion and SOC change from using cover crops compared to no cover crops.

2) There are no differences in the benefits of cover crops between continuous corn and corn soybean.

3) There are no differences in the benefits of cover crops between reduced till and no till.

4) There are no differences in the benefits of cover crops between Land Capability Class (LCC) ratings.

Why use a linear regression with dummy variables instead of ANOVA? Both linear regression and ANOVA with interactions calculate the same mean for each group and the same statistical significance of each group. Note that ANOVA without interactions or main effects only would calculate the same mean, but the hypotheses tested would be different. ANOVA with interactions finds the mean of each group and report a p-value to determine if the means of the groups are statistically different. The coefficients of a linear regression with dummy variables represent the difference in the group mean of the dummy variable with the mean of the intercept. However, the intercept is just the dummy variable left out of the model to avoid the dummy variable trap.

The intercept is often referred to as the base case or reference case. For this model the reference case is the result from using no cover crops, corn soybean rotations, no till and no residue harvest on soil with LCC rating 1. The p-value of the coefficient measures the statistical significance of the difference of the mean of the dummy variable from the mean intercept. If the p-value determines that the coefficient of the dummy variable is significant, then the difference between the mean of the dummy variable is statistically significant from the mean of the intercept. Linear regression is used because it is the most common tool used in econometrics. In the opinion of the author, the results are easier to interpret with linear regression.

CHAPTER 4: ECONOMETRIC RESULTS

The results of the econometrics model discussed in Chapter 3 provide the mean impact on environmental factors from each management practice, Land Capability Class (LCC) rating and their interactions. From these results the mean environmental impact from a combination of management practices and soil types can be calculated. Then the difference in outcomes between using cover crops and not using cover crops will represent the benefit of cover crops. Figures 3 to 6 provide a visual outline of the results.

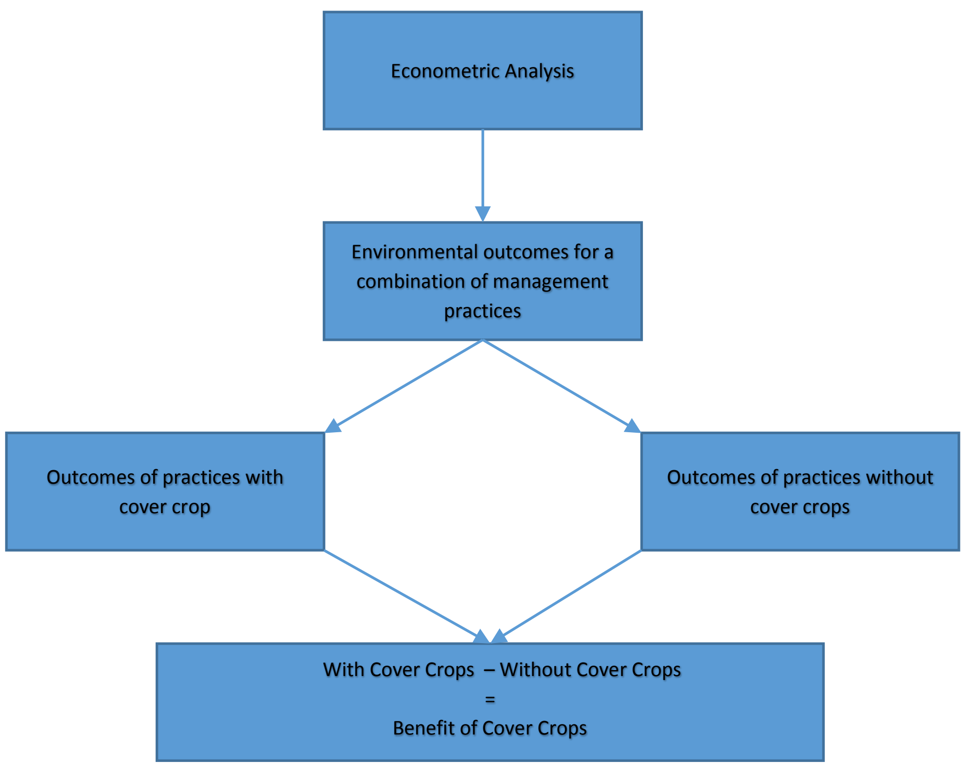

Figure 3: Roadmap of Results

Once the benefits of cover crops have been established, the next step is to find out under which management practices cover crops provide the greatest benefit. First, the benefits of cover crops will be compared across land capability class ratings. An increase in land capability class rating corresponds to increasingly marginal soil. If cover crops have greater impact on soil with a higher land capability class rating, then cover crops provide more benefit on poor soils than prime cropland.

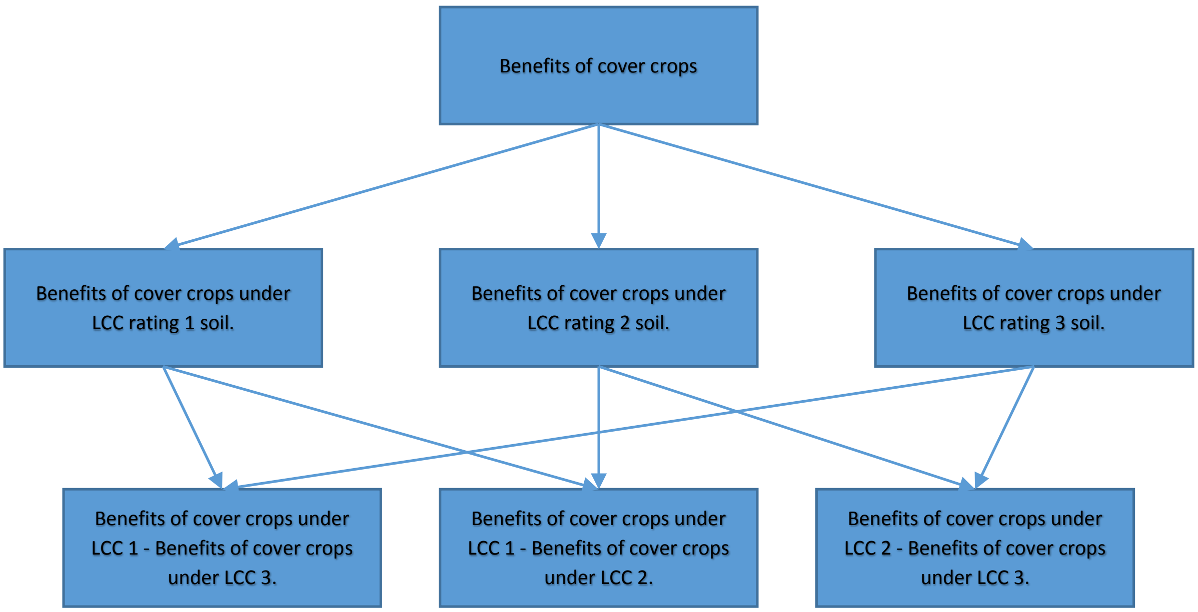

Figure 4: Difference in Cover Crop Benefits between Land Capability Class Ratings.

Second, the benefits of cover crops will be compared between tillage practices. If there are differences in the benefits between no till and reduced till, then cover crops are more valuable under one or the other of the tillage practices.

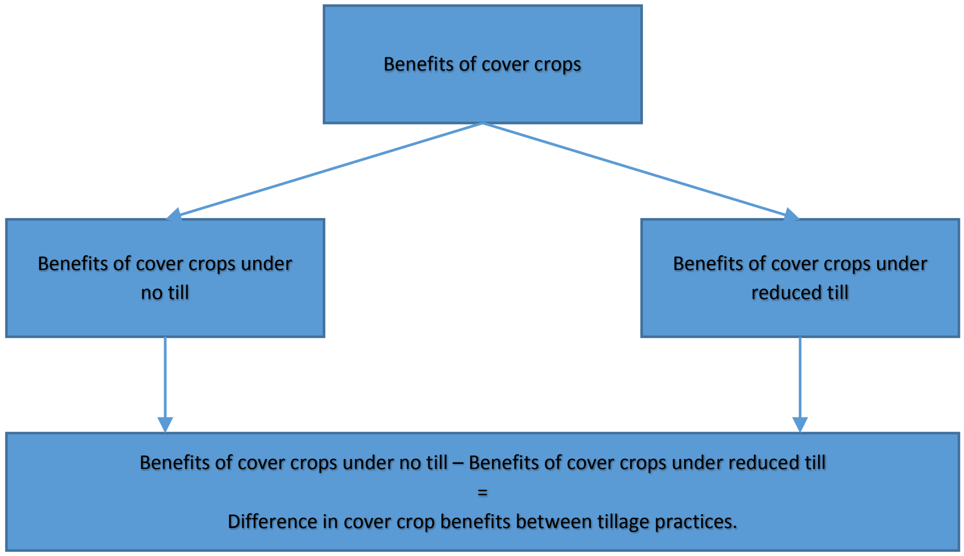

Figure 5: Differences in Cover Crop Benefits between No Till and Reduced Till.

Third, the benefits of cover crops will be compared between crop rotations. Given that corn and soybeans are different plants, it is reasonable to expect there to be some differences in the impact of using cover crops. If there are differences between crop rotations, then it may be more valuable to use cover crops in certain crop rotations.

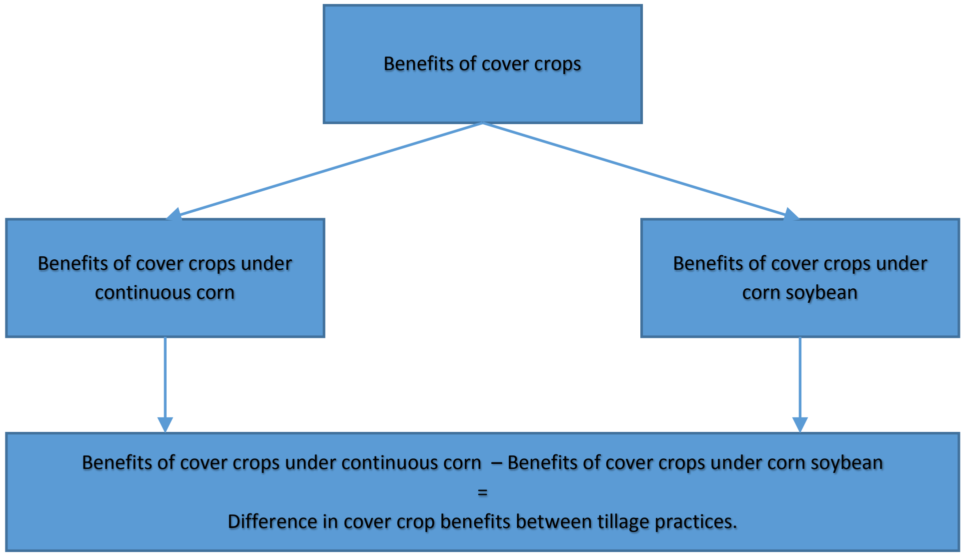

Figure 6: Differences in Cover Crop Benefits between Continuous Corn and Corn Soybean.

4.1 Soil Erosion

Cover crops reduce soil erosion for all management practices and LCC ratings. However, the magnitude of the soil erosion reduction is dependent on crop rotation, tillage practice, residue harvest, and land capability rating. The benefits of cover crops as a method of reducing soil erosion are most prominent under high residue harvest. The reduction in soil erosion from cover crop usage increases as land capability class increases; however, this increase is not always statistically significant. Land under reduced till has greater benefits from cover crops in reducing soil erosion than land under no till. The difference in soil erosion reduction benefits between continuous corn and corn soybean rotations is inconclusive. Table 4 provides description of abbreviations used in this chapter.

The statistical significance in this model is not the conventional statistical significance. Since LEAF is deterministic, there is no randomness. The source of error comes is all from spatial heterogeneity rather than measurement error.

Tables 5 and 6 provides the mean of the total quantity of soil erosion that will occur under each combination of management practices. Each practice results in a quantity of erosion that is statistically significant from zero at the 1% level except for when cover crops, high residue harvest and reduced till is used under continuous corn rotations. This is because the standard errors are much higher under high residue harvest than other levels of residue harvest. The total amount of soil erosion that occurs is highly dependent on the management practice used and the LCC rating. The lowest amount of projected soil erosion is .05 (tons/acre-year) and occurs on class 1 soil under continuous corn, no till, no residue harvest and cover crops. The highest amount of projected soil erosion is 39.74 (tons/acre-year) and occurs on class 3 soil under continuous corn, reduced till, high residue harvest and no cover crops. To put these numbers in perspective, the rate of soil formation varies depending on geological characteristics, but for Indiana estimates are between 2 tons/acre-year and 5 tons/acre-year. How soil is managed makes a large difference on soil erosion.

Table 4: Abbreviations for Residue Removal Practices

None	No Residue Harvest	0% removal
Low	Low residue harvest	35% removal
Med	Medium residue harvest	52% removal
High	High Residue Harvest	83% removal

Table 5: Total Soil Erosion (tons/acre-year) for Each Management Practice and LCC Rating under Continuous Corn.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	0.05** (0.00)	0.13** (0.01)	0.60** (0.16)	1.20** (0.05)
	LOW	0.09** (0.00)	0.32** (0.01)	0.87** (0.18)	1.72** (0.06)
	MED	0.34** (0.01)	0.87** (0.04)	1.01** (0.19)	2.20** (0.08)
	HIGH	0.65** (0.03)	11.87** (1.09)	0.38 (1.68)	11.01** (0.90)
LCC Rating 2					
	NONE	0.06** (0.00)	0.18** (0.00)	0.90** (0.16)	1.94** (0.06)
	LOW	0.11** (0.00)	0.46** (0.01)	1.26** (0.18)	2.76** (0.08)
	MED	0.48** (0.01)	1.34** (0.04)	1.48** (0.20)	3.48** (0.10)
	HIGH	0.94** (0.02)	13.11** (0.45)	0.32 (1.59)	13.33** (0.40)
LCC Rating 3					
	NONE	0.07** (0.00)	0.24** (0.02)	1.29** (0.19)	3.76** (0.22)
	LOW	0.14** (0.01)	0.66** (0.05)	1.76** (0.22)	5.57** (0.31)
	MED	0.64** (0.05)	2.01** (0.15)	2.09** (0.25)	7.30** (0.39)
	HIGH	1.45** (0.10)	37.70** (2.56)	1.53 (1.69)	39.34** (2.63)

Note: Standard errors are in parentheses, ** $p < .01$

Table 6: Total Soil Erosion (tons/acre-year) for Each Management Practice and LCC Rating under Corn Soybean Rotations.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	0.28** (0.01)	0.43** (0.02)	2.31** (0.09)	2.98** (0.12)
	LOW	0.37** (0.02)	0.60** (0.03)	2.48** (0.09)	3.33** (0.13)
	MED	0.53** (0.02)	0.87** (0.04)	2.58** (0.10)	3.58** (0.14)
	HIGH	0.73** (0.03)	6.61** (0.60)	2.91** (0.11)	8.94** (0.66)
LCC Rating 2					
	NONE	0.40** (0.01)	0.64** (0.02)	3.51** (0.09)	4.53** (0.12)
	LOW	0.53** (0.01)	0.91** (0.03)	3.75** (0.10)	5.05** (0.13)
	MED	0.79** (0.02)	1.34** (0.04)	3.91** (0.10)	5.41** (0.14)
	HIGH	1.10** (0.03)	7.15** (0.23)	4.41** (0.11)	11.02** (0.30)
LCC Rating 3					
	NONE	0.57** (0.05)	0.99** (0.08)	7.62** (0.40)	10.47** (0.53)
	LOW	0.76** (0.06)	1.42** (0.11)	8.15** (0.42)	11.67** (0.59)
	MED	1.14** (0.09)	2.10** (0.16)	8.47** (0.44)	12.47** (0.62)
	HIGH	1.73** (0.12)	19.62** (1.30)	9.73** (0.51)	30.87** (1.96)

Note: Standard errors are in parentheses. ** $p < .01$

Tables 7 and 8 provide the difference in soil erosion between management practices using cover crops and not using cover crops. This difference is the reduction in soil erosion benefit of cover crops. The range of the soil erosion reduction benefits of cover crops is from .081 tons/acre-year to 36.24 tons/acre-year, depending on LCC rating and management practice. The reduction in soil erosion from cover crops is significant at the 1% level for all management practices and land capability classes. These results have two implications. The first implication is that cover crops actually reduce soil erosion. The second implication is that given the wide variation in the soil erosion reduction benefits, it is necessary to evaluate the benefits by group.

Table 7: Reduction in Soil Erosion (tons/acre-year) with Cover Crops for Continuous Corn.

No Till		
	Residue Removal Rate	Benefits of Cover Crops
LCC Rating 1		
	NONE	0.08
	LOW	0.23
	MED	0.53
	HIGH	11.22
LCC Rating 2		
	NONE	0.12
	LOW	0.35
	MED	0.86
	HIGH	12.17
LCC Rating 3		
	NONE	0.17
	LOW	0.52
	MED	1.37
	HIGH	36.25
Reduced Till		
LCC Rating 1		
	NONE	0.60
	LOW	0.85
	MED	1.19
	HIGH	11.38
LCC Rating 2		
	NONE	1.04
	LOW	1.51
	MED	2.01
	HIGH	13.01
LCC Rating 3		
	NONE	2.46
	LOW	3.81
	MED	5.21
	HIGH	37.81

Note: The Benefit of Cover Crops column is the result of the hypotheses test ($F(1,49280)$) comparing the difference in soil erosion with cover crops and without cover crops. All cases are statistically significant at the 1% level.

Table 8: Reduction in Soil Erosion (tons/acre-year) with Cover Crops for Corn Soybean.

No Till		
	Residue Removal Rate	Benefits of Cover Crops
LCC Rating 1		
	NONE	0.15
	LOW	0.23
	MED	0.33
	HIGH	5.88
LCC Rating 2		
	NONE	0.25
	LOW	0.38
	MED	0.56
	HIGH	6.06
LCC Rating 3		
	NONE	0.42
	LOW	0.66
	MED	0.96
	HIGH	17.89
Reduced Till		
LCC Rating 1		
	NONE	0.67
	LOW	0.85
	MED	0.99
	HIGH	6.03
LCC Rating 2		
	NONE	1.02
	LOW	1.29
	MED	1.50
	HIGH	6.61
LCC Rating 3		
	NONE	2.85
	LOW	3.52
	MED	4.00
	HIGH	21.14

Note: The Benefit of Cover Crops column is the result for the hypotheses test ($F(1,49280)$) comparing the difference in soil erosion with cover crops and without cover crops. All cases are statistically significant at the 1% level.

Land under high residue harvest has the largest reduction in soil erosion from cover crop usage. Soil erosion reduction benefits while using high residue harvest range from 5.87 tons/acre-year to 37.81 tons/acre-year (Table 9). There are two implications from these results. The first is that high residue harvest is extremely damaging with regards to soil erosion. The second implication is that without cover crops you cannot engage in long term high residue harvest. The T-factor is an estimate of the maximum amount of soil erosion that can occur yearly while maintaining current soil levels. T-factors used in this data ranged from 2 tons/acre-year to 5 tons/acre-year. Under high residue harvest, cover crops are preventing more soil leaving than soil is being created.

Table 9: Reduction in Soil Erosion (tons/acre-year) Benefits of Cover Crops for High Residue Harvest.

High Residue Harvest				
	Continuous Corn		Corn Soybean	
	No Till	Reduced Till	No Till	Reduced Till
LCC Rating 1	11.22	11.38	5.87	6.03
LCC Rating 2	12.16	13.00	6.05	6.61
LCC Rating 3	36.24	37.81	17.89	21.14

Cover crops provide greater benefits as land capability class rating increases. An increase in the land capability class rating implies that the land is less productive in crop production. These results suggest cover crops are more beneficial on marginal soil. However, not all of the differences are statistically significant. The difference between soil erosion reduction benefits from cover crops between class 1 and class 2 under high residue harvest regardless of tillage or crop rotation is not statistically significant. The difference in soil erosion benefits between class 1 and class 2 is not significant under corn soybean, reduced till, no residue harvest ($F(1,49280) = 2.85$, $p=.0911$) and Moderate Harvest ($F(1,49280) = 3.68$, $p=.0551$).

Tables 10 and 11 provide the difference in soil reduction benefits of cover crops between reduced till and no till practices. There are greater soil erosion reduction benefits from cover crop usage under reduced till than no till. The difference in the benefits of cover crops between tillage practices is the greatest under class 3 soils, where benefits range from 2.29 tons/acre-year to 3.84 tons/acre-year depending on crop rotation and residue harvest. For class 1 and class 2 soils, the difference is between 0.52 tons/acre-year and 1.15 tons/acre-year. As the level of residue harvest increases, so does the difference in the benefit of cover crops between reduced till than no till. However, the difference in benefits between no till and reduced till under high residue harvest is not statistically significant for all LCC ratings and crop rotations. When using reduced till, there is more erosion than no till. Similarly, as residue harvest increases, so does the amount of soil erosion. Thus, the amount of erosion that cover crops can prevent increases. These results also further support that cover crops have the greatest benefit on marginal soils.

Table 10: Difference in Soil Erosion Reduction Benefits (tons/acre-year) of Cover Crops between Reduced Till and No Till for Continuous Corn.

Benefits under Reduced Till – Benefits under No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	0.52	12.24**	0.0005
	LOW	0.62	14.51**	0.0001
	MED	0.65	14.15**	0.0002
	HIGH	0.15	0.03	0.8592
LCC Rating 2				
	NONE	0.92	29.6**	0
	LOW	1.15	34.11**	0
	MED	1.14	25.54**	0
	HIGH	0.84	0.22	0.6374
LCC Rating 3				
	NONE	2.29	62.34**	0
	LOW	3.28	72.97**	0
	MED	3.84	61.14**	0
	HIGH	1.56	0.15	0.6986

Note: Degrees of freedom were F(1,49280) for all test, ** p < .01

Table 11: Difference in Soil Erosion Reduction Benefits (tons/acre-year) of Cover Crops between Reduced Till and No Till for Corn Soybean.

Benefits under Reduced Till – Benefits under No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	0.52	12.24**	0.0005
	LOW	0.62	14.51**	0.0001
	MED	0.65	14.15**	0.0002
	HIGH	0.15	0.03	0.8592
LCC Rating 2				
	NONE	0.77	26.70**	0
	LOW	0.91	30.23**	0
	MED	0.94	28.17**	0
	HIGH	0.55	1.94	0.164
LCC Rating 3				
	NONE	2.42	13.26**	0.0003
	LOW	2.86	15.21**	0.0001
	MED	3.03	14.93**	0.0001
	HIGH	3.24	1.82	0.1776

Note: Degrees of freedom were F(1,49280) for all test, ** $p < .01$

The difference in benefits of cover crops between continuous corn and corn soybean rotations is less clear (Table 12). About half of the results are statistically significant. Sometimes continuous corn has the larger reduction in erosion from cover crops, other times it is corn soybean. One observation is that under high residue harvest, continuous corn has greater benefits from cover crops than corn soybeans.

Table 12: Difference in Soil Erosion Benefits (tons/acre-year) of Cover Crops between Continuous Corn and Corn Soybean.

Benefits under Continuous Corn – Benefits under Corn Soybean				
No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	0.07	7.49**	0.0062
	LOW	0.00	0.01	0.9381
	MED	-0.20	11.50**	0.0007
	HIGH	-5.35	18.48**	0
LCC Rating 2				
	NONE	0.13	33.65**	0
	LOW	0.03	0.93	0.3359
	MED	-0.31	26.86**	0
	HIGH	-6.11	147.03**	0
LCC Rating 3				
	NONE	0.25	7.61**	0.0058
	LOW	0.13	0.94	0.3316
	MED	-0.41	2.80	0.0943
	HIGH	-18.36	40.89**	0
Reduced Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	0.67	7.49**	0.0062
	LOW	0.85	0.01	0.9381
	MED	0.99	11.50**	0.0007
	HIGH	6.03	18.48**	0
LCC Rating 2				
	NONE	0.02	0.01	0.9374
	LOW	0.21	0.70	0.404
	MED	0.51	3.24	0.0718
	HIGH	6.39	13.25**	0.0003
LCC Rating 3				
	NONE	-0.38	0.28	0.5939
	LOW	0.29	0.13	0.7218
	MED	1.21	1.84	0.1753
	HIGH	16.67	19.99**	0

Note: Degrees of freedom were $F(1,49280)$ for all test, ** $p < .01$

4.2 Nitrate Leaching

Cover crops reduce the amount of nitrate leaching for all management practices and LCC ratings. The benefits are the most prominent under continuous corn rotations. The majority of the differences in the nitrate leaching reducing benefits of cover crops are not statistically significant between LCC ratings. Similarly, all of the differences in the nitrate leaching reducing benefits of cover crops are not statistically significant between tillage practices. However, there are statistically significant differences in the benefits of cover crops between continuous corn rotations and corn soybean rotations.

Tables 13 and 14 provide the total amount of nitrate leaching that occurs under each combination of management practice and LCC rating. The amount of nitrate leaching that occurs for each management practice is statistically significant from zero at the 1% level. The lowest amount of nitrate leaching that occurs is 29.79 lbs/acre-year and happens under no till, high residue harvest, cover crops and corn soybeans. The highest amount of nitrate leaching is 94.34 lbs/acre-year and happens under reduced till, high residue harvest, no cover crops and continuous corn. Continuous corn rotations have higher nitrate leaching levels than corn soybean rotations. This is because nitrogen fertilizer is added during corn years, but not during soybean years.

Table 13: Projected Amount of Nitrate Leaching (lbs/acre-year) for Continuous Corn by LCC Rating and Management Practice.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	50.44** (1.34)	72.44** (1.76)	43.23** (3.75)	60.94** (1.91)
	LOW	55.10** (1.35)	77.49** (1.78)	51.03** (3.69)	69.50** (1.86)
	MED	57.37** (1.36)	74.16** (1.84)	62.41** (3.58)	76.37** (1.76)
	HIGH	58.78** (1.36)	78.02** (1.88)	63.99** (3.62)	80.43** (1.8)
LCC Rating 2					
	NONE	54.02** (0.57)	76.69** (0.68)	44.28** (4.16)	64.56** (0.78)
	LOW	59.22** (0.57)	82.15** (0.69)	53.85** (4.06)	73.95** (0.76)
	MED	61.73** (0.58)	80.56** (0.70)	65.99** (3.94)	82.67** (0.73)
	HIGH	63.64** (0.58)	84.38** (0.72)	68.56** (3.94)	86.67** (0.74)
LCC Rating 3					
	NONE	61.97** (2.3)	81.31** (2.34)	62.71** (5.06)	81.00** (3.00)
	LOW	65.28** (2.27)	84.48** (2.32)	70.60** (4.97)	87.93** (2.89)
	MED	66.76** (2.26)	78.16** (2.21)	81.61** (4.85)	90.79** (2.57)
	HIGH	67.27** (2.25)	81.48** (2.26)	82.37** (4.81)	94.34** (2.59)

Note: Standard errors reported in parentheses, **p < .01

Table 14: Projected Amount of Nitrate Leaching (lbs/acre-year) for Corn Soybean by LCC Rating and Management Practice.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	31.66** (1.07)	40.14** (1.06)	33.29** (1.3)	37.46** (1.3)
	LOW	31.04** (1.05)	39.35** (1.03)	33.68** (1.27)	38.07** (1.25)
	MED	29.84** (1.01)	37.71** (0.96)	34.70** (1.18)	39.73** (1.14)
	HIGH	29.79** (1.01)	37.65** (0.96)	34.72** (1.18)	39.76** (1.14)
LCC Rating 2					
	NONE	34.16** (0.46)	43.44** (0.49)	33.56** (0.57)	39.7** (0.59)
	LOW	33.67** (0.45)	42.86** (0.47)	34.29** (0.56)	40.83** (0.58)
	MED	32.85** (0.43)	41.67** (0.45)	36.01** (0.54)	43.44** (0.55)
	HIGH	32.82** (0.43)	41.62** (0.45)	36.04** (0.53)	43.49** (0.55)
LCC Rating 3					
	NONE	40.96** (2.1)	48.83** (2.1)	46.15** (2.67)	51.60** (2.68)
	LOW	39.83** (2.05)	47.45** (2.05)	46.12** (2.67)	51.59** (2.68)
	MED	37.64** (1.94)	44.47** (1.91)	46.18** (2.61)	52.33** (2.45)
	HIGH	37.56** (1.93)	44.40** (1.91)	46.18** (2.49)	52.31** (2.45)

Note: Standard errors reported in parentheses, $^{**}p < .01$

Table 15 and 16 provide the difference in nitrate leaching between management practices using cover crops and not using cover crops. This difference is nitrate leaching reduction benefit of cover crops. The nitrate leaching reduction benefit of cover crops is statistically significant at the 5% level for the majority of management practices and LCC rating. The statistically significant reductions in nitrate leaching range from 4.16

lbs/acre-year to 23.38 lbs/acre-year. The largest source of variation was between crop rotations. Corn soybean experienced nitrate leaching reduction between 4.16 lbs/acre-year to 9.28 lbs/acre-year. Continuous corn had much larger benefits ranging from 9.17 lbs/acre-year to 22.38 lbs/acre-year. For continuous corn, the only case not statistically significant occurred under class 3 soil, reduced till and medium residue harvest ($F(1,49280) = 2.79$, $p = .0951$). For corn soybean rotations, the not statistically significant cases occur for all management practices under class 3 soil and reduced till.

Table 15: Reduction in Nitrate Leaching (lbs/acre-year) from Cover Crops for Continuous Corn.

No Till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	22.01	99.65**	0
	LOW	22.39	101.08**	0
	MED	16.79	54.44**	0
	HIGH	19.24	69.04**	0
LCC Rating 2				
	NONE	22.68	643.77**	0
	LOW	22.93	651.71**	0
	MED	18.83	428.73**	0
	HIGH	20.74	505.44**	0
LCC Rating 3				
	NONE	19.33	34.79**	0
	LOW	19.20	35.01**	0
	MED	11.39	13.00**	0.0003
	HIGH	14.21	19.90**	0
Reduced Till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	17.70	29.91**	0
	LOW	18.47	33.25**	0
	MED	13.95	19.90**	0
	HIGH	16.43	27.12**	0
LCC Rating 2				
	NONE	20.28	22.96**	0
	LOW	20.09	23.56**	0
	MED	16.67	17.30**	0
	HIGH	18.11	20.35**	0
LCC Rating 3				
	NONE	18.29	9.64**	0.0019
	LOW	17.32	9.05**	0.0026
	MED	9.17	2.79	0.0951
	HIGH	11.96	4.79**	0.0287

Note: Degrees of freedom were $F(1,49280)$ for all test, ** $p < .01$

Table 16: Reduction in Nitrate Leaching (lbs/acre-year) from Cover Crops for Corn Soybean.

No till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	8.48	31.96**	0
	LOW	8.31	32.14**	0
	MED	7.87	32.25**	0
	HIGH	7.85	32.16*8	0
LCC Rating 2				
	NONE	9.29	189.67**	0
	LOW	9.19	195.48**	0
	MED	8.82	198.32**	0
	HIGH	8.8	197.71**	0
LCC Rating 3				
	NONE	7.87	7.04**	0.008
	LOW	7.62	6.94**	0.0084
	MED	6.83	6.31**	0.012
	HIGH	6.84	6.35**	0.0117
Reduced Till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	4.17	5.16**	0.0231
	LOW	4.39	6.12**	0.0134
	MED	5.03	9.43**	0.0021
	HIGH	5.05	9.50**	0.0021
LCC Rating 2				
	NONE	6.14	55.90**	0
	LOW	6.54	66.45**	0
	MED	7.44	93.64**	0
	HIGH	7.46	94.42**	0
LCC Rating 3				
	NONE	5.44	2.07	0.1506
	LOW	5.73	2.40	0.1215
	MED	6.15	3.10	0.0785
	HIGH	6.13	3.08	0.0791

Note: Degrees of freedom were $F(1,49280)$ for all test, ** $p < .01$

For most cases, cover crops provide statistically significant greater benefits for continuous corn than corn soybeans. The difference in benefits range from 8.92 lbs/acre-year to 14.14 lbs/acre-year. Since there is more nitrogen being added in continuous corn rotations than corn soybean rotations, cover crops have more opportunity to absorb nitrogen that would otherwise leave the soil.

However, not all of the difference in cover crop benefits between continuous corn and corn soybean rotations are statistically significant (Table 17). Under no till and LCC rating 3, both medium residue harvest and high residue harvest do not have a statistically significant differences between continuous corn and corn soybean rotations ($F(1,49280) = 1.2$, $p = .2734$ and $F(1,49280) = 3.1$, $p = .0782$). The differences in the benefits of cover crops between continuous corn and corn soybean are not statistically significant for all management practices under reduced till on soils with LCC rating 3.

Table 17: Difference in Nitrate Leaching Reduction Benefits (lbs/acre-year) of Cover Crops between Continuous Corn and Corn Soybean.

Benefits under Continuous Corn – Benefits under Corn Soybean				
No till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	13.53	25.75**	0
	LOW	14.08	27.89**	0
	MED	8.92	11.22**	0.0008
	HIGH	11.39	17.82**	0
LCC Rating 2				
	NONE	13.39	143.08**	0
	LOW	13.74	152.49**	0
	MED	10.01	82.23**	0
	HIGH	11.95	114.86**	0
LCC Rating 3				
	NONE	11.46	6.72*8	0.0095
	LOW	11.58	7.09**	0.0077
	MED	4.56	1.20	0.2734
	HIGH	7.37	3.10	0.0782
Reduced Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	13.53	25.75**	0
	LOW	14.08	27.89**	0
	MED	8.92	11.22**	0.0008
	HIGH	11.39	17.82**	0
LCC Rating 2				
	NONE	14.14	10.76*8	0.001
	LOW	13.55	10.32**	0.0013
	MED	9.24	5.12**	0.0237
	HIGH	10.65	6.79**	0.0092
LCC Rating 3				
	NONE	12.84	3.36	0.0666
	LOW	11.59	2.87	0.0904
	MED	3.02	0.22	0.6424
	HIGH	5.84	0.81	0.3681

Note: Degrees of freedom were $F(1,49280)$ for all test, ** $p < .01$

Tillage practice does not affect the nitrate leaching reduction benefits of cover crops (Tables 18 and 19). The difference in the nitrate leaching reduction benefits of cover crops between no till and reduced till is not statistically significant at the 5% level for any management practice on any class of soil. Cover crops reduce the same amount of nitrate leaching regardless of tillage practice.

Table 18: Difference in Nitrate Leaching Reduction Benefits (lbs/acre-year) of Cover Crops between No Till and Reduced Till for Continuous Corn.

Benefits under No Till – Benefits Under Reduced Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	4.31	3.31	0.069
	LOW	3.92	2.89	0.089
	MED	2.84	1.75	0.186
	HIGH	2.81	1.71	0.1906
LCC Rating 2				
	NONE	2.40	0.31	0.5793
	LOW	2.84	0.45	0.5029
	MED	2.16	0.27	0.6001
	HIGH	2.63	0.41	0.5232
LCC Rating 3				
	NONE	1.04	0.02	0.8768
	LOW	1.88	0.08	0.7763
	MED	2.22	0.12	0.7263
	HIGH	2.24	0.13	0.7231

Note: Degrees of freedom were F(1,49280) for all observations.

Table 19: Difference in Nitrate Leaching Reduction Benefits (lbs/acre-year) of Cover Crops between No Till and Reduced Till for Corn Soybeans.

Benefits under No Till – Benefits under Reduced Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	4.31	3.31	0.069
	LOW	3.92	2.89	0.089
	MED	2.84	1.75	0.186
	HIGH	2.81	1.71	0.1906
LCC Rating 2				
	NONE	3.15	8.79**	0.003
	LOW	2.64	6.49**	0.0109
	MED	1.38	1.94	0.164
	HIGH	1.34	1.82	0.177
LCC Rating 3				
	NONE	2.43	0.25	0.614
	LOW	1.89	0.16	0.6878
	MED	0.68	0.02	0.8783
	HIGH	0.71	0.03	0.8721

Note: Degrees of freedom were $F(1,49280)$ for all test, ** $p < .01$

For the majority of cases, the benefits of cover crops do not change when LCC rating is increased. The difference in the nitrate leaching reduction benefits of cover crops is not statistically significant at the 5% level for all but two cases. These two cases are the difference in benefits between soils with LCC rating 2 and 3 under medium residue harvest and high residue harvest ($F(1,49280) = 5.11$, $p = .0238$ and $F(1,49280) = 3.89$, $p = .0487$). With the exception of those two cases mentioned above, cover crops reduce the same amount of nitrate leaching on better land as on marginal land.

4.3 Soil Organic Carbon Change

Cover crops increase soil organic carbon whenever used. This increase is statistically significant at the 5% level for almost all cases. For most cases without cover crops, medium residue harvest and high residue harvest result in SOC loss. The difference in SOC gain from using cover crops is not statistically significant between land capability classes. Similarly, the difference in SOC gain from using cover crops is not statistically significant between tillage practices. The SOC gain from using cover crops is significantly greater under continuous corn than corn soybeans.

Tables 20 and 21 provide the total amount of SOC change that occurs under each combination of management practice and LCC rating. The amount of SOC change that occurs for each management practice is statistically significant from zero at the 1% level. When cover crops are used, the yearly SOC change is always positive, regardless of management practice. If cover crops are not used, the highest level of residue harvest that can be used without experiencing a decrease in SOC is low residue harvest (35% removal). The only exception to this is corn soybean rotations on soil with LCC rating 1, where any amount of residue can be harvested without experiencing a SOC loss, with or without cover crops. Cover crops are necessary to sustainably remove greater than 35% residue, unless on soil with LCC rating 1 under a corn soybean rotation.

Table 20: Total Soil Organic Carbon Change (lbs/acre-year) for each Management Practice and LCC Rating under Continuous Corn.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	509.23** (9.50)	383.95** (10.21)	611.24** (26.85)	496.86** (12.48)
	LOW	370.37** (7.81)	233.47** (8.59)	442.61** (23.20)	316.71** (9.94)
	MED	297.75** (7.21)	-67.40** (7.51)	282.68** (21.3)	-76.67** (8.28)
	HIGH	189.73** (7.11)	-73.28** (7.51)	173.00** (21.28)	-84.49** (8.30)
LCC Rating 2					
	NONE	452.07** (4.48)	310.81** (4.73)	562.48** (29.11)	428.74** (5.97)
	LOW	311.27** (4.33)	159.86** (4.56)	386.66** (25.06)	235.55** (5.66)
	MED	238.04** (4.34)	-138.28** (4.67)	219.43** (7.93)	-159.97** (16.94)
	HIGH	129.03** (4.45)	-144.06** (4.68)	102.03** (3.53)	-167.67** (38.18)
LCC Rating 3					
	NONE	400.70** (18.19)	268.55** (17.49)	462.03** (37.78)	332.58** (24.24)
	LOW	279.21** (17.23)	138.99** (16.55)	315.27** (34.14)	175.07** (22.97)
	MED	216.96** (16.89)	-118.85** (15.22)	165.90** (32.55)	-148.97** (21.12)
	HIGH	123.96** (16.36)	-123.82** (15.19)	75.44* (32.02)	-155.22** (21.08)

Note: Standard errors reported in parentheses, **p < .01

Table 21: Total Soil Organic Carbon Change (lbs/acre-year) for each Management Practice and LCC Rating under Corn Soybean rotations.

		No Till		Reduced Till	
	Residue Removal Rate	Cover Crop	No Cover Crop	Cover Crop	No Cover Crop
LCC Rating 1					
	NONE	339.58** (8.23)	274.51** (8.69)	410.42** (10.52)	356.24** (10.80)
	LOW	262.32** (7.93)	195.31** (8.17)	309.56** (9.06)	253.54** (9.63)
	MED	109.08** (7.88)	42.75** (7.87)	111.93** (8.47)	51.39** (8.99)
	HIGH	106.22** (7.88)	39.98** (7.86)	108.19** (8.48)	47.47** (8.99)
LCC Rating 2					
	NONE	274.24** (4.79)	200.37** (4.84)	331.86** (6.06)	262.86** (6.18)
	LOW	196.89** (4.80)	121.40** (4.82)	232.74** (6.00)	160.85** (6.12)
	MED	42.47** (4.92)	-32.27** (4.9)	35.85** (6.13)	-39.81** (6.21)
	HIGH	39.64** (4.92)	-35.02** (4.90)	32.06** (6.13)	-43.64** (6.21)
LCC Rating 3					
	NONE	231.53** (18.90)	166.79** (18.25)	280.89** (25.53)	217.46** (25.02)
	LOW	169.25** (18.50)	102.53** (17.85)	201.05** (25.03)	135.64** (24.54)
	MED	44.13* (17.88)	-23.10 (17.32)	43.80 (24.26)	-24.70 (23.77)
	HIGH	41.80* (17.87)	-25.38 (17.31)	40.84 (24.23)	-27.73 (23.78)

Note: Standard errors reported in parentheses, **p < .01

Table 22 provides the benefit in SOC gain from using cover crops for continuous corn. All of the benefits are statistically significant at the 1% level. Table 23 provides the benefit in SOC gain from using cover crops for corn soybean rotations. For corn soybean rotations, there are instances where the benefits that are not statistically significant at the 5% level. The benefit from no residue harvest and low residue harvest on soils with LCC rating 3 is not statistically significant at the 5% level.

Table 22: SOC Gain (lbs/acre-year) from Using Cover Crops for Continuous Corn.

No Till		
	Residue Removal Rate	Benefits of Cover Crops
LCC Rating 1		
	NONE	125.29
	LOW	136.90
	MED	365.15
	HIGH	263.01
LCC Rating 2		
	NONE	141.26
	LOW	151.41
	MED	376.33
	HIGH	273.09
LCC Rating 3		
	NONE	132.15
	LOW	140.22
	MED	335.81
	HIGH	247.77
Reduced Till		
LCC Rating 1		
	NONE	114.38
	LOW	125.90
	MED	359.35
	HIGH	257.49
LCC Rating 2		
	NONE	133.74
	LOW	151.11
	MED	379.40
	HIGH	269.70
LCC Rating 3		
	NONE	129.45
	LOW	140.20
	MED	314.87
	HIGH	230.65

Note: The benefit of cover crops column is the result of the hypotheses test ($F(1,49280)$) comparing the difference in SOC change with cover crops and without cover crops. All cases are statistically significant at the 1% level.

Table 23: SOC Gain (lbs/acre-year) from Using Cover Crops for Corn Soybean.

No Till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	65.07	29.58**	0
	LOW	67.02	34.63**	0
	MED	66.33	35.49**	0
	HIGH	66.24	35.41**	0
LCC Rating 2				
	NONE	73.87	117.62**	0
	LOW	75.49	123.21**	0
	MED	74.74	115.99**	0
	HIGH	74.65	115.65**	0
LCC Rating 3				
	NONE	64.74	6.07**	0.0137
	LOW	66.72	6.74**	0.0095
	MED	67.23	7.30**	0.0069
	HIGH	67.17	7.30**	0.0069
Reduced Till				
	Residue Removal Rate	Benefits of Cover Crops	F- statistic	P-value
LCC Rating 1				
	NONE	54.17	12.90**	0.0003
	LOW	56.02	17.96**	0
	MED	60.54	24.01**	0
	HIGH	60.72	24.12**	0
LCC Rating 2				
	NONE	69.00	63.47**	0
	LOW	71.89	70.37**	0
	MED	75.66	75.22**	0
	HIGH	75.70	75.28**	0
LCC Rating 3				
	NONE	63.43	3.15**	0.076
	LOW	65.41	3.48**	0.062
	MED	68.50	4.06*	0.0438
	HIGH	68.56	4.08*	0.0434

Note: Standard errors reported in parentheses, ** $p < .01$, * $p < .05$

None of the differences in cover crop benefits to SOC are statistically significant between LCC ratings except for one case. That case is the difference between LCC ratings 2 and 3 under low residue harvest and continuous corn ($F(1,49280) = 3.94$, $p = .0472$). There are also no statistically significant differences in the SOC benefits of cover crops between tillage practices (Tables 24 and 25). All of the differences are not statistically significant at the 5% level.

Table 24: Difference in SOC change (lbs/acre-year) from Cover Crops between Reduced Till and No Till for Continuous Corn.

Benefits under Reduced Till – Benefits under No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	10.90	0.32	0.5712
	LOW	10.99	0.40	0.5286
	MED	5.80	0.12	0.7275
	HIGH	5.52	0.11	0.7399
LCC Rating 2				
	NONE	7.52	0.06	0.8049
	LOW	0.30	0.00	0.9909
	MED	-3.07	0.02	0.9012
	HIGH	3.39	0.02	0.8911
LCC Rating 3				
	NONE	2.71	0.00	0.9581
	LOW	0.02	0.00	0.9997
	MED	20.94	0.22	0.6415
	HIGH	17.12	0.15	0.6996

Note: Degrees of freedom were $F(1,49280)$ for all observations.

Table 25: Difference in SOC Change (lbs/acre-year) from Cover Crops between Reduced Till and No Till for Corn Soybean.

Benefits under Reduced Till – Benefits under No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	10.90	0.32	0.5712
	LOW	10.99	0.40	0.5286
	MED	5.80	0.12	0.7275
	HIGH	5.52	0.11	0.7399
LCC Rating 2				
	NONE	4.87	0.20	0.6587
	LOW	3.60	0.11	0.7424
	MED	-0.92	0.01	0.9343
	HIGH	-1.05	0.01	0.925
LCC Rating 3				
	NONE	1.31	0.00	0.9764
	LOW	1.31	0.00	0.976
	MED	-1.27	0.00	0.976
	HIGH	-1.39	0.00	0.9737

Note: Degrees of freedom were F(1,49280) for all observations.

Continuous corn rotations benefit more from cover crops than corn soybean rotations (Table 26). However, the differences are not always statistically significant. All of the insignificant differences occur on soil with LCC rating 3. Differences in SOC gains range from 60.21 lbs/acre-year to 301.58 lbs/acre-year depending primarily on the level of residue harvest.

Table 26: Difference in SOC change (lbs/acre-year) from Cover Crops between Continuous Corn and Corn Soybean.

Benefits under Continuous Corn – Benefits under Corn Soybean				
No Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	60.21	10.74**	0.0011
	LOW	69.88	18.46**	0.00
	MED	298.81	384.24**	0.00
	HIGH	196.77	167.68**	0.00
LCC Rating 2				
	NONE	67.39	51.08**	0.00
	LOW	75.93	67.19**	0.00
	MED	301.58	1023.85**	0.00
	HIGH	198.44	438.17**	0.00
LCC Rating 3				
	NONE	67.41	3.43*	0.0642
	LOW	73.50	4.39**	0.0362
	MED	268.58	63.49**	0.00
	HIGH	180.60	29.21**	0.00
Reduced Till				
	Residue Removal Rate	Difference in benefits	F- statistic	P-value
LCC Rating 1				
	NONE	60.21	10.74**	0.0011
	LOW	69.88	18.46**	0.00
	MED	298.81	384.24**	0.00
	HIGH	196.77	167.68**	0.00
LCC Rating 2				
	NONE	64.74	4.37*	0.0365
	LOW	79.22	8.55*	0.0034
	MED	303.74	142.04**	0.00
	HIGH	193.99	57.96**	0.00
LCC Rating 3				
	NONE	66.01	1.32	0.25
	LOW	74.79	1.91	0.1664
	MED	246.37	22.82**	0.00
	HIGH	162.09	10.02**	0.0016

Note: Standard errors reported in parentheses, ** $p < .01$, * $p < .05$

4.4 Econometric Analysis Conclusions

The results of the dummy variable model provide the mean environmental outcome for each different combination of management practices. Cover crops always result in better environmental outcomes than no cover crops. Cover crops reduce soil erosion between 0.081 tons/acre-year to 36.24 tons/acre-year, with the greatest benefits occurring under high residue harvest. Nitrate leaching is reduced from cover crop usage between 4.16 lbs/acre-year to 23.38 lbs/acre-year. SOC increases from cover crop usage range from 54.17 lbs/acre-year to 379.40 lbs/acre-year. The benefits of cover crops are not always statistically significant. However, the results that are not statistically significant are usually limited to soil with LCC rating 3 and/or high residue harvest.

Cover crops provide the greatest benefit as a method of soil erosion reduction under high residue harvest. This is because without cover crops, the transition from medium residue harvest to high residue harvest results in dramatically increased soil erosion. With cover crops, the increase in erosion when transitioning from medium residue harvest to high residue harvest is more controlled. The benefits of cover crops increase as LCC rating increases. This implies that the benefits of cover crops are greater on marginal land than prime cropland. Erosion is reduced more with cover crops under reduced till than no till. One explanation for this is that there is more erosion under reduced till than no till, so cover crops are able to prevent more erosion.

Cover crops reduce nitrate leaching the most under continuous corn rotations. This is because nitrogen fertilizer is applied every year in continuous corn rotations, while in corn soybean rotations, nitrogen fertilizer is applied only on corn years. Difference in crop rotations explained most of the variation in the reduced nitrate leaching benefits of cover crops. The difference in the amount of nitrate leaching reduced by using cover crops is usually statistically insignificant between LCC ratings. This suggest that the benefit of cover crops are dependent on how much nitrate is applied rather than the suitability of the soil for crop production.

Cover crops increase soil organic carbon. The difference in the SOC gain from cover crops is greater under continuous corn rotations than corn soybean rotations. Cover crops are often needed to maintain positive SOC if moderate high harvest or high residue harvest are to be used.

4.5 Economic Interpretation of Econometric Results

The previous section quantified the physical benefits of cover crops by comparing the amount of soil erosion, nitrate leaching and soil organic carbon change that occurs with and without cover crops. This section seeks to develop the economic implications of these physical benefits. While there is a market cost for cover crops, there is no market value for soil erosion, nitrate leaching and soil organic carbon change. To derive economic implications, it is necessary to estimate prices for soil erosion, nitrate leaching and soil organic carbon change. Different scenarios are created to reflect the private and social benefits of cover crops. However, since the private benefits do not reflect yield changes, the private benefits will be referred to as nutrient benefits to avoid confusion about the scope of the analysis.

Table 27 provides the prices used for the environmental outcomes. Table 28 - 31 provide the nutrient and social benefits of cover crops. The largest source of benefits are from reduced soil erosion and increased SOC. The reduced nitrate leaching benefit of cover crops was relatively small compared to the benefits from reduced soil erosion and increased SOC. Nutrient benefits from soil erosion reduction ranged from 0.08 $/acre-year to 38.19 $/acre-year. Social benefits from soil erosion reduction ranged from 0.48 $/acre-year to 225.73 $/acre-year. Nutrient and social benefits from SOC gain range from 3.03 $/acre-year to 21.75 $/acre-year. Social benefits from reduced nitrate leaching range from 0.90 $/acre-year to 4.93 $/acre-year.

Different management practices experience greater benefit from cover crops. The reduction in soil erosion benefits from cover crops for continuous corn rotations and high residue harvest range from 11.33 $/acre-year to 38.18 $/acre-year for nutrient benefits and 66.98 $/acre-year to 225.72 $/acre-year for social benefits. The difference in soil erosion benefits between land capability classes range from 0.09 \$/acre-year to 26.69 \$/acre-year for nutrient benefits and 0.57 \$/acre-year to \$157.79 \$/acre-year for social benefits. The difference in soil erosion benefits between tillage practices range from 0.52 \$/acre-year to 3.88 \$/acre-year for nutrient benefits and 3.10 \$/acre-year to 22.93 \$/acre-year for social benefits. The difference in nitrate leaching benefits between crop rotations range from 1.91 \$/acre-year to 3.02 \$/acre-year for social benefits. The difference in SOC benefits between crop rotations range from 3.37 \$/acre-year to 17.00 \$/acre-year for nutrient and social benefits.

Reduced till benefits more from cover crops than no till. Nutrient benefits of cover crops for no till range from 3.79 \$ acre^{-1} year^{-1} to 50.49 \$ acre^{-1} year. Nutrient benefits of cover crops for reduced till range from 3.71 \$ acre^{-1} year to 51.11 \$ acre^{-1} year^{-1}. Social benefits of cover crops for no till range from 6.36 \$ acre^{-1} year^{-1} to 233.34 \$ acre^{-1} year. Social benefits of cover crops for reduced till range from 7.93 \$ acre^{-1} year to 241.22 \$ acre^{-1} year^{-1}.

Continuous corn rotations benefit more from cover crops than corn soybean rotations. Nutrient benefits of cover crops for continuous corn rotations range from 7.02 \$ acre^{-1} year^{-1} to 51.11 \$ acre^{-1} year^{-1}. Nutrient benefits of cover crops for corn soybean rotations range from 3.71 \$ acre^{-1} year^{-1} to 25.19 \$ acre^{-1} year^{-1}. Social benefits of cover crops for corn soybean rotations range from 12.23 \$ acre^{-1} year^{-1} to 241.22 \$ acre^{-1} year^{-1}. Social benefits of cover crops for corn soybean rotations range from 6.36 \$ acre^{-1} year^{-1} to 131.37 \$ acre^{-1} year^{-1}.

Soils with higher LCC ratings benefit the most from cover crops. This implies that cover crops provide more benefit on marginal soil than on prime cropland. Nutrient benefits of cover crops on soils with LCC rating 1 range between 3.71 \$ acre^{-1} year^{-1} to 26.06 \$ acre^{-1} year^{-1}. Nutrient benefits of cover crops on soils with LCC rating 2 range between 4.39 \$ acre^{-1} year^{-1} to 28.24 \$ acre^{-1} year^{-1}. Nutrient benefits of cover crops on soils with LCC rating 3 range between 4.05 \$ acre^{-1} year^{-1} to 51.11 \$ acre^{-1} year^{-1}. Social benefits of cover crops on soils with LCC rating 1 range between 6.36 \$ \$ acre^{-1} year^{-1} to 85.89 \$ acre^{-1} year^{-1}. Social benefits of cover crops on soils with LCC rating 2 range between 7.63 \$ $acre^{-1}$ $year^{-1}$ to 96.66 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops on soils with LCC rating 3 range between 7.83 \$ $acre^{-1}$ $year^{-1}$ to 241.22 \$ $acre^{-1}$ $year^{-1}$.

Are cover crops worth it? The econometrics section quantified the improvement of environmental outcomes from using cover crops. Are these improvements in environmental outcomes worth the cost of cover crops? It depends.

According to Pratt, et al. (2013) the mean cost of planting 100% rye was 34.43 $/acre-year. Cover crops and 100% rye will be used interchangeably. Cover crops have the greatest benefit when engaging in medium residue harvest and high residue harvest. Both of these levels of residue harvest can be extremely damaging to the environment without cover crops. For all but two cases, the nutrient benefits from cover crop usage was less than 34.43 $/acre-year. These two cases both occurred under continuous corn, high residue harvest and soil with LCC rating 3. The social benefits of cover crops are higher than the nutrient benefits of cover crops. For the majority of cases, even the social benefits did not exceed the cost of cover crop use. For continuous corn, the social benefits of cover crops exceeded the cost for all high residue harvest and certain cases of medium residue harvest. For corn soybean, only high residue harvest had social benefits greater than the cost of cover crops.

Table 27: Value of Environmental Outcomes.

	Nutrient Scenario	Social Scenario	Units	Source
On-Site Soil Erosion	1.01	1.01	$/ton	Hansen and Ribaudo (2008)
Off-Site Soil Erosion	0	4.96	$/ton	Hansen and Ribaudo (2008)
SOC change	0.056	0.056	$/lb	Lal (2014)
Nitrate Leaching	0	0.21	$/lb	Christianson, et al. (2013)

Table 28: Nutrient Benefits of Cover Crops under Continuous Corn.

No Till	Cover Crop Benefits			Nutrient Benefits			
	Soil Erosion	Nitrate Leaching	SOC Gain	Soil Erosion	Nitrate Leaching	SOC Gain	Total
	tons acre^{-1} year^{-1}	lbs acre^{-1} year^{-1}	lbs acre^{-1} year^{-1}	\$ acre^{-1} year^{-1}	\$ acre^{-1} year^{-1}	\$ acre^{-1} year^{-1}	\$ acre^{-1} year^{-1}
LCC Rating 1							
NONE	0.08	22.01	125.29	0.08	0	7.02	7.10
LOW	0.23	22.39	136.90	0.23	0	7.67	7.90
MED	0.53	16.79	365.15	0.54	0	20.45	20.99
HIGH	11.22	19.24	263.01	11.33	0	14.73	26.06
LCC Rating 2							
NONE	0.12	22.68	141.26	0.12	0	7.91	8.03
LOW	0.35	22.93	151.41	0.35	0	8.48	8.83
MED	0.86	18.83	376.33	0.87	0	21.07	21.94
HIGH	12.17	20.74	273.09	12.29	0	15.29	27.58
LCC Rating 3							
NONE	0.17	19.33	132.15	0.17	0	7.40	7.57
LOW	0.52	19.20	140.22	0.53	0	7.85	8.38
MED	1.37	11.39	335.81	1.38	0	18.81	20.19
HIGH	36.25	14.21	247.77	36.61	0	13.88	**50.49**
Reduced Till							
LCC Rating 1							
NONE	0.60	17.70	114.38	0.61	0	6.41	7.02
LOW	0.85	18.47	125.90	0.86	0	7.05	7.91
MED	1.19	13.95	359.35	1.20	0	20.12	21.32
HIGH	11.38	16.43	257.49	11.49	0	14.42	25.91

Table 28 continued

LCC Rating 2							
NONE	1.04	20.28	133.74	1.05	0	7.49	8.54
LOW	1.51	20.09	151.11	1.53	0	8.46	9.99
MED	2.01	16.67	379.40	2.03	0	21.25	23.28
HIGH	13.01	18.11	269.70	13.14	0	15.10	28.24
LCC Rating 3							
NONE	2.46	18.29	129.45	2.48	0	7.25	9.73
LOW	3.81	17.32	140.20	3.85	0	7.85	11.70
MED	5.21	9.17*	314.87	5.26	0*	17.63	22.89
HIGH	37.81	11.96	230.65	38.19	0	12.92	**51.11**

Note: * values are not statistically significant at the 5% level. In bold are practices where nutrient or social cost are greater than estimated cost of 100% rye ($34.43/acre-year)

Table 29: Social Benefits of Cover Crops under Continuous Corn.

No Till	Cover Crop Benefits			Social Benefits			
	Soil Erosion	Nitrate Leaching	SOC Gain	Soil Erosion	Nitrate Leaching	SOC Gain	Total
	tons $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$
LCC Rating 1							
NONE	0.08	22.01	125.29	0.48	4.73	7.02	12.23
LOW	0.23	22.39	136.9	1.37	4.81	7.67	13.85
MED	0.53	16.79	365.15	3.16	3.61	20.45	27.22
HIGH	11.22	19.24	263.01	66.98	4.14	14.73	**85.85**
LCC Rating 2							
NONE	0.12	22.68	141.26	0.72	4.87	7.91	13.50
LOW	0.35	22.93	151.41	2.09	4.93	8.48	15.50
MED	0.86	18.83	376.33	5.13	4.05	21.07	30.25
HIGH	12.17	20.74	273.09	72.65	4.46	15.29	**92.40**
LCC Rating 3							
NONE	0.17	19.33	132.15	1.01	4.15	7.40	12.56
LOW	0.52	19.20	140.22	3.10	4.13	7.85	15.08
MED	1.37	11.39	335.81	8.18	2.45	18.81	29.44
HIGH	36.25	14.21	247.77	216.41	3.05	13.88	**233.34**
Reduced Till							
LCC Rating 1							
NONE	0.60	17.7	114.38	3.58	3.8	6.41	13.79
LOW	0.85	18.47	125.90	5.07	3.97	7.05	16.09
MED	1.19	13.95	359.35	7.10	3.00	20.12	30.22
HIGH	11.38	16.43	257.49	67.94	3.53	14.42	**85.89**
LCC Rating 2							
NONE	1.04	20.28	133.74	6.21	4.36	7.49	18.06
LOW	1.51	20.09	151.11	9.01	4.32	8.46	21.79
MED	2.01	16.67	379.40	12.00	3.58	21.25	**36.83**
HIGH	13.01	18.11	269.7	77.67	3.89	15.10	**96.66**

Table 29 continued

LCC Rating 3							
NONE	2.46	18.29	129.45	14.69	3.93	7.25	25.87
LOW	3.81	17.32	140.20	22.75	3.72	7.85	34.32
MED	5.21	9.17*	314.87	31.10	1.97*	17.63	**50.70**
HIGH	37.81	11.96	230.65	225.73	2.57	12.92	**241.22**

Note: * values are not statistically significant at the 5% level. In bold are practices where nutrient or social cost are greater than estimated cost of 100% rye ($34.43/acre-year)

Table 30: Nutrient Benefits of Cover Crops under Corn Soybeans.

No Till	Cover Crop Benefits			Social Benefits			
	Soil Erosion	Nitrate Leaching	SOC Gain	Soil Erosion	Nitrate Leaching	SOC Gain	Total
	tons $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$
LCC Rating 1							
NONE	0.15	8.48	65.07	0.15	0	3.64	3.79
LOW	0.23	8.31	67.02	0.23	0	3.75	3.98
MED	0.33	7.87	66.33	0.33	0	3.71	4.04
HIGH	5.88	7.85	66.24	5.94	0	3.71	9.65
LCC Rating 2							
NONE	0.25	9.29	73.87	0.25	0	4.14	4.39
LOW	0.38	9.19	75.49	0.38	0	4.23	4.61
MED	0.56	8.82	74.74	0.57	0	4.19	4.76
HIGH	6.06	8.80	74.65	6.12	0	4.18	10.30
LCC Rating 3							
NONE	0.42	7.87	64.74	0.42	0	3.63	4.05
LOW	0.66	7.62	66.72	0.67	0	3.74	4.41
MED	0.96	6.83	67.23	0.97	0	3.76	4.73
HIGH	17.89	6.84	67.17	18.07	0	3.76	21.83
Reduced Till							
LCC Rating 1							
NONE	0.67	4.17	54.17	0.68	0	3.03	3.71
LOW	0.85	4.39	56.02	0.86	0	3.14	4.00
MED	0.99	5.03	60.54	1.00	0	3.39	4.39
HIGH	6.03	5.05	60.72	6.09	0	3.40	9.49
LCC Rating 2							
NONE	1.02	6.14	69.00	1.03	0	3.86	4.89
LOW	1.29	6.54	71.89	1.30	0	4.03	5.33
MED	1.50	7.44	75.66	1.52	0	4.24	5.76
HIGH	6.61	7.46	75.7	6.68	0	4.24	10.92

Table 30 continued

LCC Rating 3							
NONE	2.85	5.44*	63.43*	2.88	0*	3.55*	6.43
LOW	3.52	5.73*	65.41*	3.56	0*	3.66*	7.22
MED	4.00	6.15*	68.50	4.04	0*	3.84	7.88
HIGH	21.14	6.13*	68.56	21.35	0*	3.84	25.19

Note: * values are not statistically significant at the 5% level. In bold are practices where nutrient or social cost are greater than estimated cost of 100% rye ($34.43/acre-year)

Table 31: Social Benefits of Cover Crops under Corn Soybeans.

No Till	Cover Crop Benefits			Social Benefits			
	Soil Erosion	Nitrate Leaching	SOC Gain	Soil Erosion	Nitrate Leaching	SOC Gain	Total
	tons $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	lbs $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$	\$ $acre^{-1}$ $year^{-1}$
LCC Rating 1							
NONE	0.15	8.48	65.07	0.90	1.82	3.64	6.36
LOW	0.23	8.31	67.02	1.37	1.79	3.75	6.91
MED	0.33	7.87	66.33	1.97	1.69	3.71	7.37
HIGH	5.88	7.85	66.24	35.10	1.69	3.71	**40.50**
LCC Rating 2							
NONE	0.25	9.29	73.87	1.49	2.00	4.14	7.63
LOW	0.38	9.19	75.49	2.27	1.98	4.23	8.48
MED	0.56	8.82	74.74	3.34	1.90	4.19	9.43
HIGH	6.06	8.80	74.65	36.18	1.89	4.18	**42.25**
LCC Rating 3							
NONE	0.42	7.87	64.74	2.51	1.69	3.63	7.83
LOW	0.66	7.62	66.72	3.94	1.64	3.74	9.32
MED	0.96	6.83	67.23	5.73	1.47	3.76	10.96
HIGH	17.89	6.84	67.17	106.8	1.47	3.76	**112.03**

Table 31 continued

Reduced Till							
LCC Rating 1							
NONE	0.67	4.17	54.17	4.00	0.90	3.03	7.93
LOW	0.85	4.39	56.02	5.07	0.94	3.14	9.15
MED	0.99	5.03	60.54	5.91	1.08	3.39	10.38
HIGH	6.03	5.05	60.72	36.00	1.09	3.40	**40.49**
LCC Rating 2							
NONE	1.02	6.14	69.00	6.09	1.32	3.86	11.27
LOW	1.29	6.54	71.89	7.70	1.41	4.03	13.14
MED	1.50	7.44	75.66	8.96	1.60	4.24	14.8
HIGH	6.61	7.46	75.7	39.46	1.60	4.24	**45.30**
LCC Rating 3							
NONE	2.85	5.44	63.43	17.01	1.17	3.55	21.73
LOW	3.52	5.73	65.41	21.01	1.23	3.66	25.90
MED	4.00	6.15	68.50	23.88	1.32	3.84	29.04
HIGH	21.14	6.13	68.56	126.21	1.32	3.84	**131.37**

Note: * values are not statistically significant at the 5% level. In bold are practices where nutrient or social cost are greater than estimated cost of 100% rye ($34.43/acre-year)

This analysis suggest that only considering soil erosion, nitrate leaching and soil organic carbon gain is usually not enough to justify the expense of cover crops. These results do not imply that cover crops are not beneficial. This analysis is only considering soil erosion, nitrate leaching and SOC gain. There are other benefits to cover crop usage such as increased soil moisture retention, a food source for pollinators, reduced compaction and potentially increased yields. Cover crops do improve environmental outcomes; however, to justify the cost either more benefits of cover crops need to be included or the values of environmental outcomes would need to be higher.

This analysis only include soil erosion, nitrate leaching and soil organic carbon. There is a debate on whether or not cover crops increase yields. If using cover crops increases yields, how much of a yield increase would there have to be to justify the cost of cover crops? Tables 32 through 35 converts to bushels of corn the difference between the benefits and costs of cover crops. The price of corn is assumed to be 3.80 $ bu^{-1}.

Table 32: Yield Increases Needed to Break Even on Cover Crops for Continuous Corn and No Till.

	Residue Removal Rate	Nutrient Case: Bushels Needed to Break Even	Social Case: Bushels Need to Break Even
LCC Rating 1			
	NONE	7.19	5.84
	LOW	6.98	5.42
	MED	3.54	1.90
	HIGH	2.20	-
LCC Rating 2			
	NONE	6.95	5.51
	LOW	6.74	4.98
	MED	3.29	1.10
	HIGH	1.80	-
LCC Rating 3			
	NONE	7.07	5.76
	LOW	6.86	5.09
	MED	3.75	1.31
	HIGH	-	-

Note: Dashes represent cases where cover crop benefits exceed the cost, corn price assumed to be 3.80 $ bu^{-1}.

Table 33: Yield Increases Needed to Break Even on Cover Crops for Continuous Corn and Reduced Till.

	Residue Removal Rate	Nutrient Case: Bushels Needed to Break Even	Social Case: Bushels Need to Break Even
LCC Rating 1			
	NONE	7.21	5.43
	LOW	6.98	4.83
	MED	3.45	1.11
	HIGH	2.24	-
LCC Rating 2			
	NONE	6.81	4.31
	LOW	6.43	3.33
	MED	2.93	-
	HIGH	1.63	-
LCC Rating 3			
	NONE	6.50	2.25
	LOW	5.98	.03
	MED	3.04	-
	HIGH	-	-

Note: Dashes represent cases where cover crop benefits exceed the cost, corn price assumed to be 3.80 \$ bu^{-1}.

Table 34: Yield Increases Needed to Break Even on Cover Crops for Corn Soybeans and No Till.

	Residue Removal Rate	Nutrient Case: Bushels Needed to Break Even	Social Case: Bushels Need to Break Even
LCC Rating 1			
	NONE	8.06	7.39
	LOW	8.01	7.24
	MED	8.00	7.12
	HIGH	6.52	-
LCC Rating 2			
	NONE	7.91	7.05
	LOW	7.85	6.83
	MED	7.81	6.58
	HIGH	6.35	-
LCC Rating 3			
	NONE	7.99	7.00
	LOW	7.90	6.61
	MED	7.82	6.18
	HIGH	3.31	-

Note: Dashes represent cases where cover crop benefits exceed the cost, corn price assumed to be 3.80 $ bu^{-1}.

Table 35: Yield Increases Needed to Break Even on Cover Crops for Corn Soybeans and Reduced Till.

	Residue Removal Rate	Nutrient Case: Bushels Needed to Break Even	Social Case: Bushels Need to Break Even
LCC Rating 1			
	NONE	8.08	6.97
	LOW	8.01	6.65
	MED	7.91	6.33
	HIGH	6.56	-
LCC Rating 2			
	NONE	7.77	6.09
	LOW	7.66	5.60
	MED	7.54	5.17
	HIGH	6.19	-
LCC Rating 3			
	NONE	7.37	3.34
	LOW	7.16	2.24
	MED	6.99	1.43
	HIGH	2.43	-

Note: Dashes represent cases where cover crop benefits exceed the cost, corn price assumed to be 3.80 $ bu^{-1}.

SOC gain is one area where cover crops may be the most beneficial. Corn stover and cover crops are both a source of carbon input for the soil. With a growing interest in corn stover as an alternative feed stock and a cellulosic fuel source, it may be more profitable for the farmer to harvest the corn stover and plant cover crops as a source of SOC.

One definitive conclusion from this analysis is that cover crops should be included as a cost to high residue harvest. The amount of erosion and loss of SOC that occurs is so catastrophically bad that the benefits from cover crops are always worth it from a societal perspective and almost worth it from a nutrient perspective. On the flip side of this, cover crops can make high residue harvest sustainable. When cover crops are used with high residue harvest, SOC change is always positive and soil erosion usually less than the T-factor.

These results run contradictory to some of the other literature on cover crops. Pratt, et al. (2013) found that most of the time cereal rye had a positive net benefit. This paper suggest the opposite. One explanation is that Pratt included more of the benefits of cover crops. Pratt, et al. (2013) considered the benefits of cover crops to be added N, increased SOM, reduced compaction, reduced erosion, and increased removable stover. This paper only considers soil erosion, soil organic carbon and nitrate leaching. Consider the reduced compaction benefit. Pratt, et al. (2013) assigns a $6.50 per acre value for the reduced compaction benefit from cover crops. This value comes from the yearly discounted rate of using deep tillage. If this $6.50 was added then there are cases where cover crops the benefits of cover crops would be greater than the cost. Pratt, et al. (2013) also uses much higher soil erosion values than this paper. The on-site damages from soil erosion used by Pratt, et al. (2013) are 10.17 \$ ton^{-1} and the off-site damages from soil erosion are 17.99 \$ ton^{-1}. These are substantially higher than the on-site damages of 1.01 \$ ton^{-1} and off-site damage of 4.96 \$ ton^{-1} used in this paper. If these values are used, then cover crops would have much larger benefits, especially on marginal soils using reduced till.

These results don’t say that cover crops are not worth it or previous work suggesting that cover crops pay is wrong. These results provide only part of the story on cover crops. The story is that only considering soil erosion, nitrate leaching, SOC change and certain estimates of their value from the literature is not usually enough to justify their use. If other benefits of cover crops are included, such as a benefit from reduced compaction, then the benefits of cover crops could exceed the cost. Also if other estimates for the value of soil erosion, nitrate leaching or SOC were used, the benefits of cover crops could exceed the cost. Are cover crops worth it? It really depends on what your goals for environmental outcomes are.

Another issue that needs to be addressed is not all of these management practices are likely to be used. For example, it would be unlikely to use continuous corn, no till, no residue harvest and cover crops because of the amount of surface biomass that would have to be managed. Including unused practices has the potential to skew the real benefits of cover crops. Another topic that needs to be addressed is the use of sub-tile drainage. Sub-tile drainage is not included in LEAF because the DNDC model only simulates the first 50 cm of the soil profile.

One potentially better way to evaluate cover crops would be to establish thresholds on environmental outcomes and then evaluate cover crops relative to other practices and technologies that can achieve the desired environmental outcomes. So instead of trying to estimate the value of soil erosion, nitrate leaching and SOC, constraints would be established on how much soil erosion, nitrate leaching and SOC loss can occur. If your goal is to maintain positive yearly SOC change, then you cannot engage in medium residue harvest or high residue harvest without cover crops.

The decision to use cover crops would depend on the price of cover crops and the opportunity cost of medium residue harvest and high residue harvest. Similarly, if the goal was to limit soil erosion, changes in tillage practice, using cover crops or limits on residue harvest could achieve this goal. Doering, et al. (1999) use a similar approach by evaluating practices relative to achieving set reductions in nitrate leaching. Since there isn’t and never will be a market that captures all of the externalities of pollution and environmental damage, instead of relying on prices it could be better to establish constraints on pollution and judge technologies relative to satisfying these constraints.

CHAPTER 6: CONCLUSIONS

The world is becoming increasingly more conscious of the environmental impacts of agricultural production. Cover crops, crops grown “off-season” for their agronomic benefits, have the potential to mitigate some of these environmental impacts. However, current cover crop usage is relatively low. One potential reason is the uncertainty in the costs and benefits of using cover crops. It is known that cover crops reduce soil erosion, reduce nitrate leaching, increase soil organic carbon (SOC), reduce soil compaction, increase soil moisture retention, provide a food source for pollinators and potentially increase yields. What is unknown is the magnitude of these benefits and if these benefits justify the cost of cover crops. This paper evaluated the environmental outcomes in Indiana of different management practices with and without cover crops. Management practices include different crop rotations, tillage practices and residue removal rates. These results were used with estimates for the price of soil erosion, nitrate leaching and SOC to illustrate the economic impact of cover crops. The purpose of this chapter is to summarize the story lines that emerged from this analysis, discuss limitations of the study, and propose a topic for future research.

6.1 Summary of Findings

Quantifying the environmental impacts of cover crops within a management practice and Land Capability Class (LCC) rating provided 7 major conclusions. (1) cover crops improve environmental outcomes (2) reduced till benefits more from cover crops than no till (3) continuous corn rotations benefit more from cover crops than corn soybean rotations (4) soils with higher LCC ratings benefit the most from cover crops (5) cover crops are needed to maintain positive SOC for medium residue harvest and high residue harvest (6) considering only the nutrient benefits of reduced soil erosion, reduced nitrate leaching and increased SOC rarely justifies the cost of cover crops (7) for high residue harvest, the social benefits of cover crops always exceed the cost.

Cover crops improve environmental outcomes. When cover crops are used soil erosion is reduced, nitrate leaching is reduced and SOC is increased. However, there are some instances where the benefits of using cover crops are not statistically significant. The soil erosion reduction benefits of cover crops range from 0.08 tons acre^{-1} year^{-1} to 200.78 tons acre^{-1} year^{-1}. The statistically significant nitrate reduction benefits of cover crops range from 4.16 lbs acre^{-1} year^{-1} to 22.93 lbs acre^{-1} year^{-1}. The statistically significant SOC benefits of cover crops range from 54.17 lbs acre^{-1} year^{-1} to 379.40 lbs acre^{-1} year^{-1}. The range of benefits is so wide because the benefits of cover crops vary among crop rotation, tillage practice, residue harvest and LCC rating.

Figures 7 to 9 compare environmental outcomes with and without cover crops. Figures for only a sample of the management practices are shown because cover crops show similar improvements in the remaining practices. For soil erosion and nitrate leaching, less is preferred to more. For SOC change, more is preferred to less.

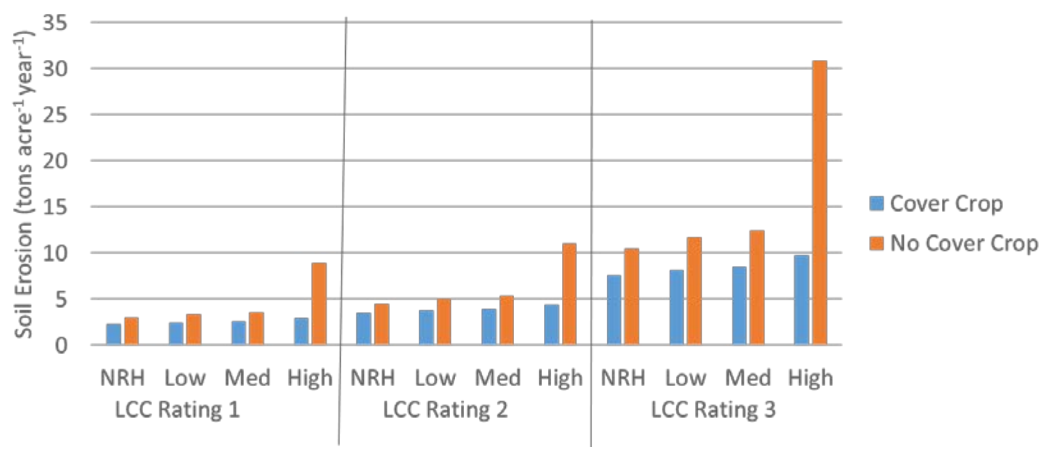

Figure 7: Soil Erosion with and without Cover Crops for Corn Soybean Rotations and Reduced Till.

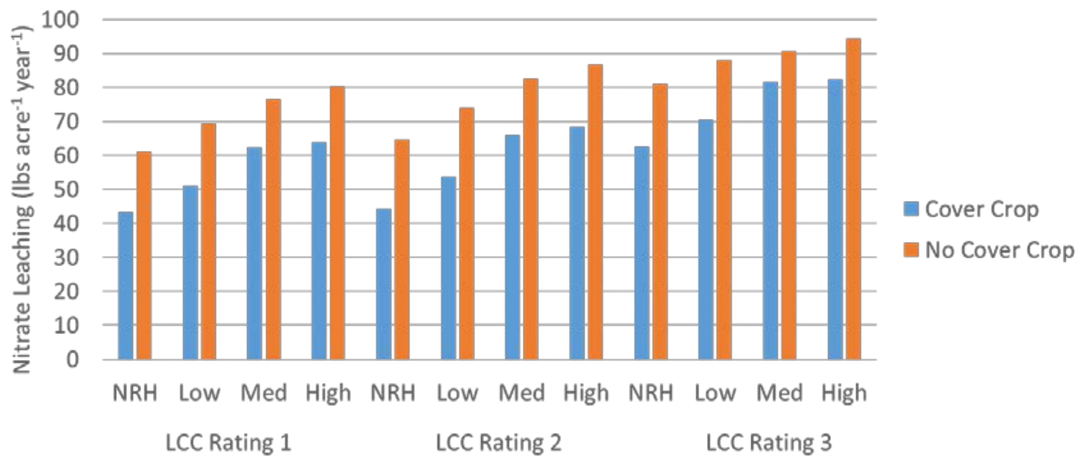

Figure 8: Nitrate Leaching with and without Cover Crops for Continuous Corn Rotations and Reduced Till.

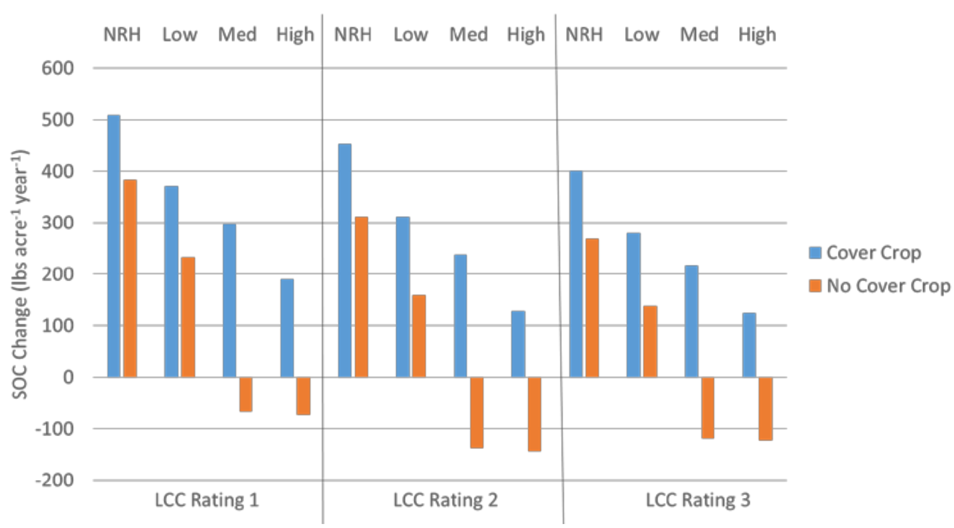

Figure 9: SOC Change with and without Cover Crops for Continuous Corn and Reduced Till.

Cover crop benefits vary by management practice. There were statistically significant differences in the benefits of cover crops between tillage practices, crop rotations and LCC ratings. Cover crops reduced erosion more for reduced till than no till.

Also, cover crops reduced more erosion on soils with higher LCC ratings. This implies that the benefit of cover crops increases as the soil becomes less suitable for crop production. Cover crops reduced nitrate leaching and increased SOC more for continuous corn rotations than for corn soybeans rotations.

Figures 10 and 11 are Tukey box plots that show the nutrient and social benefits of cover crops by groups. The box represents the values between the first and third quartiles and the line in the box represents the median. The length of the whiskers show the highest and lowest data points within 1.5 times the difference between the 3rd quartile and 1st quartile. This difference is known as the Interquartile Range (IQR). Points outside of the box and whiskers are points whose distance from the 3rd quartile exceed 1.5 times the IQR.

Reduced till benefits more from cover crops than no till. Nutrient benefits of cover crops for no till range from 3.79 \$ $acre^{-1}$ $year^{-1}$ to 50.49 \$ $acre^{-1}$ year. Nutrient benefits of cover crops for reduced till range from 3.71 \$ $acre^{-1}$ year to 51.11 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops for no till range from 6.36 \$ $acre^{-1}$ $year^{-1}$ to 233.34 \$ $acre^{-1}$ year. Social benefits of cover crops for reduced till range from 7.93 \$ $acre^{-1}$ year to 241.22 \$ $acre^{-1}$ $year^{-1}$.

Continuous corn rotations benefits more from cover crops than corn soybean rotations. Nutrient benefits of cover crops for continuous corn rotations range from 7.02 \$ $acre^{-1}$ $year^{-1}$ to 51.11 \$ $acre^{-1}$ $year^{-1}$. Nutrient benefits of cover crops for corn soybean rotations range from 3.71 \$ $acre^{-1}$ $year^{-1}$ to 25.19 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops for corn soybean rotations range from 12.23 \$ $acre^{-1}$ $year^{-1}$ to 241.22 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops for corn soybean rotations range from 6.36 \$ $acre^{-1}$ $year^{-1}$ to 131.37 \$ $acre^{-1}$ $year^{-1}$.

Soils with higher LCC ratings benefit the most from cover crops. This implies that cover crops provide more benefit on marginal soil than on prime cropland. Nutrient benefits of cover crops on soils with LCC rating 1 range between 3.71 \$ $acre^{-1}$ $year^{-1}$ to 26.06 \$ $acre^{-1}$ $year^{-1}$. Nutrient benefits of cover crops on soils with LCC rating 2 range between 4.39 \$ $acre^{-1}$ $year^{-1}$ to 28.24 \$ $acre^{-1}$ $year^{-1}$. Nutrient benefits of cover crops on soils with LCC rating 3 range between 4.05 \$ $acre^{-1}$ $year^{-1}$ to 51.11 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops on soils with LCC rating 1 range between 6.36 \$ \$ $acre^{-1}$ $year^{-1}$ to 85.89 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops on soils with LCC rating 2 range between 7.63 \$ $acre^{-1}$ $year^{-1}$ to 96.66 \$ $acre^{-1}$ $year^{-1}$. Social benefits of cover crops on soils with LCC rating 3 range between 7.83 \$ $acre^{-1}$ $year^{-1}$ to 241.22 \$ $acre^{-1}$ $year^{-1}$.

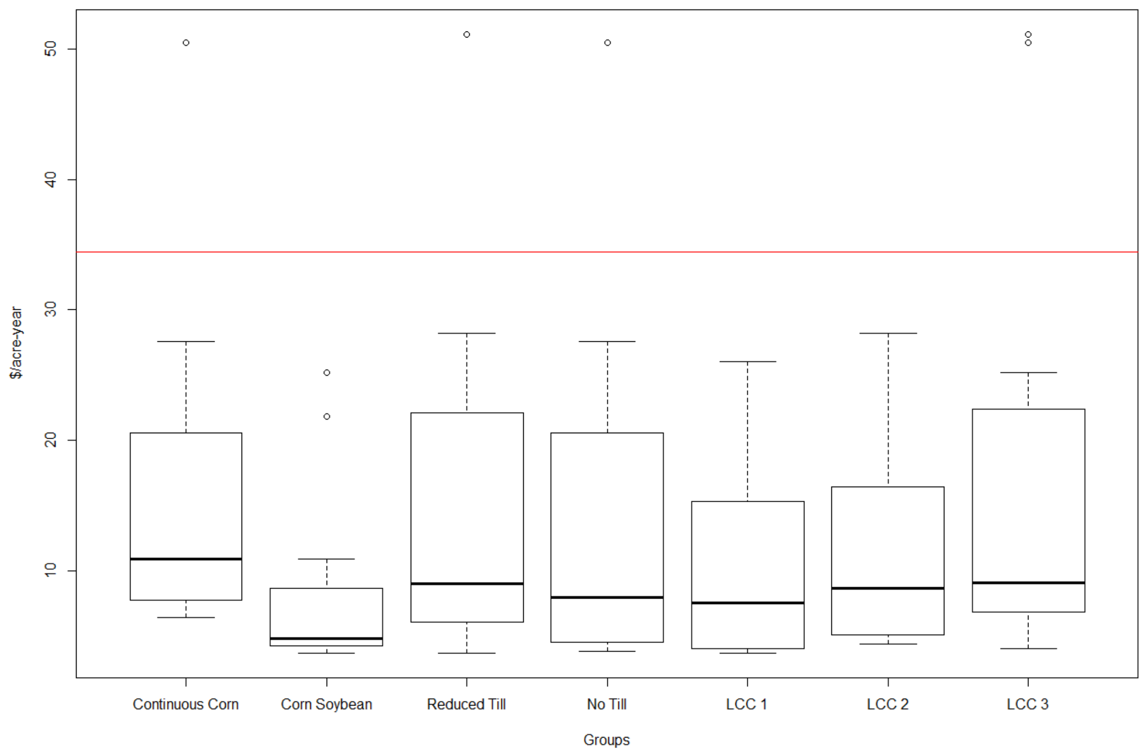

Figure 10: Nutrient Benefits of Cover Crops by Groups.
Note: Red line at $34.43 represents cost estimate for 100% rye.

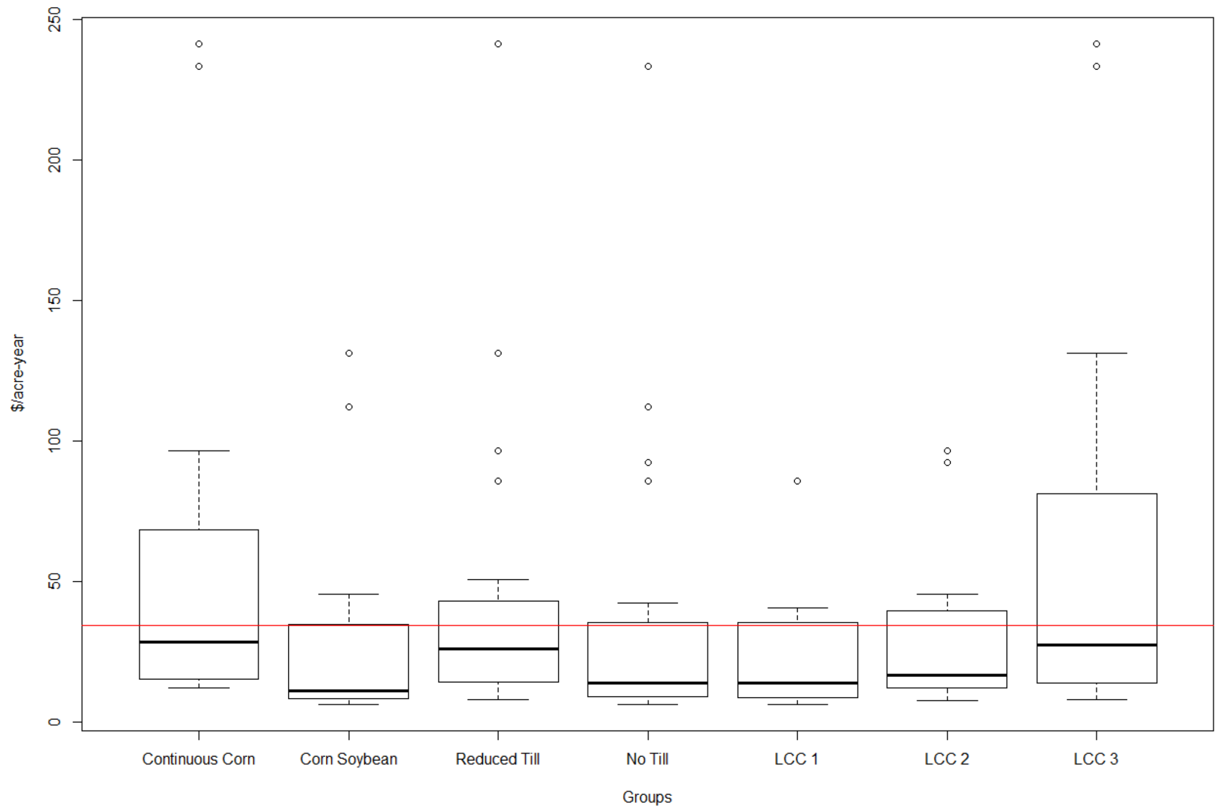

Figure 11: Social Benefits of Cover Crops by Groups.
Note: Red line at $34.43 represents cost estimate for 100% rye.

Cover crops are needed to maintain positive SOC change for low residue harvest and high residue harvest. When cover crops are used, yearly SOC change is always positive, regardless of the residue harvest, tillage practice, crop rotation or LCC rating. When cover crops are not used, yearly SOC change is negative for medium residue harvest and high residue harvest. The only exception to this is for corn soybean rotations on soil with LCC rating 1, where all management practices have positive yearly SOC change. Figures 12-15 show the yearly SOC change for each combination of management practices.

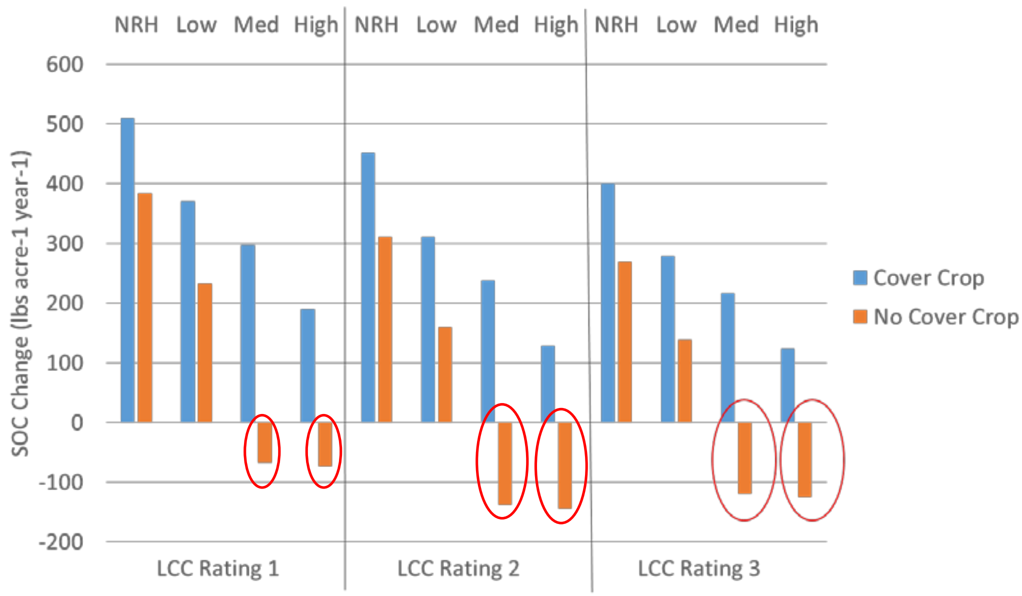

Figure 12: SOC Change for Continuous Corn Rotations and No Till.
Note: Vertical lines represent transition between LCC ratings.

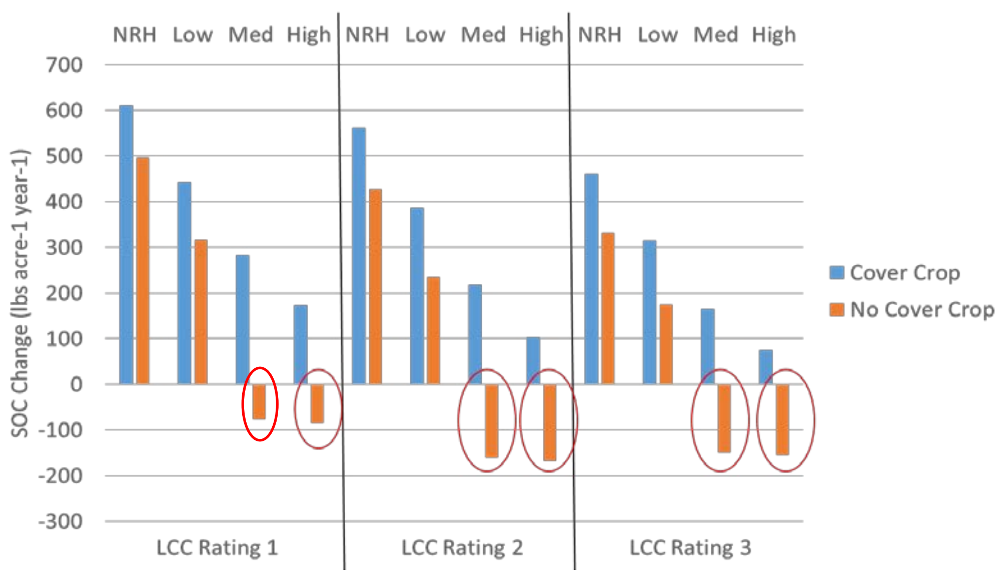

Figure 13: SOC Change for Continuous Corn Rotations and Reduced Till.
Note: Vertical lines represent transition between LCC ratings.

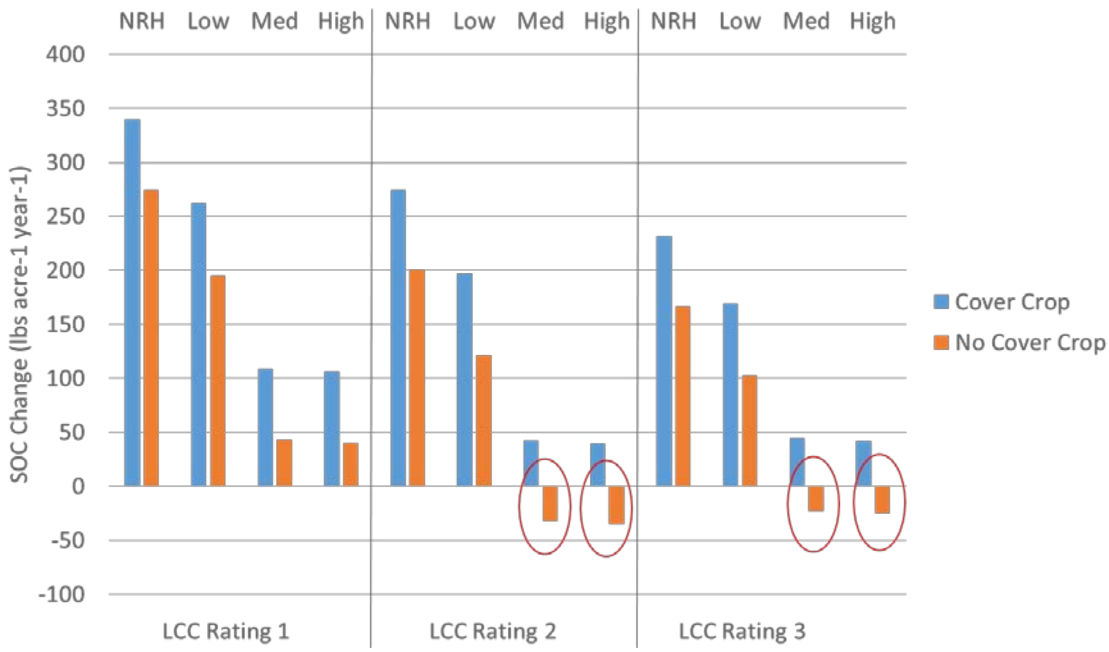

Figure 14: SOC Change for Corn Soybean Rotations and No Till.
Note: Vertical lines represent transition between LCC ratings.

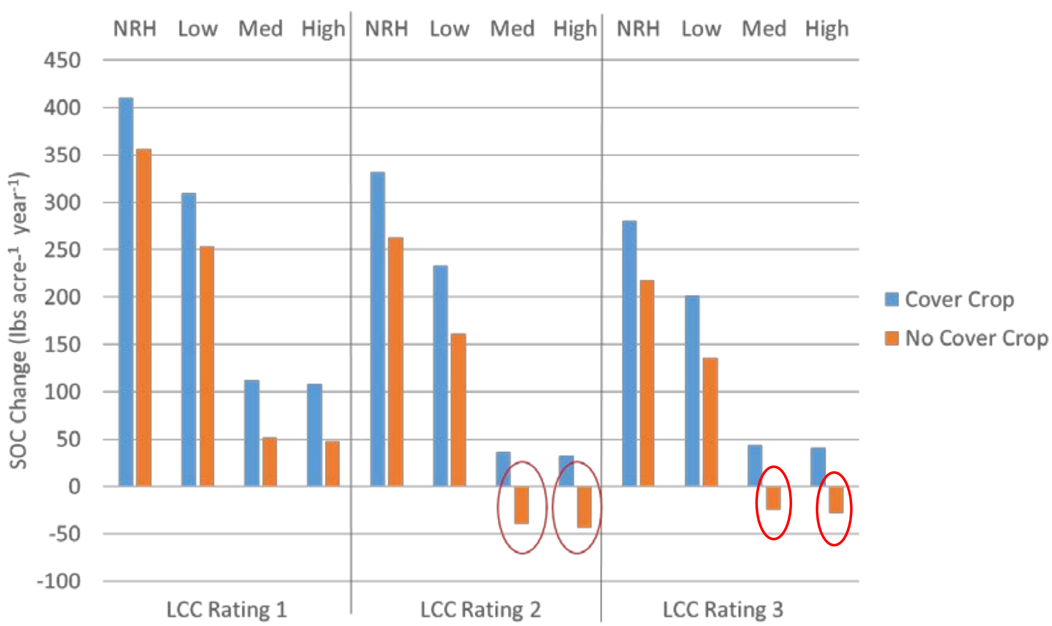

Figure 15: SOC Change for Corn Soybean Rotations and Reduced Till.
Note: Vertical lines represent transition between LCC ratings

Considering only the nutrient benefits of reduced soil erosion, reduced nitrate leaching and increased SOC rarely justifies the cost of cover crops. The primary reason for this is that the nutrient cost of soil erosion is low, 1.01 \$ $acre^{-1}$ $year^{-1}$, compared to the social cost of erosion, 4.96 \$ $acre^{-1}$ $year^{-1}$. The difference in nutrient and social costs is because a producer would not include off-site damage of soil erosion in their production function. Another reason why nutrient benefits of cover crops is low is because there are no nutrient benefits to preventing nitrate leaching. However, there are social benefits to preventing nitrate leaching.

For high residue harvest, the social benefits of cover crops always exceed the cost. This is because the amount of soil erosion that occurs is so high when high residue harvest is used without cover crops. The amount of soil erosion that occurs under high residue harvest without cover crops ranges from 6.60 tons $acre^{-1}$ $year^{-1}$ to 39.34 tons $acre^{-1}$ $year^{-1}$. However, when cover crops are used with high residue harvest, the amount of soil erosion ranges from 0.64 tons $acre^{-1}$ $year^{-1}$ to 9.72 tons $acre^{-1}$ $year^{-1}$. The social soil erosion benefits of cover crops for high residue harvest range from 35.10 \$ $acre^{-1}$ $year^{-1}$ to 225.73 \$ $acre^{-1}$ $year^{-1}$. Which is greater than the estimated cost for 100% rye. Figures 16 – 19 compare the nutrient and social benefits of cover crops to the cost of cover crops.

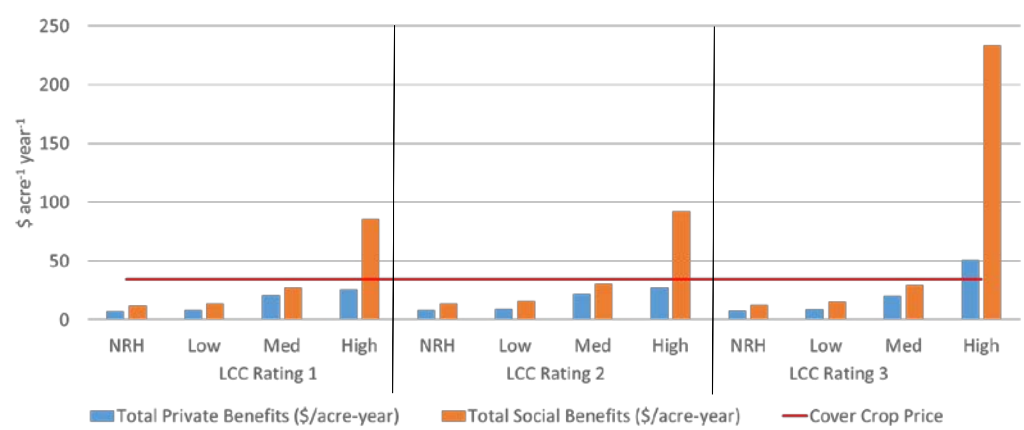

Figure 16: Nutrient and Social Benefits of Cover Crops for Continuous Corn and No Till.
Note: Vertical line marks the transition between LCC ratings.

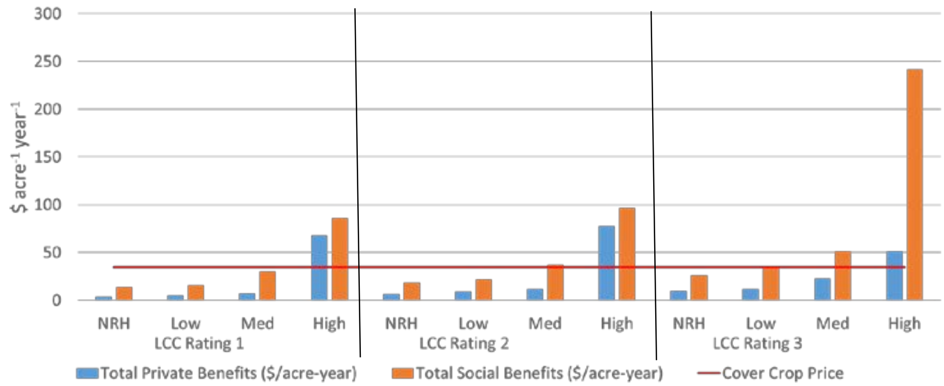

Figure 17: Nutrient and Social Benefits of Cover Crops for Continuous Corn and Reduced Till.
Note: Vertical line marks the transition between LCC ratings.

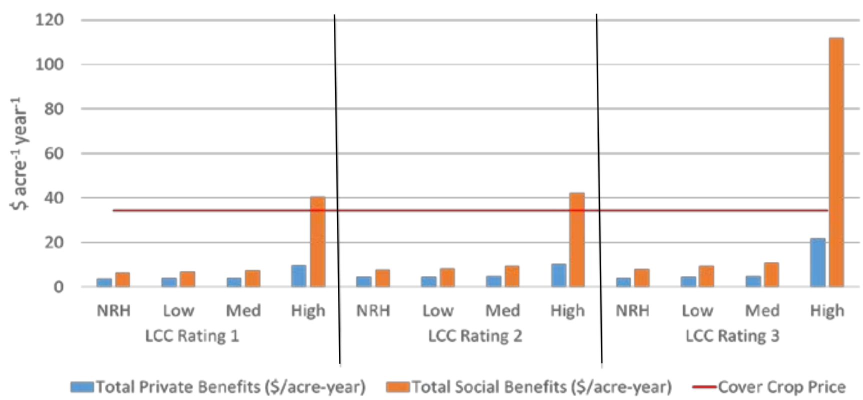

Figure 18: Nutrient and Social Benefits of Cover Crops for Corn Soybean and No Till.
Note: Vertical line marks the transition between LCC ratings.

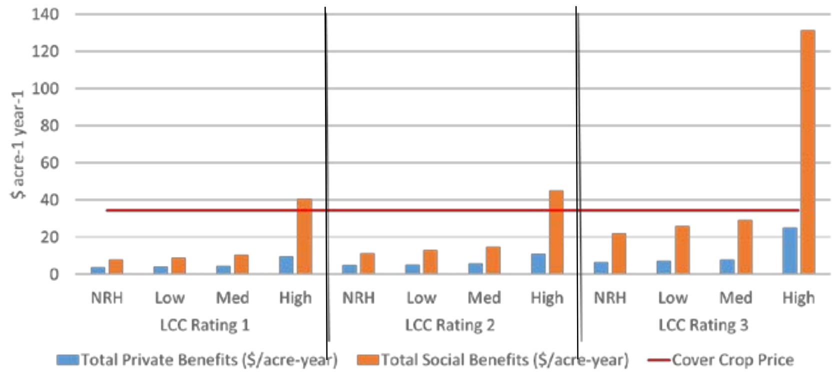

Figure 19: Nutrient and Social Benefits of Cover Crops from Corn Soybean and Reduced Till.
Note: Vertical line marks the transition between LCC ratings.

Putting everything together we find that:

- Cover crops improve environmental outcomes.
- Reduced till benefits more from cover crops than no till
- Continuous corn rotations benefits more from cover crops than corn soybean rotations.
- Soils with higher LCC ratings benefit the most from cover crops.
- Cover crops are needed to maintain positive SOC for medium residue harvest and high residue harvest.
- Considering only the nutrient benefits of reduced soil erosion, reduced nitrate leaching and increased SOC rarely justifies the cost of cover crops.
- For high residue harvest, the social benefits of cover crops always exceed the cost.

6.2 Limitations

There are many limitations to this study. The first limitation is relying on LEAF to simulate environmental outcomes. The second limitation is the values used to evaluate the environmental outcomes. The third limitation is only considering some of the benefits of cover crops.

LEAF is extremely useful as a tool to provide an educated guess about environmental outcomes under a variety of management practices when experimental data is unavailable. Ironically, the models used in LEAF need to be calibrated and parameterized based on experimental findings. Long term experimental data is still needed to validate these results.

Cover crops do more than just reduce soil erosion, reduce nitrate leaching, and increase SOC. There are other benefits to cover crop usage such as increased soil moisture retention, a food source for pollinators, reduced compaction and potentially increased yields. None of these are included in this analysis. The value of these benefits, especially increased soil moisture retention and reduced compaction, could be enough to justify cover crop use. If the reduced compaction benefit from Pratt, et al. (2013) was included, there would be more instances where the nutrient and social benefits of cover crops exceeded the cost.

The nutrient and social benefits are highly dependent on the valuation of soil erosion, nitrate leaching and SOC change. All of these valuations are extremely difficult to estimate. While it is convenient to make decisions if all of the outcomes are assigned prices, it may be misleading to do so. A potentially better way to evaluate cover crops would be to establish constraints on environmental outcomes and evaluate cover crops relative to other management practices and technologies to achieve these outcomes. So instead of trying to estimate the value of soil erosion, nitrate leaching and SOC, constraints would be established on how much soil erosion and nitrate leaching can occur. If your goal is to maintain positive yearly SOC change, then you cannot engage in medium residue harvest or high residue harvest without cover crops. The decision to use cover crops would depend on the price of cover crops and the opportunity cost of medium residue harvest and high residue harvest. Similarly, if the goal was to limit soil erosion, changes in tillage practice, use cover crops or limits on residue harvest could achieve this goal. (Doering, et al. (1999)) use a similar approach by evaluating practices relative to achieving set reductions in nitrate leaching. Since there isn't and never will be a market that captures all of the externalities of pollution and environmental damage, instead of relying on prices it would be better to establish constraints on pollution and judge technologies relative to satisfying these constraints.

6.3 Future Research

There is plenty research needed on cover crops. The most needed piece of research is long term experimental studies of cover crops in a variety of locations. Without this research we are really just guessing at the impact of cover crops. This study was only limited to Indiana, a handful of management practices and 100% rye cover crop. The benefits of cover crops still need to be evaluated for other locations, management practices and cover crops. Future research could include cover crop benefits such as increased soil moisture retention, a food source for pollinators, reduced compaction and potentially increased yields.

LIST OF REFERENCES

LIST OF REFERENCES

Abodeely, J., et al. (2012) "A Multi-Factor Analysis of Sustainable Agricultural Residue Removal Potential." In *Meeting Proceedings*. pp. 1-6.

Baker, J.M., et al. 2007. "Tillage and soil carbon sequestration—What do we really know?" *Agriculture, ecosystems & environment* 118:1-5.

Barbier, E.B. "The economics of soil erosion: theory, methodology and examples." Economy and Environment Program for Southeast Asia (EEPSEA).

Bonner, I.J., et al. 2014. "Opportunities for Energy Crop Production Based on Subfield Scale Distribution of Profitability." *Energies* 7:6509-6526.

Bonner, I.J., et al. 2014. "Modeled impacts of cover crops and vegetative barriers on corn stover availability and soil quality." *BioEnergy Research* 7:576-589.

Brandi-Dohrn, F.M., et al. 1997. "Nitrate leaching under a cereal rye cover crop." *Journal of Environmental Quality* 26:181-188.

Christianson, L., J. Tyndall, and M. Helmers. 2013. "Financial comparison of seven nitrate reduction strategies for Midwestern agricultural drainage." *Water Resources and Economics* 2:30-56.

Clark, E.H. 1985. "The off-site costs of soil erosion." *Journal of Soil and Water Conservation* 40:19-22.

Colacicco, D., T. Osborn, and K. Alt. 1989. "Economic damage from soil erosion." *Journal of Soil and Water Conservation* 44:35-39.

Comly, H.H. 1945. "Cyanosis in infants caused by nitrates in well water." *Journal of the American Medical Association* 129:112-116.

Creamer, N.G., and S.M. Dabney. 2002. "Killing cover crops mechanically: Review of recent literature and assessment of new research results." *American Journal of Alternative Agriculture* 17:32-40.

CTIC. "2013-2014 Cover Crop Survey Report."

Diaz, R.J., and A. Solow. 1999. "Ecological and economic consequences of hypoxia: topic 2 report for the integrated assessment on hypoxia in the Gulf of Mexico."

Doering, O.C., et al. "Evaluation of the economic costs and benefits of methods for reducing nutrient loads to the Gulf of Mexico." NOAA Coastal Ocean Program.

English, A., et al. 2013. "Environmental tradeoffs of stover removal and erosion in Indiana." *Biofuels, Bioproducts and Biorefining* 7:78-88.

Foster, G.R. 2001. "Keynote: soil erosion prediction technology for conservation planning." *Sustaining Global Farm*:847-851.

Hansen, L., and M. Ribaudo. 2008. "Economic measures of soil conservation benefits." *USDA, September*.

Havlin, J., et al. 1990. "Crop rotation and tillage effects on soil organic carbon and nitrogen." *Soil Science Society of America Journal* 54:448-452.

Helms, D. 1992. "Readings in the history of the Soil Conservation Service." *Historical notes (USA)*.

Himes, F. 1998. *Nitrogen, sulfur, and phosphorus and the sequestering of carbon*: CRC Press, Boca Raton, FL.

Hotta, K.F.N.S. 2004. "Wind erosion from cropland in the USA: a review of problems, solutions and prospects." *Geoderma*:157–167.

Kern, J., and M. Johnson. 1993. "Conservation tillage impacts on national soil and atmospheric carbon levels." *Soil Science Society of America Journal* 57:200-210.

Kladivko, E., et al. 2004. "Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system." *Journal of Environmental Quality* 33:1803-1813.

Labarta, R.A., et al. "Economic analysis approaches to potato-based integrated crop systems: issues and method." Michigan State University, Department of Agricultural, Food, and Resource Economics.

Lal, R. 2014. "Societal value of soil carbon." *Journal of Soil and Water Conservation* 69:186A-192A.

Lang, B.J., J.E. Sawyer, and S.K. Barnhart. 2007. "Dealing with sulfur deficiency in northeast Iowa alfalfa production." *Animal Industry Report* 653:28.

Mann, L., V. Tolbert, and J. Cushman. 2002. "Potential environmental effects of corn (< i> Zea mays</i> L.) stover removal with emphasis on soil organic matter and erosion." *Agriculture, ecosystems & environment* 89:149-166.

Moore, E., et al. 2014. "Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage–Soybean Cropping Systems." *Soil Science Society of America Journal* 78:968-976.

Mutchler, C., and L. McDowell. 1990. "Soil loss from cotton with winter cover crops." *Transactions of the ASAE* 33:432-436.

Muth, D., and K. Bryden. 2013. "An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems." *Environmental Modelling & Software* 39:50-69.

Pratt, M., et al. 2013. "Synergies between cover crops and corn stover removal." *Purdue Extension Renewable Energy Series RE-7-W*.

Puget, P., and L. Drinkwater. 2001. "Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure." *Soil Science Society of America Journal* 65:771-779.

Rawls, W., et al. 2003. "Effect of soil organic carbon on soil water retention." *Geoderma* 116:61-76.

Reeves, D. 1994. "Cover crops and rotations." *Advances in Soil Science: Crops Residue Management*:125-172.

S. S. Snapp, S.M.S., R. Labarta, D. Mutch, J. R. Black, R. Leep, J. Nyiraneza, and K. O’Neil. 2005. "Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches." *Agron. J.*

Shukla, M., R. Lal, and M. Ebinger. 2006. "Determining soil quality indicators by factor analysis." *Soil and Tillage Research* 87:194-204.

Singer, J., S. Nusser, and C. Alf. 2007. "Are cover crops being used in the US corn belt?" *Journal of Soil and Water Conservation* 62:353-358.

Snapp, S., et al. 2005. "Evaluating cover crops for benefits, costs and performance within cropping system niches." *Agronomy Journal* 97:322-332.

Weil, R., C. White, and Y. Lawley. 2009. "Forage radish: new multi-purpose cover crop for the Mid-Atlantic." *Fact Sheet* 824.

West, T.O., and W.M. Post. 2002. "Soil organic carbon sequestration rates by tillage and crop rotation." *Soil Science Society of America Journal* 66:1930-1946.

Wilhelm, W.W., et al. 2010. "Review: balancing limiting factors & economic drivers for sustainable Midwestern US agricultural residue feedstock supplies." *Industrial Biotechnology* 6:271-287.

Williams, J., et al. 1980. "Soil erosion effects on soil productivity: a research perspective." *Journal of Soil and Water Conservation*.

Wischmeier, W.H., and D.D. Smith. 1978. "Predicting rainfall erosion losses-A guide to conservation planning." *Predicting rainfall erosion losses-A guide to conservation planning*.