# THE EFFECTS OF WINTER COVER CROPPING ON NUTRIENT LEACHING THROUGH REPACKED SOIL COLUMNS

BY

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THESIS

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# ABSTRACT

Winter cover cropping has been identified as a conservation practice with the potential to decrease nutrient transport from agricultural fields, which consequently reduces nutrient loading to water bodies, eutrophication, hypoxia, and degradation of local ecosystems. This study utilized laboratory-scale soil columns and the one-dimensional water and solute transport model HYDRUS-1D to quantify and understand the potential decrease in nitrogen and phosphorus loss through tile drainage due to cover crops, as well as compare the amount of nitrogen and phosphorus available in the soil at cash crop planting, with and without a cover crop.

Information from a method development period and literature review was used to design, construct, and execute an outdoor/indoor soil column experiment, which allows for both realistic weather conditions and an increased amount of experimental control. A 50/50 mixture of oats *(Avena sativa*) and hairy vetch (*Vicia villosa*) was grown in Flanagan silt loam soil columns August 2014 – January 2015 in Champaign, IL. In August, 201.8 kg $ha^{-1}$ $NO_3$-N and 50.4 kg $ha^{-1}$ $PO_4$-P were applied to a growing cover crop. Deionized water was applied at a rate of 4 L every two weeks in addition to natural precipitation. A well-established stand of oats/hairy vetch cover crop had 92% less nitrate leaching (total mass) over the growing period than bare soil. Additionally, a 65% increase in cover crop growth was shown to significantly decrease nitrate leaching compared to a thinner stand of cover crops within 95% confidence limits. Both drainage volumes and nitrate concentrations were reduced as a result of cover cropping. However, average nitrate concentrations from both bare and cover cropped soil columns were above 10 mg $L^{-1}$, which is the acceptable limit for drinking water. This experiment simulates a "worst-case scenario" for nitrate leaching by combining fall fertilizer application with soil directly above a tile, but a "best-case scenario" with a profile initially free of macropores.

Orthophosphate leaching was 2 – 3 orders of magnitude less than nitrate leaching (0.7 mg of orthophosphate and 87 mg of nitrate lost over growing season from densely cover cropped columns), but also decreased with cover crop use by 46%.

The HYDRUS-1D model was successfully calibrated and validated for water flow from cover cropped and bare soil columns. However, the model under-predicted the effects of cover cropping on water and nitrate leaching. Future experiments conducted to provide model data for cover cropping should include measurements of root growth, leaf area index (LAI), soil pH, and estimations for crop nutrient uptake potential.

Limitations of studies with repacked soil column were encountered and are addressed in detail. Recommendations for future soil column studies include increasing the time period allowed for natural settling of the soil column and introducing earthworms, quantifying the effects of soil temperature on nitrification and denitrification under cover cropping, and measuring nitrate concentrations throughout the profile in addition to bottom leachate. Another potential area of research would be in utilizing cover crops to reclaim extremely compacted or poorly drained soils.

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# CHAPTER 1

# INTRODUCTION

Nitrogen (N) and phosphorus (P) are plant macronutrients that are essential for crop growth and development. These nutrients are supplied naturally by fertile soils through complex cycles involving microbes, and their abundance is affected by many factors including temperature, precipitation, crop rotation, soil type, other nutrients, pH, etc. To maximize yield potential, farmers routinely apply synthetic and natural forms of N and P to croplands. When a factor other than N or P becomes the limiting growth factor (e.g. drought, pests, disease), these nutrients build up in the soil and are subjected to loss through runoff and leaching. Leaching occurs when nitrogen and phosphorus in the soil are dissolved into water, which enter ground water or subsurface tile drains and are transported. Tile drains and channelized streams, which have been installed extensively across Illinois and other portions of the Midwest, are intended to expedite the flow of water from agricultural fields. This highly-engineered landscape provides a method of draining fertile soils, but has also become an accelerated pathway for N and P, as well as other nutrients, pathogens, and chemicals, to enter nearby water bodies and continue downstream to the Gulf of Mexico. Elevated levels of N and P in surface water can lead to an increased rate of eutrophication, which reduces the dissolved oxygen in the water and impairs the surrounding ecosystems. Due to a combination of factors including tile drainage and fertilizer application, N and P transported from agricultural lands in the Mississippi River Basin are the largest contributing factor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 1996; Dale et al., 2007; David et al., 2010).

Winter cover cropping is one conservation practice that has the potential to reduce nutrient transport from fields. Fall planting of grass cover crops, such as oats *(Avena sativa*) and cereal rye (*Secale cereale* L.), has been shown to significantly reduce nitrate ($NO_3$-N) concentrations in drainage water in Illinois and Iowa (Kaspar et al., 2012; Lacey and Armstrong, 2012). Additionally, by including a legume cover crop in the mixture, such as hairy vetch (*Vicia villosa*), to fix nitrogen from the atmosphere, there is potential to accumulate soil N and reduce the need for fertilizer inputs after cover crops (Tosti et al., 2013; Moller et al., 2007; Sullivan and Andrews, 2012; Ranells and Wagger, 1997). Studies on grass-legume cover crop mixtures have primarily been conducted in other states and countries; however, implementing this practice may have similar benefits for Illinois farmers as well. Although cover cropping is a common practice in some regions of the world and United States, study and adoption of cover crops in the Mississippi River Basin, including Illinois, remains low. A National Wildlife Federation survey conducted by Bryant et al. (2013) estimated that in 2011 less than 2% of land in the Mississippi River Basin was planted with cover crops. By conducting experiments under local conditions (soil types, weather, management practices, etc.) on the benefits of grass-legume cover crop mixtures in Illinois, more information on regional benefits and challenges of specific cover crop species will be gained.

Field-scale studies have been conducted to investigate the effect of grass-legume cover crop mixtures on N leaching and accumulation. However, field-scale studies often introduce variables that are difficult to control, quantify, and/or replicate, for example non-uniform and unknown distributions of precipitation, nutrient content in precipitation, soil heterogeneity, and groundwater flow. Laboratory-scale research into grass-legume cover crop mixtures that is applicable to the Mississippi River Basin, and specifically Illinois, will provide further insight into the mechanisms and effectiveness of cover cropping to manage soil nutrients. Although the effects of cover crop mixtures on the N cycle have been investigated by many researchers, the effects on P transport remains largely unstudied. While P leaching through tile drains is of minimal concern compared to N leaching, P is usually more limiting than N for primary production in freshwater ecosystems and should not be ignored (Alexander et al., 2008).

Accompanying both field-scale and laboratory-scale studies, computer models can be useful tools to simulate the results of an experiment, provide further understanding of the observations and processes that govern the experiment, and allow for potential extrapolation of the results to make predictions. This project will compare experimental data gained through semi-controlled soil column experiments with HYDRUS-1D model simulations to determine and predict the drainage flow and nutrient leaching effects of grass-legume winter cover crop mixtures.

# CHAPTER 2

# OBJECTIVES

The overall aim of this research is to study the nutrient cycling effects of a grass-legume cover crop mixture using semi-controlled soil column experiments and model simulations. The specific objectives of this study are to:

- Establish methods to study nutrient leaching under cover cropped conditions through a soil column in a semi-controlled laboratory-scale experiment.
- Determine the effects of a grass-legume cover crop mixture on nitrogen and phosphorus leaching through tile drains, both during the growing period and after the cover crop is suppressed.
- Calculate a water and nutrient mass-balance utilizing data collected from soil column experiments as well as plant biomass.
- Employ HYDRUS-1D, a one-dimensional water and solute transport model, to simulate the experiment and compare the results with the laboratory data.

# CHAPTER 3

# REVIEW OF LITERATURE

The objectives of this literature review are to 1) Explain causes and concerns of nutrient leaching from agricultural lands; 2) Identify benefits of cover cropping to manage soil nutrients and mitigate nutrient leaching; 3) Evaluate previous soil column studies; and 4) Pinpoint needed areas of research to encourage wider adoption of cover cropping practices in the Midwestern United States. Additionally, this literature review is intended as a justification of need for a Master's thesis investigating the differences in nitrogen and phosphorus leaching from tile drained land with and without grass-legume cover cropping. The experiments will be performed in reconstructed soil columns in an outdoor environment. To achieve the goals of the literature review, many studies were considered from diverse backgrounds and time periods, but an emphasis was placed on research that is current and regionally relevant.

## 3.1 Nutrient Leaching from Agricultural Lands in the Midwest

### 3.1.1 Fertilizer Use

Nitrogen (N) and phosphorus (P) are plant macronutrients, which are routinely applied to agricultural croplands via synthetic fertilizers and manure. In 2013 in Illinois alone, 4.9 million hectares (12 million ac) of corn and 3.8 million hectares (9.5 million ac) of soybeans were planted, making Illinois the second leading producer of both corn and soybeans in the United States (USDA NASS, 2013). According to the United States Department of Agriculture Economic Research Service (USDA ERS), in Illinois in 2010, farmers applied an average of 187 kg ha$^{-1}$ (167 lb ac$^{-1}$) of nitrogen to 98% of corn acres and 104 kg ha$^{-1}$ (93 lb ac$^{-1}$) of phosphate to

85% of corn acres (USDA ERS, 2013). Poor field or weather conditions and management errors are possible reasons for not applying N and P fertilizer to corn. In the case of phosphorus, unfertilized corn could also be attributed to high soil test P values or enrollment in Conservation Reserve Programs (CRP) with regulations on P fertilizer inputs. CRP enrollment has been about 1 million acres in Illinois in recent years (USDA FSA). In 2012 in Illinois, farmers applied an average of 29 kg $ha^{-1}$ (26 lb $ac^{-1}$) of nitrogen to 19% of soybean acres and 78 kg $ha^{-1}$ (70 lb $ac^{-1}$) of phosphate to 23% of soybean acres (USDA ERS, 2013). According to these statistics, approximately 900 million kilograms (2 billion lb) of nitrogen and 500 million kilograms (1.1 billion lb) of phosphate are being applied yearly to Illinois soils.

### 3.1.2 Subsurface Drainage

Nitrogen and phosphorus in the soil naturally, or supplied by fertilizers, can be leached through the soil profile when dissolved into water and enter ground water or subsurface tile drains and be transported to surface waters. Tile drains are intended to expedite the flow of water from agricultural fields, thereby draining once swampy soils and providing central Illinois with very fertile and productive farmland (Kalita et al., 2007). These tile drainage systems, while engineered to increase productivity, also provide an accelerated pathway for nutrients such as nitrogen and phosphorus to enter nearby water bodies. In Illinois, over 4 million hectares of cropland (10 million acres) are drained by tile drainage, with new drainage systems installed every year (Kalita et al., 2007; USDA NASS, 2012; University of Illinois Extension). The current area of tile drained land in Illinois has likely increased since 2012, but no existing public record of recent installations could be found from which to calculate a more accurate estimate.

### 3.1.3 Environmental Consequences

Elevated levels of nitrogen and phosphorus in surface water can lead to an increased rate of eutrophication, which reduces the dissolved oxygen in the water and impairs the surrounding ecosystems (Rabalais, 2002). Due to a combination of factors including tile drainage and fertilizer application, nitrogen and phosphorus transported from agricultural lands in the Mississippi River Basin are the largest contributing factor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 1996; Dale et al., 2007; David et al., 2010).

The environmental consequences of nutrient loading in surface waters can also be seen in the Chesapeake Bay watershed where poor water quality has deteriorated ecosystems and negatively affected wildlife (USEPA). In 2009 President Obama requested as part of an Executive Order that the federal government lead an effort to restore and protect the Chesapeake Bay watershed (USEPA). As a result, the United States Environmental Protection Agency (USEPA) has published several documents on Total Maximum Daily Loads (TMDL) and suggested management practices, such as cover cropping, to motivate action to reduce nutrient loads in Chesapeake Bay watershed (USEPA). Several states in the Chesapeake Bay watershed have implemented cost-share programs to encourage farmers to use cover crops. For example, Maryland pays farmers $45 - $100 per acre of cover cropped ground (MDOA).

### 3.1.4 Nutrient Loading and Hypoxia

Throughout the U.S. Cornbelt, but especially in Central Illinois and Iowa, tile drainage is frequently implemented on poorly drained Mollisols, which are highly productive soils when drained (David et al., 2010). Current farming practices include applying higher rates of nitrogen fertilizers to soils with higher yield potentials, such as tile-drained Mollisols. A modeling analysis conducted by David et al. (2010) concluded that growing fertilized crops on tile-drained land is strongly correlated to fertilizer nitrogen ($r = 0.61$) applications and large riverine nitrate loads.

A study by Alexander et al. (2008) using the SPARROW water quality model found that 52% of the total nitrogen and 21% - 25% of the total phosphorus entering the Gulf of Mexico can be attributed to agricultural lands planted with corn and soybeans. According to the model, corn and soybean production are the largest contributors of nitrogen and second largest contributors of phosphorus to the Gulf of Mexico (Alexander et al., 2008). Furthermore, Illinois is the largest contributor of both nitrogen and phosphorus to the Gulf of Mexico, supplying 16.8% of the total nitrogen flux and 12.9% of the total phosphorus flux (Alexander et al., 2008).

### 3.1.5 Phosphorus Accumulation and Leaching

Nitrate, a water-soluble anion, is widely accepted as having high leaching potential through tile drains. However, as phosphorus content in the soil increases, leaching losses of phosphorus can also increase and can be significant if the iron, aluminum, and/or calcium adsorption capacity of the soil is saturated (Bennett et al., 2001). Phosphorus accumulation in agricultural lands from 1958 – 1998 was estimated to be 8 Tg $yr^{-1}$($1 \text{ Tg} = 10^{12}$ g) worldwide, which is a substantial fraction of the excess phosphorus storage in the global budget (Bennett et al., 2001). An estimated 5 Tg $yr^{-1}$ of phosphorus accumulation has occurred in developed nations from 1958 - 1998, such as the United States (Bennett et al., 2001). Not all of this accumulated phosphorus will be leached. Long-term field studies have determined that of all P losses from agricultural land, 75% - 90% of P is transported as particulate P during erosion events (Sharpley et al., 1993). Only some forms of phosphorus are prone to leaching, such as dissolved P. However, dissolved P is more available for use by algae than particulate P (Sharpley et al., 1993). In weakly acidic or basic conditions, such as soil solution and drainage water effluent, the dissolved forms of phosphorus $H_2PO_4^-$ or $HPO_4^{2-}$ dominate, respectively. Dissolved phosphorus may also be referred to as orthophosphate or dissolved reactive phosphorus (DRP) and is available for plant uptake.

### 3.1.6 Cover Crop Adoption

Although cover cropping practices are widely used in many areas of the world and United States for nutrient management, soil arability, and erosion and nutrient loss prevention from agricultural lands, study and adoption of this conservation practice in the Midwestern United States is limited. A modeling study by Kladivko et al. (2014) used Vermillion and Grundy counties to estimate that about 60% of agricultural lands in East Central Illinois are suitable for cover crop implementation. Factors that may limit the applicability of cover crops include fall tillage and crop production other than corn and soybeans (Kladivko et al., 2014). Despite the majority of land being suitable for cover crops, a survey conducted by Conservation Technology Information Center (CTIC) in 2010 found that of the survey participants only 7% in Illinois and 9% in Iowa currently use cover crops. Since only 719 farmers responded and participation was voluntary, the percentage of cover crop adoption in the Midwest may be even lower than the CTIC survey estimates (CTIC, 2010). Local nutrient transport studies on cover crop mixtures that are applicable to the Midwest are necessary to demonstrate the benefits and address the challenges of cover crops from both a conservation and economic standpoint to encourage wider adoption.

### 3.2 Effects of Cover Cropping on Soil Nutrients

Cover cropping with legumes and grass-legume mixtures has been identified as a possible strategy for adding nitrogen to the soil in an effort to reduce the amount of additional synthetic fertilizer required (Buciene et al., 2005; Moller et al., 2007; Stenberg et al., 2011; Lacey and Armstrong, 2012; Sullivan and Andrews, 2012; Tosti et al., 2014). Most of these nutrient cycling experiments have studied common grasses, legumes, and grass-legume mixtures in field-scale studies, but controlled laboratory-scale experiments have not been performed. Field studies introduce many variables that are difficult to quantify, control, or replicate such as soil heterogeneity, nutrient content in precipitation, groundwater flow, and weather patterns.

#### 3.2.1 Nutrient Uptake during Cover Crop Growth

Field experiments performed by Lacey and Armstrong (2012) at Illinois State University compared the soil nitrogen effects of pure stands of clover, cereal rye, and tillage radish with 200 kg ha$^{-1}$ of fall-applied nitrogen. Averaged over 2 years, cover crop uptake of nitrogen was found to be highest with cereal rye (Lacey and Armstrong, 2012).

However, adding nitrogen to a legume cover crop mixture has been shown to reduce the nitrogen fixation and competitiveness of the legumes (Moller et al., 2007). The added nitrogen allows other crops to compete with the legumes potentially leading to a nitrogen shortage for the mixture later in the growing period (Moller et al., 2007). Moller et al. (2007) also looked at phosphorus uptake of vetch and found that cover crop mixtures comprised of 90% vetch absorbed 20.7 kg P ha$^{-1}$ from the soil.

### 3.2.2 Nutrient Availability after Cover Crop Incorporation

The date of cover crop incorporation into the soil had a significant impact on nutrients available in the soil (Moller et al., 2007). Incorporation/termination of the cover crop is performed so that subsequent cash crops, such as corn and soybeans, do not have to compete with the cover. Spraying herbicide and using tillage are common ways to terminate cover crops, and the method used to terminate the cover crop could have an effect on nutrient availability. Sullivan and Andrews (2012) recommended that a 50/50 mixture of grasses and legumes be incorporated two weeks prior to the boot stage of the cereal and the bud stage of the legume to achieve maximum plant available nitrogen, including ammonium and nitrate, in the soil. Following incorporation, legumes can be expected to release about half of their nitrogen as plant available nitrogen, which would be about 56 kg $ha^{-1}$ of plant available nitrogen and 44.8 kg $ha^{-1}$ nitrogen in soil organic matter for a pure stand of common vetch with 3359.3 kg $ha^{-1}$ of dry mass (Sullivan and Andrews, 2012). The pure stand of vetch and the cereal rye-vetch mixture were found to provide similar amounts of plant available nitrogen, at 44.8 – 78.4 kg $ha^{-1}$ after 10 weeks (Sullivan and Andrews, 2012). The need for inorganic nitrogen fertilizer may be reduced anywhere from 56 – 112 kg $ha^{-1}$ through the use of legume cover crops or grass-legume mixtures (Sullivan and Andrews, 2012). Tosti et al. (2014) studied the use of barley and vetch as a cover crop mixture and concluded that although soil nitrogen accumulation did occur with the mixture, it was less than the accumulation in a pure stand of vetch.

Lacey and Armstrong (2012) collected soil samples in weekly increments from cover crop termination to one week after corn planting and analyzed the samples for $NO_3$-N. At corn planting in the spring of 2012, the bare plots had slightly higher soil nitrate levels (110 kg $ha^{-1}$ $NO_3$-N) than the cereal rye (100 kg $ha^{-1}$ $NO_3$-N) and crimson clover (90 kg $ha^{-1}$ $NO_3$-N), but the tillage radish plots had approximately double the soil nitrate levels of the other three treatments (200 kg $ha^{-1}$ $NO_3$-N). At planting in the spring of 2013, the bare plots, tillage radish, and crimson clover had similar soil nitrate levels (90 – 100 kg $ha^{-1}$ $NO_3$-N), with the cereal rye plot nitrate levels being lower than the other three treatments (70 kg $ha^{-1}$ $NO_3$-N). Soil nitrate levels increased with time after cover crop termination in both years. It is important to note that the 2012 growing season was extremely hot and dry, while the following spring of 2013 was uncharacteristically wet. (Lacey and Armstrong, 2012)

### 3.3 Effects of Cover Cropping on Nutrient Leaching Through Subsurface Drainage

By including grasses in legume cover crop mixtures, reduction of nutrients in drainage water has been seen as an additional environmental benefit in some studies (Tosti et al., 2014; Moller et al., 2007; Sternberg et al., 2011; Kaspar et al., 2012). Some of these studies have addressed the amount of nutrients that certain cover crops may take up from the soil during growth, reducing nutrient leaching, but the effects from the previous cover crop on nutrient transport after incorporation has been studied minimally.

#### 3.3.1 Nitrogen Leaching Reduction

After cover crop termination, but before spring plowing, Lacey and Armstrong (2012) found that soil nitrate was higher at all depths under fallow conditions compared to cover crops. At shallow depths (around 5 cm) small differences were seen in soil nitrate concentrations between cover cropped soils and bare soils, but large differences were seen at deeper depths (Lacey and Armstrong, 2012). In the spring of 2013, the largest soil nitrate concentration was present at 50 cm with 86 kg $ha^{-1}$ of $NO_3$-N in bare soils and only 44 kg $ha^{-1}$ of $NO_3$-N in cover cropped soils on average, and this difference was larger in the spring of 2012 due to higher bare soil nitrate concentrations (Lacey and Armstrong, 2012). Although the clover and cereal rye decreased the amount of soil nitrate available at depths around 0 – 20 cm, the percentage of soil nitrates distributed in those depths increased compared to the rest of the soil profile (Lacey and Armstrong, 2012). With lower soil nitrate concentrations, it makes sense that the results also showed a nitrate leaching reduction with cover crops, with the largest reduction seen from cereal rye (Lacey and Armstrong, 2012).

Tosti et al. (2014) found that a mixture of barley and vetch could be as effective at reducing nitrate leaching as a pure barley cover crop. Mineral N ($NO_3$ and $NH_4$) leaching has been correlated to many factors that should be studied in more detail including crop growth, drainage volumes, soil total N, and soil organic matter (SOM) (Buciene et al., 2005; McLaughlin and Kalita, 2001). Malone et al. (2014) used Root Zone Water Quality Model (RZWQM) to estimate that on average a winter cereal rye cover crop could reduce nitrogen loss through tile drainage across the Midwest by 23.9% - 42.5%, depending on management practices. A regression analysis of the model further showed that the most important factors affecting this reduction are temperature and precipitation during the cover crop growing season, nitrogen fertilizer rates applied to corn, and corn yield (Malone et al., 2014). These factors imply a strong correlation between nitrate reductions and the amount of growth of the cover crop, nitrogen in the soil, and residue available to induce immobilization of nitrogen.

A field plot study conducted by Kaspar et al. (2012) found that cereal rye cover crops planted after harvest reduced nitrate concentrations in drainage by 48%, but did not significantly reduce nitrate loads due to lower nitrogen fertilizer rates and higher cumulative drainage. In a previous study at the same location, Kaspar et al. (2007) found that a cereal rye cover crop reduced nitrate loads by 61% on average over four years in a no-till corn-soybean rotation in Iowa, so it was supposed that the effectiveness of the practice to reduce nitrate pollution may potentially decrease after four years of annual establishment (Kaspar et al., 2012). The study also looked at oats broadcast into corn and soybeans, and this practice was found to be only about half as effective at reducing nitrate concentrations as the cereal rye cover cropping practice (Kaspar et al., 2012). The reduced effectiveness of the oats likely could be attributed to the less total plant growth of the oats compared to the cereal rye (Kaspar et al., 2012).

### 3.3.2 Phosphorus Leaching Reduction

Phosphorus cycling effects due to cover cropping have not been studied extensively. Some studies have been conducted on phosphorus leaching in general and found that concentrations in drainage water are correlated to soil type, fertilization, particulate loading, and Al-extractable phosphorus in soils (Svanbäck et al., 2013; Reddy et al., 1977; Buciene et al., 2005). Clay soils with high organic matter contents were found by Reddy et al. (1977) to have higher amounts of phosphorus leached through the soil. The fraction of dissolved reactive phosphorus in the leachate was found to increase with Al-extractable phosphorus, and of the many loamy soil types included in the study by Svanbäck et al. (2013) this fraction was found to be the largest in silty clay loams.

## 3.4 Laboratory-scale Nutrient Leaching Experiments

Laboratory experiments are advantageous for the high level of environmental control and repeatability of experiments. When constructing a laboratory-scale experiment, it is important to study previous research that has had similar goals and methods, scrutinize the approaches, address any concerns, and learn from conclusions.

### 3.4.1 Soil Column Design and Repacking

Lewis and Sjöstrom (2010) synthesized the available literature on soil column experiments to determine the optimal design of packed/undisturbed and saturated/unsaturated soil columns for solute transport studies. A crucial difference between packed and undisturbed soil columns is the presence or absence of macropores (Lewis and Sjöstrom, 2010). The absence of macropores in packed soil columns leads to reproducible, but less realistic experiments than if undisturbed columns are studied (Lewis and Sjöstrom, 2010). The heterogeneity of macropores in soil, which contribute significantly to solute transport, requires a large number of undisturbed column studies in order to conduct sound statistical analyses (Lewis and Sjöstrom, 2010). A study by Akhtar et al. (2003) determined that 90 columns were necessary to ensure a significant probability of studying solute transport via macropores. Additionally, the excavation of large undisturbed soil columns is a time-consuming, labor-intensive process (Corwin, 2000) and may lead to soil compaction that would influence the solute transport behavior of the soil column (Miller et al., 2002).

However, the process of packing a soil column is also tedious and must be done properly to achieve a realistic bulk density, prevent preferential flow paths, and ensure hydraulic connectivity between soil layers (Lewis and Sjöstrom, 2010). Dry or damp soil packing is the most common method employed by researchers and involves the addition of soil in 0.2 cm (Oliveira et al., 1996) – 15 cm (Plummer et al., 2004) layers with manual or mechanical packing between each layer (Lewis and Sjöstrom, 2010). Plummer et al. (2004) also noted that scarification between soil layers is necessary to prevent the stratification of soil layers (Lewis and Sjöstrom, 2010). Another method of soil compaction in a disturbed column study is passive weathering, which requires that a soil column be placed outside for a minimum of 3 years to achieve maximum bulk density (Colman and Hamilton, 1947). Natural bulk densities of silt and clay soils are 1.0 – 1.7 g $cm^{-3}$ (Lewis and Sjöstrom, 2010). The packing process may cause columns with a bulk density $< 1.01$ g $cm^{-3}$ to have a significantly lower dispersivity than columns with a bulk density $> 1.01$ g $cm^{-3}$ (Bromly et al., 2007). Dispersivity is a measure of solute spreading throughout a soil (Bromly et al., 2007).

Utilizing unsaturated soil columns in solute transport experiments introduces other challenges, such as sidewall flow and negative pressure potential (Lewis and Sjöstrom, 2010). Improper packing techniques or flexing of the soil column after packing can lead to preferential flow along the edges of the soil column (Lewis and Sjöstrom, 2010). Several methods have been utilized to prevent sidewall flow, such as roughening the edges of the soil column (Smajstrla, 1985), gluing sand to the sidewalls (Sentenac et al., 2001), and packing the walls of the soil column with a swelling clay (Lewis and Sjöstrom, 2010). Furthermore, unsaturated soil columns have a negative pressure potential, in other words the pressure in the soil pores is lower than atmospheric pressure, so collecting leachate from a soil column requires either suction or partial saturation (Lewis and Sjöstrom, 2010). Rigid porous materials, such as fiberglass wicks, can only apply a maximum of 101.325 kPa of suction to collect pore water samples and also have a tendency to clog (Lewis and Sjöstrom, 2010). Free drainage is another method used frequently in the literature, which requires the column to be installed on a bed of sand or gravel and the soil matric potential to reach at least 100 kPa before drainage begins (Lewis and Sjöstrom, 2010). One hundred kilopascals of matric potential corresponds to a 30 cm deep saturation zone in sand

and up to a 90 cm deep zone in loam at the base of the column, so realistically the column would have to be mostly saturated before drainage would occur (Boulding and Ginn, 2004). Also, transport and flow data from these experiments will be biased because hydraulic properties change significantly as soil pores desaturate (Derby et al., 2002; Flury et al., 1999).

### 3.4.2 Experimental Methods

To investigate the effect of nutrient and pathogen leaching to tile drains, McLaughlin and Kalita (2001) employed reconstructed soil columns at the University of Illinois at Urbana-Champaign (UIUC) Agricultural and Biological Engineering (ABE) department (Figure 3.1). The columns were constructed of corrugated double-walled 38 cm diameter PVC. The bottom of the columns were capped, filled with concrete, and sealed. A 2.5 cm PVC pipe with holes was installed in a layer of sand above the concrete base to simulate a tile drain. (McLaughlin and Kalita, 2001)

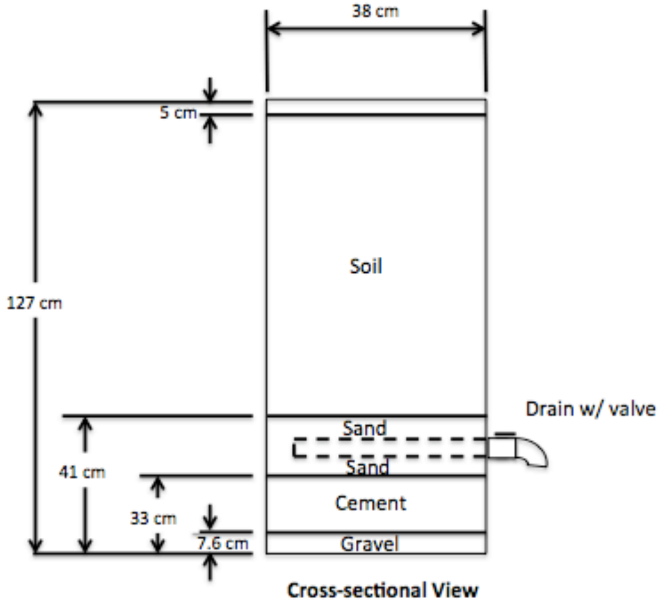


**Figure 3.1: Schematic of soil column apparatus used by McLaughlin and Kalita (2001) for laboratory leaching experiments at the University of Illinois ABE Department, not to scale**

The soil columns were filled by collecting Catlin and Newberry soil samples in 15 cm layers, reconstructing the columns layer-by-layer in the PVC pipe, and using saturation to establish natural compaction. Pathogens, 500 mL of 25 mg $L^{-1}$ nitrogen, and 500 mL of 25 mg $L^{-1}$ phosphorus were added to the soil columns once the grasses planted in the columns (Brome, Reed Canary, and Kentucky Blue grass) had grown to be at least 5 cm tall. Drainage was induced by applying 7 L of distilled water to the tops of the columns. Leached water samples were collected by opening the ball valve on the drain pipe after 1 hour, 7 days, and 14 days and analyzed for pathogens, nitrate, orthophosphate, and total phosphorus. This 14-day process of drainage induction and sample collection was performed three times during the growing season. (McLaughlin and Kalita, 2001)

On a similar scale, Jha (2014) studied the soil-water and solute transport dynamics of rice paddies using a 100-cm deep and 60-cm diameter pot. The soil pots (Figure 3.2) were repacked into three soil layers of lateritic sandy loam, with emitters and piezometers installed at the base of each layer (denoted in Figure 3.2 as S1, S2, and S3) to collect soil-water samples and measure the pressure head at different profile depths (Jha, 2014).

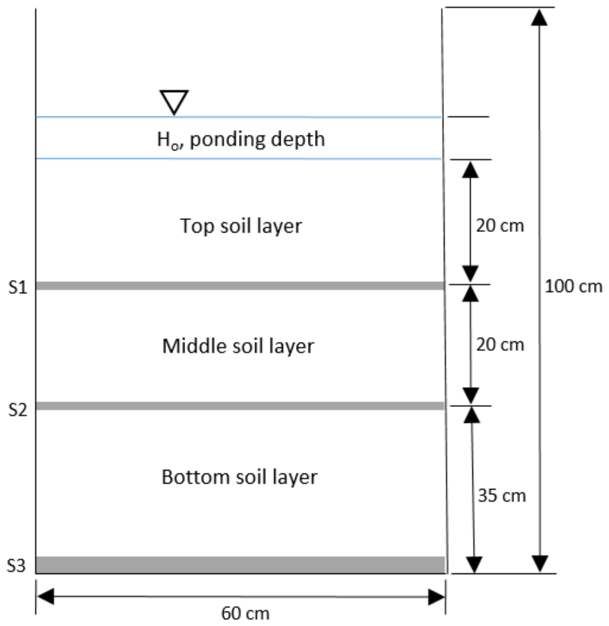


**Figure 3.2: Cross-sectional schematic of soil pot apparatus used by Jha (2104) for soil-water and solute transport experiments at the Indian Institute of Technology Agricultural and Food Engineering Department, not to scale**

Rice paddies were transplanted into four pots, one of the pots was left unfertilized and the other three pots were applied with a 140:50:50 kg ha$^{-1}$ fertilizer, and the experiment was conducted for a period of 75 days (Jha, 2014). Irrigation supplemented precipitation to ensure a ponded surface at the top of the pot. Water samples were collected from each depth bi-weekly and analyzed for $NO_3$-N (Jha, 2014).

Svanbäck et al. (2013) conducted a much smaller bench-scale laboratory experiment using 20 cm deep undisturbed soil columns to study phosphorus leaching. The small soil columns allowed the study of many different soil types with different nutrients available and different management practices (Svanbäck et al., 2013).

### 3.4.3 Relevant Outcomes

McLaughlin and Kalita (2001) found very different results between the two soil types. Grasses were well established in the Catlin silt loam and effectively reduced leached nitrate concentrations compared to the bare columns. However, the bare soil in the Newberry silt loam columns had lower leached nitrate concentrations in general than the vegetated columns, with increased nitrate leaching in bare columns and decreased nitrate leaching in vegetated columns after the second application. No leachate volume or total nitrate load data was presented, so it is possible that the bare Newberry silt loam nitrate concentrations were diluted by large drainage volumes. The trends in leached nitrate concentrations of the Newberry silt loam may suggest a buildup of soil nitrate in the bare columns and plant uptake of nitrate in the vegetated columns. Orthophosphate and total P concentrations were low compared to nitrates, but no definite trends were seen in the data. (McLaughlin and Kalita, 2001)

The paddy-culture pot experiment by Jha (2014) revealed that nitrate concentrations and pressure head decreased with increasing depth of the soil profile. The amount of water lost through deep percolation at the base of the pot was larger by 30 mm in the control pot, as compared to the average water lost from the fertilized pots, which is likely attributed to an increased root and plant growth in the fertilized pots. Considering the amount of $NO_3$-N applied, an average of 12% (±0.47) was lost to deep percolation and 1.6% (±0.16) was retained in plant matter. (Jha, 2014)

Svanbäck et al. (2013) concluded that to reduce phosphorus leaching, long-term fertilization should be balanced with phosphorus removal by way of harvested products. The results also showed a positive correlation between phosphorus concentrations in the leachate and Al-extractable P in the soil (Svanbäck et al., 2013).

### 3.4.4 Areas of Concern

The low phosphorus concentrations in leachate detected by McLaughlin and Kalita (2001) were likely due to a low phosphorus build-up in the soils. It is impossible to know without data on how much nitrogen and phosphorus was already in the soil, but the application rate of nutrients to the columns was very low and is proportional to only 1.7 kg $ha^{-1}$ of added nitrogen and phosphorus. Analyzing the initial nutrient concentrations in the soil could have potentially added insight into the differences in leaching trends between the two soil types. With sample collection dates 7 days apart, it is also possible that stagnant water gathered at the base of the column could have led to nitrogen losses through denitrification. However, since the results are based largely on comparison, the same processes were likely occurring in both vegetated and bare columns and conclusions should not have been affected.

No data were provided on the nitrate concentrations from the control pot in the rice paddy experiment conducted by Jha (2014). This data would have been useful in quantifying how the fertilizer affects nutrient loss by deep percolation, since there would be both an increase in plant growth and an increase in nitrogen in the system in the fertilized pots as compared to the control pot. This would have been especially relevant since one of the goals of the research was to determine an optimum ponding depth to reduce nitrate loss through deep percolation.

Also, neither soil column study employed any preventive measures to reduce preferential flow along the sides of the containers. It is possible that applied water and nutrients bypassed much of the soil column by creating pathways around the outside edges of the pot, as this would be a path of less resistance. These edge-effects might be reduced with increasing pot diameter or the addition of bentonite clay around the pot edges to prevent flow between the soil and the plastic pot surface. There are also concerns in soil column experiments about the soil-water dynamics in a repacked soil column as compared to an undisturbed soil column and/or the natural environment. Repacking soil destroys structure and existing macropores, changing how water and solutes move through the soil.

### 3.5 One-dimensional Solute Transport Modeling

Using computer modeling to simulate the results of an experiment can lead to greater understanding of the results and processes that govern the experiment. Two one-dimensional flow models have been identified as possible tools for further understanding the data of a soil column leaching experiment: HYDRUS 1-D and Root Zone Water Quality Model.

#### 3.5.1 HYDRUS-1D

The HYDRUS 1-D model solves the Richards' equation for saturated or unsaturated flow conditions and has the capacity to estimate processes such as precipitation, soil water storage, drainage, solute transport, and plant root water and nutrient uptake, just to name a few (Simunek, 2012). The modified Richards' equation implemented in HYDRUS-1D to simulate uniform one-dimensional water movement in equilibrium is as follows (Simunek et al., 2005):

$$\frac{\partial \theta(h,t)}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} + \theta\right)\right] - S \qquad (3.1)$$

where
$h$ = water pressure head (L)
$\theta$ = volumetric water content ($L^3 L^{-3}$)
$t$ = time (T)
$z$ = spatial coordinate, positive upward (L)
$S$ = sink term ($L^3 L^{-3} T^{-1}$)
$K$ = unsaturated hydraulic conductivity ($L T^{-1}$)

Van Genuchten's equation provides a method for calculating unsaturated hydraulic conductivity, K, and establishes a relationship between h and θ (Simunek et al., 2005):

$$K = K_s\sqrt{\frac{\theta-\theta_r}{\theta_s-\theta_r}}\left[1-\left(1-\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{1}{1-\frac{1}{n}}}\right)^{1-\frac{1}{n}}\right]^2 \qquad (3.2)$$

where
$K$ = unsaturation hydraulic conductivity (L $T^{-1}$)
$K_s$ = saturated hydraulic conductivity (L $T^{-1}$)
$\theta_s$ = saturated volumetric moisture content
$\theta_r$ = residual volumetric moisture content
n = van Genuchten parameter

$$\theta = \frac{\theta_s-\theta_r}{[1+(-\alpha h)^n]^{1-\frac{1}{n}}}+\theta_r \qquad (3.3)$$

where
$\theta_s$ = saturated volumetric moisture content
$\theta_r$ = residual volumetric moisture content
α, n = van Genuchten parameters

The model provides several options for estimating any missing hydraulic parameters including calibration, catalog entries by textural class, database entries, and/or pedotransfer functions using the Rosetta computer program (Simunek, 2012).

The HYDRUS-1D model was employed in an experiment by Elmi et al. (2011) to better understand the distribution and transport of phosphorus through reconstructed soil columns. Elmi et al. (2011) pieced together three undisturbed soil core sections to create each reconstructed soil column and saturated the columns from the bottom up to restore pore connectivity within the columns. Soil samples throughout the column were tested for total phosphorus and available phosphate, as well as soil moisture, organic matter, particle size, iron, and aluminum, and water samples throughout the column and drainage water were tested for orthophosphate (Elmi et al., 2011). Preferential flow paths such as macropores and gaps between the soil and edge of the PVC column were unaccounted for in the model and likely caused the simulation to underestimate drainage time and overestimate phosphorus adsorption to the soil by 34.5% (Elmi et al., 2011). Despite the preferential flow paths, the laboratory experiments found that 99% of the phosphorus added to the columns was retained, mostly in the upper 0.2 m of the column (Elmi et al., 2011).

Jha (2014) used experimental soil pot data to calibrate and validate the HYDRUS-1D model in order to determine an optimal ponding depth to reduce nitrate leaching. The soil hydraulic parameters were calibrated for pressure head analysis with the control pot and validated with two treatment pots (Jha, 2014). For nitrate analysis, the nutrient transport parameters were calibrated with deep percolation data from one treatment pot and validated with the other two treatment pot replicates (Jha, 2014). HYDRUS-1D was able to simulate pressure head and $NO_3$-N concentrations with $R^2$ values of 0.85 and 0.92 for pressure head and 0.90 and 0.93 for nitrate (Jha, 2014). It was found that the total residence time of $NO_3$-N was reduced with increasing ponding depth (Jha et al, 2014).

### 3.5.2 Root Zone Water Quality Model

Another model that has the capability to estimate plant growth and water and nutrient movement through the soil is the Root Zone Water Quality Model (RZWQM) utilized by Abrahamson et al. (2006) to simulate tile drainage and nitrate flows for a cereal rye winter cover crop. The RZWQM was created in the Midwestern United States and accurately simulated the drainage volume and nitrate leaching in a three year calibration study with corn and cereal rye cover crop rotation, but overestimated drainage volume in subsequent experiments on cotton and cereal rye rotations (Abrahamson et al., 2006). The inaccuracy of the drainage volume estimations was partially due to differences in evapotranspiration and runoff estimation, but largely attributed to the incorrect prediction that the water table would rise and drain out through the tiles (Abrahamson et al., 2006). However, in the calibration study the model was able to calculate nitrate leaching, drainage volume, and corn production within 15% of experimental values both with and without utilizing the model's estimation of macroporosity (Abrahamson et al., 2006). During the corn and cereal rye rotation, cereal rye cover cropping was found to lower tile flow by 11% and nitrate leaching by 13% (Abrahamson et al., 2006).

### 3.6 Conclusions from Review of Literature

A few field studies have shown that cover crop mixtures of grasses and legumes have the potential to reduce nitrogen leaching as well as atmospherically fix nitrogen for use by subsequent crops. However, many gaps in the current body of research still exist that should be addressed to encourage further adoption of the practice in the Midwestern United States. Phosphorus cycling effects of cover cropping is one area that has not been widely addressed in the literature. Also, it has been shown that grasses and grass-legume mixtures can reduce nutrient leaching during growth, but nutrient leaching from cover cropped fields after incorporation may be an area that requires further research as cover crop roots create additional preferential flow paths through the soil. A controlled laboratory experiment that can isolate certain variables may be the best way to study some of these processes, but methods to do so have not yet been established.

# CHAPTER 4

# METHODOLOGY

## 4.1 Soil Column Design and Construction

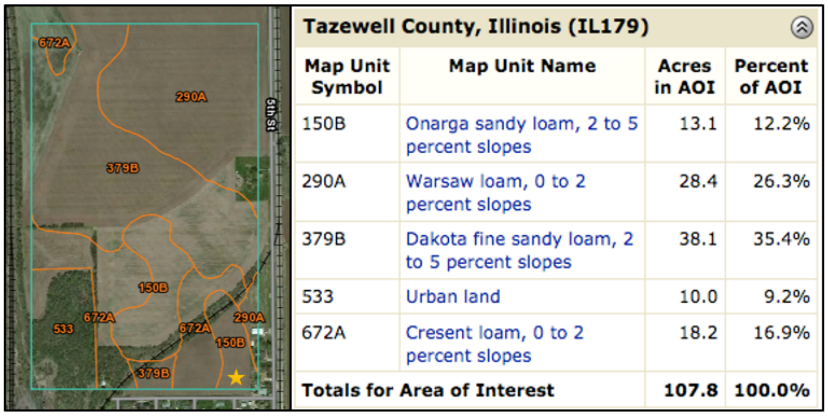
Soil columns were utilized to study how nitrogen and phosphorus move through soil layers and exit the soil profile through tile drainage (Figure 4.1). The columns were constructed from 30.5 cm inside diameter double-sided PVC pipe that was cut to 1 m lengths and filled with 8 cm of concrete, followed by an 8 cm layer of sand. Small drainage holes were drilled into the side of the PVC columns just above the concrete layer. Water discharged by the soil columns drained into smooth-bottomed plastic tubs, from which the leachate samples were collected. Employing two wedges cut at 4.8° angles, the collection tubs were sloped to move the leachate flow toward a drain spout in one corner of the tub while keeping the column upright. One PVC wedge was used inside the tub at the base of the soil column, and a wooden wedge was used underneath the tub. Standard methods called for the use of glass bottles to store orthophosphate samples, so there were initially concerns about PVC and plastic materials reacting with the orthophosphate concentrations of the water samples. However, experiments were performed to analyze orthophosphate samples after being collected and stored in plastic bottles and tubs, and no detectable effect on the concentrations was found. While soil columns were outside of laboratory conditions, plastic bags were used to enclose the collection tub to minimize evaporation of the sample and prevent contamination by precipitation or other foreign material. Five rain gauges were installed at even spacing throughout the middle of the experimental setup to monitor precipitation depth on a daily basis.

**Figure 4.1: (a) Photograph of four silt loam soil columns during the growing season, (b) Scaled drawing of a soil column, and (c) Diagram of outdoor experimental setup including soil columns and rain gauges**

## 4.2 Soil Collection and Column Repacking

Local soil samples (locations in Figures 4.3 and 4.4) were collected in six 14 cm layers (Figure 4.2), and the soil profiles were reconstructed in the double-sided PVC columns. Five columns were filled with each of two different Illinois soil types, Onarga sandy loam and Flanagan silt loam, for a total of ten columns.

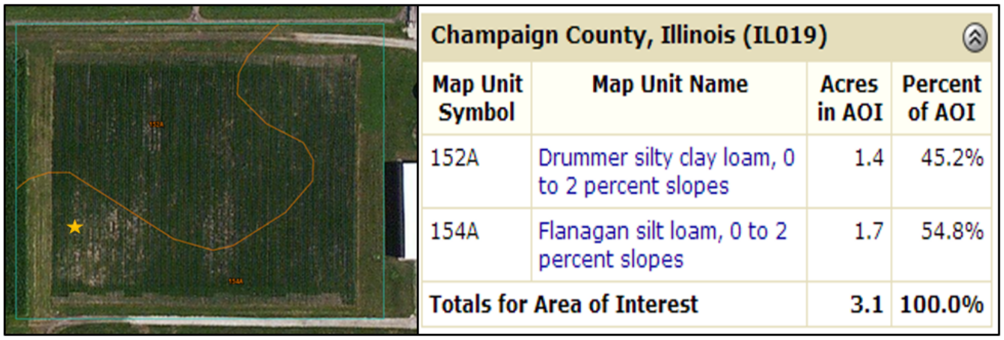
**Figure 4.2 Soil collection method using a post-hole auger**



**Tazewell County, Illinois (IL179)**

| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
|---|---|---|---|
| 150B | Onarga sandy loam, 2 to 5 percent slopes | 13.1 | 12.2% |
| 290A | Warsaw loam, 0 to 2 percent slopes | 28.4 | 26.3% |
| 379B | Dakota fine sandy loam, 2 to 5 percent slopes | 38.1 | 35.4% |
| 533 | Urban land | 10.0 | 9.2% |
| 672A | Cresent loam, 0 to 2 percent slopes | 18.2 | 16.9% |
| **Totals for Area of Interest** | | **107.8** | **100.0%** |

**Figure 4.3: 150B Onarga sandy loam was collected from the southeast corner of the above field in South Pekin, IL (★represents soil collection point), which had been previously planted with corn (NRCS)**



**Champaign County, Illinois (IL019)**

| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
|---|---|---|---|
| 152A | Drummer silty clay loam, 0 to 2 percent slopes | 1.4 | 45.2% |
| 154A | Flanagan silt loam, 0 to 2 percent slopes | 1.7 | 54.8% |
| **Totals for Area of Interest** | | **3.1** | **100.0%** |

**Figure 4.4: 154A Flanagan silt loam was collected from the southwest corner of the above field at the ABE South Farms in Urbana, IL (★represents soil collection point), which had been previously planted with corn (NRCS)**

Granular bentonite was used to minimize preferential flow between the soil and the edge of the PVC column. Bentonite clay swells when exposed to moisture and was intended to seal potential drainage pathways between the soil and the PVC, forcing water to flow through the soil profile and minimize edge effects. The bentonite perimeter (installation shown in Figure 4.5) swelled to an average of 3 cm, reducing the size of the soil portion of the column to a diameter of 24.5 cm.

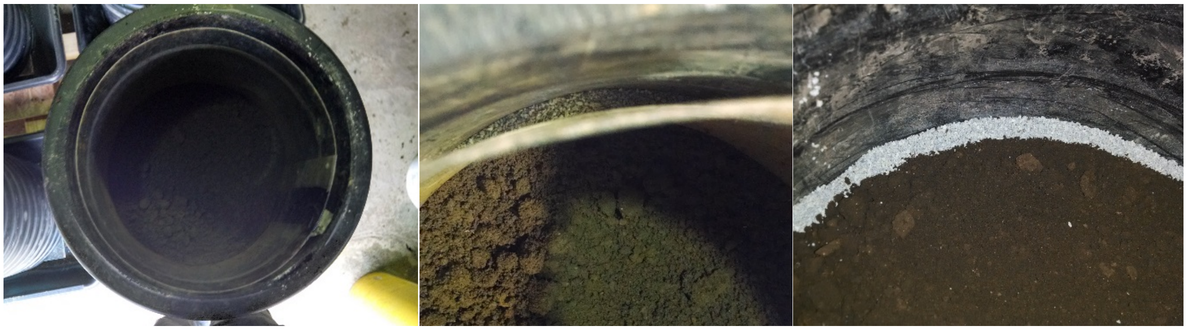


**Figure 4.5: Granular bentonite around edges of soil columns to prevent sidewall flow**

The initial amount of soil moisture, organic matter, nitrate, total nitrogen, available phosphate, and total phosphorus in each soil layer was determined through soil analysis. Soil samples were collected at the time of soil column construction and frozen until analysis could be conducted. The reconstructed soil columns were leached with deionized water for several weeks to establish natural compaction and allow for soil settling before the experiment was initiated. It should be noted that natural preferential flow paths take many years to form, but this was not feasible within the confines of the experiment timeline. As the columns were compacted through natural settling, the volume of deionized water used to saturate the columns was measured both entering and exiting the columns. Additionally, the concentrations of nitrate, total nitrogen, orthophosphate, and total phosphorus in the drainage water was analyzed on a daily basis as long as leachate was present in the collection tubs. Deionized water was assumed to have zero nutrients present. Sample bottles were soaked in nitric acid and rinsed with deionized water between each use. Orthophosphate water samples were immediately filtered using a 0.45 µm filter and refrigerated at 4°C or frozen until analysis. All leachate samples collected throughout the experiment were analyzed using standard methods (Section 4.5). Total phosphorus, nitrate, and total nitrogen samples were also stored refrigerated at 4°C or frozen until analysis. The plastic collection tubs were rinsed with deionized water between every collection cycle to ensure that no soil particles or foreign material would contaminate the water samples (e.g. sediment and organic material).

### 4.3 Planting Cover Crops

A 50:50 mixture of oats and hairy vetch (HV) was decided upon by using the Midwest Cover Crop Council (MCCC) Cover Crop Decision Tool. The online educational tool utilizes grower-provided information such as location, soil drainage class, and goals of the cover crop to choose and rank appropriate species and mixtures. Once a cover crop species or mixture is chosen, the grower can also obtain detailed information about his/her chosen species (e.g.

planting date, seeding rate, termination information, etc.) through the MCCC Cover Crop Decision Tool. This method was used to simulate the cover crop decision-making and information-gathering tools available to any grower in the Midwest.

After several cycles of soil column saturation were performed, a mixture of oats and hairy vetch was planted in three columns (Flanagan only) at a rate proportional to the recommended seeding rate. The cover cropped columns were intentionally not placed directly next to each other in the experimental setup to prevent the spindly hairy vetch plants in different columns from growing together. A protocol deviation occurred during column settling that prevented the sandy loam columns from being planted with cover crops. Deviations are described in detail in Chapter 5. The recommended 13.5 kg $ha^{-1}$ (12 lb $ac^{-1}$) hairy vetch seeding rate translated to four seeds per column. Similarly, 13 oat seeds were planted to simulate a 39.2 kg $ha^{-1}$ (35 lb $ac^{-1}$) seeding rate. Due to the small amount of seeds needed, the seeds were first germinated and then transplanted into the columns to increase the chances of full establishment. The hairy vetch seeds were coated with a vetch/pea/lentil inoculant before germination as directed by MCCC. During the three-week establishment period, plants were watered with roughly 1000 mL of water every other day, either by rainfall or deionized water application. Leachate samples were taken daily as necessary. Cover crop growth was evaluated periodically with chlorophyll measurements, orthographic aerial-view photographs, and height measurements when applicable. Chlorophyll measurements were calculated from an average of 10 – 30 measurements taken on each crop type from each column using a SPAD chlorophyll meter.

## 4.4 Leachate Collection

When the cover crop was well established, the equivalent of a one-time application of 201.8 kg ha$^{-1}$ (180 lb ac$^{-1}$) N (200 mL of 7360.5 mg L$^{-1}$ $NO_3$-N) and 50.4 kg ha$^{-1}$ (45 lb ac$^{-1}$) P (200 mL of 1840.1 mg L$^{-1}$ P) was delivered to all five of the Flanagan soil columns. Deionized water was added to the columns at a rate of 4 L every 2 weeks to induce drainage in addition to natural precipitation. This rate is equivalent to 11 cm mo$^{-1}$, about 51% higher than the average rainfall in Champaign, IL in the months September – March according to NOAA. Large irrigation volumes were used to insure that column saturation and drainage would occur and leachate samples would be large enough to detect differences between the treatments. The leachate volumes and concentrations of nitrate, total nitrogen, orthophosphate, and total phosphorus and volumes from each water application were measured daily for as long as drainage occurred.

The soil columns were kept outside until January 13th, 2015. Prior to this date, two extended periods of below freezing temperatures had occurred. The 16 days preceding 01/13/15 experienced average air temperatures below freezing with a minimum temperature of -22°C and a maximum temperature of 4°C. The columns were then brought indoors under grow lights in a controlled 21°C environment with 12 hours of light per day to simulate spring. Both outdoor and indoor experimental setups are shown in Figure 4.6. Bringing the soil columns indoors to simulate spring was necessary due to approaching deadlines for the study. After six days the columns were completely thawed, and the plants were killed by cutting the above ground portion at the stem 2.5 cm above the soil surface. The biomass was weighed fresh, oven dried, and dry biomass was weighed again. Nine-gram samples of oats and hairy vetch biomass were analyzed from each cover cropped column for total nitrogen, available phosphate, nitrate, and total carbon, and the remaining majority of biomass was returned to the column to contribute to organic matter, as would happen in an agricultural field. Pfeifer and Kline (1960) found that oats typically winterkill at soil temperatures of -5°C at 2.5 cm depth. In central Illinois, oats are known to winterkill and hairy vetch is potentially winter hardy, but the opposite actually occurred. Oats were very hardy and the hairy vetch seemed to winter-kill, so soil temperature may not have been low enough to kill the oats. Application of deionized water continued at the rate of 4 L every two weeks, 14% higher than the average rainfall for Champaign, IL in April. The leachate volumes and concentrations were measured on a daily basis when drainage water was present in the collection tubs. Soil moisture, organic matter, nitrate, total nitrogen, available phosphate, and total phosphorus were measured two, four, and six weeks after the cover crops were suppressed (in columns S4, S1, and S2, respectively) to determine the levels of soil nutrients that would be available for the subsequent cash crop. This was performed by taking a soil core from a different column each sampling period since soil sampling of the columns creates large preferential flow paths. It was only viable to take one soil core from each column due to size constraints and bentonite expansion. This sampling technique prevented replication between columns for the soil and water samples taken after cover crop suppression, but allowed the study of nutrient level fluctuations in the leachate and soil over time due to mineralization and/or immobilization. Bulk density was measured for each silt loam soil column, and particle size analysis by hydrometer method was conducted for each soil type. Unforeseen soil behaviors in the two bare columns caused a protocol deviation, which prevented the bare soil leachate to be compared to the cover cropped leachate during the simulation of spring conditions. A summary of dates of main events throughout the experiment can be found in Table 4.1 below.

**Figure 4.6: (a) Outdoor experimental setup from experiment initiation until the beginning of spring simulation and (b) Indoor experimental setup during spring simulation**

**Table 4.1: Timeline of experiment events**

| | |
|---|---|
| Experiment Initiation | 06/16/14 |
| Cover Crop Planting | 07/28/14 |
| 10% Canopy Cover | 08/12/14 |
| N and P Application | 08/19/14 |
| 80% Canopy Cover | 09/03/14 |
| Last irrigation cycle until spring | 11/03/14 |
| Ground Freeze (approx.) | 12/05/14 |
| Spring Simulation Begins | 01/13/15 |
| Ground Completely Thawed | 01/16/15 |
| Cover Crop Termination | 01/19/15 |
| S4 & S5 Sampled | 02/04/15 (2 wks) |
| S1 Sampled | 02/18/15 (4 wks) |
| S2 & S3 Sampled | 03/04/15 (6 wks) |

### 4.5 Nutrient Analysis

National Environmental Methods Index (NEMI) Standard Methods 4500 were used to analyze water samples. Water and soils were analyzed for total nitrogen and nitrate/nitrite-N (more generally referred to as nitrate or $NO_3$-N) using the Automated Hydrazine Reduction Method and for total phosphorus and orthophosphate using the Ascorbic Acid Reduction Method

(NEMI). All steps of nutrient analysis were conducted by or under the guidance of the UIUC ABE Water Quality Laboratory Manager/Analyst, Duane Kimme. Duplicate samples, standard solutions, and spiked samples were incorporated into nutrient analysis for quality control.

Unpaired t-tests assuming unequal variance were conducted to determine if there were significant differences in nitrate concentration between the bare and cover cropped treatments. Two-sided 95% confidence intervals were used to test three different time periods (before, during, and after cover crops) as well as the entire experimental period average. Bare columns (S3 and S5), densely cover cropped (dense CC) columns (S2 and S4), and the thinly cover cropped (thin CC) column (S1) were all tested against each other. Dense CC columns had an average of 9325 kg $ha^{-1}$ of cover crop biomass growth, and the thin CC column had 5650 kg $ha^{-1}$ of growth.

Mass of nutrients were calculated using the following equation:

$$M_s = V * C_s \qquad (4.1)$$

where
$M_s$ = mass of solute (mg)
V = volume of drainage water (L)
$C_s$ = concentration of solute in drainage water (mg $L^{-1}$)

The percentage of $NO_3$-N in total N and $PO_4$ in total P were calculated by the following equation:

$$R_m = \frac{M_m}{M_t} * 100\% \qquad (4.2)$$

where
$R_m$ = percentage of $NO_3$ or $PO_4$ forms in total amount of nutrient (%)
$M_m$ = mass of $NO_3$ or $PO_4$ forms of in drainage water (mg)
$M_t$ = mass of all forms of nutrient (total) in drainage water (mg)

### 4.6 HYDRUS 1-D Model Simulation

Verification of the results from the soil column experiment was performed by comparing observed data to simulations by HYDRUS-1D, a one-dimensional transport model capable of representing the vertical flow of water and solutes in a soil column, as well as root uptake and growth. The 168 day growing season was simulated using an initial time step of 0.001 days, a minimum time step of $1 \mathrm{x} 10^{-6}$ days, and a maximum time step of 0.1 days.

#### 4.6.1 Boundary Conditions

Time variable boundary conditions for daily total water added (precipitation + irrigation), potential evaporation, potential transpiration, and solute concentration of infiltrating water were inputs for the model. The atmospheric boundary condition with a surface layer was used to represent the upper boundary of the soil column, which was open to the atmosphere and had a lip that allowed for 3 cm of head. A free drainage boundary condition was used to represent the lower boundary of the soil column, which drained by gravity into a collection tub.

#### 4.6.2 Estimating Potential Evaporation and Transpiration

Crop evapotranspiration ($ET_c$) is the evapotranspiration from healthy crops in optimal growing conditions and is estimated by multiplying the reference evapotranspiration by a crop coefficient, $K_c$, or $ET_c = ET_0 * K_c$. The $ET_c$ can also be adjusted for non-standard conditions such as pests, disease, low soil fertility, drought, and flood. The estimated actual evapotranspiration from any surface, whether cropped or bare, can be referred to as $ET_a$. An estimate of actual evaporation from a bare surface can be calculated similarly to a cropped surface using an adjusted coefficient, such as $ET_a = ET_0 * K_a$. For a non-cropped surface, transpiration is zero. (Allen et al., 1998)

The reference evapotranspiration ($ET_0$) is the evapotranspiration from a reference surface of grass and is determined using only climatic parameters and the FAO Penman-Monteith equation (Allen et al., 1998). The FAO Penman-Monteith equation for $ET_0$ has been derived by Allen et al. (1998) as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (4.3)$$

where
$ET_0$ = daily reference evapotranspiration (mm day$^{-1}$)
$R_n$ = net radiation at crop surface (MJ m$^{-2}$ day$^{-1}$), calculated from temperature, elevation, extraterrestrial radiation, and actual vapor pressure using the Angstrom formula and Stefan-Boltzmann law
G = soil heat flux density, 0 MJ m$^{-2}$ day$^{-1}$ for daily calculations
$(e_s - e_a)$ = saturation vapor pressure deficit for air (kPa)
$\Delta$ = slope of the saturation vapor pressure temperature relationship (kPA $^{\circ}$C$^{-1}$)
T = mean daily air temperature at 2 m height (°C)
$\gamma$ = psychrometric constant (kPA °C$^{-1}$)
$e_s$ = saturation vapor pressure (kPa)
$e_a$ = actual vapor pressure (kPa)
$u_2$ = average daily wind speed at 2 m height (m s$^{-1}$)

In order to use the FAO Penman-Monteith Equation 4.1 to calculate daily $ET_0$, site latitude (degrees north or south) and elevation above sea level (m) are required in addition to obtaining or estimating daily air temperature (°C), humidity (%), radiation (MJ m$^{-2}$ day$^{-1}$), and wind speed (m s$^{-1}$) data (Allen et al., 1998). Radiation data was not available on site, so it was estimated as described by Allen et al. (1998) using temperature differentials, latitude, day of the year, and known constants.

Based on an estimation by Smith (2011), crop coefficient, $K_c$, for small grains can be estimated from the percent canopy cover. $K_c$ for small grain cover crops, such as oats, is about 0.25 during stand establishment ($K_{c,initial}$ from planting to 10% canopy cover) and 1.2 at maximum canopy cover stage, increasing between stages at a rate proportional to the canopy cover (Smith 2011). This is similar to estimations of $K_c$ for vetch and other legumes (Allen et al., 1998). A curve of cover crop mixture coefficient values was constructed based on observed canopy cover data, which was analyzed using USDA SamplePoint software from orthographic images of the cover crop at incremental periods during the growing season. SamplePoint superimposes an array of 100 crosshairs (up to 225; shown by + in Figure 4.7) over an image, allowing for streamlined manual classification, and outputs ground cover statistics in Excel files.

NOTE: Rotate Image First, then adjust image parameters!

...\Users\honegge1\Documents\Sample Point\Nadir S4\Nadir S4 08181454.jpg

**Figure 4.7: SamplePoint software user interface for determining percent canopy cover from orthographic photographs**

According to the FAO Penman-Monteith method described by Allen et al. (1998), the initial period crop coefficient, $K_{c,initial}$, must be adjusted to consider soil wetting frequency, depth of precipitation, and $ET_0$. Since $K_{c,initial}$ is also used as an estimation for the crop coefficient after cover crop termination and the season-long coefficient, $K_a$, for bare soils (i.e. uncropped soil columns), this adjustment was performed on a daily basis throughout the entire experimental period. Using Figures 29 and 30 in the FAO Irrigation and Drainage Paper No. 56 by Allen et al. (1998), $K_{c,initial}$ values were determined daily based on experimental data and methods. A season-long coefficient for the bare soil columns, $K_a$, was calculated by taking an average of the $K_{c,initial}$ adjusted values during the period between experiment initiation and the beginning of spring simulation. $K_{c,initial}$ for the cover cropped soil columns was found by taking an average of the $K_{c,initial}$ adjusted values during the period between experiment initiation and a canopy cover of 10% (the initial growing period). Constant post-termination $K_c = K_a = 0.2$ was estimated for both the cropped and bare columns during the spring simulation period based on a wetting interval of 14 days, > 40 mm infiltration depth, and $ET_0$ of 7.6 mm $day^{-1}$, which was constant due to the controlled environmental conditions of the laboratory. The adjusted coefficient values are shown in Figure 4.9(a).

The crop coefficient must be further adjusted during periods of frost and snow cover (Figure 4.8), as frozen ground prevents evaporation from the soil and vegetation may be nonresponsive (Allen et al., 1998). In an experiment conducted in Kimberly, Idaho, the United States, Wright (1982) found $K_c = 0.25$ during periods of frost. Evaporation is zero when the soil is frozen, so $K_a = 0$ during periods of frost for the bare columns. Furthermore, when snow cover is present less shortwave radiation is available and some energy is expended in the process of melting the snow (Allen et al., 1998). Wright (1982) found $ET_c = 0.4$ during periods where snow cover was 50% or greater. These estimated $K_c$, $K_a$, and $ET_c$ values for frozen and snow-covered ground were used to further adjust evapotranspiration values during the winter months of the growing season. The final coefficient values are shown in Figure 4.9(b).

Figure 4.8: Snowfall on outdoor soil columns on 01/06 before spring simulation began

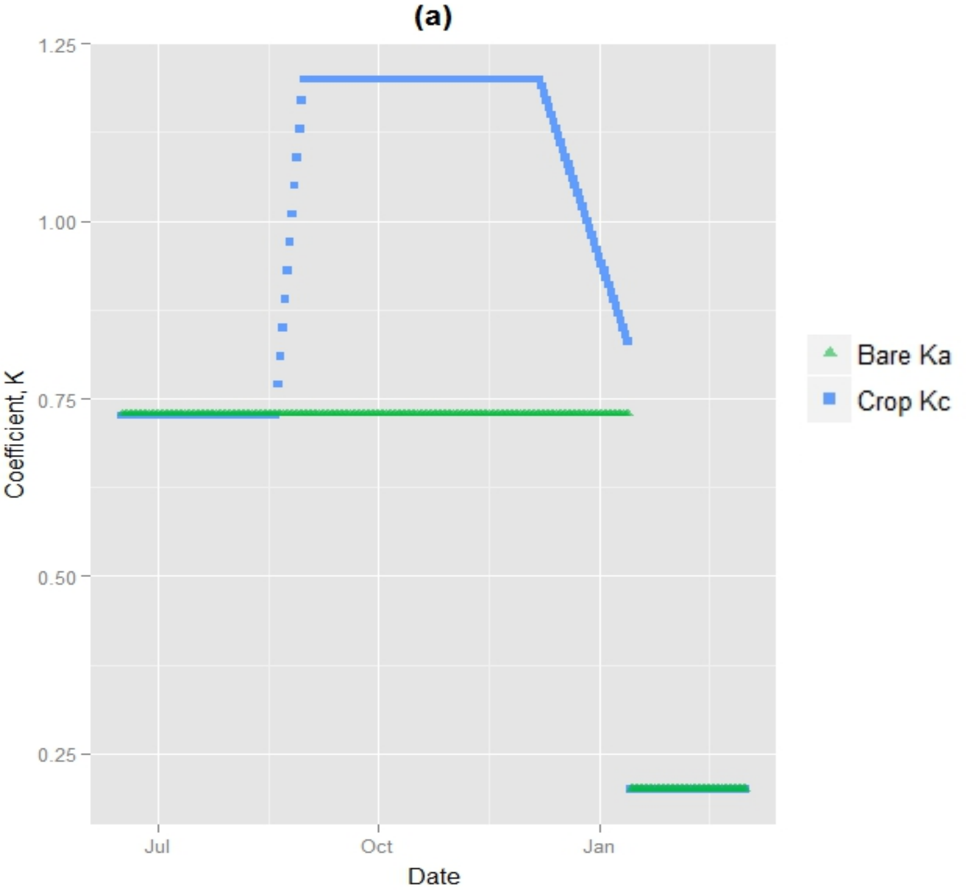


Figure 4.9: Coefficient values constructed from suggested methods by Allen et al. (1998) and canopy cover measurements and adjusted for (a) Wetting frequency, depths of precipitation, and $ET_0$ during periods of no/minimal cover, and further adjusted for (b) Periods of frost and snow cover as recommended by Wright (1982)

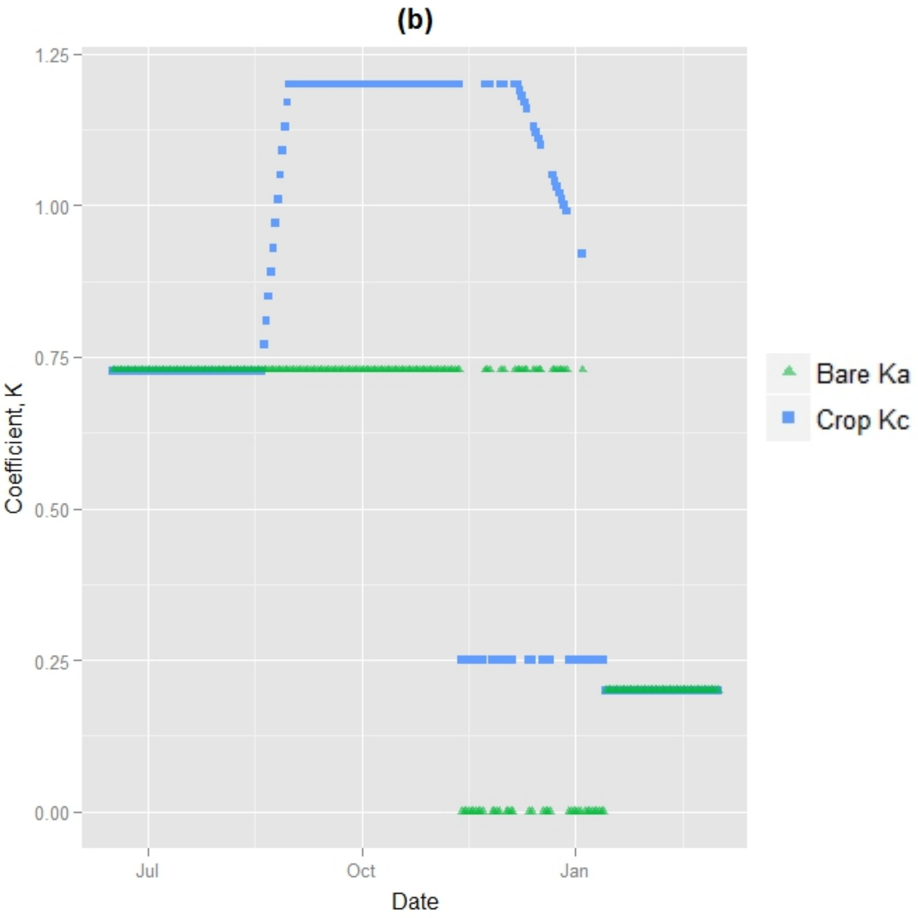


**Figure 4.9 (Continued from previous page): Coefficient values constructed from suggested methods by Allen et al. (1998) and canopy cover measurements and adjusted for (a) Wetting frequency, depths of precipitation, and $ET_0$ during periods of no/minimal cover, and further adjusted for (b) Periods of frost and snow cover as recommended by Wright (1982)**

An estimation of actual evapotranspiration was then calculated for both cover cropped and bare soil columns using the coefficients determined in Figure 4.9(b) and the reference evapotranspiration calculated using the FAO Penman-Monteith equation. This is an estimation of evapotranspiration using many known meteorological and experimental parameters. Due to the large number of factors and assumptions that go into these equations, error between the estimated actual evapotranspiration and the experimentally determined actual evapotranspiration, calculated from the water balance, is expected to be large.

A water balance for the growing season was calculated using experimental data. The depth of evapotranspiration depended on the amount of plant biomass, which varied between cover cropped columns. To account for these differences while running HYDRUS-1D, the daily $ET_c$ values were scaled up proportionally according to the estimated modeling error, assuming soil moisture storage between cover crop planting and termination was negligible. Observed evapotranspiration was calculated using the following water balance equation:

$$S = (P + I) - (L + ET_{obs}) \tag{4.4}$$

where
S = soil moisture storage (mm)
P = precipitation (mm)
I = irrigation (mm)
L = leaching loss (mm)
$ET_{obs}$ = observed evapotranspiration (mm)

Modeling error was calculated by:

$$\text{Modeling error} = \frac{ET_{obs} - ET_{pm}}{ET_{obs}} \tag{4.5}$$

where
$ET_{obs}$ = observed evapotranspiration calculated from water balance (mm)
$ET_{pm}$ = theoretical evapotranspiration calculated from FAO Penman-Monteith (mm)

A water balance for the entire experimental period was also calculated. Soil moisture storage was estimated using experimentally determined soil moisture content for each layer in each column at the beginning and end of the experimental period. Soil moisture content was determined by the gravimetric method, where soil samples are weighed before and after oven drying to determine mass of water and dry soil.

Potential evapotranspiration can be partitioned into potential evaporation and potential transpiration using the LAI, or leaf area index. Since only canopy cover and not LAI was measured in this study, an assumption based on knowledge of the two processes was used to estimate potential evaporation and potential transpiration. Evaporation occurs from the soil surface and transpiration occurs through plant leaves. Evaporation will dominate when there is no crop or when canopy cover is less than 10% and transpiration dominates when the canopy cover is over 90%. For bare soils, no transpiration will occur and potential evaporation was set equal to the estimated evapotranspiration, calculated from the Penman-Monteith equation and adjusted based on observed ET, $E_p = ET_{a,adj}$. Likewise, it was assumed that $E_p = ET_{c,adj}$ when canopy cover is less than 10%. Potential transpiration was set equal to $ET_{c,adj}$ when the canopy cover was greater than 90%, $T_p = ET_{c,adj}$. Between 10% and 90% canopy cover the partitioning of evaporation and transpiration was performed proportionally according to the average canopy cover.

### 4.6.3 Root Growth and Water/Solute Uptake

The Feddes et al. (1978) root water uptake model was used assuming no water stress. Feddes' parameters include pressure head below which roots start to extract soil water ($P_0$ = 0 cm); Pressure head below which roots extract soil water at the maximum rate ($P_{Opt}$ = -1 cm); Pressure head below which roots cease to extract soil water at the maximum rate ($P_{2H/2L}$); and permanent wilting point ($P_3$ = -16000 cm). $P_{2H}$ and $P_{2L}$ for small grains in the vegetative period were estimated by Taylor and Ashcroft (1972) as -400 cm and -500 cm respectively. An assumption was made that 50% of root growth had occurred after 50% of the growing season, since root measurements during the growing season would have compromised the integrity of the soil column by introducing macropores. The model was found to be insensitive to the depth distribution of root water uptake, but this was represented in the profile summary section by the following function (Simunek et al., 1996):

$$b = a * \exp(-az) \qquad (4.6)$$

where
b = Root water uptake distribution function ($cm^{-1}$)
a = Constant, 0.05
z = Depth from soil surface (cm)

Solute uptake by plant roots was assumed to occur exclusively through passive uptake. The maximum concentration for passive uptake ($cRoot_{max}$) was set to an arbitrarily large concentration, 10,000 mg $cm^{-2}$, which would never be exceeded.

### 4.6.4 Initial Conditions

The initial pressure heads throughout the column profile were estimated using a constant flow rate simulation of HYDRUS-1D. Initial nitrate concentration of each of the six 14 cm soil layers was determined through laboratory analysis and assumed equal for all silt loam soil columns. Concentrations were converted from mg $g^{-1}$ of dry soil to mg $L^{-1}$ soil water using initial moisture content of the soils, determined through gravimetric methods. The initial nutrient concentrations throughout the soil profile were used in the HYDRUS-1D profile summary for simulating solute transport.

Although the initial nitrate and total nitrogen concentrations were analyzed throughout the soil profile, the HYDRUS-1D simulation began after several wetting and drying cycles of the columns took place. So, the concentrations of nitrate within the soil profile at the beginning of the model simulation period (at cover crop planting) were still unknown. A simulation of the 44-day column settling period, June 16th, 2015 – July 30th, 2015, was conducted using the initial soil nitrate profile from experimental data, calibrated soil hydraulic parameters, and estimates for solute transport and reaction parameters from literature.  The nitrate concentrations measured at experiment initiation and simulated at cover crop planting are in Figure 5.17.  HYDRUS-1D requires all solute concentrations to be in mass of solute per volume of soil water, so measured soil nitrate concentrations were converted to soil water concentrations using soil moisture measurements.

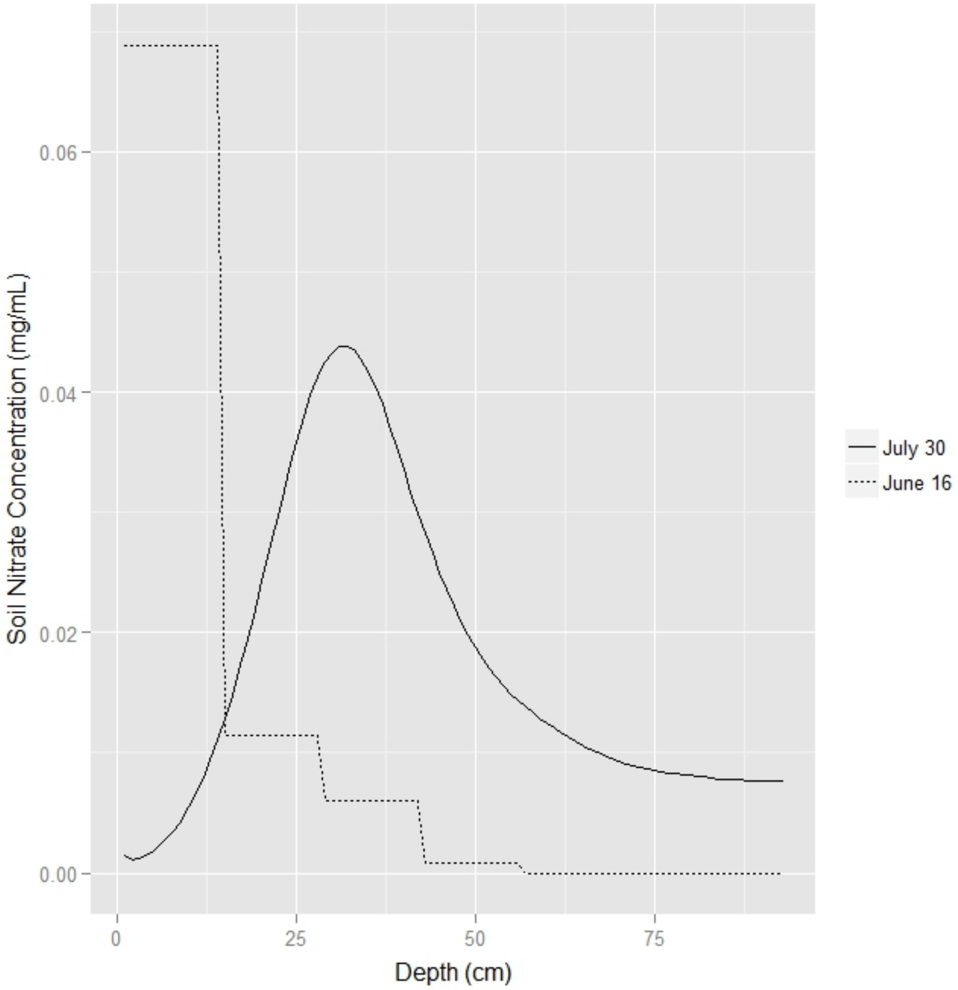


**Figure 4.10: Measured (June 16) and corresponding simulated (July 30) nitrate concentrations in the silt loam soil columns at varying depths throughout the profile**

### 4.6.5 Soil Hydraulic Parameter Optimization

The soil column profile of the Flanagan silt loam was approximately categorized into three distinct layers of silt loam (0 – 42 cm), silty clay loam (42 – 84 cm), and sand (84 – 92 cm). Using the inverse procedures of HYDRUS 1-D with no internal weighting, the soil hydraulic parameters were optimized for soil column S2. The soil hydraulic parameters that need to be optimized for each layer include residual moisture content ($\theta_r$), saturated moisture content ($\theta_s$), van Genuchten parameters ($\alpha$ and n), saturated hydraulic conductivity ($K_s$), and a tortuosity parameter (l). Average values based on soil texture for these soil parameters indicated by Carsel and Parrish (1988) were used as initial estimates. Maximum and minimum bounds on the hydraulic parameters were imposed at ± 10% of the average value for the corresponding soil type for each layer to prevent a calibration using unreasonable hydraulic parameters. The cumulative bottom flux depths (cm) were fitted to observed experimental cumulative bottom flux depths at daily intervals for the growing season for soil column S2, which had cover crops. HYDRUS-1D also has the capability to fit bottom flux rate (cm day$^{-1}$) at specified times. However, the experimental bottom flux data was collected only once daily to represent cumulative daily bottom flux (cm). The bottom flux rate (cm day$^{-1}$) was not measured precisely over the course of leaching events, so using the experimental data as instantaneous bottom flux at specified times rather than cumulative bottom flux would introduce error.

### 4.6.6 Solute Transport Parameter Optimization

Longitudinal dispersivity, $D_L$, is typically 0.5 - 2 cm for packed laboratory soil column studies (Radcliffe and Simunek, 2010). The model was insensitive to $D_L$ for the bottom sand layer, and was set to 50 cm. The molecular diffusion coefficient of nitrate in water, $D_w$, was set to 1.64 $cm^2$ $day^{-1}$ (Shekofteh et al., 2013). For bulk density, $\rho_b$, a 5-column average was used from core sample measurements in Tables 5.5 and 5.6, and the sand layer was assumed to have a bulk density of 1.5 g $cm^{-3}$. The adsorption isotherm coefficient, $K_d$, is multiplied by bulk density in the model equations, so it must have the inverse units of $\rho_b$. Hanson et al. (2006) assumed $K_d$= 0 $cm^3$ $g^{-1}$ for nitrate and $K_d$ = 3.5 $cm^3$ $g^{-1}$ for ammonium. While the adsorption of nitrate and other anions is very low compared to cations, nitrate adsorption is higher for finer textured soils such as clays and silts (Akosman and Ozdemir, 2010). The model was very sensitive to $K_d$, so it was considered non-zero and optimized for both cover cropped and bare columns. Nitrate adsorption was assumed to be negligible for the sand layer. The rates of mineralization, immobilization, nitrification, and denitrification were not measured experimentally, so the net effect of zero-order and first-order reaction terms in the model was assumed negligible and compensated for in the other solute transport and reaction parameters. HYDRUS-1D was manually calibrated for $D_L$ and $K_d$ for each of three layers in the silt loam soil profile. Model output was compared to experimental values for daily cumulative leached nitrate (mg $cm^{-2}$) for soil column S2, as with the hydraulic parameter calibration, and additionally for soil column S5.

### 4.6.7 Model Performance Evaluation

Goodness-of-fit criterion proposed by ASCE (1993) and Nash and Sutcliffe (1970) to evaluate watershed model performance include the coefficient of determination ($R^2$), weighted coefficient of determination ($wR^2$), deviation of seasonal [leached] volumes or masses ($D_v$), and the Nash-Sutcliffe Efficiency (NS), are calculated by:

$$R^2 = \left( \frac{\sum_{i=1}^{n}(O_i - \bar{O})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2}} \right)^2 \qquad (4.7)$$

where
$R^2$ = coefficient of determination
$O_i$ = observed cumulative leached volume or mass on a daily basis (mm or mg)
$\bar{O}$ = mean observed cumulative leached volume or mass (mm or mg)
$M_i$ = modeled cumulative leached volume or mass on a daily basis (mm or mg)
$\bar{M}$ = mean modeled cumulative leached volume or mass (mm or mg)
n = number of data points (168 days in the growing season)

$$\begin{aligned} &\text{for } b < 1: \quad wR^2 = b * R^2 \\ &\text{for } b > 1: \quad wR^2 = b^{-1} * R^2 \end{aligned} \qquad (4.8)$$

where
$wR^2$ = weighted coefficient of determination
b = slope of regression line
$R^2$ = coefficient of determination

$$D_v = \frac{V_o - V_m}{V_o} * 100 \qquad (4.9)$$

where
$D_v$ = deviation of seasonal leached volume or mass (%)
$V_o$ = observed seasonal leached volume or mass (mm or mg)
$V_m$ = modeled seasonal leached volume or mass (mm or mg)

$$NS = 1 - \frac{\sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (4.10)$$

where
NS = Nash-Sutcliffe efficiency
$O_i$ = observed cumulative leached volume or mass on a daily basis (mm or mg)
$\bar{O}$ = mean observed cumulative leached volume or mass (mm or mg)
$M_i$ = modeled cumulative leached volume or mass on a daily basis (mm or mg)
n = number of data points (168 days in the growing season)

$R^2$ values may range from 0 to 1, with 1 indicating that the observed dispersion is explained fully by the prediction (Krause et al., 2005). The coefficient of determination compares the effectiveness of the model to predict over simply using the mean value to predict (ASCE, 1993). Therefore, the $R^2$ value is expected to be higher in this case of fitting cumulative daily flux or mass values, as opposed to daily rate values, because the cumulative mean is not an average of the daily rates. Only dispersion is considered in the $R^2$ value, so the equation of the linear regression line should also be considered to determine goodness of fit (Krause et al., 2005). If the slope of the regression line is 1 and the intercept is 0, then there is an exact fit between observed and modeled cumulative leached volumes on a daily basis (Krause et al., 2005). If the slope of the regression line is less than 1, then the model is generally under-estimating observed values. The weighted $R^2$ is a reflection of model performance considering both dispersion and under-prediction or over-prediction (Krause et al., 2005).

The deviation of seasonal leached values, $D_v$, can be any number, but lower $D_v$ values indicate that the model is performing better (ASCE, 1993). In other words, $D_v$ is a measure of how closely the model predicted the cumulative value at the end of the growing season. A negative $D_v$ value means that the model over-estimated the total seasonal leached volumes or masses. The Nash-Sutcliffe efficiency ranges between $-\infty$ and 1, with 1 representing a perfect fit and $< 0$ indicating that the mean value is a better prediction than the model (Krause et al., 2005). However, because the differences are squared in the NS calculation, model performance is over-represented toward the end of the growing season when cumulative values are high and under-represented at the beginning of the growing season when cumulative values are low (Krause et al., 2005).

# CHAPTER 5

# RESULTS AND DISCUSSION

## 5.1 Summary of Protocol Deviations

This experiment was performed on Flanagan silt loam using one replication for the fallow columns and two replications for the cover cropped columns (i.e. two fallow columns and three cropped columns). During the process of natural settling, it was determined that the repacked sandy loam soil columns would take much longer to develop natural flow paths than the silt loam columns. The act of repacking the sandy loam soil into the PVC columns destroyed the soil structure. After 6 weeks of settling, the repacked sandy loam columns did not have enough soil micropore structure to allow water to flow through the columns. This led to very poorly drained sandy loam soil columns, which would remain flooded on the surface even after small amounts of rainfall (Figure 5.1). Since sandy loam soils are well drained in a field environment, the sandy loam columns were not behaving similarly enough to field conditions to continue with the experiment as planned.

**Figure 5.1: Water-logged sandy loam soil columns caused by repacking and lack of soil structure**

Two methods were employed in an attempt to encourage water to pass through the columns. It was thought that an airlock or impermeable clay layer could have developed during the settling process. Four 2-mm diameter, 40-cm deep artificial macropores were created in S1, a silt loam soil collected from the South Farms, and P6, a sandy loam soil from Pekin, IL, to compare the drainage of the two soil types (Figure 5.2). The initially poor drainage of S1 may have led to less cover crop establishment and subsequently more leaching losses in the S1 column throughout the remainder of the study, compared to other silt loam columns (refer to Figures 5.10 and 5.11). Artificial macropores were then created in all sandy loam columns to penetrate any possible clay layers and saturate any possible airlocks. Also, four additional cycles of wetting and drying were conducted in an attempt to create pathways for water flow. Theoretically, the wetting and drying process would develop cracks in the soil over time to serve as water pathways. However, neither method proved to be a lasting solution to the water-logged columns, so cover crops could only be planted in the Flanagan columns. Therefore, the sandy loam columns were not usable for a leaching experiment within the time constraints of the research project.

**Figure 5.2: (a) Artificial macropore creation in sandy loam columns and (b) Subsequent soil settling**

This restructuring or settling process of repacked soil columns is one drawback to disturbed soil column experiments. However, the sandy loam columns remained outside throughout the duration of the experiment, and samples were taken periodically after large rain events to determine natural N and P concentrations in the leachate. The sandy loam columns were also used to determine freezing and thawing depths of the soil columns without disturbing the experiments in the silt loam columns. The quicker restructuring process of the silt loam soil could be due to the higher organic matter content of the soils, as compared to the sandy loam.

Additional issues with poor drainage occurred when the silt loam soil columns were moved to an indoor laboratory environment to simulate spring. After the columns had thawed and the resulting drainage water was collected from each, three more cycles of irrigation were planned. However, the soil columns S3 and S5 (bare columns) failed to allow any drainage or complete infiltration of the irrigation water. Vacuums were used to apply suction to the base of the soil column, as shown in Figure 5.3. Small samples were collected for nutrient testing, but the entire volume of irrigation water would not infiltrate, so drainage volumes and concentrations during this period were unrepresentative for the bare columns S3 and S5. Without macropores created by plant roots, earthworms, or higher levels of soil structure, which can take years to achieve, the bare soil columns would not allow water to pass through them. These issues with poor soil structure and drainage are noteworthy limitations to soil column studies.

**Figure 5.3 Vacuum applying suction at base of bare soil column S3 to force drainage**

The organic matter content was measured using ASTM D 2974 for both the silt loam and sandy loam soil types in order to determine the reason that the sandy loam soil failed to provide enough structure when repacked into a soil column (ASTM, 2005). The sandy loam had 35% less soil organic matter in the top 28 cm (11 in) of soil than the silt loam (Table 5.1). Soil organic matter stabilizes both micro-aggregates and larger aggregates (Dexter, 1988). Micro-aggregate stabilizing soil organic matter is incorporated into small pores and largely not affected by farm management, unlike the soil organic matter that stabilizes larger aggregates, which is highly dependent on cropping and farm management (Dexter, 1988). The rapid wetting of larger soil aggregates at the soil surface can cause them to be broken down into micro-aggregates, reducing the pore size between them (Dexter, 1988). Decreased pore size between aggregates leads to a slower infiltration rate (Dexter, 1988). Any dispersed clay may also block the already small pores between the micro-aggregates leading to an even lower infiltration rate (Dexter, 1988). The breaking down of the aggregates can be minimized with slower precipitation/irrigation rates and a higher initial water content (Dexter, 1988). High soil pH and low electrolyte concentrations in the infiltrating water can increase clay swelling and dispersion (Dexter, 1988). The use of deionized water, which has low electrolyte concentrations, for irrigation water may have increased clay dispersion in both the sandy loam and silt loam soil columns. When clay particles are dispersed, the lowest order of soil structure is destroyed, which means that all higher orders of structure are also destroyed (Dexter, 1988).

Organic matter takes time to build up in the soil, and no noteworthy changes were observed after one cover crop growing season. Table 5.1 and 5.2 show initial and final results of soil organic matter content in the silt loam soil columns. In addition to the benefits of creating soil structure, organic matter is an important factor in the nitrogen cycle as it can be mineralized to provide available nitrogen in the soil. Although the soil organic matter was lower in the sandy loam than the silt loam, the organic matter was likely not low enough to be the sole factor in the lack of structure in the sandy loam columns.

**Table 5.1: Initial soil organic matter content in silt loam and sandy loam**

| Depth (cm) | Initial silt loam OM (%) | Initial sandy loam OM (%) | Difference (%) |
|---|---|---|---|
| 0 - 14 | 4.7 | 3.0 | 35.7 |
| 14 - 28 | 4.0 | 2.6 | 34.5 |
| 28 - 42 | 3.2 | 3.4 | -5.2 |
| 42 - 56 | 3.2 | 3.2 | 1.0 |
| 56 - 70 | 3.5 | 2.8 | 18.3 |
| 70 – 84 | 3.3 | 1.9 | 41.6 |

**Table 5.2: Final soil organic matter content in silt loam columns at different depths**

| Depth (cm) | Final S2 , dense CC OM (%) | Final S4, dense CC OM (%) | Final S1, thin CC OM (%) | Final S3, bare OM (%) | Final S5, bare OM (%) |
|---|---|---|---|---|---|
| 0 - 14 | 4.1 | 4.3 | 4.6 | 4.4 | 4.6 |
| 14 - 28 | 4.1 | 4.4 | 4.2 | 3.7 | 4.2 |
| 28 - 42 | 3.3 | 3.2 | 3.2 | 3.3 | 3.2 |
| 42 - 56 | 3.0 | 3.4 | 3.1 | 3.3 | 3.3 |
| 56 - 70 | 3.0 | 3.2 | 3.2 | 3.2 | 3.1 |
| 70 + | 3.1 | 3.0 | 3.0 | ---- | 3.0 |

The hydrometer method by Gee and Bauder (1979) was used to determine the percentage of sand, silt, and clay in each soil type (Table 5.3). Official soil series descriptions of Flanagan and Onarga showed clear divisions between the A and B horizons around 42 cm, so one sample from the middle of the A horizon and one sample from the middle of the B horizon from each soil type were collected for analysis. Clay contents were found to be 20% – 29% and 14% in the silt loam and sandy loam, respectively. Rapidly applying deionized water to the surface of the soil columns likely contributed to the very low infiltration rates of the sandy loam soil, and eventually bare silt loam columns as well. This methodology combined with the lower organic matter content of the sandy loam compared to the silt loam, shown in Table 5.1, and pore-clogging clay content made the sandy loam soil unsuitable for a study requiring repacked soil columns.

**Table 5.3: Particle size analysis of the two soil types**

| | Flanagan 0 - 42 cm | Flanagan 42 - 84 cm | Onarga 0 - 42 cm | Onarga 42 - 84 cm |
|---|---|---|---|---|
| Clay (%) < 2 µm | 20 | 29 | 14 | 14 |
| Silt (%) 2 – 50 µm | 38 | 45 | 7 | 7 |
| Sand (%) 50 µm – 2 mm | 42 | 26 | 79 | 79 |
| USDA classification | Loam | Clay loam | Sandy loam | Sandy loam |

Wetting and drying cycles cause aggregation in a homogeneous soil. Soil colloids shrink creating cracks between aggregates (> 0.25 mm), which remain through subsequent wetting and drying cycles as planes of weakness. It takes a number of years for an equilibrium level of aggregation to develop. Biological process can also lead to soil aggregation. Clods (aggregates > 25 mm) are caused by compaction through machinery. However, study time constraints did not allow for years of wetting and drying cycles to occur, and the structure of the soils in the repacked soil columns suffered as a result. (Dexter, 1988)

Final bulk density was measured at the end of the experiment for each silt loam column to determine if differences in bulk density could be contributing to the decreased infiltration and drainage rates of the bare columns compared to the cover cropped columns (Table 5.5). Settling distances were also observed. At the end of the experiment, the bare columns had settled more than the cover cropped columns, and were therefore more compacted with higher bulk densities. Naturally occurring bulk densities of silt loam soils are around 1.3 g cm$^{-3}$, so these soil columns were less compacted than soils in a field environment. Initial bulk densities for the entire column were estimated based on the mass of soil in each column, calculated from final bulk densities, volumes, and initial volume of soil (Table 5.4). Bulk density, measured using a 2-inch diameter soil core, was similar between all five silt loam soil columns. The bulk densities of loosely repacked soil columns are expectedly lower than natural soil because the soil columns have not had the same extreme pressures applied to it over time.

**Table 5.4: Initial and final bulk densities and settling distance of silt loam columns**

| | S2, dense CC | S4, dense CC | S1, thin CC | S3, bare | S5, bare |
|---|---|---|---|---|---|
| Initial $\rho_b$ (g cm$^{-3}$) | 0.79 | 0.77 | 0.87 | 0.83 | 0.87 |
| Settling distance (cm) | 6 | 5 | 8 | 15 | 10 |
| Final $\rho_b$ (g cm$^{-3}$) | 0.81 | 0.76 | 0.89 | 0.92 | 0.93 |

**Table 5.5: Final bulk densities of silt loam columns at different depths**

| Depth (cm) | S2, dense CC $\rho_b$ (g cm$^{-3}$) | S4, dense CC $\rho_b$ (g cm$^{-3}$) | S1, thin CC $\rho_b$ (g cm$^{-3}$) | S3, bare $\rho_b$ (g cm$^{-3}$) | S5, bare $\rho_b$ (g cm$^{-3}$) |
|---|---|---|---|---|---|
| 0 - 14 | 0.89 | 0.89 | 0.98 | 0.93 | 0.81 |
| 14 - 28 | 0.77 | 0.92 | 1.02 | 1.06 | 1.09 |
| 28 - 42 | 1.04 | 0.71 | 1.01 | 0.84 | 1.00 |
| 42 - 56 | 0.66 | 0.61 | 0.79 | 0.76 | 0.89 |
| 56 - 70 | 0.69 | 0.66 | 0.67 | 0.99 | 0.86 |
| Average | 0.81 | 0.76 | 0.89 | 0.92 | 0.93 |

## 5.2 Cover Crop Growth

Cover crop growth was monitored by taking chlorophyll readings and orthographic photographs of the columns throughout the growing season. Soil columns S2 an S4 had very similar cover crop growth, but the cover crop growth in S1 lagged behind and was overall less than in the other two columns (Table 5.6 and Figure 5.5). This could have been due to poor drainage of the soil pores and/or an imbalance of nutrients due to pH. Although the soil columns were constructed identically, random differences are still conceivable. It is unlikely that the under-establishment of S1 was caused by nutrient deficiencies or a lack of soil moisture because Flanagan silt loam is known to be both extremely fertile and poorly drained. Ten percent canopy cover was achieved about 15 days after cover crop planting and 80% canopy cover was achieved about 36 days after planting for soil columns S2 and S4, while soil column S1 required replanting for adequate establishment and cover crop growth lagged behind the other two soil columns. Mid-season dives in canopy cover data shown in Figure 5.4 may be attributed to a couple of factors. If it was windy while orthographic photographs were taken, the canopy cover calculation could have errors. Also, the uniform grid and manual analysis techniques used by SamplePoint could potentially lead to inconsistencies in the canopy cover data. In general, the canopy cover growth curves generated from the orthographic photographs and SamplePoint show the realistic trends of rapid crop growth at the beginning of the growing season, leveling off at > 90% canopy cover for the majority of the fall months, and a slight decline during the winter months as crops begin to die.

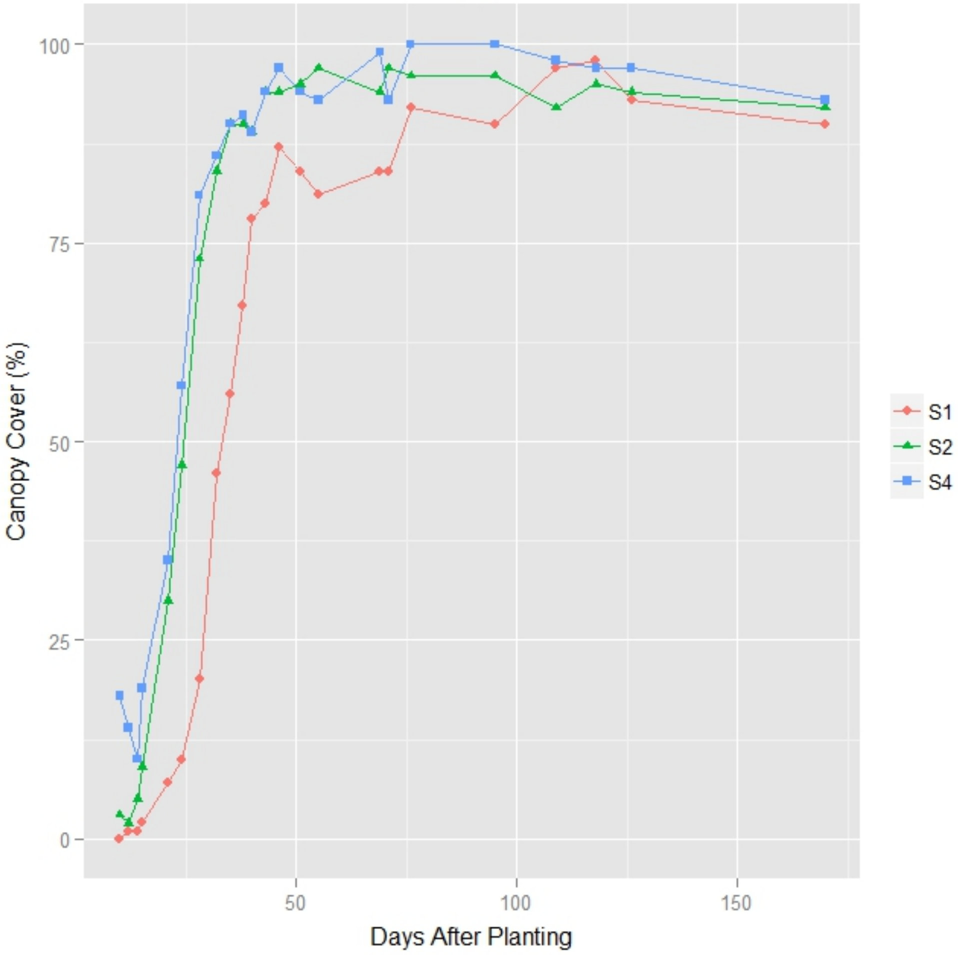


**Figure 5.4: Percent canopy cover determined by analyzing orthographic photographs of the cover crops using SamplePoint software**

**Table 5.6: Cover crop biomass at termination**

| | Oats final biomass (g) | HV final biomass (g) | Total (g) |
|---|---|---|---|
| S1 | 20.2 | 21.0 | 41.2 |
| S2 | 39.0 | 29.3 | 68.3 |
| S4 | 37.7 | 29.7 | 67.4 |

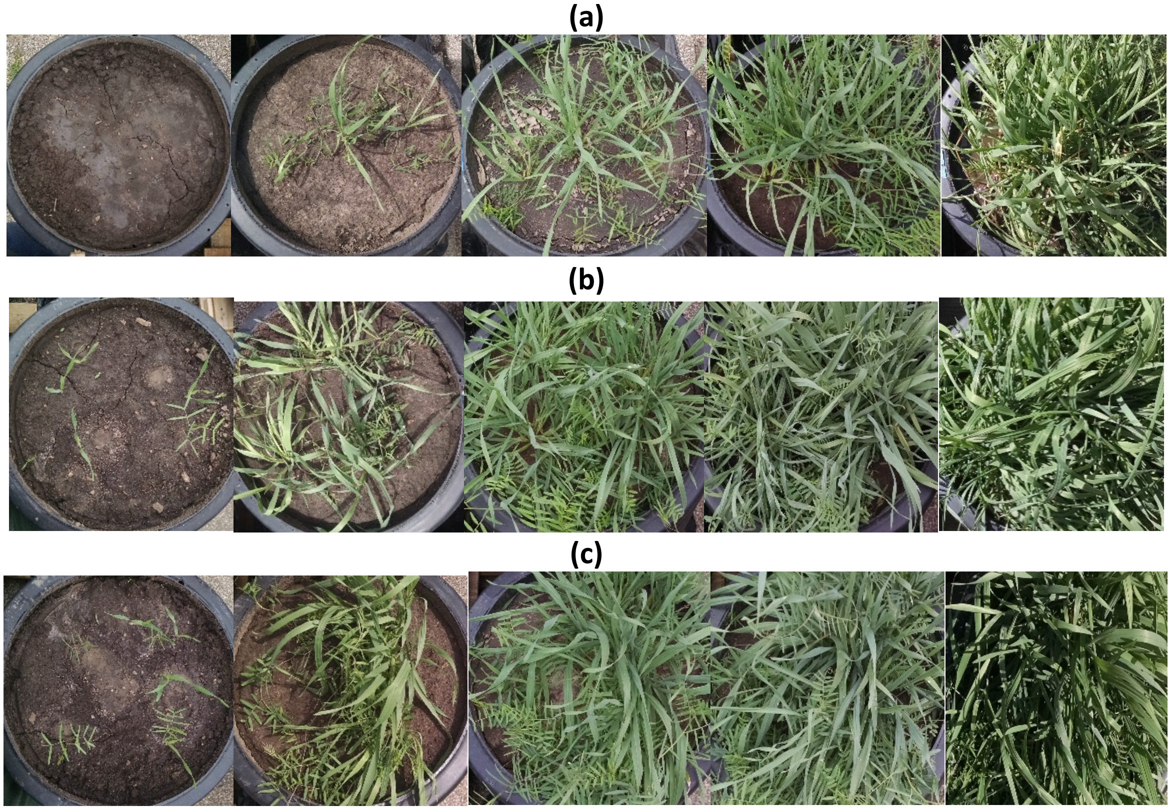


**Figure 5.5: Progression of cover crop growth; orthographic photographs taken on 08/07, 08/21, 08/29, 09/06, and 09/21 of soil columns (a) S1 thin CC, (b) S2 dense CC, and (c) S4 dense CC**

Chlorophyll measurements showed no differences in crop health between soil columns (Table 5.7). Higher SPAD values in Table 5.7 indicate higher concentrations of chlorophyll per unit area in the leaf measured. This supports the supposition that less cover crop growth in S1 was not caused by a nutrient deficiency. The hairy vetch had lower chlorophyll readings than the oats until October when the two crops showed comparable chlorophyll levels. However, the slight purpling of a few oat blades in soil columns S2 and S4 at the beginning of spring simulation may indicate that minor phosphorus or other nutrient imbalances occurred, possibly due to cold temperatures and/or lack of root growth.

**Table 5.7: Chlorophyll measurements for each cover cropped silt loam soil column**

| | S1 | | S2 | | S4 | |
|---|---|---|---|---|---|---|
| | Oats | HV | Oats | HV | Oats | HV |
| 08/21/15 | 27 | 20 | 32 | 21 | 29 | 25 |
| 08/29/15 | 37 | 23 | 40 | 24 | 40 | 24 |
| 09/16/15 | 32 | 21 | 37 | 24 | 38 | 24 |
| 10/01/15 | 32 | 32 | 36 | 27 | 34 | 29 |
| 10/16/15 | 34 | 36 | 37 | 35 | 37 | 33 |
| 11/01/15 | 37 | 39 | 36 | 35 | 35 | 33 |
| 11/17/15 | 39 | 30 | 30 | 29 | 36 | 35 |
| 01/14/15 | 25 | --- | 26 | --- | 22 | --- |
| Average | 33 | 29 | 34 | 28 | 34 | 29 |

### 5.3 Water Balance

Meteorological and experimental data (examples in Figure 5.6) were used to estimate the daily variation in evapotranspiration (Figure 5.7). The FAO Penman-Monteith method was found to estimate the actual evapotranspiration for the entire experimental period, calculated from a water balance, within 43% - 49%, varying by soil column (Table 5.9). A water balance for the growing season only was also calculated, neglecting soil moisture changes (Table 5.8). However, as described earlier, this error includes many factors from the experiment such as measurement errors, instrumentation errors, recording errors, and parameter estimation errors, in addition to any errors resulting from assumptions and approximations made when utilizing the FAO Penman-Monteith equation. Also, it is difficult to account for all water losses from the soil columns using a volume-based mass balance calculation. As predicted, cover crops reduced total drainage volumes during the cover crop growing season and led to increased drainage volumes after cover crop suppression, compared to bare soils (Figure 5.8). The differences during the cover crop growing season can be primarily attributed to the increase in water uptake and evapotranspiration due to cover crop roots and leaves. After cover crop suppression, decaying roots left macropores, which transported water through the soil profile to the bottom of the column when there was no growing crop to take up the water. This led to an increased amount of drainage from the once cover cropped columns after cover crop suppression, compared to the bare columns.

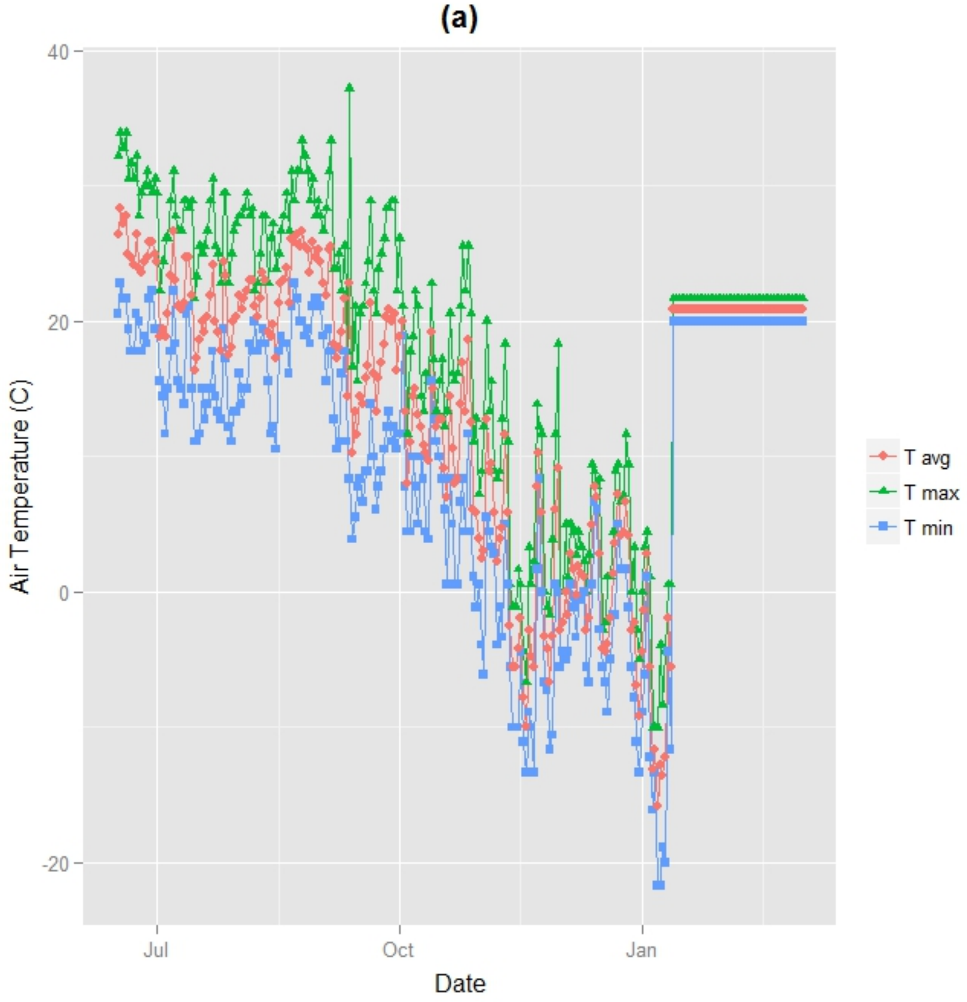


**Figure 5.6: Data for the entire experiment duration on (a) Average, maximum, and minimum daily air temperatures (°C) recorded at Willard Airport in Champaign, IL; (b) Irrigation + precipitation water (mm $d^{-1}$) added to soil columns; (c) Net radiation (MJ $m^{-2}$ $d^{-1}$) calculated from the FAO Penman-Monteith equation; and (d) Reference evapotranspiration (mm $d^{-1}$) calculated from the FAO Penman-Monteith equation**

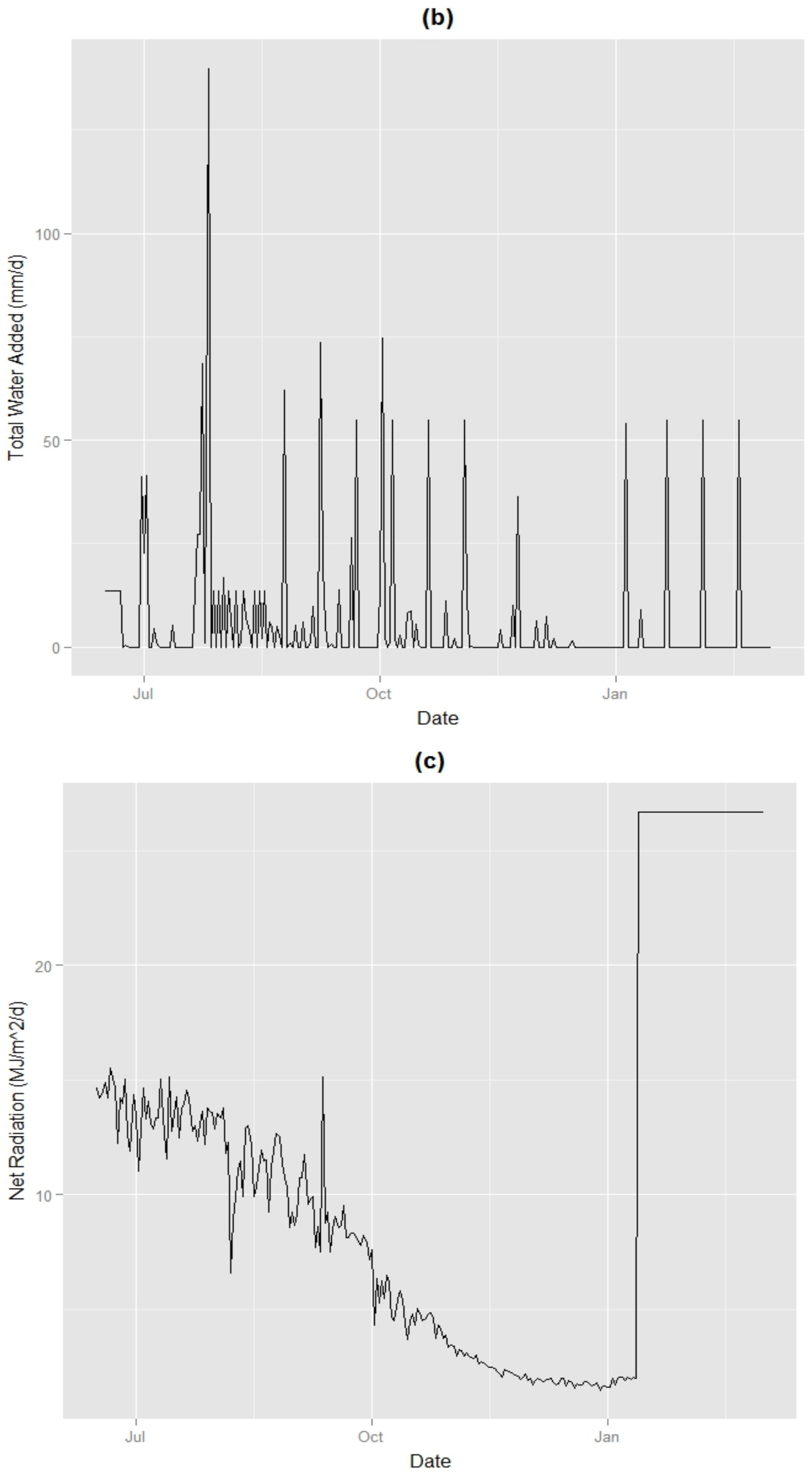


**Figure 5.6 (Continued from previous page): Data for the entire experiment duration on (a) Average, maximum, and minimum daily air temperatures (°C) recorded at Willard Airport in Champaign, IL; (b) Irrigation + precipitation water (mm d$^{-1}$) added to soil columns; (c) Net radiation (MJ m$^{-2}$ d$^{-1}$) calculated from the FAO Penman-Monteith equation; and (d) Reference evapotranspiration (mm d$^{-1}$) calculated from the FAO Penman-Monteith equation**

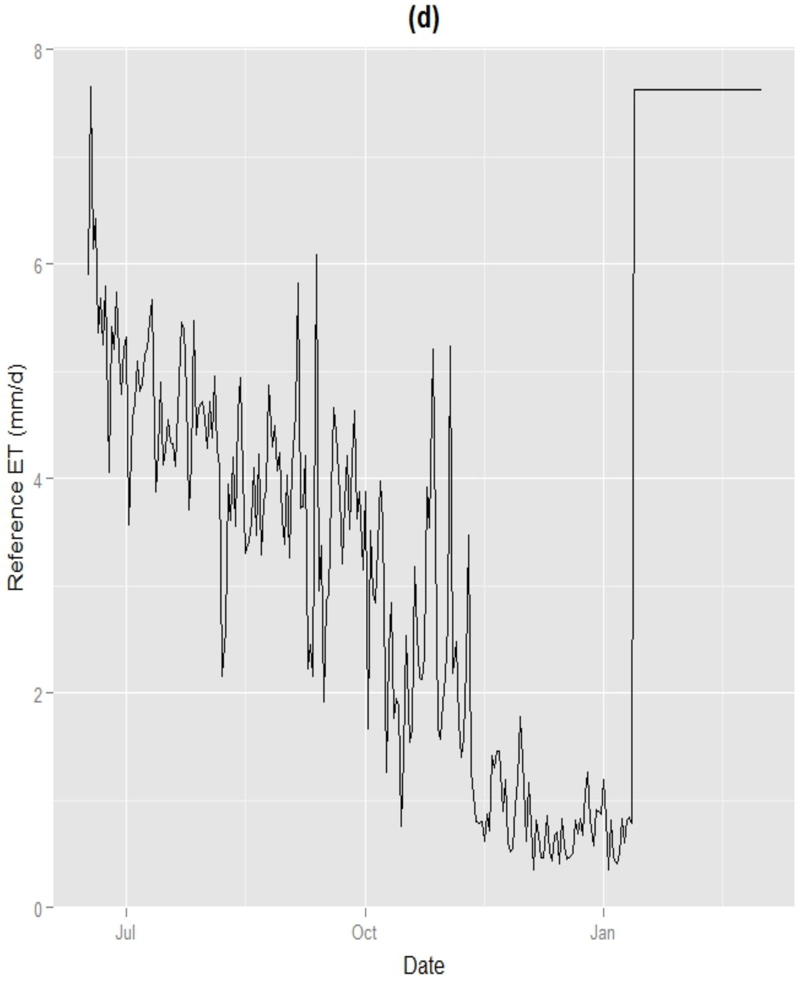


**Figure 5.6: Data for the entire experiment duration on (a) Average, maximum, and minimum daily air temperatures (°C) recorded at Willard Airport in Champaign, IL; (b) Irrigation + precipitation water (mm $d^{-1}$) added to soil columns; (c) Net radiation (MJ $m^{-2}$ $d^{-1}$) calculated from the FAO Penman-Monteith equation; and (d) Reference evapotranspiration (mm $d^{-1}$) calculated from the FAO Penman-Monteith equation**

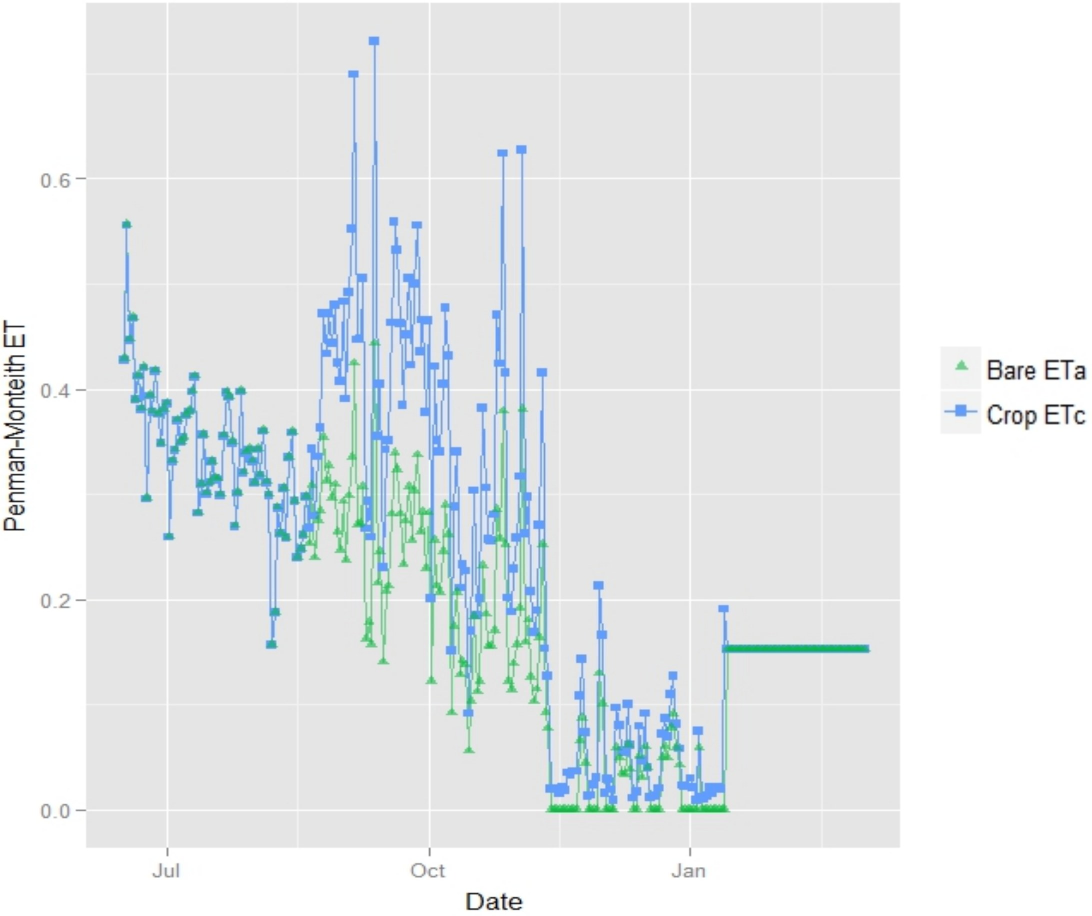


**Figure 5.7: Estimation of crop/actual evapotranspiration by the FAO Penman-Monteith equation described in Allen et al. (1998)**

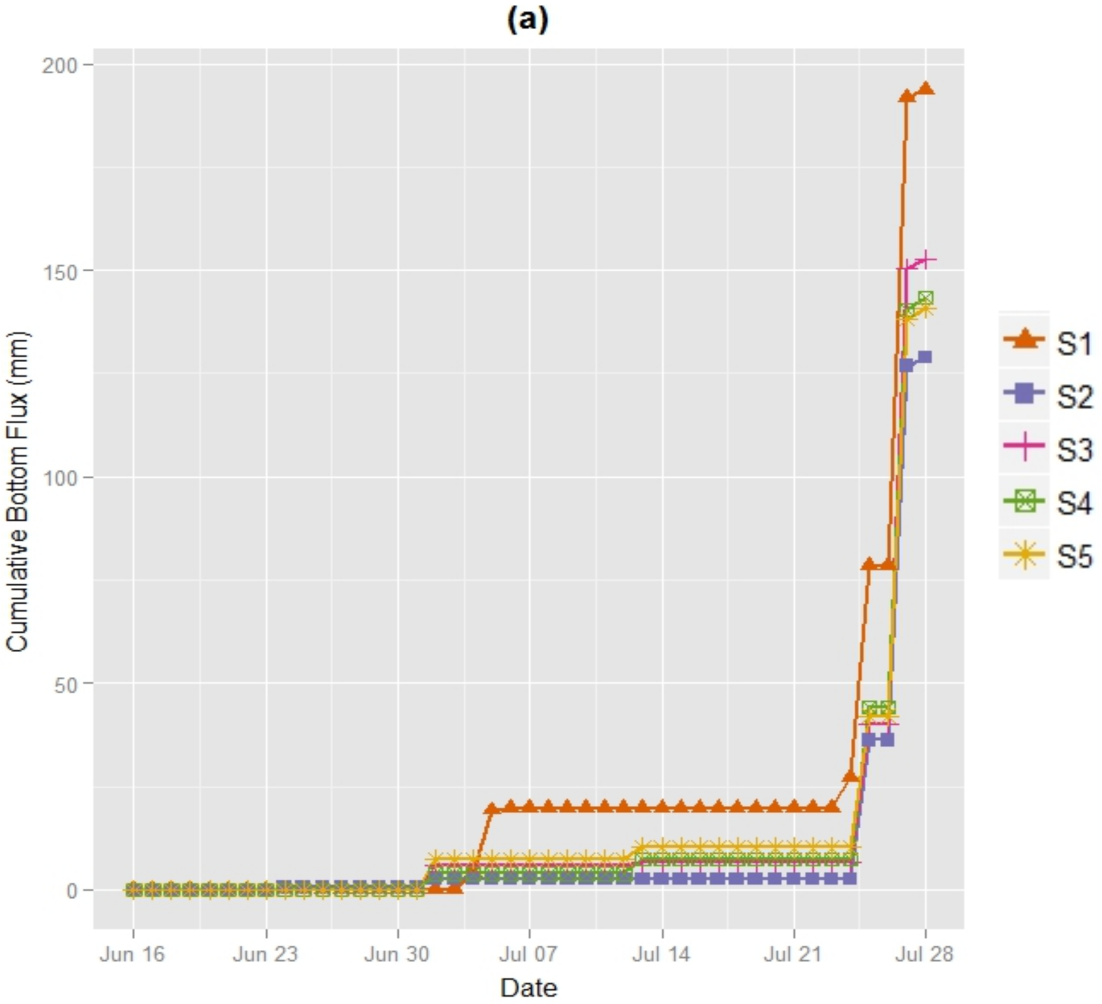


**Figure 5.8: Cumulative bottom flux (drainage water) (a) Before cover crop planting and (b) After cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

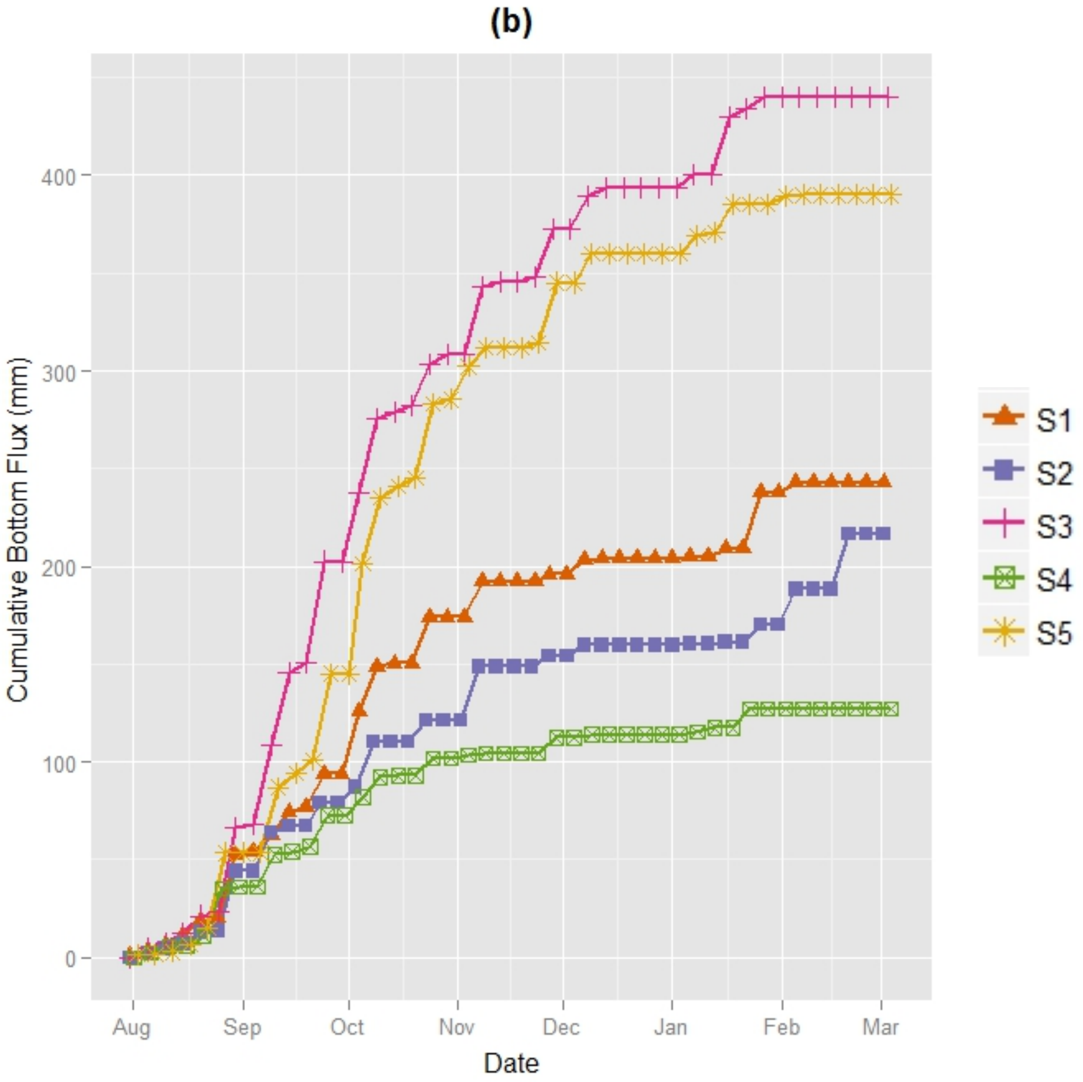


Figure 5.8 (Continued from previous page): Cumulative bottom flux (drainage water) (a) Before cover crop planting and (b) After cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)

**Table 5.8: Growing season water balance**

| | Precipitation + Irrigation (mm) | Leaching loss (mm) | Observed ET (mm) | Penman-Monteith ET (mm) | Modeling Error, ET |
|---|---|---|---|---|---|
| S2, dense CC | 881 | 162 | 718 | 402 | 0.44 |
| S4, dense CC | 875 | 118 | 757 | 402 | 0.47 |
| S1, thin CC | 850 | 209 | 641 | 402 | 0.37 |
| S3, bare | 881 | 409 | 471 | 272 | 0.42 |
| S5, bare | 875 | 372 | 503 | 272 | 0.46 |

**Table 5.9: Experimental period water balance**

| | Precip. + Irr. (mm) | Leaching loss (mm) | Soil storage (mm) | Observed ET (mm) | PM ET (mm) | Modeling error, ET |
|---|---|---|---|---|---|---|
| S2, dense CC | 1552 | 347 | 15 | 1219 | 635 | 0.48 |
| S4, dense CC | 1443 | 271 | 15 | 1187 | 635 | 0.46 |
| S1, thin CC | 1537 | 438 | 22 | 1121 | 635 | 0.43 |
| S3, bare | 1483 | 593 | 16 | 906 | 504 | 0.44 |
| S5, bare | 1443 | 532 | 69 | 980 | 504 | 0.49 |

Since change in soil moisture storage is only a small factor in the experimental period water balance, it is reasonable to assume that it is also a minor component in the growing season water balance. The modeling error is large, but this error is more than a measure of the ET estimation error. There could be many sources of error in this outdoor experiment over a 243 day experimental period. Some possible sources of error include human error in the volume measurements of irrigation water, precipitation, and leachate, human and instrument error of the scale and oven in the gravimetric soil moisture procedure, instrument error of the weather station, meteorological parameter variation from weather station to experiment site, and crop coefficient estimates could all contribute to the modeling error, as well as possible recording and calculation errors.

### 5.4 Calibration of HYDRUS-1D for Water Transport

Optimized hydraulic parameters and the resulting simulation can be found in Table 5.10 and Figure 5.9, respectively. Initial estimates and ±10% boundaries were based off of the assumption that Flanagan silt loam is silt loam from 0 – 42 cm and silty clay loam from 42 – 84 cm. However, in the hydrometer analysis it was determined that these layers were actually loam and clay loam using the USDA Textural Soil Classification system. This may have contributed to slight differences between modeled and observed results.

**Table 5.10: Optimized hydraulic parameters from calibration of HYRDUS-1D for S2**

| | $\theta_r$ ( - ) | $\theta_s$ ( - ) | $\alpha$ ($cm^{-1}$) | n ( - ) | $K_s$ (cm $day^{-1}$) | l ( - ) |
|---|---|---|---|---|---|---|
| 0 – 42 cm<br>(Silt loam) | 0.0737 | 0.405 | 0.018 | 1.31 | 11.88 | 0.51 |
| 42 – 84 cm<br>(Silty clay loam) | 0.0979 | 0.387 | 0.011 | 1.21 | 1.705 | 0.52 |
| 84 – 92 cm<br>(Sand) | 0.0495 | 0.387 | 0.131 | 2.51 | 784.1 | 0.45 |

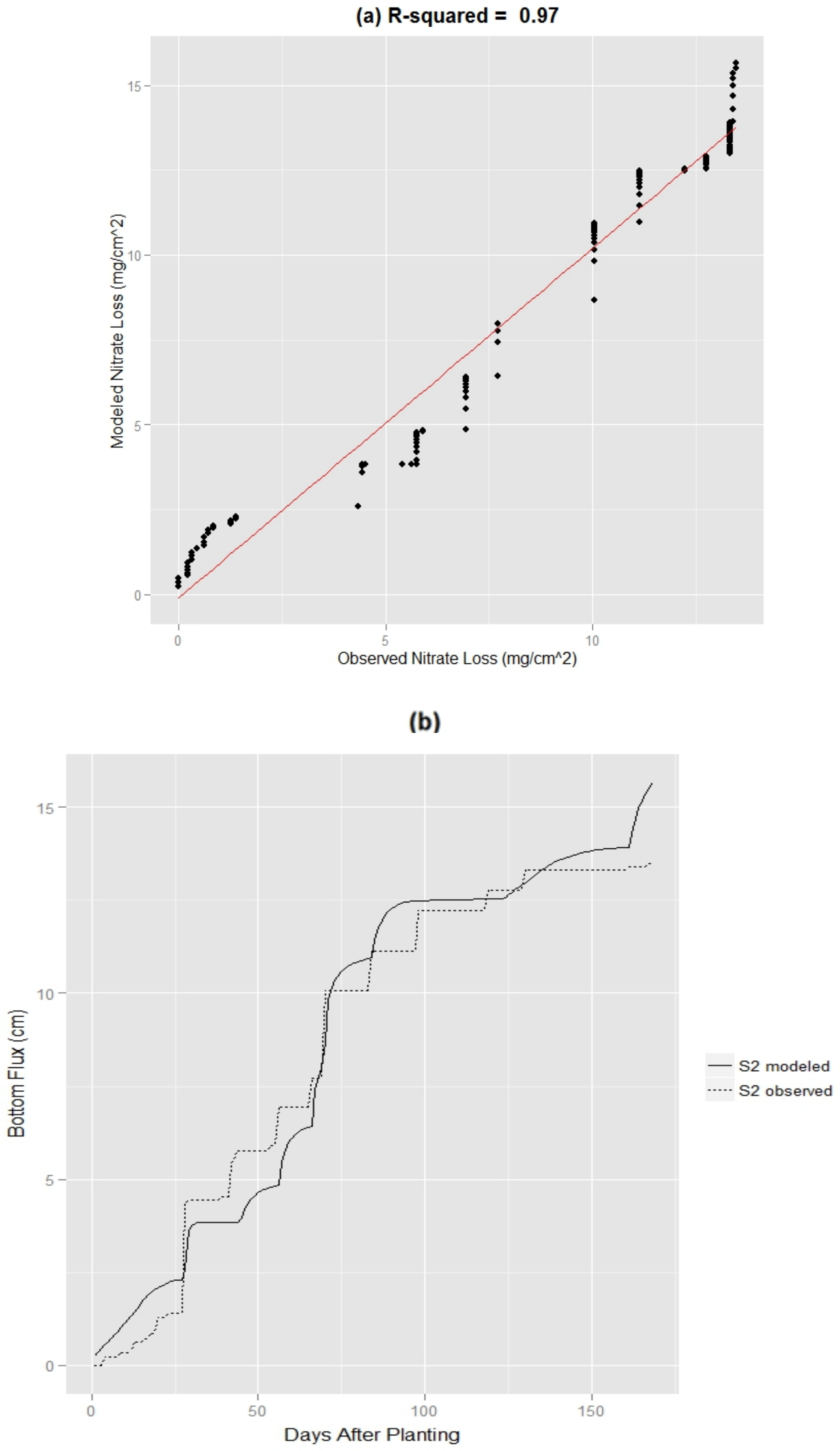


**Figure 5.9: Hydraulic parameter calibration of HYDRUS 1-D for soil column S2 (a) Observed and modeled cumulative bottom water flux values with linear fit ($y = 1.03x + 0.10$, $R^2 = 0.97$) and 95% confidence intervals; (b) Observed and modeled cumulative bottom water flux during growing season**

The model performance parameters can be found in Table 5.11. In order to obtain these results, two experimental points were adjusted based on observations of possible errors during data collection. On September 9, 2014, 42 days after planting (DAP = 42), a cut in the inner-wall of the PVC column was discovered and immediately filled with bentonite. However, it is likely that the corresponding DAP = 42 observed bottom flux depth is larger than it would have been without the cut. The cut in the inner-wall of the PVC could have been a pathway for irrigation and precipitation water to bypass the soil column and flow straight into the collection tub. For this reason, the S2 DAP = 42 observed bottom flux depth was replaced with the S4 DAP = 42 bottom flux depth, as the two columns are replicates and should represent similar conditions. On November 4, 2014 (DAP = 98) it was recorded in observation notes that a very high sediment content was present in the leachate from S2, which was different than what was previously observed. This observation could indicate that something in the soil column changed at DAP = 98, and this bottom flux value occurred under different conditions than the previous values. S2 DAP = 98 bottom flux depth was replaced with S2 DAP = 84 bottom flux value because the two values had similar precedent conditions and S4 DAP = 98 bottom flux depth was also a potentially problematic value.

**Table 5.11: Model performance parameters for calibration of HYDRUS-1D for S2**

| | |
|---|---|
| Coefficient of determination, $R^2$ | 0.97 |
| Weighted $R^2$ | 0.94 |
| Deviation of seasonal volume, $D_v$ | -16% |
| Nash-Sutcliffe efficiency, NS | 0.97 |

### 5.5 Validation of HYDRUS-1D for Water Transport

Table 5.12 show the results of the model validation with the optimized parameters using the remaining four soil columns. On October 6, 2014 and November 4, 2014 (DAP = 70 and DAP = 98, respectively), the water application system fell off of the S4 column before the entire intended 4 L had been added. For this reason, the leachate depths for S4 on these dates is likely less than if the entire 4 L had been added. The corresponding daily bottom flux depths were estimated using column S2 from these dates, as S2 had the most similar conditions to S4.

On September 9, 2014 (DAP = 42) an observation was made that there was standing water in the top of soil column S5 indicating that some of the precipitation may have overtopped the edges of the column and not contributed to bottom flux. So, the S3 DAP = 42 value was used to estimate this value for S5.

**Table 5.12: Model performance parameters for validation of HYDRUS-1D**

| | S4, dense CC | S1, thin CC | S3, bare | S5, bare |
|---|---|---|---|---|
| Coefficient of determination, $R^2$ | 0.97 | 0.99 | 0.98 | 0.99 |
| Weighted $R^2$ | 0.83 | 0.90 | 0.72 | 0.72 |
| Deviation of seasonal volume, $D_v$ | 2.4% | -6.1% | 20% | 18% |
| Nash-Sutcliffe efficiency, NS | 0.90 | 0.98 | 0.70 | 0.79 |

### 5.6 Nitrogen Balance

Drainage water samples from the silt loam soil columns were analyzed for total N and $NO_3$-N. The cover cropped columns had both reduced concentrations in the leachate, as well as reduced total loads (mass) of total N and $NO_3$-N compared to the bare soil columns. The percentage of total N that was in $NO_3$-N form in drainage water was similar between bare and cover cropped columns for every period during the experiment (80 – 90%), except after cover crop termination. After termination, soil columns S2 and S4 had lower $NO_3$-N/Total N ratios (20

– 40%) than both the other columns during the same period and the same columns during the previous periods. Figure 5.10 shows that N loss between columns was similar before cover crop planting. Soil column S1 shows increased N loss in early July due to a short macropore experiment. Extra irrigation water was added to S1 after the creation of artificial macropores in the column. The N concentrations in the drainage water from S1 before cover crop planting were similar to the other columns, and the increase in N load is due mainly to the increased amount of drainage water.

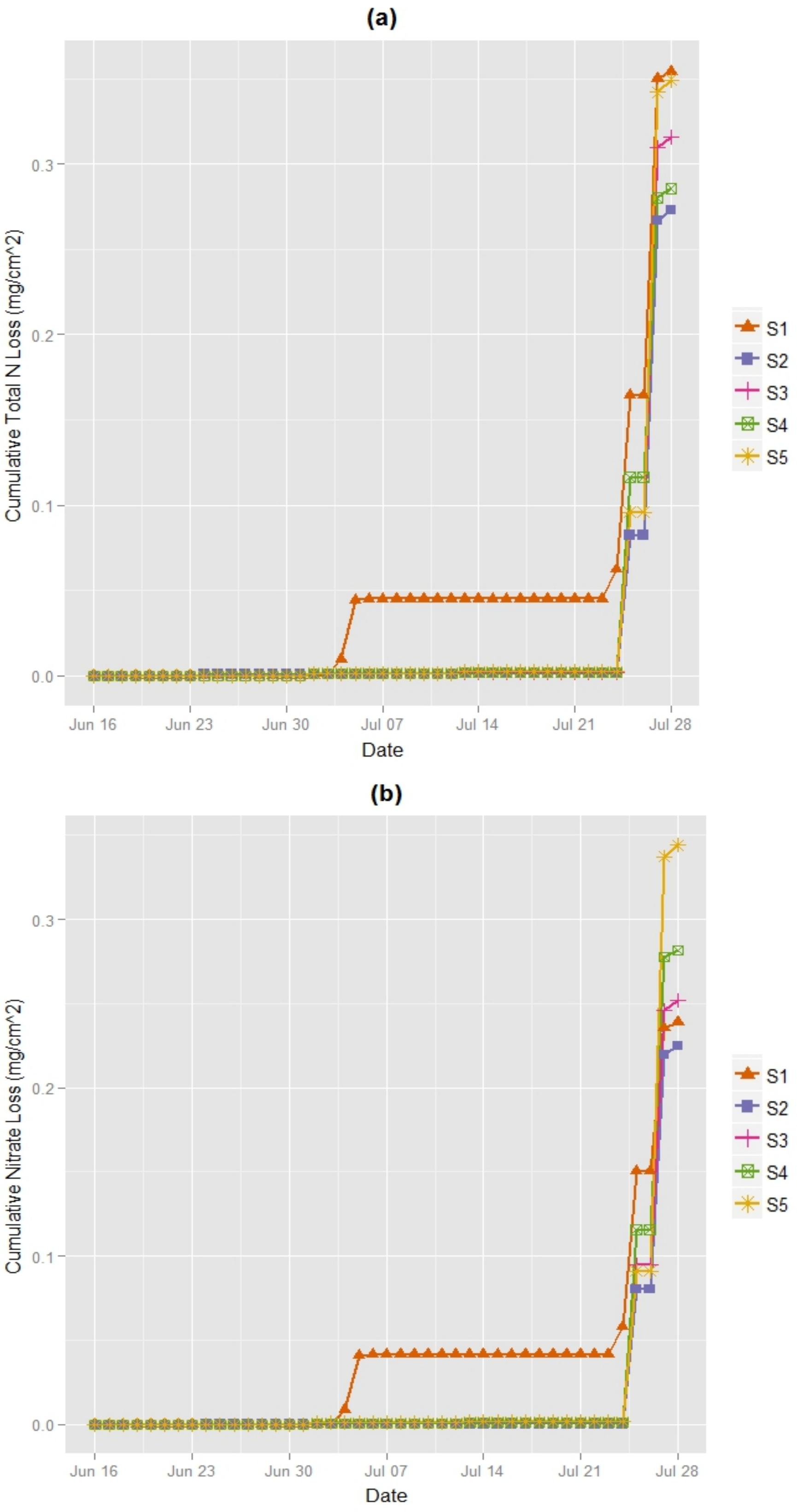


**Figure 5.10: Cumulative mass per unit area of (a) Total nitrogen and (b) $NO_3$-N lost before cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

Figure 5.11 shows the cumulative N loss throughout the experiment. Cooler temperatures and/or high (> 30:1) C:N ratios in the soil likely caused the decrease in N loading rates from the bare columns starting in mid-October and continuing throughout the winter. Microbes utilize nitrate to break down roots and organic matter, consequently reducing nitrate leaching, when immobilization exceeds mineralization at high C:N ratios. Additionally, the curves for S1, S2, and S4 in Figure 5.11 plateau, which demonstrates that N loss from the cover cropped columns actually stopped during the winter, or became very small, and did not resume during spring simulation with irrigation and warmer temperatures. The last irrigation cycle was on November 3rd, but N leaching in soil columns S2 and S4 reached a plateau before then, demonstrating that cover crops take up excess N in the soil and prevent it from leaching.

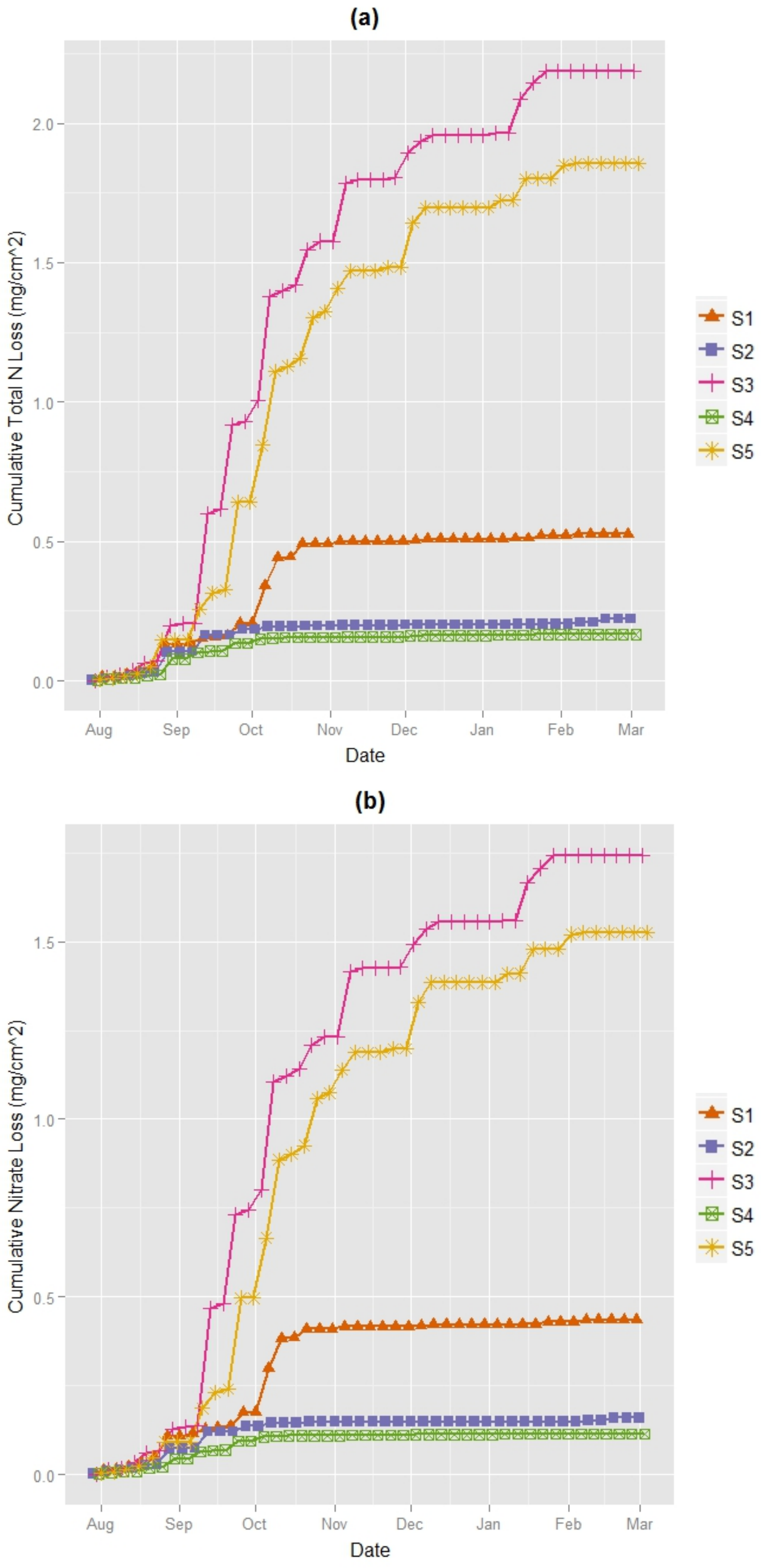


**Figure 5.11: Cumulative mass per unit area of (a) Total nitrogen and (b) $NO_3$-N lost after cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

This experiment represents a "worst-case scenario" in the respect that the soil column setup simulates the ground directly above a tile drain. The soil directly above a tile drain is often disturbed from tile installation and provides an expedited pathway for nutrients to travel through the soil profile, since they do not have to move laterally to enter a tile. The three treatments, bare, dense CC, and thin CC, were found to be significantly different from each other at a 95% confidence interval during and after cover crops, but not significantly different before cover crops. Dense CC soil columns S2 and S4 were not significantly different from each other; and likewise, bare soil columns S3 and S5 were not different at a 95% confidence interval. Figure 5.12 shows one column from each of the three treatments as an example of nitrate concentrations over the experimental duration. Table 5.13 shows average nitrate concentrations in drainage water during different periods of the experiment and results from the t-test. The average concentration of nitrate in drainage water from both bare and cover cropped columns exceeded the drinking water standard of $< 10$ mg $L^{-1}$ of $NO_3$-N, but this is not uncommon for agricultural watersheds. A study by Mueller and Spahr (2005) found that stream nitrate concentrations in 13% of agricultural watersheds exceeded this value. However, nitrate concentrations varied greatly between drainage events, even just a few days apart. Furthermore, median nitrate concentrations were similar to average nitrate concentrations, so the data was not skewed. No correlation between daily nitrate concentration and drainage volume was detected. Table 5.14 shows that cover crop growth also led to a decrease in the total mass of nitrate leached from the columns. After cover crop termination, macropores in the cover cropped soil columns created by plant roots were expected to allow for more nutrient loss because of the void left by decaying plant roots. Since the bare columns did not drain as anticipated during spring simulation, this hypothesis was not thoroughly investigated. However, it can be concluded that increased drainage results from macropore flow due to differences between drainage volumes from the cover cropped and bare columns after cover crop termination. Nitrogen concentrations in the few samples that were collected from the bare soil columns were very high. This could be because the drainage water was extracted by suction and the drainage volumes were much smaller than expected. Larger drainage volumes would have likely diluted the leachate and led to lower nutrient concentrations. Also, this experiment simulated a fall fertilizer application, but many farmers choose instead to apply fertilizer in the spring between cover crop termination and corn planting. Spring fertilizer application could increase the amount of N lost during this period through macropores created by cover crop roots, especially under wet weather conditions.

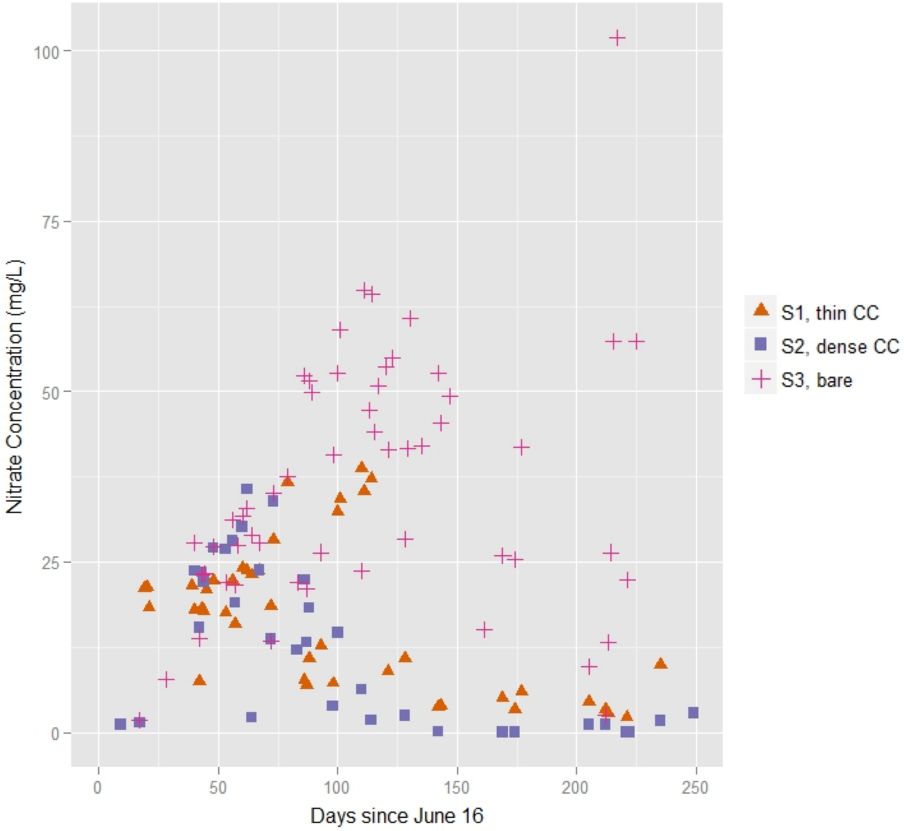


**Figure 5.12: Nitrate concentrations throughout the experimental period (S1 thin CC, S2 dense CC, S3 bare)**

**Table 5.13: Average and median nitrate concentrations in drainage water for different periods over the experimental duration**

| | Dense CC S2, S4 (mg $L^{-1}$) | | Thin CC S1 (mg $L^{-1}$) | | Bare S3, S5 (mg $L^{-1}$) | | $H_0$: $\mu_b = \mu_{cc}$ |
|---|---|---|---|---|---|---|---|
| | Avg. | Med. | Avg. | Med. | Avg. | Med. | |
| Experimental period (June – Feb.) | 11.3 | 10.0 | 16.9 | 17.9 | 38.2 | 34.2 | Reject |
| Before CC planting (June - July) | 14.1 | 16.1 | 18.0 | 18.3 | 17.6 | 23.2 | Fail to reject |
| CC growing season (Aug. – Jan.) | 11.7 | 10.8 | 17.3 | 16.7 | 38 | 37.1 | Reject |
| After CC termination (Feb.) | 1.0 | 0.4 | 6.1 | 6.1 | 62.8 | 57.4 | Reject |

**Table 5.14: Average total nitrate lost per soil column in drainage water for different periods over the experimental duration**

| | Dense CC S2, S4 (mg) | Thin CC S1 (mg) | Bare S3, S5 (mg) |
|---|---|---|---|
| Experimental period (June – Feb.) | 278 | 492 | 1427 |
| Before CC planting (June - July) | 186 | 177 | 219 |
| CC growing season (Aug. – Jan.) | 87 | 307 | 1102 |
| After CC termination (Feb.) | 4 | 8 | 106 |

More nitrate and total nitrogen were removed by the cover crops in soil columns S2 and S4 compared to S1, which is likely due to differences in cover crop growth. Soil column S2 and S4 had over 60% more total biomass than S1, with different proportions of oats to hairy vetch (HV). Soil column S1 had nearly equal amounts of oats and HV on a mass basis, while S2 and S4 had nearly 50% more oats than HV. No definite trend was seen in nitrate removal between the two cover crop species; however, HV did contain a higher mass percentage of total N than oats. An unknown amount of nitrogen in the HV biomass is from atmospheric $N_2$ fixation and not a result of uptake from the soil column. Total mass of nitrate, total N, and total C removed from each column due to each species of cover crop (without considering fixation of HV) are in Table 5.16. Soil samples were taken from soil columns S4 and S5 two weeks after cover crop termination, from S1 four weeks after termination, and S2 and S3 six weeks after termination. Four to six weeks after cover crop termination, some of the organic nitrogen from the decomposing cover crops had likely mineralized. So, it makes sense that the plow layers for S1 and S2 have higher nitrate levels than S4. However, S1 and S2 also lost some of this nitrate through wetting cycles during the period after termination. The bare columns had higher soil nitrate levels in the lower layers of the soil profile than the cover cropped columns. Cover cropping had no effect on final total N content of the soils, in either concentration or total mass. Masses of total N and P are calculated from soil concentration and bulk density, and therefore include errors from both of these measurements. Total mass of N and P was found to be very sensitive to variations in bulk density, so errors in total masses of nutrients may be large if bulk density measurements are not accurate. It was noted that bulk density measurements in the lower layers of S5 were taken too closely to the edge of the column, and some bentonite was incorporated into the soil core, decreasing the accuracy of the measurement. As a result, the calculated mass of total N in soil column S5 may not be representative of the true value.

When considering soil nitrate values in Table 5.15, a few observations should be considered. Before soil sampling, the bare soil columns were holding water, potentially leading to denitrification under flooded anaerobic conditions in the surface soil layer. Furthermore, conducting a study in a soil column raises the temperature of the lower soil compared to natural conditions, which may lead to unrealistically large amounts of microbial activity in those layers. These factors may have contributed to the low levels of nitrate in the plow layer of the bare soil columns and high levels of nitrate in the lower soil layers. It should also be noted that all of the nitrogen applied in the fall was supplied as nitrate, which is readily leached or taken up by plants and microbes. It is possible that applying a different form of nitrogen in the fall, such as ammonium, would lead to less nitrate leaching and higher nitrate levels throughout the soil profile in the spring, due to nitrification in the spring. Table 5.17 shows the experimental period total nitrogen balance calculated from soil and water samples. However, the extremely large amounts of total N in the soil initially, and errors associated with the analysis of total N, overshadow any effects that the cover crops may have had on total N amounts.

**Table 5.15: Nitrate in silt loam soil column profiles before and after cover crops**

| Depth (cm) | Initial (kg ha$^{-1}$) | Final S2, dense CC (kg ha$^{-1}$) | Final S4, dense CC (kg ha$^{-1}$) | Final S1, thin CC (kg ha$^{-1}$) | Final S3, bare (kg ha$^{-1}$) | Final S5, bare (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 0 - 14 | 32.1 | 5.4 | 0.8 | 6.7 | 3.9 | 1.7 |
| 14 - 28 | 6.0 | 2.0 | 4.5 | 5.8 | 10.4 | 6.0 |
| 28 - 42 | 3.1 | 0.4 | 2.1 | 0.1 | 8.1 | 3.4 |
| 42 - 56 | 0.5 | <DL | 0.1 | 1.2 | 6.4 | 1.1 |
| 56 - 70 | <DL | <DL | 0.1 | 1.1 | 6.7 | 2.9 |
| 70 + | <DL | 1.0 | 2.5 | 1.6 | --- | 5.8 |

**Table 5.16: Nitrogen and carbon content of cover crop biomass at termination**

| | $NO_3$-N (ppm) | $NO_3$-N (mg) | Total-N (%) | Total-N (g) | Total-C (g) | C:N |
|---|---|---|---|---|---|---|
| S1 oats | 53 | 1.1 | 2.00 | 0.4 | 9.0 | 22.2 |
| S1 HV | 53 | 1.1 | 3.68 | 0.8 | 9.9 | 12.7 |
| S1 total | --- | 2.2 | --- | 1.2 | 18.8 | 16.0 |
| S2 oats | 67 | 2.6 | 2.36 | 0.9 | 17.5 | 19.0 |
| S2 HV | 82 | 2.4 | 3.53 | 1.0 | 13.6 | 13.1 |
| S2 total | --- | 5.0 | --- | 2.0 | 31.1 | 15.9 |
| S4 oats | 53 | 2.0 | 1.95 | 0.7 | 16.7 | 22.8 |
| S4 HV | 96 | 2.8 | 4.85 | 1.4 | 13.4 | 9.3 |
| S4 total | --- | 4.8 | --- | 2.2 | 30.2 | 13.9 |

**Table 5.17: Experimental period total nitrogen balance**

| | Initial soil (mg) | Applied (mg) | Leaching loss (mg) | Crop removal (mg) | Final soil (mg) | Error (%) |
|---|---|---|---|---|---|---|
| S2, dense CC | 50970 | 1472 | 341 | 2000 | 41343 | 21 |
| S4, dense CC | 49680 | 1472 | 335 | 2200 | 45546 | 7 |
| S1, thin CC | 56132 | 1472 | 643 | 1200 | 45204 | 23 |
| S3, bare | 53551 | 1472 | 1825 | 0 | 41017 | 30 |
| S5, bare | 56132 | 1472 | 1652 | 0 | 51883 | 8 |

## 5.7 Calibration of HYDRUS-1D for Solute Transport

Optimized nitrate transport and reaction parameters and resulting simulations are in Table 5.18 and Figures 5.13 and 5.14. The model was very sensitive to changes in $K_d$ and not very sensitive to changes in $D_L$ or $\rho_b$. It was determined that the adsorption coefficient, $K_d$, values must be lower for columns with less and/or no cover in order for the model to sufficiently predict the experimental data ($K_{d,cc} > K_{d,b}$). Since larger volumes of water leached at a faster rate from the bare columns, compared to the densely cover cropped columns, it is likely that there was less opportunity for nitrate to adsorb to soil particles in the bare columns as well.

**Table 5.18: Solute transport and reaction parameters (*Optimized through calibration)**

| | $\rho_b$ (g cm$^{-3}$) | $D_L$ (cm)* | $K_{d,cc}$ (cm$^3$ g$^{-1}$)* | $K_{d,b}$ (cm$^3$ g$^{-1}$)* |
|---|---|---|---|---|
| 0 – 42 cm (Silt loam) | 0.93 | 1 | 0.4 | 0 |
| 42 – 84 cm (Silty clay loam) | 0.76 | 0.8 | 0.6 | 0.1 |
| 84 – 92 cm (Sand) | 1.5 | 50 | 0 | 0 |

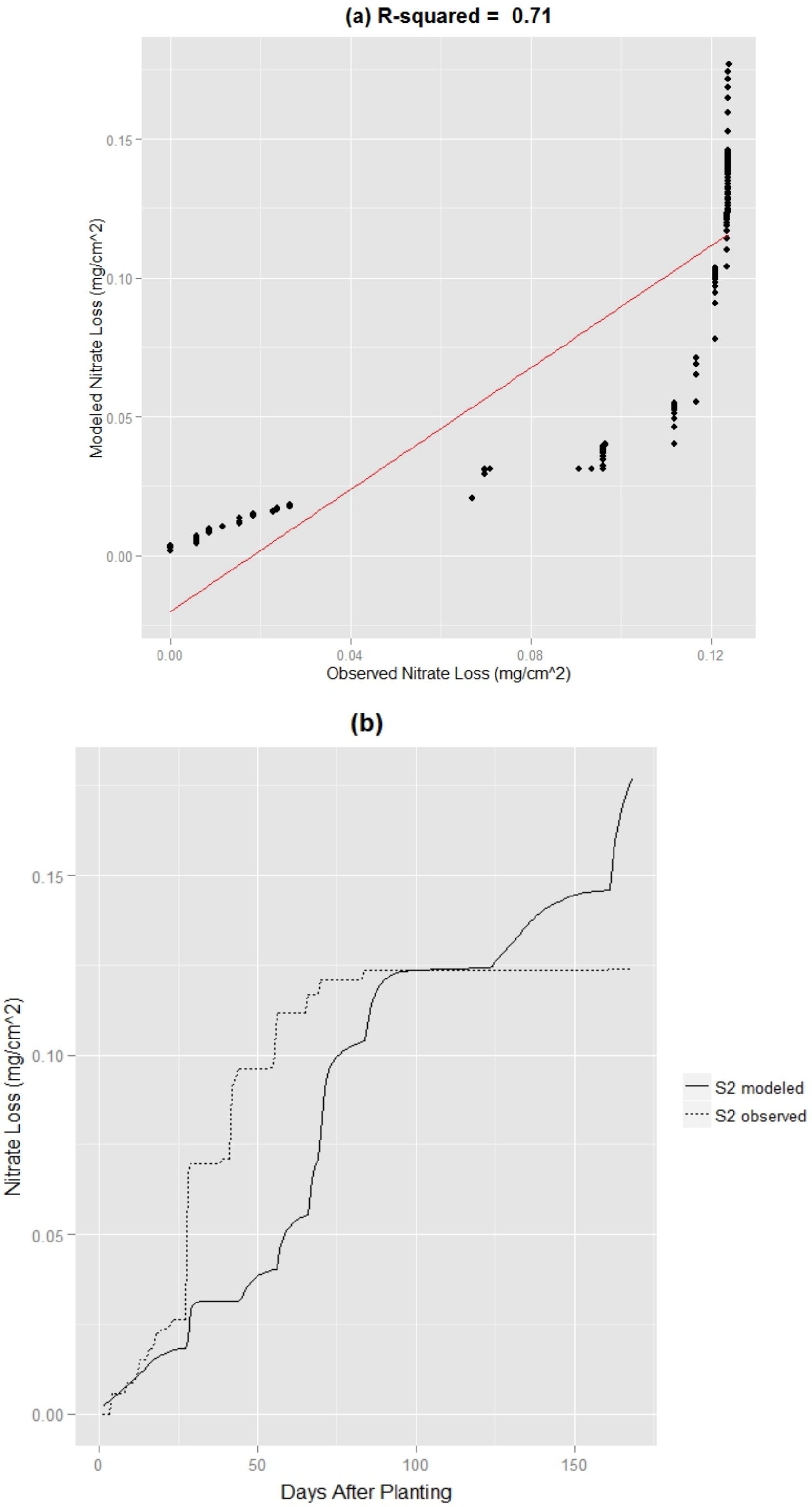


Figure 5.13: Solute parameter calibration of HYDRUS 1-D for soil column S2 (a) Observed and modeled cumulative nitrate flux values with linear fit ($y = 1.10x + 0.02$, $R^2 = 0.71$) and 95% confidence intervals; (b) Observed and modeled cumulative nitrate flux during growing season

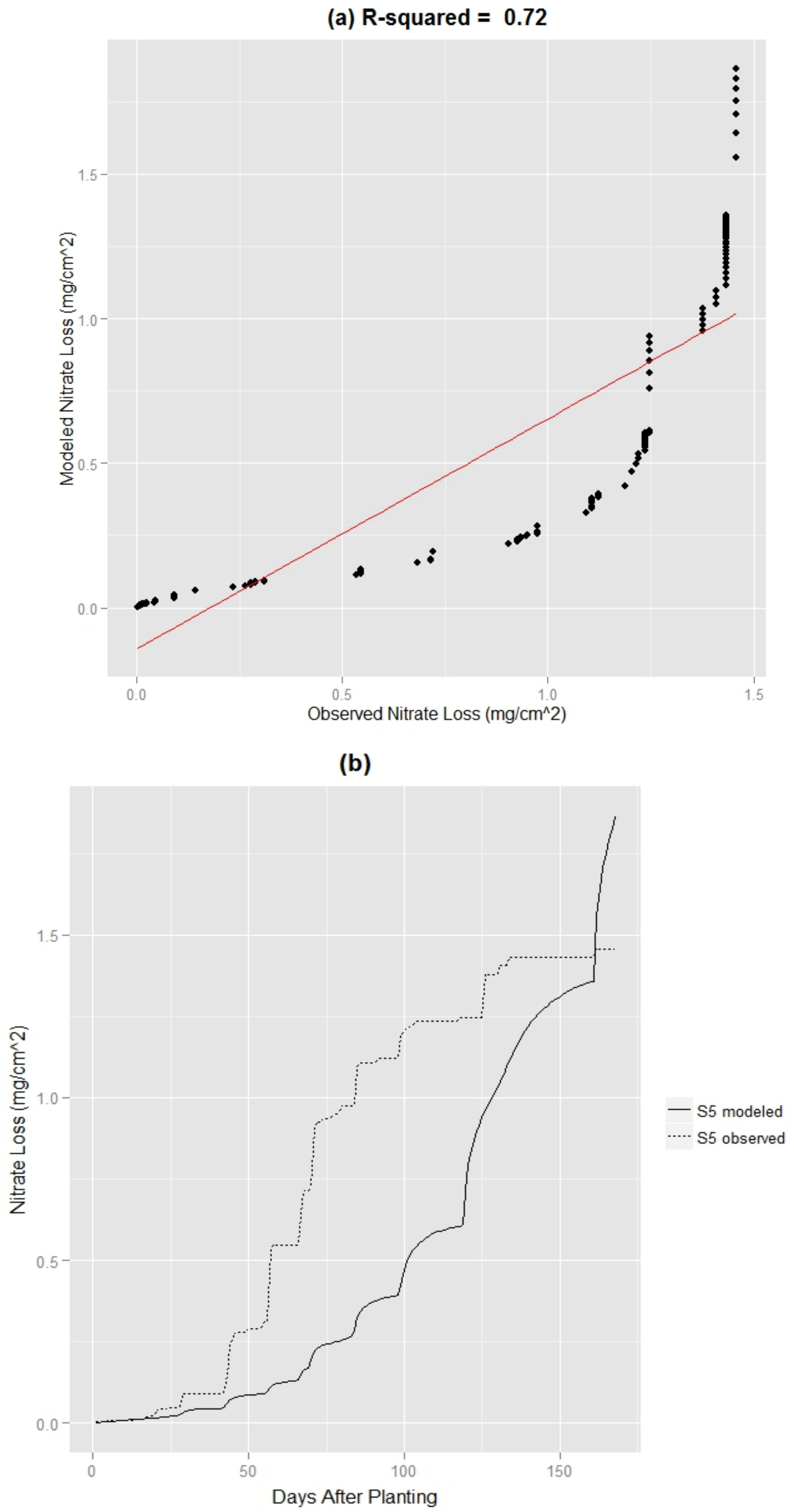


**Figure 5.14: Solute parameter calibration of HYDRUS 1-D for soil column S5 (a) Observed and modeled cumulative nitrate flux values with linear fit ($y = 0.80x - 0.14$, $R^2 = 0.72$) and 95% confidence intervals; (b) Observed and modeled cumulative nitrate flux during growing season**

Model performance statistics are detailed in Table 5.19. There is a large difference between the model prediction and the observed nitrate leaching towards the end of the growing season on January 13th, 2015 (161 days after cover crop planting), which leads to high $D_v$ values. The soil columns were left unmonitored for two weeks over the holiday season. The total precipitation over the two-week period was measured and added to the model at once on 01/13/15. So, the model shows a large leaching event after this precipitation occurred, but that is not realistic since the precipitation was actually applied over a period much longer than one day. Additionally, the precipitation amount and leachate from this period was difficult to collect and measure due to extremely cold temperatures and snow.

**Table 5.19: Model performance parameters for solute calibration of HYDRUS-1D for soil columns S2 and S5**

| | S2 | S5 |
|---|---|---|
| Coefficient of determination, $R^2$ | 0.71 | 0.72 |
| Weighted $R^2$ | 0.65 | 0.58 |
| Deviation of seasonal mass, $D_v$ | -43% | -28% |
| Nash-Sutcliffe efficiency, NS | 0.43 | 0.41 |

### 5.8 Validation of HYDRUS-1D for Solute Transport

For all columns, the model predicted a lag in nitrate leaching from the column, compared to experimental data. Multiple strategies were employed to adjust the model parameters to better fit the experimental data, including adjusting root growth and uptake parameters, including hysteresis, and using zero-order and first-order reaction parameters, but the shape of the modeled curve could not be shifted forward to fit the shape of the observed data curve. This could mean that factors that were not directly considered in the model, such as temperature dependent reactions and soil moisture content, could have large impacts on the results. Nitrification ceases below 10°C (Stanford et al., 1973), which describes the latter half of the cover crop growing season from October - January. However, at the beginning of the growing season, temperatures were around 22°C and optimal for nitrification (Stanford et al., 1973). While modeling a constant rate of nitrification was investigated, calibrating the model for temperature dependence of nitrate reactions was not attempted, due to a lack of soil temperature data, and could have potentially accounted for the lag in predicted nitrate leaching. HYDRUS-1D does have the capability to model heat transport through the soil column if soil temperature data were available to calibrate the model. The lag is exaggerated in the bare soil columns, which could mean that it is also partially attributed to errors in daily potential evaporation and hydraulic parameter estimates. The model's hydraulic parameters were calibrated using S2, a densely cover cropped column, only. So, limitations in the hydraulic parameter calibration for the bare columns, S3 and S5, are carried through to the simulation of nitrate transport. Similarly, errors in nitrate transport simulations for any soil column are a result of both water and solute transport model assumptions, settings, and parameters.

Table 5.20 shows the model performance for S1, S3, and S4 using the optimized solute transport and reaction parameters from S2 and S5. With the exception of the time period covering late December and early January, the HYDRUS-1D model was satisfactory in predicting cumulative nitrate leaching from soil columns S2 and S4. However, the model was less accurate in simulations of soil columns with no cover crop (S3 and S5). The model was unsatisfactory in predicting nitrate leaching from soil column S1 using the solute parameters calibrated from S2. For the same reason that bare and cover cropped columns had differing optimal $K_d$ values, the S1 soil column is not well predicted by the model using $K_{d,cc}$ coefficients optimized from soil column S2. S1 had less cover crop growth and more drainage than the other two cover cropped columns (S2 and S4), so less adsorption may have occurred. The negative NS efficiency for soil column S1 indicates that using the average value to predict cumulative nitrate leaching would be a better prediction than the model.

**Table 5.20: Model performance parameters for validation of HYDRUS-1D**

| | S4 | S1 | S3 |
|---|---|---|---|
| Coefficient of determination, $R^2$ | 0.84 | 0.95 | 0.68 |
| Weighted $R^2$ | 0.81 | 0.32 | 0.45 |
| Deviation of seasonal mass, $D_v$ | -20% | 54% | -26% |
| Nash-Sutcliffe efficiency, NS | 0.70 | -0.73 | 0.31 |

## 5.9 Phosphorus Balance

Phosphorus leaching was very minimal compared to nitrogen leaching from the soil columns, and P loads in drainage water were 2 – 3 orders of magnitude smaller than N loads. However, this was expected since P is known to be displaced mostly by adhesion to soil particles and erosion, rather than through tile drainage. Similar trends were demonstrated with P leaching as with N leaching. P leaching loads were similar before cover crop planting, with the exception of S1, which was higher possibly due to artificial macropore creation and larger irrigation volumes (Figure 5.15).

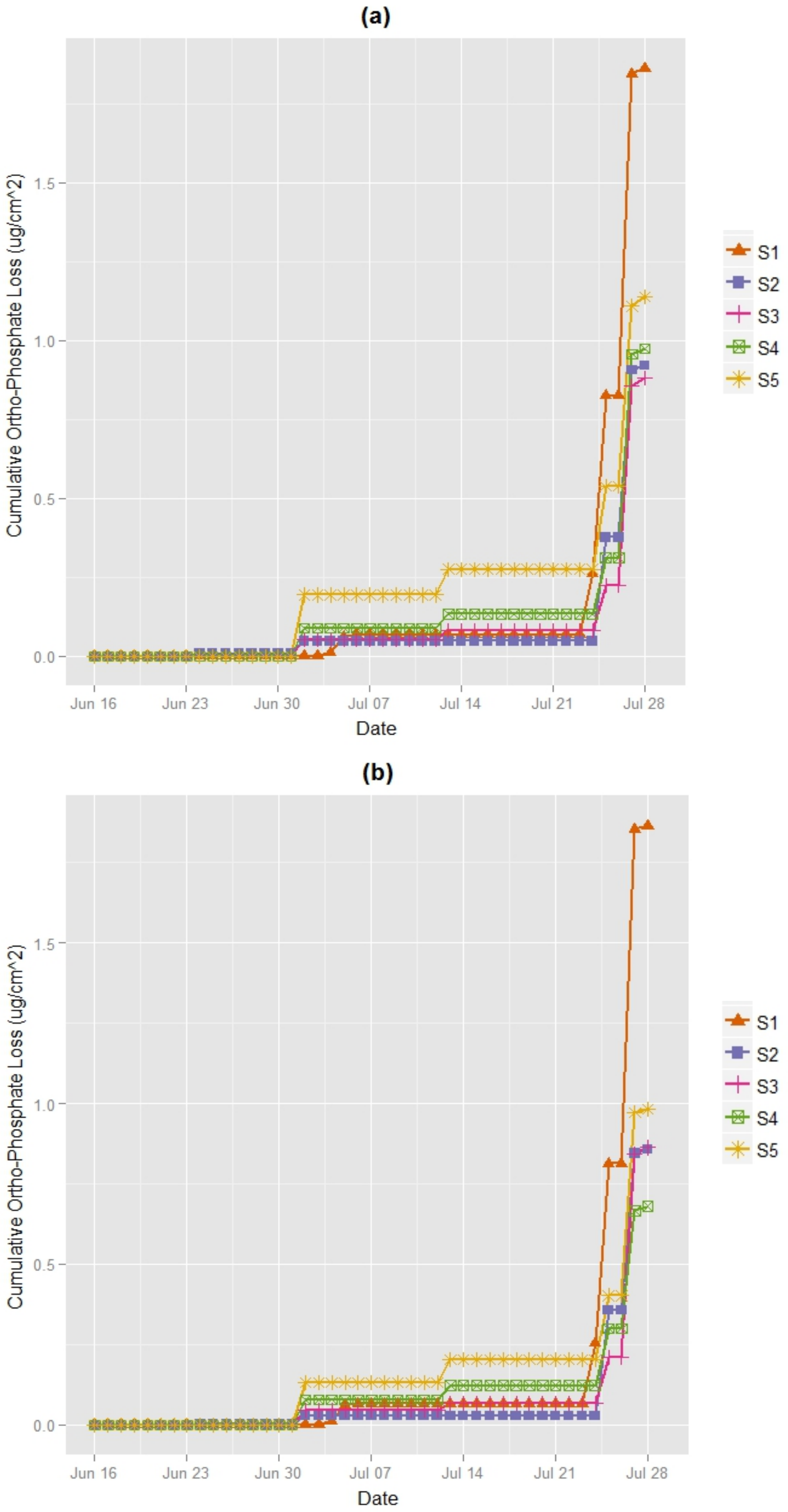


**Figure 5.15: Cumulative mass per unit area of (a) Total phosphorus and (b) Orthophosphate-P lost before cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

After cover crop planting, total P leached during the growing season increases with decreasing cover crop growth (Figure 5.16). However, the bare column S5 had only slightly higher total P and orthophosphate leaching loads than the cover cropped columns. Total P and orthophosphate concentrations in drainage water were similar between the cover cropped and bare columns, so leached P mass differences are due to the difference in drainage water volumes.

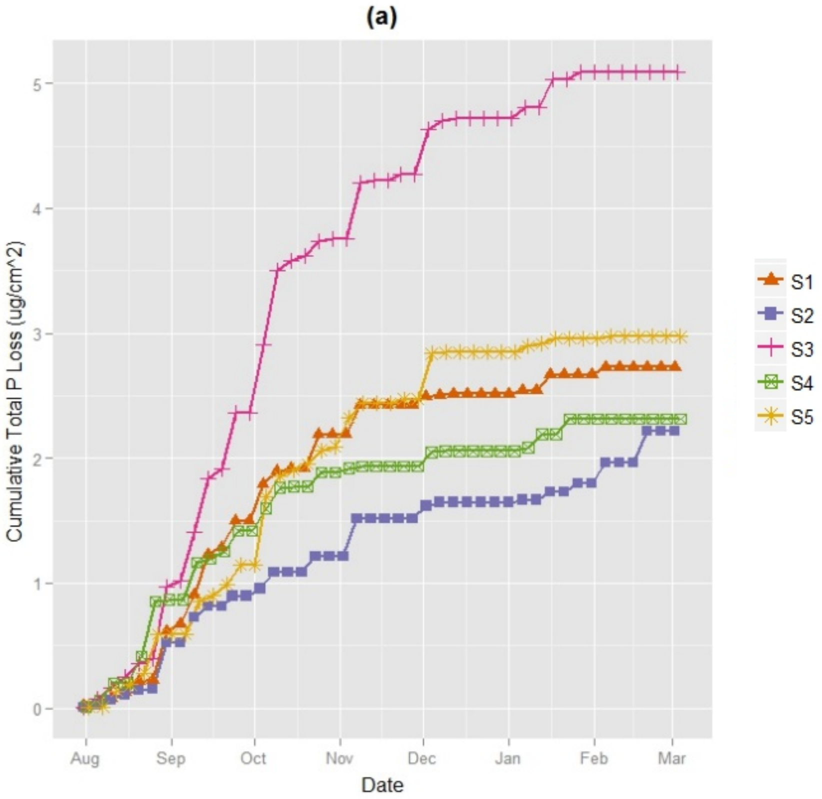


**Figure 5.16: Cumulative mass per unit area of (a) Total phosphorus and (b) Orthophosphate-P lost after cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

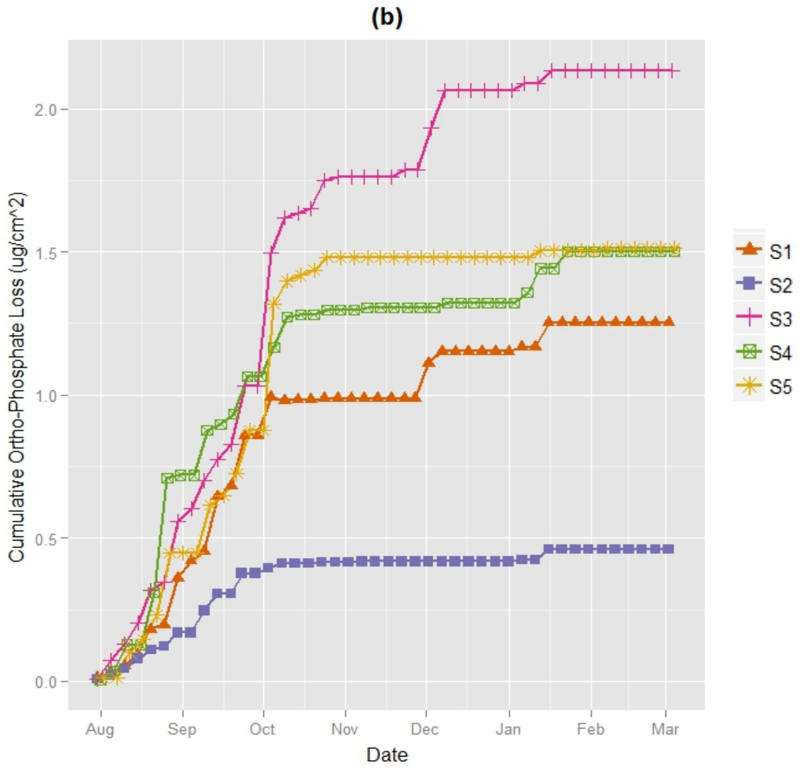


**Figure 5.16 (Continued from previous page): Cumulative mass per unit area of (a) Total phosphorus and (b) Orthophosphate-P lost after cover crop planting (S1 thin CC, S2 dense CC, S3 bare, S4 dense CC, S5 bare)**

The amount of available phosphate in the silt loam soils before and after cover cropping is in Table 5.21. An available phosphate mass balance was conducted based on soil and water data, but it should be noted that this is not a total P balance and that phosphorus changes forms due to microbial activity in soils (Table 5.23). Quantifying total P in biomass was not an option at the laboratory where plant nutrient analysis was conducted. The concentration of phosphate in oats was much higher than the concentration in HV (Table 5.22).

**Table 5.21: Available phosphate in silt loam soil column profiles before and after cover crops**

| Depth (cm) | Initial (kg ha$^{-1}$) | Final S2, dense CC (kg ha$^{-1}$) | Final S4, dense CC (kg ha$^{-1}$) | Final S1, thin CC (kg ha$^{-1}$) | Final S3, bare (kg ha$^{-1}$) | Final S5, bare (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 0 - 14 | 92.2 | 29.9 | 95.3 | 99.2 | 104.8 | 190.7 |
| 14 - 28 | 52.2 | 25.3 | 61.7 | 42.6 | 41.3 | 123.4 |
| 28 - 42 | 15.3 | 6.4 | 3.5 | 7.1 | 3.9 | 7.1 |
| 42 - 56 | 8.0 | 4.6 | 3.1 | 2.9 | 0.6 | 6.1 |
| 56 - 70 | 4.7 | 0.7 | 2.3 | 2.7 | 2.3 | 4.7 |
| 70 + | 6.3 | 1.0 | 3.6 | 2.3 | --- | 7.2 |

**Table 5.22: Phosphate content of cover crop biomass at termination**

|  | $PO_4$-P (ppm) | $PO_4$-P (mg) |
|---|---|---|
| S1 oats | 2396 | 48.4 |
| S1 HV | 592 | 12.5 |
| S1 total | --- | 60.8 |
| S2 oats | 2009 | 78.3 |
| S2 HV | 594 | 17.4 |
| S2 total | --- | 95.7 |
| S4 oats | 2462 | 92.8 |
| S4 HV | 1048 | 31.1 |
| S4 total | --- | 123.9 |

**Table 5.23: Experimental period available phosphate balance**

|  | Initial soil (mg) | Applied (mg) | Leaching loss (mg) | Crop uptake (mg) | Final soil (mg) | Changed form (mg) |
|---|---|---|---|---|---|---|
| S2. dense CC | 688 | 368 | 1.0 | 96 | 259 | 700 |
| S4, dense CC | 688 | 368 | 1.6 | 124 | 647 | 283.4 |
| S1, thin CC | 688 | 368 | 2.3 | 61 | 610 | 382.7 |
| S3, bare | 688 | 368 | 2.2 | 0 | 596 | 457.8 |
| S5, bare | 688 | 368 | 1.8 | 0 | 991 | 63.2 |

## 5.10 Summary of Data and Comparison to Literature

Table 5.24 contains data and estimates from both the soil column experiments detailed in this thesis and studies from the review of literature. This study found slightly lower P uptake than was found by Moller et al. (2007). This discrepancy could be attributed to differences in cover crop species (oats and HV compared to oilseed radish and vetch from Moller et al. (2007)). N returned to the soil by the cover crop was estimated from experimental data in two ways. The plow layer soil nitrate levels, after cover crop suppression with and without cover crops, were compared to estimate the amount of soil nitrate provided from the cover crop organic matter. However, this estimation was much lower than was found by Sullivan and Andrews (2012). Sullivan and Andrews (2012) estimated that about half of the total N in cover crop biomass would be returned to the soil. Using this approximation and data from the soil column experiment, the estimation of plant available N (PAN = nitrate + ammonium) from the cover crop mixture is comparable to the literature, considering the difference in cover crop biomass. However, soil ammonium was not measured in this study, so it is not possible to quantify PAN directly from experimental data. Soil nitrate levels in the soil column experiment were very low compared to a field study by Lacey and Armstrong (2012). These differences may be attributed to differences in experimental methods. N was applied to the soil columns as $KNO_3$, whereas Lacey and Armstrong (2012) applied N in the form of anhydrous ammonia. Nitrate is readily leached through the soil profile and lost, but anhydrous ammonia is first converted to ammonium, which is more likely to be immobilized to organic N than to be lost through leaching. When temperatures increased in the spring, organic N in the soil may have been mineralized and then converted to nitrate, leading to higher nitrate levels in the field experiment than in the soil column. Nitrate concentration and load reductions in drainage water were higher in the soil column than were observed in the literature (Kaspar et al., 2007; Kaspar et al, 2012;

Malone et al., 2014). In addition to the form of N applied to the columns, this could also be partially due to the early planting date of the cover crops in the soil column experiment. Typically, cover crops would not be planted until late August or September, leaving a smaller window for nitrate leaching to occur before nitrification slows due to low temperatures and ground freezing. Also, the soil columns represent the ground directly above a tile drain, so the difference between nitrate leaching from cover cropped and bare soil may be exaggerated.

## Table 5.24: Comparison of experimental data to literature

| | **This study** | **Literature** | **Source** |
|---|---|---|---|
| P uptake by vetch mixture | 8.3 – 17.0 kg $ha^{-1}$<br>($PO_4$-P, oats and 43% – 51% HV) | 20.7 kg $ha^{-1}$<br>(oilseed radish and 90% vetch, silt loam) | Moller et al., 2007 |
| N returned to soil by cover crop | 4.6 – 5.9 kg $ha^{-1}$<br>(extra soil $NO_3$-N after 4 – 6 wks,<br>5650 – 9325 kg $ha^{-1}$ oats/HV)<br>82 - 151 kg $ha^{-1}$<br>(est. PAN* from 50% TN in CC) | 45 – 78 kg $ha^{-1}$<br>(PAN* after 10 wks,<br>3350 kg $ha^{-1}$ rye/vetch, silt loam & sandy loam) | Sullivan and Andrews, 2012 |
| Soil nitrate without cover crop | 3.5 – 7.1 kg $ha^{-1}$ | 110 kg $ha^{-1}$ | Lacey and Armstrong, 2012 |
| Depth of highest soil nitrate concentration | 0 – 14 cm (CC after 4 – 6 wks)<br>14 – 28 cm (CC after 2 wks, bare) | 50 cm (Pure stand rye, clover, & bare) | Lacey and Armstrong, 2012 |
| Soil nitrate after cover crop | 1.5 – 2.8 kg $ha^{-1}$<br>(after 2 – 6 wks, oats/HV) | 90 & 100 kg $ha^{-1}$<br>(after 4 wks, pure stand rye & clover) | Lacey and Armstrong, 2012 |
| Percentage of applied nitrate lost in drainage water | 18% – 33% (oats/HV) | 12% (rice, sandy loam) | Jha, 2014 |
| Nitrate concentration reduction in drainage water | 54% – 69% (oats/HV) | 24% & 48% (pure stand oats & rye, silt loam) | Kaspar et al., 2012 |
| Nitrate loss reduction (mass/load) | 72% – 92% (oats/HV) | 61% & 0% (rye in 2007 & 2012, silt loam)<br>24% – 43% (rye, est. from RZWQM) | Kaspar et al., 2007<br>Kaspar et al., 2012<br>Malone et al., 2014 |

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Experimental Methods Development

Many valuable outcomes, both expected and unexpected, have been realized throughout the process of this soil column experiment. Methods were established to construct and monitor repacked soil columns in an outdoor environment for nutrient transport with and without cover crops. Findings from both literature and experimental trials suggest that adding granular bentonite around the edges of a soil column is an effective strategy for eliminating sidewall flow. Bentonite was also used to patch cuts in the inner wall of the PVC columns, which occurred twice and noticeably altered the drainage volume. However, the bentonite should be added as a mixture with soil or sand and only a very small amount is needed, as the clay expands 4 – 5 times its initial size when exposed to moisture. The extreme expansion of bentonite may have been a factor in the decreased drainage ability of the soil columns. In the initial method development trials, bentonite was not used and the soil columns did not have any strikingly obvious sidewall flow issues, but a direct comparison of the two techniques was not conducted.

The principal flaw in the soil column experimental design was the creation of impenetrable layers in the sandy loam columns and the silt loam columns during spring simulation. This unexpected behavior of the columns to hold water and inhibit infiltration and drainage prevented the collection of realistic leachate samples in the two cases described. In large part, the existence of macropores would have resolved this issue, which is a major limitation of repacked soil columns. The use of deionized water during the column settling and spring simulation periods may have increased clay dispersion in the columns. Soils with a high clay content may be more susceptible to clogging because very fine soil particles can block pores and prevent water movement. The rapid re-wetting of the soil columns, dispersed clay particles, and/or rapid thawing process may have also contributed to the lack and collapse of soil structure. The low organic matter and lack of natural structure also likely contributed to the low infiltration rates of the sandy loam columns. In future soil column studies, tap water, instead of deionized water, should be used for irrigation. Additionally, a great deal of care should be taken to uniformly repack the soil columns to a realistic bulk density and allow gradual settling to establish natural flow paths. Achieving a certain bulk density can be done by measuring the weight of the soil in each layer of the column and packing the layers to the volume corresponding to the wanted density. The addition of earthworms may also be one strategy to establish natural macropores in repacked columns.

## 6.2 Water and Nutrient Transport

Although three exact replicates were planned for the silt loam cover cropped columns, soil column S1 had statistically lower biomass growth than S2 and S4. The lower total biomass growth stemmed from establishment issues early on in the experiment due possibly to drainage issues and/or nutrient imbalances. However, this allowed for comparison of effects from both densely and thinly cover cropped stands.

Before cover crop planting, the five silt loam soil columns had statistically similar leachate volumes and concentrations of nitrogen and phosphorus. During the cover crop growing season, both densely and thinly cover cropped columns had less leachate volume than the bare columns, which is due to the increased water uptake and subsequent transpiration of the water through the plant leaves. Nitrate and total N mass loads and concentrations in the drainage water leached from the bare columns was significantly higher at a 95% confidence limit than from the cover cropped columns. Additionally, the thinly cover cropped columns showed significantly higher N concentrations and loads in leachate than the densely cover cropped columns. Soil columns S2 and S4 had 65% more biomass growth than S1, which led to an over 3.5 times reduction in cumulative nitrate load while cover crops were present August – January. Additionally, soil columns S2 and S4 reduced cumulative nitrate loads compared to the bare columns by 92% during the cover crop growing season. The percentage of $NO_3$-N in total N in the drainage water was not affected by cover cropping and was around 80 – 90% nitrite/nitrate for all silt loam columns both before and during cover cropping. No definite conclusions can be drawn about nitrogen and phosphorus leaching from the columns after cover crop termination due to the impermeable layers that formed in the bare soil columns during spring simulation. However, it can be concluded that drainage volume due to macropore flow is substantial.

Four to six weeks after cover crop termination, soil nitrate levels were on average 3.3 kg ha$^{-1}$ higher in the plow layer (0 – 14 cm) of the cover cropped columns, compared to the bare columns. However, nitrate levels in the 14 – 28 cm layer were on average 4.3 kg ha$^{-1}$ higher in the bare columns. Cover crops, like any crop, take up nitrogen by way of roots from lower layers of the soil profile and redistribute the nitrogen to the plow layer upon biomass decomposition by microbes. Two weeks after cover crop termination, soil column S4 had lower levels of nitrate in the plow layer than the bare columns. This confirms that cover crops should be terminated at least four to six weeks prior to cash crop planting in order to realize the benefits of nitrogen redistribution at the time of cash crop seed germination and the initial growth period. Nitrogen will continue to be made available to the cash crop as the cover crop decomposes. If cover crops are terminated longer than 4 – 6 weeks before cash crop planting, some of the nitrogen from the decomposing cover crops may be prone to leaching losses. Also, nitrate levels in the lower layers of the soil profile were higher in the bare columns compared to the cover cropped columns. When no crop is present, nitrate in the lower levels of the profile is readily leached, and so this nitrate would have likely leached had spring simulation been carried out as planned. Total nitrogen (ammonia + nitrite/nitrate + organically bound N) is so large in the silt loam soils used in this experiment that measurement errors were larger than the effect that cover cropping had on total nitrogen supplies. Nitrate was only a very small fraction, less than 0.5%, of the total N resources.

Phosphorus leaching from the soil columns was 2 – 3 orders of magnitude less than nitrogen leaching. However, the drainage water from the cover cropped columns contained both lower orthophosphate and total P concentrations and loads in August – January compared to the bare columns. Oat biomass had higher concentrations of phosphate than the hairy vetch, which shows that oats would be more effective in reducing orthophosphate leaching than hairy vetch.

### 6.3 HYDRUS-1D Model Simulations of Water and Nitrate Transport

HYDRUS-1D was sufficiently calibrated and validated for water transport for all silt loam soil columns. Weighted R-squared values, which take into account both the coefficient of determination and the slope of the regression line, were over 0.7, and the deviation between the modeled and actual season-long cumulative bottom flux was less than 20% for all silt loam columns. Additionally, Nash-Sutcliffe efficiencies for all columns were 0.7 and higher. The hydraulic parameter calibration was performed with a densely cover cropped column and then all plant growth parameters were removed to simulate the bare columns. While the model performed satisfactorily, it did under predict cumulative bottom flux for the bare columns. In other words, the model under-predicted the effect of the cover crop on the bottom flux. This could be due to errors in estimations of root growth, uptake, and/or transpiration.

The model was then calibrated for solute (nitrate) transport and reaction parameters, again using S2. The under-prediction of bottom flux in the bare columns was carried over in the model when adding the simulation of nitrate transport. However, the amount of under estimation increased beyond an acceptable level in the case of nitrate leaching. Data from soil column S1, which had less cover crop growth than S2, was correlated very well with the model for water bottom flux, but very poorly for nitrate leaching. This suggests that errors in parameters having to do with biomass growth, and not considered for water transport, are contributing to the under-prediction of nitrate transport in the cases of less or no cover crop growth. The nitrate model was very sensitive to the adsorption isotherm coefficient, $K_d$, and re-calibrating this parameter for the bare column S5 increased the correlation between modeled and observed data for the bare columns. It is possible that less adsorption occurred in the bare soil columns because adsorption increases with contact time, which decreased with large fluxes of water through the column, as was the case in the bare soil columns. Even with re-calibrated adsorption coefficient values, the lag in the prediction curve for nitrate values prevented the model from providing an acceptable fit between actual and simulated values for the bare columns. While all of the columns had acceptable R-squared values, only the two densely cover cropped columns (S2 and S4) were modeled with an acceptable weighted R-squared value above 0.6. Experimental data from S1 was not acceptably validated with the model solute reaction and transport parameters optimized with S2.

## 6.4 Recommendations for Future Work

Cover crops may be a method of reclaiming overly compacted soils. In this study, cover crops were not planted in the water-logged sandy loam columns. However, if cover crops could be established in these soil columns, the ability of cover crops to increase soil drainage could be studied further. Possible methods would be to cover the tops of the columns to prevent flooding or drill holes in the sides of the columns to allow drainage during cover crop establishment and then plug the holes during the experiment.

Although estimation methods of many parameters exist in HYDRUS-1D, any additional parameters that can be measured experimentally would lead to more accurate simulations of the effect of cover cropping on nitrate transport. When simulating both water and nitrate transport, the model predicted that plant uptake would have a smaller effect on nitrate leaching than was determined experimentally. Future experiments to learn more specifically about the mechanisms driving cover crop root water and nitrogen uptake could be examined by looking more closely at growth measurements. In particular, adjusting the experimental setup to collect root growth and uptake data would be a valuable input for the model. For example, root growth could be monitored using additional soil columns that would not be used for the leaching experiments and could be disturbed to collect root data. Also, measuring LAI and correlating the data with canopy cover would be a useful input for HYDRUS-1D. Another improvement to the experimental setup would be to install collection tubes along the side of the soil columns to collect nitrate concentrations and pressure head throughout the soil profile.

It would be interesting in future controlled soil column studies to attempt to quantify some of the aspects of the nitrogen cycle that were not directly investigated in this study. Specifically, the quantitative effects of individual processes such as nitrogen fixation, nitrification, and denitrification under cover cropping versus bare ground could be studied by collecting data on ammonium and nitrogen gasses within and exiting the soil profile.

The curve of simulated nitrate leaching predicted a lag in the peak nitrate load. Zero-order and first-order reactions throughout the growing season were found to be inadequate in predicting a more realistic nitrate leaching curve. Nitrification and denitrification processes are heavily temperature dependent. For this reason, these reactions should only be considered above 10°C. In future studies, measuring soil temperature and incorporating temperature dependence of ammonium/nitrate conversion could lead to a more thorough understanding of the processes affecting nitrate leaching to drainage water.

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# APPENDIX A

# ADDITIONAL NITROGEN DATA

### Table A.1: Average and median total N concentrations in drainage water for different periods over the experimental duration

| | Dense CC S2, S4 (mg $L^{-1}$) | | Thin CC S1 (mg $L^{-1}$) | | Bare S3, S5 (mg $L^{-1}$) | |
|---|---|---|---|---|---|---|
| | Avg. | Med. | Avg. | Med. | Avg. | Med. |
| Experimental period (June – Feb.) | 14.0 | 13.9 | 19.9 | 19.9 | 46.6 | 42.5 |
| Before CC planting (June - July) | 17.0 | 19.4 | 20.6 | 20.4 | 19.8 | 25.3 |
| CC growing season (Aug. – Jan.) | 14.4 | 14.7 | 20.5 | 20.8 | 46.7 | 44.4 |
| After CC termination (Feb.) | 2.6 | 2.1 | 8.0 | 8.0 | 75.3 | 67.9 |

### Table A.2: Average total N lost per soil column in drainage water for different periods over the experimental duration

| | Dense CC S2, S4 (mg) | Thin CC S1 (mg) | Bare S3, S5 (mg) |
|---|---|---|---|
| Experimental period (June – Feb.) | 338 | 643 | 1739 |
| Before CC planting (June - July) | 205 | 261 | 245 |
| CC growing season (Aug. – Jan.) | 125 | 370 | 1368 |
| After CC termination (Feb.) | 8 | 11 | 126 |

### Table A.3: Total N in silt loam soil column profiles before and after cover crops

| Depth (cm) | Initial (kg $ha^{-1}$) | Final S2, dense CC (kg $ha^{-1}$) | Final S4, dense CC (kg $ha^{-1}$) | Final S1, thin CC (kg $ha^{-1}$) | Final S3, bare (kg $ha^{-1}$) | Final S5, bare (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|
| 0 - 14 | 4583 | 2541 | 3249 | 3541 | 2707 | 3541 |
| 14 - 28 | 3416 | 2749 | 2999 | 2291 | 2416 | 2832 |
| 28 - 42 | 1832 | 1790 | 2124 | 1624 | 1540 | 1790 |
| 42 - 56 | 1332 | 1540 | 1624 | 1207 | 1790 | 1374 |
| 56 - 70 | 2124 | 1332 | 1499 | 1082 | 1249 | 1499 |
| 70 + | 874 | 1290 | 1290 | 1165 | --- | 1290 |

### Table A.4: Experimental period $NO_3$-N balance in silt loam columns

| | Initial soil (mg) | Applied (mg) | Leaching loss (mg) | Crop removal, some mineralized (mg) | Final soil (mg) | Changed form (mg) |
|---|---|---|---|---|---|---|
| S2, dense CC | 166.8 | 1472 | 265 | 5 | 34 | 1335 |
| S4, dense CC | 166.8 | 1472 | 291 | 5 | 37 | 1306 |
| S1, thin CC | 166.8 | 1472 | 492 | 2 | 70 | 1075 |
| S3, bare | 166.8 | 1472 | 1454 | 0 | 150 | 35 |
| S5, bare | 166.8 | 1472 | 1400 | 0 | 90 | 149 |

### Table A.5: $NO_3$-N in sandy loam soil column profile initially

| Depth (cm) | Initial (kg $ha^{-1}$) |
|---|---|
| 0 - 14 | 53 |
| 14 - 28 | 14 |
| 28 - 42 | 9 |
| 42 - 56 | 7 |
| 56 - 70 | 5 |
| 70 + | 2 |

# APPENDIX B

# ADDITIONAL PHOSPHORUS DATA

**Table B.1: Average and median total P concentrations in drainage water for different periods over the experimental duration**

| | Dense CC S2, S4 (mg $L^{-1}$) | | Thin CC S1 (mg $L^{-1}$) | | Bare S3, S5 (mg $L^{-1}$) | |
|---|---|---|---|---|---|---|
| | Avg. | Med. | Avg. | Med. | Avg. | Med. |
| Experimental period (June – Feb.) | 0.17 | 0.13 | 0.14 | 0.12 | 0.12 | 0.11 |
| Before CC planting (June - July) | 0.11 | 0.08 | 0.10 | 0.09 | 0.13 | 0.10 |
| CC growing season (Aug. – Jan.) | 0.19 | 0.16 | 0.16 | 0.12 | 0.13 | 0.12 |
| After CC termination (Feb.) | 0.10 | 0.09 | 0.07 | 0.07 | 0.05 | 0.04 |

**Table B.2: Average total P lost per soil column in drainage water for different periods over the experimental duration**

| | Dense CC S2, S4 (mg) | Thin CC S1 (mg) | Bare S3, S5 (mg) |
|---|---|---|---|
| Experimental period (June – Feb.) | 2.3 | 3.4 | 3.7 |
| Before CC planting (June - July) | 0.7 | 1.4 | 0.7 |
| CC growing season (Aug. – Jan.) | 1.4 | 1.9 | 2.9 |
| After CC termination (Feb.) | 0.2 | <DL | 0.1 |

### Table B.3: Average and median orthophosphate-P concentrations in drainage water for different periods over the experimental duration

| | Dense CC S2, S4 (mg $L^{-1}$) | | Thin CC S1 (mg $L^{-1}$) | | Bare S3, S5 (mg $L^{-1}$) | |
|---|---|---|---|---|---|---|
| | Avg. | Med. | Avg. | Med. | Avg. | Med. |
| Experimental period (June – Feb.) | 0.10 | 0.08 | 0.09 | 0.07 | 0.06 | 0.05 |
| Before CC planting (June - July) | 0.08 | 0.06 | 0.09 | 0.07 | 0.10 | 0.07 |
| CC growing season (Aug. – Jan.) | 0.11 | 0.09 | 0.10 | 0.07 | 0.06 | 0.05 |
| After CC termination (Feb.) | 0.01 | <DL | <DL | <DL | 0.01 | <DL |

### Table B.4: Average total orthophosphate-P lost per soil column in drainage water for different periods over the experimental duration

| | Dense CC S2, S4 (mg) | Thin CC S1 (mg) | Bare S3, S5 (mg) |
|---|---|---|---|
| Experimental period (June – Feb.) | 1.3 | 2.3 | 2.0 |
| Before CC planting (June - July) | 0.6 | 1.4 | 0.7 |
| CC growing season (Aug. – Jan.) | 0.7 | 0.9 | 1.3 |
| After CC termination (Feb.) | <DL | <DL | <DL |

### Table B.5: Total P in silt loam soil column profiles before and after cover crops

| Depth (cm) | Initial (kg $ha^{-1}$) | Final S2, dense CC (kg $ha^{-1}$) | Final S4, dense CC (kg $ha^{-1}$) | Final S1, thin CC (kg $ha^{-1}$) | Final S3, bare (kg $ha^{-1}$) | Final S5, bare (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|
| 0 - 14 | <DL | 251 | 4233 | 1148 | 2332 | 3695 |
| 14 - 28 | 332 | 2906 | <DL | 1955 | 395 | 466 |
| 28 - 42 | 430 | 1148 | 1758 | 1614 | 861 | <DL |
| 42 - 56 | 386 | 1435 | 1327 | 735 | 1471 | 646 |
| 56 - 70 | 529 | 215 | 1040 | 726 | 1148 | 897 |
| 70 + | 556 | 2116 | 1327 | 1148 | --- | 179 |

**Table B.6: Available phosphate in sandy loam soil column profile initially**

| Depth (cm) | Initial (kg $ha^{-1}$) |
|---|---|
| 0 - 14 | 92 |
| 14 - 28 | 72 |
| 28 - 42 | 42 |
| 42 - 56 | 52 |
| 56 - 70 | 26 |
| 70 + | 33 |