THE EFFECTS OF WATER TABLE MANAGEMENT ON EDGE-OF-FIELD WATER QUALITY AND COMPARING SOIL PHYSICAL AND HYDRAULIC PROPERTIES FROM AN UNDRAINED, CULTIVATED ROW CROP FIELD TO A REMNANT PRAIRIE IN SOUTHWEST MINNESOTA

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CHAPTER 1. A History and Introduction to Drainage and Water Table Management

INTRODUCTION

The history of drainage in Minnesota began in 1858 with the passage of Chapter 73 which allowed private corporations to be formed for the purpose of draining lands and creating water privileges. Minnesota's first comprehensive drainage law was passed in 1887. This 121-year-old law established a process that is similar to the approaches still used in Minnesota state drainage law today. Between 1858 and 1920 drainage was encouraged to promote increased crop yield and reduced yield variability, increased land value, improved public highways, increased tonnage and decreased maintenance costs of transportation companies, and reduce public health risks. Between 1920 and 1960 societal views concerning land drainage began to change. Water conservation became more popular because of the drought of the 1930's. From 1960 to the present marks a period of conservation and awareness of the consequences due to drainage. By 1980 the progress of drainage had dramatically slowed (Fausey et al., 1995), due in part to the increase in public concerns about drainage impacts on the environment and the movement of our population and economy towards urban areas and away from rural areas (Wilson, 2004).

1. Drainage

Without subsurface drainage, many poorly drained soils throughout the upper Midwest would not be considered some of the most agriculturally productive soils in the world (Fausey et al., 1995; Sands et al., 2003; Skaggs and Chescheir III, 2002; Stone et al., 1992; Zucker and Brown, 1998). In Minnesota, approximately 40% of all cropland is drained (Zucker and Brown, 1998) and the practice mainly consists of subsurface drainage.

Water table management practices include any assortment of surface drainage, subsurface drainage, controlled drainage or subirrigation that influence the level of the shallow water table (Evans et al., 1991) and allow the owner/operator to more intensively manage their fields to increase yields and improve production efficiency on land already in cultivation while trying to reduce the impact agricultural drainage water has on the environment. Water table management through conventional subsurface drainage is accomplished by burying pipe, which can be made out of clay, concrete, or more commonly used today, perforated, corrugated plastic tubing (Zucker and Brown, 1998), beneath the soil surface in a parallel, herringbone or random pattern (Appelboom and Fouss, 2006) at a specified depth and grade (Lalonde et al., 1996; Sands, 2001). Excess soil water is removed from the crop root zone and transported away from the field to a ditch, stream, or river. Removal of excess water lowers the water table and enables aeration of the soil to occur. This aeration allows for the soil to dry and warm faster permitting favorable conditions for seedbed preparation, planting, harvesting and other field operations (Appelboom and Fouss, 2006; Dinnes et al., 2002; Evans et al., 1992; Evans et al., 1995; Fausey et al., 1995; Shirmohammadi, et al., 1995; Skaggs et al., 1994; Stone et al., 1992; Tan et al., 2002; Wesström et al., 2001; Zucker and Brown, 1998). The number of days available for planting and harvesting crops as well as the yield can increase (Fausey et al., 1995) when agricultural land is drained. Drainage also protects plants from excessive soil water conditions during the growing season (Evans et al., 1992; Fausey et al., 1995; Shirmohammadi et al., 1995; Skaggs et al., 1994; Tan et al., 2002; Zucker and Brown, 1998). In some cases, excess drainage may reduce soil water available to plants and increase drought stress during unusually dry periods (Evans and Skaggs, 1989; Evans et al., 1992). In addition, more drainage than necessary may leach fertilizer nutrients and other agricultural products from the soil, transporting them to surface waters where they may lead to water quality impairments.

1.1. Environmental Consequences of Conventional Drainage

Some of the world's most valuable agricultural production occurs on poorly drained soils that are artificially drained. Artificial drainage has gained a reputation as being a major contributor of harmful off-site impacts. The processes and mechanisms that control the volume and quality of drainage water leaving agricultural land is very complex. Land use, manure and nutrient management practices, drainage system design, antecedent soil moisture, soil properties, climate, rainfall intensity, watershed size, the location of drainage improvements in relation to the point of impact assessment, and characteristics of the pollutants are involved in complex interactions that impact water quantity and quality (Drury et al., 1996; Skaggs et al., 1994; Wesström et al., 2004; Zucker and Brown, 1998).

Artificially drained soils are often located adjacent to or are hydrologically connected to environmentally sensitive surface waters that provide natural drainage outlets. Artificial subsurface (tile) drainage has been identified as one of the primary sources of nitrate entering surface water (Randall and Goss, 2001). Subsurface drainage has also been associated with the delivery of sediment, particulate and dissolved phosphorus, pesticides, and coliform bacteria to surface waters (Carpenter et al., 1998; Scott et al., 1998; Gilliam et al., 1999; Kladivko et al., 1999; Addiscott et al., 2000; Randall and Goss, 2001; Jamieson et al., 2002; Davic et al., 2003). Also, the removal of wetlands, through drainage, have caused a reduction in habitat for wildlife, disruption of flyways for migrating birds, and removed natural filters that cleanse drainage water from adjacent lands (Skaggs et al., 1994; Zucker and Brown, 1998).

There are five general trends that artificial subsurface drainage has been found to effect: (1) increases in soluble nutrient losses, (2) reductions in surface runoff, (3) decreases in sediment and other nutrient losses – phosphorus, organic nitrogen and pollutants attached to sediments, (4) increases in the total annual outflow of water from drained fields, and (5) increases in peak outflow rates when compared with natural, undeveloped conditions.

Research has shown that in regions where a large percentage of the agricultural land is artificially drained, disproportionately large amounts of nitrate (NO_3^-) can be transported to surface water (Fenelon and Moore, 1998; Jaynes et al., 1999; David and Gentry, 2000). Nonpoint source pollution of surface waters by nitrogen has been well documented in the USA (Gilliam et al., 1999; Randall and Goss, 2001). Excess nitrogen in surface water contributes to eutrophication in lakes, streams, and rivers, hypoxia in coastal estuaries, and the need for some municipalities to purchase expensive drinking water purification systems. Skaggs et al., 1994 performed an extensive literature review on hydrologic and water quality impacts of agricultural drainage and noted the increase in soluble nutrient losses is to be expected because the modification in land use, changes the route and rate of water and how it is removed from the field. It was also concluded that the degree of increase in nutrient losses was dependent upon nutrient management practices, soil aeration, preferential flow, and type of soil and drainage because these factors influence nutrient movement. Kladivko et al., 1991 found that most (usually > 90%) of the nitrate losses in drainage water occurred during the nongrowing season (fall and late winter to early spring with thawing).

Artificial subsurface drainage has resulted in reductions in surface runoff because the water table is lowered to the drain depth which provides more storage for infiltration from subsequent rainfall events (Evans et al., 1989; Fausey et al., 1995; Gilliam and Skaggs, 1986; Mitsch et al., 1999; Shirmohammadi et al., 1995; Skaggs et al., 1994; Stone et al., 1992; Thomas et al., 1992; Wesström et al., 2003; Zucker and Brown, 1998). The intensity of the drainage systems also played a key role on runoff and erosion because by placing the drains closer together or deeper in the soil profile, drainage intensity would increase, further reducing runoff and sediment losses (Skaggs et al., 1994). There are exceptions in which surface runoff may not be reduced. This can depend on frequency, intensity, and duration of storm events, soil texture, and antecedent soil moisture conditions. If a high intensity short duration storm event occurs runoff may likely occur.

Research has also shown that subsurface drainage decreases runoff and erosion of sediment and other nutrients including phosphorus, organic nitrogen, and other pollutants fixed to soil particles because the soil profile is drier allowing for more infiltration and less runoff of water to occur (Evans et al., 1991; Evans et al., 1995; Fausey et al., 1995; Gilliam and Skaggs, 1986; Mitsch et al., 1999; Shirmohammadi et al., 1995; Skaggs et al., 1994; Stone et al., 1992; Thomas et al., 1992; Wesström et al., 2001; Wesström et al., 2003; Wesström et al., 2004; Zucker and Brown, 1998). Research reviewed by Skaggs et al., 1994, found studies that showed a decrease in organic nitrogen losses, but the increase in nitrate-nitrogen losses overshadowed them, resulting in losses of total nitrogen (TN). It should also be noted that in situations with high soil test phosphorus levels or in soils which exhibit preferential flow that leaching of phosphorus may occur.

Artificial subsurface drainage results in greater total annual outflow of water from fields, but the increases are generally less than 5%-10% when compared to natural, undeveloped conditions (Evans et al., 1991; Evans et al., 1995; Skaggs et al., 1994). Research has also shown increases in peak outflow rates from subsurface drainage systems when compared with natural, undeveloped conditions (Evans et al., 1989; Evans et al., 1995; Fausey et al., 1995; Gilliam and Skaggs, 1986; Magner et al., 2004; Wesström et al., 2001; Zucker and Brown, 1998). In many cases this statement was found to be true, but Zucker and Brown, 1998 discovered the opposite of this trend. They looked at drainage studies in the Midwest and found that when land was already used for agricultural production artificial drainage reduced the peak outflow rates compared to undrained agricultural land.

2. Controlled Drainage Technique

Today, research is directed towards finding ways to improve the interactions between drainage systems and the environment. Sustaining the high productivity of artificially drained soils for food, fiber, bioenergy feedstock production and protecting the environment is a balancing act, and there are many ways in which this balance can be reached. A water table management (WTM) practice, like controlled drainage, has the potential to increase agricultural productivity, nutrient use efficiency, and reduce off-site environmental impacts (Mitsch et al., 1999; Skaggs et al., 1994).

Controlled drainage (CD) provides drainage during wet periods but also incorporates water table management control through the management of structures at the drainage outlet to reduce excess drainage during dry periods. These systems can also be managed to provide subirrigation during the growing season. This technique has been practiced in North Carolina since 1969 (Evans and Skaggs, 2004) and has been the subject of research in colder climates recently (Drury et al., 1996; Fisher et al., 1999; Kalita et al., 1992; Kanwar and Kalita, 1990; Kanwar et al., 1993; Lalonde et al., 1996; Luo et al., 2010; Mejia and Madramootoo, 1998; Ng et al., 2002; Tan et al., 2002; Thorp et al., 2008; Wesström et al., 2001; Wesström et al., 2003; Wesström et al., 2004; Zucker and Brown, 1998). In general, this technique makes it possible to vary the drainage intensity with the variation in drainage demand, which in turn controls the amount of water and soluble nutrients flowing out of the system (Wesström et al., 2001). This technique is simple and involves using different heights of risers in the drain outlet. More specifically, there are flashboard risers or weir boards placed in water control structures to elevate the outlet of the system (Figure 1.1). The depth of the water table in the field may then be at or below that outlet elevation, depending on precipitation conditions. The area controlled by one water control structure represents a management zone. If there is more than one water control structure placed in the field then there is more than one management zone (Evans and Skaggs, 1989). Each zone can be managed independently, if so desired. When the water table becomes elevated a large part of the subsoil is saturated, causing the retention time of water in the soil to increase, in turn leaving more water available for evapotranspiration, plants, and interim storage of soluble nutrients (Thomas et al., 1992; Wesström et al., 2001). In order for water to flow out of the system it has to rise up to the level of the weir boards before being discharged (Figure 1.2) (Appelboom and Fouss, 2006; Bucks and Spofford, 2005; El-Sadek et al., 2002; Gilliam and Skaggs, 1986; Jia et al., 2006; Mejia and Madramootoo, 1998; Mitsch et al., 1999; Shirmohammadi et al., 1992; Stone et al., 1992; Thomas et al., 1992; Wesström et al., 2001; Wesström et al., 2004). No additional water is added to the system other than precipitation.

2.1. Management Techniques for CD

Water table management generally occurs in two ways, depending on the desired outcome. One management technique is to install the weir boards during the winter season only. Research has shown in some climates that 50% of the drainage water is transported from the field carrying slightly more than 50% of the nutrients (Gilliam and Skaggs, 1986). The second technique is to manage the water table throughout the entire year (Figure 1.3). This management technique lowers the weir boards in the spring and fall to allow for planting, harvesting, and field operations to take place. The weir boards are then raised during the growing season in order to create the potential to store water for crop use. The weir boards are then raised again during the non-growing season in an effort to maintain the water table close to the soil surface to reduce delivery of NO_3^- to surface water.

2.2. Design considerations for CD

When designing and managing a drainage system for water table management extra requirements need to be taken into account, especially when maximum agronomic and environmental results want to be achieved. Thomas et al., 1992 illustrated the proper components that should be considered when evaluating the feasibility of a site for CD. Factors include soil type and drainage class, topography, and an adequate drainage outlet.

Soil type and arrangement of soil horizons along with hydraulic properties can help to determine drain line depth and spacing for CD. Controlled drainage systems are usually designed with relatively narrower drain spacing than conventional drainage because this allows for the management of a flatter water table (Evans et al., 1991).

Generally, controlled drainage is only implemented on relatively flat landscapes (less than one percent surface slopes) because as slope increases the number of water control structures to maintain a uniform water table increases. This can cause the technique to become economically unfeasible because the cost per acre increases. Usually the limiting factor is economics rather than physical slope conditions. Also, a good gravity outlet provides an adequate flow capacity for peak discharges.

A private company on behalf of Agricultural Drainage Management Coalition (ADMC) performed a cost benefit analysis for the CD technique (CVision, 2006). It was determined that if CD were to be implemented on a flat (less than 1% slope) square 40-acre field consisting of 3 water control structures, a tile main, and 24,000 ft of laterals, the total investment cost of the project would be $441.74 per acre. If it were to be implemented on a field that was not flat (>1% slope) and it consisted of 9 water control structures, a tile main, and 24,000 ft of laterals, the total investment cost would be $629.25 per acre. This analysis helps to quantify the point that the CD technique may not be economically feasible on landscapes greater than one percent slope.

Many of the poorly drained soils in the U.S.A. already have a conventional drainage system in place. So, in some cases it may be possible to retrofit the existing drainage systems for controlled drainage if the site meets the required design criteria (Evans and Skaggs, 1989). In cases where slopes are 1%, designing the drainage system along elevation contours can enable the use of controlled drainage.

Finally, the last requirement that should be taken into consideration is the goal of the drainage system. In general, there are two conflicting goals: economic versus environmental quality. El-Sadek et al., 2002 believes that the optimum design and management of a drainage system is one that maximizes profits and minimizes off-site environmental impacts. If the environmental goal is of greater importance, these systems can be designed and managed to improve the environment while still providing an adequate profit (El-Sadek et al., 2002; Evans et al., 1991). The right balance between these two objectives needs to be found. Evans et al., 1991 believes that water table management strategies can have a positive effect on drainage water quality, especially when managed during the nongrowing season.

2.3. Advantages of CD

Controlled drainage can provide many benefits to the farmer as well as the environment. Some possibilities for the farmer include greater utilization of applied fertilizer (Drury et al., 1996; Fisher et al., 1999; Mejia and Madramootoo, 1998; Zucker and Brown, 1998), and increases and stabilization of crop yields (Mejia and Madramootoo, 1998; Fisher et al., 1999; Zucker and Brown, 1998). Other advantages for the environment include flood control (Lalonde et al., 1996; Shirmohammadi et al., 1992; Stone et al., 1992), reduced outflow of water at the field edge (El-Sadek et al., 2002; Lalonde et al., 1996; Shirmohammadi et al., 1992; Stone et al., 1992; Thomas et al., 1992), improved water quality, more specifically nitrogen and phosphorus reductions, (El-Sadek et al., 2002; Evans et al., 1992; Evans et al., 1995; Gilliam and Skaggs, 1986; Jia et al., 2006; Shirmohammadi et al., 1992; Stone et al., 1992; Thomas et al., 1992; Wesström et al., 2001), and increased evapotranspiration (Skaggs and Chescheir III, 2002).

Nitrogen and phosphorus reductions at the field's edge are attributed to five different mechanisms. The first mechanism is retention of nutrients in the profile (Dinnes et al., 2002; Mitsch et al., 1999). This happens because drainage outflows are reduced, not allowing nutrients to leave the field. The second is assimilation of nutrients by plants (Wesström et al., 2001). Since the outflow is reduced, this allows for the plant roots to use the nutrients in the field. The third is an increase in denitrification. This could occur because the soils are wetter due to the rise in the level of the water table, which produces anaerobic conditions, amplifying the ability of denitrification to take place (Dinnes et al., 2002; El-Sadek et al., 2002; Evans et al., 1995; Gilliam and Skaggs, 1986; Jia et al., 2006; Mitsch et al., 1999; Shirmohammadi et al., 1992; Shirmohammadi et al., 1995; Wesström et al., 2001). Nutrient (nitrogen) incorporation into micro-organisms (Wesström et al., 2001) is the fourth mechanism for nutrient reduction. The fifth and final mechanism is a decrease in leaching potential (Dinnes et al., 2002). The higher water table created by CD causes the depth of the soil profile through which water can percolate to be reduced.

Evapotranspiration (ET) is believed to increase during the growing season when CD is practiced. This can be important for farmers because higher yields may result in an increase in ET as well as an increase in the amount of N removed by the crop (Skaggs and Chescheir III, 2002). If less nitrogen is exported from the field and more is used by the crop this greatly increases N fertilizer use efficiency.

There are other benefits that controlled drainage offers that make it appealing to producers. Most CD systems do not alter the physical status of the current drainage system, which can be restored at any time (Jia et al., 2006). If a producer's current drainage system is adequate and only slight modifications need to be made in order to implement CD, it may be more easily accepted by producers. Also, it may help the producer/land owners to understand that reduced drainage will not lower their crop yields, but in turn might allow the adoption of more reasonable drainage practices (Jia et al., 2006).

2.4. Disadvantages of CD

There are considerations and disadvantages with every practice that need to be understood before adoption and implementation occurs. Summarized below are some potential disadvantages associated with CD.

As stated above the CD technique is only economically feasible on relatively flat landscapes that have less than one percent surface slopes (Evans et al., 1992; Evans et al., 1995; Evans and Skaggs, 1989; Mitsch et al., 1999; Shirmohammadi et al., 1992; Stone et al., 1992). There is also concern with this practice that there may be an increase in deep and lateral seepage and potential transport of nutrients to groundwater, especially nitrate-nitrogen. This occurs because of the decreased outflow of water and corresponding increase in pressure head due to a higher water table (Skaggs and Chescheir III, 2002; Thomas et al., 1992; Wesström et al., 2001). In addition, surface runoff is also thought to increase because the soils are wetter not allowing for as much infiltration of water to occur (Drury et al., 1996; El-Sadek et al., 2002; Skaggs et al., 1995; Skaggs and Chescheir III, 2002; Tan et al., 2002; Thomas et al., 1992; Wesström et al., 2001).

Along with this technique there are additional maintenance and management requirements that need to take place. If the system is not managed properly or minimally, the potential benefits may not be realized. Unlike a conventional drainage system that requires minimal maintenance and management following system installation, CD requires that the weir boards be removed, installed, or adjusted depending on the time of year and management objectives. Skaggs and Chescheir III, 2002 believe that farmers fear a negative impact on crop production, so they do not place the same priority on management during the off-season as they do during the growing season. Consequently, the outlets are not always managed for optimum water quality benefits, especially during the winter and early spring months when it is most effective.

Another concern with the practice of CD is how well it will work in cold climates like Minnesota. There has been a lot of research done in North Carolina that have shown this technique to be successful at mitigating environmental effects while increasing crop yields, but the climate, soils and farming practices in the Southeast are much different than in the Midwest. In Minnesota, freezing conditions in the winter months result in low infiltration rates and increased surface runoff as rainfall and snowmelt occur (Luo et al., 2000). In Minnesota, drainage primarily occurs during the spring months of April through June. This is the time when the weir boards would be taken out and conventional drainage would take place to allow for timely field operations. If a majority of the nutrients and drainage water leave during this time then the result could be a no net benefit from CD.

Very limited research on CD has been done in the Northern Corn Belt states of the Upper Midwest and Mitsch et al., 1999 believe there are three reasons why: (1) the undulating, pothole topography limits the area in which WTM can economically and practically be used, (2) raising the water table in the late fall and spring when soils are cold and wet would not lead to as much denitrification as has been measured in the southern United States, and (3) no sense of urgency to try the technique. Although, there has been some CD research done in the Midwestern United States, Canada, and Sweden under similar soil and climatic conditions as Minnesota (Drury et al., 1996; Fisher et al., 1999; Kalita et al., 1992; Kanwar and Kalita, 1990; Kanwar et al., 1993; Lalonde et al., 1996; Luo et al., 2010; Mejia and Madramootoo, 1998; Ng et al., 2002; Tan et al., 2002; Thorp et al., 2008; Wesström et al., 2001; Wesström et al., 2003; Wesström et al., 2004; Zucker and Brown, 1998).

3. Results Published

Many studies have published results on the effect of CD on water quality in North Carolina (Deal et al., 1986; Evans and Skaggs, 1989; Evans et al., 1989; Evans et al., 1991; Evans et al., 1995; Evans and Skaggs, 2004; Gilliam et al., 1978; Gilliam et al., 1979; Gilliam and Skaggs, 1986; Jia et al., 2006; Skaggs and Gilliam, 1981; Skaggs et al., 1994; Skaggs et al., 1995; Skaggs and Chescheir III, 2002; Stone et al., 1992), Iowa (Kalita et al., 1992; Kanwar and Kalita, 1990; and Kanwar et al., 1993), Ohio (Fisher et al., 1999), Michigan (Zucker and Brown, 1998), Canada (Drury et al., 1996; Lalonde et al., 1996; Mejia and Madramootoo, 1998; Ng et al., 2002; Tan et al., 2002) and Sweden (Wesström et al., 2001; Wesström et al., 2003; Wesström et al., 2004). They all found their results to vary seasonally as well as with soil type, rainfall, type of drainage system, and management intensity. The results are divided into seven categories that illustrate the effects of CD on (1) evapotranspiration, (2) surface runoff, (3) crop yield, (4) groundwater, (5) outflow, (6) nitrogen and (7) phosphorus transport and concentration which are described in the sections that follow.

3.1. Evapotranspiration

As mentioned earlier, increases in ET can positively affect crop yield and the ability of the crop to remove nitrogen. A study by Tan et al., 2002 looked at the effect of tillage and CD on ET, surface runoff, tile drainage and soil water content under maize on clay loam soil over a three year period (1992-1994) and found significantly higher soil water content and ET during the two dry years, but not during the wet year. It was also discovered that the tile drainage was significantly reduced in all three years of the study period. Another study performed by Ng et al., 2002 found 50 % greater transpiration rates under controlled drainage and subirrigation treatments (47.4 $mg/m^2/s$) than under conventional drainage treatments (31.7 $mg/\ m^2/s$). The additional water supplied by subirrigation contributed to the difference.

3.2. Surface Runoff

Studies by Drury et al., 1996, Skaggs et al., 1995, and Tan et al., 2002 found surface runoff to increase under CD. The researchers believe this was due to the reduction in soil air volume available for water storage because of the rise in the water table. Tan et al., 2002, found the surface runoff to be significantly ($P < 0.05$) higher for CD as compared to conventional drainage for all three years studied. They also found this to be true throughout the cropping (April – October) and non-cropping season (November – March). The cropping season produced 31% of the total annual surface runoff, while the remaining 69% occurred in the non-cropping season during heavy precipitation events and snowmelt. They believe this could be reduced by installing the tile at a deeper depth.

3.3. Crop Yield

Corn and soybean yields were shown to increase in all the studies that were looked at when comparing conventional drainage to CD (Fisher et al., 1999; Madramootoo et al., 1993; Mejia et al., 2000; Ng et al., 2002). A study by Mejia et al., 2000 in Canada looked at the effect of CD on corn and soybean yields and found them to be higher under CD systems as compared to conventional drainage. Over the two year study period (1995-1996) corn yields averaged 7.5% higher and soybean yields averaged 22.7% higher. The weather conditions were found to be wetter than average during July and August so the researchers believe that during drier years the yield increases could be expected to be even larger. Another study from Canada found corn yields to increase from 6.7 to 11.0 Mg/ha, which resulted in a 64% increase. This study did have subirrigation practices implemented. Madramootoo et al, 1993 compared soybean yields against conventional drainage and three different CD treatments (0.4, 0.6, and 0.8 meters) and found soybean yields increased by 20% under all three CD treatments. These researchers recommend the water table be maintained between 0.6 and 0.8 m below the soil surface, as that results in the best water quality benefits and the maximum soybean yields.

3.4. Groundwater

Two studies, performed by Evans et al., 1989 and Stone et al., 1992, established no evidence of increased nitrate to groundwater because of the reduction of outflow. Evans et al., 1989 showed that there were minor fluctuations in nitrate concentrations in shallow wells to a depth of 4 meters; however, the fluctuations occurred in all of their study treatments, with and without drainage control. Both studies believe this suggests denitrification upon contact with the saturated zone.

3.5. Outflow

All studies that published results on outflow showed that it was reduced at the field's edge, as compared to conventional drainage, but the studies varied in the quantity of reduction. Researchers in North Carolina reported numbers ranging from 13% to 50% (Evans et al., 1989; Evans et al., 1991; Gilliam et al., 1979; Jia et al., 2006), while researchers in Sweden reported values from 73% to 95% (Wesström et al., 2001; Wesström et al., 2004) and researchers in Canada reported ranges of 24 to 65% (Drury et al., 1996; Lalonde et al., 1996; Mejia and Madramootoo, 1998; Valero et al, 2007). Studies in North Carolina and Canada (Evans et al., 1991; Evans et al., 1995; Mitsch et al., 1999) believe that during dry periods outflow is reduced and may be even totally eliminated, but during wet periods there may be little to no effect on outflow and in some cases CD may even increase outflow. Two studies in Canada (Drury et al., 1996; Tan et al., 2002) and one study in North Carolina (Gilliam et al., 1979) found that more outflow occurred in the winter season. Tan et al., 2002 found 65% of the drainage that occurred was during the winter season while Drury et al., 1996 found 81% to 87%, respectively. They believe this was due to the lower evapotranspiration losses during the late fall and early spring period, when there is no crop growth.

3.6. Nitrogen Transport and Concentration

All studies that published results on nutrient transport showed that total nitrogen (TN) was reduced at the field's edge. Studies that published results for nutrient concentration showed inconsistent data for TN. There were many studies that showed nitrate-nitrogen concentrations to be reduced when compared to conventional drainage (Drury et al., 1996; Kalita et al., 1992; Kanwar and Kalita, 1990; Kanwar et al., 1993; Lalonde et al.; 1996 and Mejia et al., 1998), while others showed that CD had little effect on the nitrate-nitrogen concentration in drainage outflow (Evans et al., 1989; Evans et al., 1995;

Gilliam et al., 1979; Skaggs and Chescheir III, 2002; Stone et al., 1992 and Wesström, et al., 2001).

3.6.1. Nitrogen Transport

North Carolina studies (Evans et al., 1989; Evans et al., 1991; Evans et al., 1995; Evans and Skaggs, 2004; Gilliam and Skaggs, 1986; Skaggs et al., 1994; Stone et al., 1992) found reductions in TN transport ranging from 30% to 46.5%. Drury et al., 1996, in Canada, found reductions of 43%, while a study in Sweden by Wesström et al., 2001 found reductions of 78% to 94%, with 64% of the losses occurring in March. Some studies reported their results as nitrate-nitrogen instead of TN and showed 94% (Mejia and Madramootoo, 1998) and 58% to 64% (Zucker and Brown, 1998) reductions in nitrate-nitrogen transport, respectively. Two simulation studies (Luo et al., 2010 and Thorp et al., 2008) found reductions of 25% and 51%, respectively, for nitrate-nitrogen transport. El-Sadek et al., 2002 believes that nitrate-nitrogen losses can be substantially reduced during the winter season with CD, while Gilliam et al., 1979 actually showed reductions of 50% for nitrate-nitrogen transport during the winter months.

3.6.2. Nitrogen Concentration

Studies in Iowa (Kalita et al., 1992, Kanwar and Kalita, 1990, and Kanwar et al., 1993) and Canada (Drury et al., 1996; Lalonde et al., 1996 and Mejia et al., 1998 and) showed that water table management systems reduced the concentration of nitrate-nitrogen in subsurface drainage. Both Mejia et al., 1998 and Drury et al., 1996 found the CD samples to be below the EPA standard for drinking water of 10 mg/L while conventional samples were not. Mejia et al, 1998 reported, on average, the samples from

CD were 1.7 mg/L the first year and 4.5 mg/L the second year while they were 10.5 mg/L and 11.6 mg/L for conventional drainage. This was a reduction of 84% for the first year and 61% for the second year. The researchers do believe that climate and agronomic practices did affect the nitrate leaching and concentration because one-third of the field was planted to corn the first year and one-half the second year, which required fertilizing. In addition, manure was applied in the second year, but not the first year. Drury et al., 1996 reported, on average, their flow weighted mean nitrate concentrations to be 7.9 mg/L, which was a 25 % reduction when compared to conventional. They also stated that 90%-95% of the nitrate losses occurred in the winter period. Lalonde et al., 1996 found that nitrate concentrations were reduced by approximately 76% over 2 years at 2 water table depths (0.25m and 0.50 m). Nitrate-nitrogen reduction was attributed to a combination of decreased drain flow, dilution effect, and enhanced denitrification.

Studies in North Carolina (Evans et al., 1989; Evans et al., 1995; Gilliam et al., 1979; Skaggs and Chescheir III, 2002; Stone et al., 1992) did not show the same reductions as above. In fact, they found that CD had little effect on the concentration of nitrate-nitrogen in the drainage outflow; instead it was the reduction in drainage volume that caused nitrogen loads to be significantly reduced. Evans et al., 1989 believe they did not see a reduction in NO_3-N concentration because it was drier than normal during their study period. If the drainage and rainfall had been near normal they believe the concentrations would have been reduced. Swedish results (Wesström, et al., 2001) showed this same trend up until late spring (April, May, and June), when CD showed a significant decrease in nitrate-nitrogen concentration. They believe this suggests anaerobic conditions caused by a rise in the level of the water table, provoking denitrification. Studies by Wesström, et al., 2001 and Mejia and Madramootoo, 1998 found nitrate concentrations to be affected by the water content and the temperature in the top soil.

3.7. Phosphorus Transport and Concentration

There has been a lot of research performed on CD and its effect on water quality, specifically related to nitrogen. Not much focus has been spent on CD specifically related to phosphorus. This could be due to the fact that more studies were assessing the water quality of drain tile effluent at the field's edge and assumed that phosphorus would not be as important because of its low mobility in soil. Generally, P is adsorbed to soil particles and associated more with surface runoff. The CD technique is performed on relatively flat landscapes where you wouldn't expect to see much surface runoff. Also, most of the studies looked at subsurface drainage and not surface drainage.

There were far less studies that addressed phosphorus transport and concentration in the drainage water as well as the mechanisms behind it. It is evident that these mechanisms are not well understood because the published research shows inconsistency and variability. Studies that published results for phosphorus showed increases while others showed decreases in TP transport. All of the studies that found decreases believe they were due to the reductions in outflow of drainage water. Studies that published results for phosphorus concentration showed inconsistent data for TP as well. More research is needed on phosphorus because of the complexity associated with phosphorus sorption and solubility.

3.7.1. Phosphorus Transport

TP results were not as conclusive as TN results. Studies in North Carolina showed both increases and decreases in TP transport when CD was used. Reductions ranging from 35% to 44% were cited by Evans et al., 1989, Evans et al, 1991, Evans et al., 1995, Skaggs et al., 1994, and Stone et al, 1992. Wesström et al., 2001 in Sweden found reductions of 57% and 85%, while in Michigan (Zucker and Brown, 1998) they found reductions of 16%. Other studies in North Carolina found increases in TP. Evans et al., 1995 and Thomas et al., 1992 believe this was caused by high amounts of surface runoff. In North Carolina this tends to happen more often because they have surface and subsurface flow contributing to drainage where in Minnesota drainage mainly consists of subsurface flow. A study in Canada by Valero et al., 2007 found increases of 89% and 98%, respectively for TP and total dissolved phosphorus (TDP) loads. Compared to conventional drainage plots, TP loads from CD were increased in spring and fall, but were reduced during the summer. The decrease in the summer months was due to the decrease in drainage outflow.

A study by Deal et al., 1986 as well as many studies reviewed by Skaggs et al., 1994 analyzed results of computer simulation models, such as DRAINMOD, to study the effects of water table management practices on water quality. The models predicted P losses to increase because of the predicted increase in surface runoff. This contradicts results found in the field in which CD has been found to reduce P outflows. Skaggs et al., 1994 believed the contradiction to be related to deep and lateral seepage because simulation models are usually programmed to assume that seepage is negligible, even though seepage from an elevated water table may be substantial (Skaggs and Chescheir III, 2002; Thomas et al., 1992; Wesström et al., 2001).

3.7.2. <u>Phosphorus Concentration</u>

Phosphorus concentrations were found to be reduced for surface runoff and increased for subsurface runoff (Evans et al., 1991; Evans et al., 1995; Thomas et al., 1992), whereas Shirmohammadi et al., 1995 found that TP concentrations were high during construction and installation phases but were reduced after those phases were complete. A study in North Carolina by Gilliam and Skaggs, 1986 compared TP loss on cropped land for two different types of soils, mineral and shallow organic, and found a large increase in TP loss from the shallow organic soil (7.6 kg/ha) versus the mineral soil (0.5 kg/ha). They believed the losses were more related to soil type. Most of the P under the organic soil that was lost was present in the drainage water as inorganic orthophosphate in solution, while most of the P lost from the inorganic soil field was present as organic P. Gilliam and Skaggs stated that P contained in fertilizers is not as readily bound to the organic matter as it is bound to the mineral soil so applied P is more likely to move with drainage water in organic soils.

In Canada, Valero et al., 2007 researched the impact that CD-subirrigation (CD-SI) had on phosphorus loads through plot studies and a laboratory soil column experiment. They found that TP, TDP, and dissolved reactive phosphorus (DRP) concentrations in drainage water from the CD-SI plots were on average increased by 131%, 136% and 178%, respectively, compared to conventional drainage plots. The average TP concentrations ranged from 0.010 mg/L to 0.061 mg/L in conventional drainage plots and from 0.031 mg/L to 0.122 mg/L in CD-SI plots. About 96% of the TP concentration was under the dissolved form, which is most readily available for plant uptake. The researchers tested the irrigation water and found it to be adding 0.84 kg P/ha to the field and so they performed a laboratory soil column experiment with P-free water added to simulate SI. They found the TP, TDP and DRP concentrations increased 75%-336% under CD-SI columns as compared to the conventional drainage columns and between 85%-98% of the TP concentration was under the dissolved form. Based on their findings between the plot studies and the laboratory studies they concluded that the presence of a shallow water table and the resulting anoxic conditions were most likely responsible for the increases in P solubility. This increase in solubility then explains the increase in P concentrations and loads.

4.0 Objectives for Minnesota

Controlled drainage research has been going on since the late 1960's and has promising effects on drainage hydrology and water quality. There is more CD research that needs to take place on different soil types and climatic conditions as well as farming practices. Minnesota has approximately 0.4 million hectares of cropland that would be potentially suitable for CD, but limited research has been performed here to understand the possible effects.

In 2005, a 40 ha field-sized experiment was initiated to assess the effects of CD versus conventional drainage on hydrology and water quality under the climatic conditions, soils, and farming practices of Southwest Minnesota. The objectives of the project are to: (1) determine the feasibility of using CD in Minnesota, (2) monitor the drainage water quality and quantity to determine if nutrient concentrations are reduced at the field's edge, (3) determine the soils physical and hydraulic properties and relate them to differences in drainage practices, and (4) use the experimental site for public demonstration, field days, and educational programming.

Figure 1.1. Diagram of a water control structure. (Source: Jeff Strock)

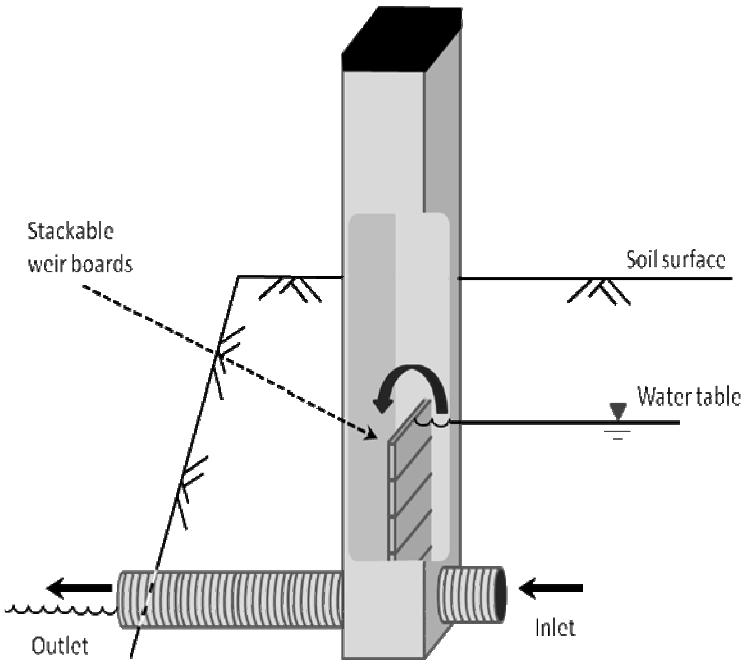


Figure 1.2. Example of a water control structure at the edge of the field. (Source: Gary Sands)

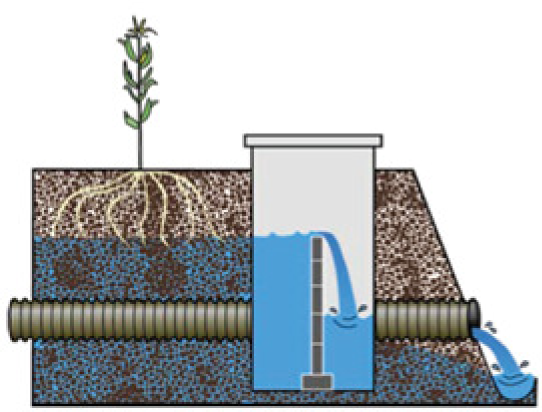
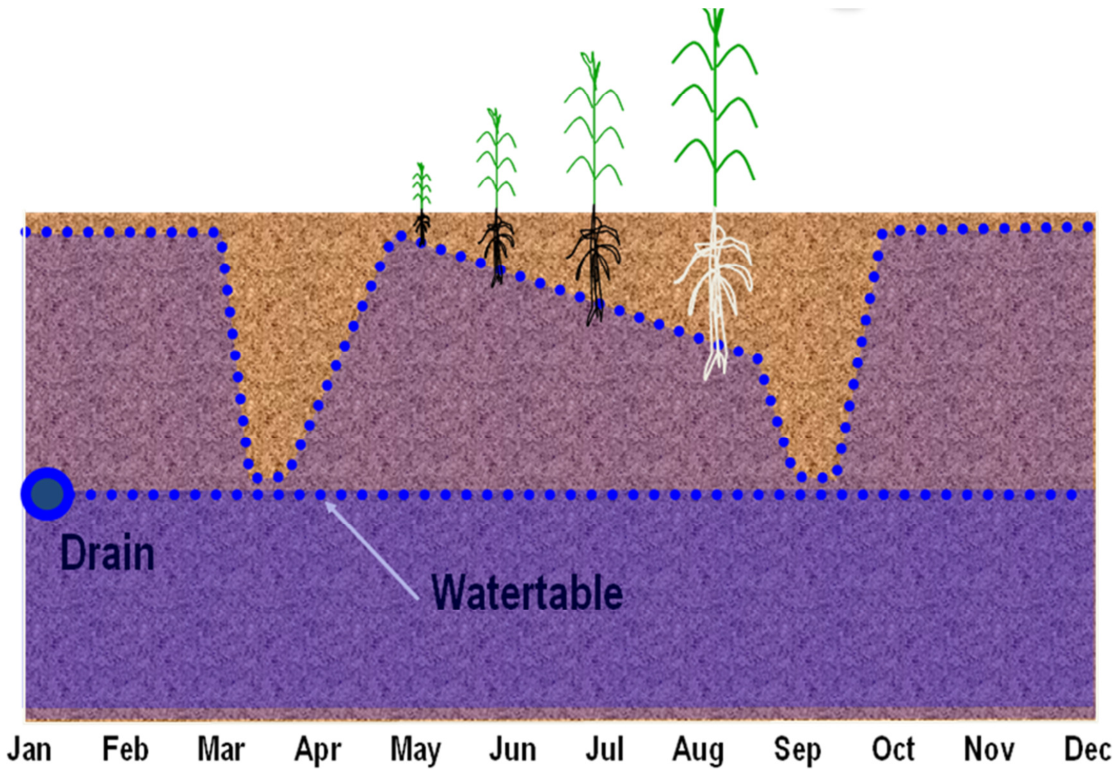


Figure 1.3. Illustration of water table management throughout the entire year. (Source: Gary Sands)



CHAPTER 2. Controlled Drainage to Improve Edge-of-Field Water Quality in Southwest Minnesota

OVERVIEW

Wet, poorly drained soils throughout the northern Cornbelt are often artificially drained to improve field conditions for timelier field operations, decrease crop damage resulting from excess water conditions, and improve crop yields. Drainage has also been identified as a contributing factor to water quality impairments in surface waters. Our objective was to quantify drain flow volume and nitrogen and phosphorus loss from a conventional free-drainage (FD) compared to a controlled drainage (CD) system in Southwest Minnesota. A field study was conducted from 2006-2009 on a tile-drained Millington loam soil (fine-loamy, mixed, calcareous, mesic Cumulic Haplaquoll). The field site consisted of two independently drained management zones, 15 and 22 ha. The project used a paired design approach to statistically evaluate treatment effects. During the calibration period (2006-2007) each zone was managed the same while during the treatment period (2008-2009) one zone was managed in FD mode and the other managed in CD mode. When comparing the slopes of the regression lines between the calibration and treatment period our results indicated positive treatment effects. Controlled drainage resulted in reductions in drain flow volume of 48%, NO_3N yields of 25%, TP yields of 68% compared to FD, flow-weighted mean NO_3N concentrations of 74%, and flow weighted mean TP concentrations of 170%. Overall, the use of CD showed environmental benefits compared to FD.

INTRODUCTION

Without subsurface drainage, many poorly drained soils throughout the upper Midwest would not be considered some of the most agriculturally productive soils in the world (Fausey et al., 1995; Sands et al., 2003; Skaggs and Chescheir III, 2002; Stone et al., 1992; Zucker and Brown, 1998). In Minnesota, approximately 40% of all cropland is drained (Zucker and Brown, 1998) and the practice mainly consists of subsurface drainage. Water table management practices include any assortment of surface drainage, subsurface drainage, controlled drainage or subirrigation that influence the level of the shallow water table (Evans et al., 1991) and allow the owner/operator to more intensively manage their fields to increase yields and improve production efficiency on land already in cultivation.

Artificial drainage removes excess soil water from the crop root zone and transports it from the field to a ditch, stream, or river. Removal of excess water lowers the water table and enables aeration of the soil to occur. This aeration allows for the soil to dry and warm faster permitting favorable conditions for seedbed preparation, planting, harvesting and other field operations (Appelboom and Fouss, 2006; Dinnes et al., 2002; Evans et al., 1992; Evans et al., 1995; Fausey et al., 1995; Shirmohammadi, et al., 1995; Skaggs et al., 1994; Stone et al., 1992; Tan et al., 2002; Wesström et al., 2001; Zucker and Brown, 1998). The number of days available for planting and harvesting crops as well as the yield can increase (Fausey et al., 1995) when agricultural land is drained. Drainage also protects plants from excessive soil water conditions during the growing season (Evans et al., 1992; Fausey et al., 1995; Shirmohammadi et al., 1995; Skaggs et al., 1994; Tan et al., 2002; Zucker and Brown, 1998). In some cases, excess drainage may reduce soil water available to plants and increase drought stress during unusually dry periods (Evans and Skaggs, 1989; Evans et al., 1992). In addition, more drainage than necessary may leach fertilizer nutrients and other agricultural products from the soil, transporting them to surface waters where they may lead to water quality impairments.

Artificially drained soils are often located adjacent to, or are hydrologically connected to, environmentally sensitive surface waters that provide natural drainage outlets. Artificial subsurface (tile) drainage has been identified as one of the primary sources of nitrate entering surface water (Randall and Goss, 2001). Subsurface drainage has also been associated with the delivery of sediment, particulate and dissolved phosphorus, pesticides, and coliform bacteria to surface waters (Addiscott et al., 2000; Carpenter et al., 1998; David et al., 2003; Gilliam et al., 1999; Jamieson et al., 2002; Kladivko et al., 1999; Randall and Goss, 2001; Scott et al., 1998).

Today, research is directed towards finding ways to improve the interactions between drainage systems and the environment. Sustaining the high productivity of artificially drained soils for food, fiber, bioenergy feedstock production and protecting the environment is a balancing act, and there are many ways in which this balance can be reached. A water table management practice, like controlled drainage, has the potential to increase agricultural productivity, nutrient use efficiency, and reduce off-site environmental impacts (Mitsch et al., 1999; Skaggs et al., 1994).

Controlled drainage (CD) provides drainage during wet periods but also incorporates water table management control through the management of structures at the drainage outlet to reduce excess drainage during dry periods. These systems can also be managed to provide subirrigation during the growing season. This technique has been practiced in North Carolina since 1969 (Evans and Skaggs, 2004) and has been the subject of research in colder climates recently (Drury et al., 1996; Fisher et al., 1999; Kalita et al., 1992; Kanwar and Kalita, 1990; Kanwar et al., 1993; Lalonde et al., 1996; Mejia and Madramootoo, 1998; Ng et al., 2002; Tan et al., 2002; Wesström et al., 2001; Wesström et al., 2003; Wesström et al., 2004; Zucker and Brown, 1998). In general, this technique makes it possible to vary the drainage intensity with the variation in drainage demand, which in turn controls the amount of water and soluble nutrients flowing out of the system (Wesström et al., 2001). This technique is simple and involves using different heights of risers in the drain outlet. More specifically, there are flashboard risers or weir boards placed in water control structures to elevate the outlet of the system. The depth of the water table in the field may then be at or below that outlet elevation, depending on precipitation conditions. The area controlled by one water control structure represents a management zone. If there is more than one water control structure placed in the field then there is more than one management zone (Evans and Skaggs, 1989). Each zone can be managed independently, if so desired. When the water table becomes elevated a large part of the subsoil is saturated, causing the retention time of water in the soil to increase, in turn leaving more water available for evapotranspiration, plants, and interim storage of soluble nutrients (Thomas et al., 1992; Wesström et al., 2001). In order for water to flow out of the system it has to rise up to the level of the weir boards before being discharged (Appelboom and Fouss, 2006; Bucks and Spofford, 2005; El-Sadek et al., 2002; Gilliam and Skaggs, 1986; Jia et al., 2006; Mejia and Madramootoo, 1998; Mitsch et al., 1999; Shirmohammadi et al., 1992; Stone et al., 1992; Thomas et al., 1992; Wesström et al., 2001; Wesström et al., 2004). No additional water is added to the system other than precipitation.

Controlled drainage research has promising effects on drainage hydrology and water quality but more research needs to take place on different soil types, climatic conditions as well as farming practices. The number of acres of cropland that would be suitable for CD in Minnesota is presently unknown but in the Minnesota River Basin and the Red River of the North Basin the areas could potentially reach up to 0.4 million hectares or more.

This paper will describe the results from 2006-2009 for precipitation, drain flow, nitrogen and phosphorus yields and concentrations. The objective of this study was to quantify differences between drain flow, and nitrogen and phosphorus yields and concentrations through subsurface drainage from conventional free-drainage (FD) and controlled drainage (CD) practices. A paired watershed approach was used with the first two years serving as the calibration period (2006-2007) and the last two years serving as the treatment period (2008-2009).

MATERIALS AND METHODS

Study Area

The study was conducted on a 37 ha field at the Hicks Family Farm located within Redwood County in Southwest Minnesota (Figure 2.1). There are two types of soils located in the study area, a Havelock clay loam (mesic Cumulic Endoaquolls), and a Du

Page loam (mesic Cumulic Hapludolls), which were both formed in calcareous alluvium (Figure 2.2). Havelock and Du Page soils are nearly level soils located on flood plains and are poorly drained and moderately well drained, respectively.

The field was planted in corn (*Zea mays* L.) in 2006, 2007 and 2009 and soybeans (*Glycine max* (L.) Merr.) in 2008. The field was fertilized with a commercial fertilizer in the spring which added 174 kg ha^{-1} N, 67 kg ha^{-1} P_2O_5 and 67 kg ha^{-1} K_2O in 2006, 179 kg ha^{-1} N, 67 kg ha^{-1} P_2O_5 and 67 kg ha^{-1} K_2O in 2007, and no fertilizer in 2008. In 2009 liquid swine manure was applied to the field in the fall of 2008 instead of a commercial fertilizer in the spring at a rate of 37,416 L ha^{-1} which added 150 kg ha^{-1} N, 99 kg ha^{-1} P_2O_5 and 143 kg ha^{-1} K_2O. This data is summarized in Table 2.2. Prior to the study taking place the field was planted to soybeans in 2004 and small grains in 2005.

The study area had no previous history of drainage until 2005. In the fall of 2005 subsurface drain tiles were placed in the field spaced approximately 15-m apart and 1.2-m below the ground surface. Laterals were 10.1 cm in diameter and connected into a tile main and two water table management structures (AgriDrain, Adair, IA) were placed in the field. The tile main connecting to the west WTMS is 30.5 cm in diameter, and the tile main connecting to the east WTMS is 38.1 cm in diameter. The water table management structures (WTMS) divided the field into two management zones, west and east, which are approximately 22 and 15 ha, respectively (Figure 2.3). The west management zone drained into the east management zone before being discharged from the field into a drainage ditch. On May 17, 2007 the tile main was separated so each management zone discharged directly into the drainage ditch.

Drainage System Management

The elevation of the weir boards in the WTMS's allow the management zones to be managed in undrained (water table near the soil surface), conventional drainage (water table at the drain depth), or drainage water management modes (water table maintained at a predetermined depth). This study area was managed using all three methods. The calibration period occurred in 2006 and 2007 and the treatment period occurred in 2008 and 2009. The east management zone was the control while the west management zone was the treatment.

In 2006 the field was drained and both east and west management zones were managed conventionally. On November 16, 2006, after harvest, the weir boards were initially installed in the WTMS's which raised the water table to 0.15 meters below the soil surface. They were then removed on April 17, 2007 so flow could occur and the water table could drop to allow for spring planting. The weir boards were placed back in the WTMS's on May 8, 2007 approximately 0.6 meters below the soil surface in the east and west (Table 2.3). Normally the weir boards would be taken out in the fall again to allow for harvesting, but the water table was not near the surface of the soil in the fall of 2007 so they were not removed. Whenever the weir boards were removed to allow for planting, harvest or conventional drainage, one weir board was always left in place. This allowed the data collection program that was in place at each of the monitoring stations to accurately calculate the flow of water passing through the WTMS's. In 2008 and 2009 the east management zone (control) was managed conventionally while the west management zone (treatment) had the weir boards placed approximately 0.6 meters below the soil surface (Table 2.3). The weir boards were removed for fall harvest and spring planting and put back in place on May 23 in 2008 and on May 11 in 2009.

Sample Collection and Analysis

Each management zone was equipped with a WTMS which were outfitted with a stilling well to measure stage height and a separate well to collect water samples for determination of drainage water quality. The monitoring stations were installed in 2005 and subsurface drainage water quantity and quality were collected using ISCO (Lincoln, NE) samplers (Model #3700) and a Campbell Scientific Inc. (Logan, UT) datalogger (CR-10X) used to collect and store stage height. Each water level control structure has an attached stilling well with a Druck pressure transducer (Model #CS-420-L) to record changes in stage height in the control structure. Surface water was not monitored. Both of the monitoring systems were housed in plastic shelters above ground and powered by solar panels.

Monitoring was conducted on a continuous basis during ice-free periods, which consisted of April - October for both the east and west management zones in 2006; February - December for the east management zone and March - December for the west management zone in 2007; March – December for both the east and west management zones in 2008; and April – October for both the east and west management zones in 2009. Data and samples were not collected from the west management zone from March 19, 2007 – April 4, 2007 because the pressure transducer malfunctioned. This data was recreated from the east management zone by comparing regression lines using “R” by analysis of variance (ANOVA). When p-values were more than 5% the simpler model was used. Also samples and data were not collected from the east and west management zones from May 17, 2007 – September 1, 2007 due to malfunctioning dataloggers; however, there was no flow of water out of the field during this time.

Water samples were collected on a time-paced basis for 2006, with 24, 1-L bottles being filled. During the first week of monitoring samples were collected every 2 hours, the second week they were collected every 6 hours, and the third week they were collected every 8 hours. After the initial period of drainage the water samples were then collected once per day for the rest of the 2006 sampling season. In 2007, 2008 and 2009 samples were collected using a flow-proportional method. The samplers were programmed to collect a 1-L samples every 5,000 cf for the west zone and every 10,000 cf for the east zone until May 22, 2007. After this the samplers were programmed to collect a sample every 10,000 cf during storm events. Between storm events, a 1-L grab sample was collected once each week to examine nutrient losses. Samples were refrigerated at 4º C until analysis.

Analysis was done using a Lachat Quickchem 8,000 Flow Injection Analysis Analyzer (Hach Company, Loveland, Colorado). The water samples were analyzed for nitrate-N, ammonium-N, total nitrogen (TN), dissolved molybdate reactive phosphorus (DMRP) and total phosphorus (TP) concentrations. Nitrate was analyzed using the colorimetric analysis by the cadmium reduction method. The sample was subsequently measured colorimetrically at 520 nm on a Lachat by flow injection analysis. Ammonium was analyzed using the colorimetric analysis by the salicylate/nitroprusside method. The ammonium reacts with salicylate in the presence of hypochlorite (oxidant) and nitroprusside (catalyst) to form an emerald green color measured colorimetrically on a Lachat at 660 nm. DMRP was analyzed using the colorimetric analysis by the molybdate-blue/ascorbic acid method using a Lachat at 880 nm. Total nitrogen and TP were simultaneously digested with persulfate. The 50 minute digestion occurred in at autoclave at 121°C and 117 kPa. Organic nitrogen and ammonium are converted to nitrate and phosphorus compounds are liberated as orthophosphate. The digested sample was analyzed colorimetrically for TN as ammonium nitrogen and TP as orthophosphate (see methods above).

Flow was calculated using the stage-discharge relationship of the WTMS with weir boards in place, or using Manning's equation when no weir boards were present in 2006. Below is the stage-discharge relationship developed:

$$Q = \frac{a}{1+e^{-\left(\frac{x-x_o}{b}\right)}}$$

Values used to calculate stage-discharge relationship for west tile main:
Q = flow (m^3s^{-1})
α = 0.0201
b = 0.259
x = stage height (m)
x_o = 0.1535

Values used to calculate stage-discharge relationship for east tile main:
Q = flow (m^3s^{-1})
α = 0.0364
b = 0.0325
x = stage height (m)
x_o = 0.1919

Nutrient yields were determined by the product of the fifteen minute flow volume (L) and concentration (mg L^{-1}). Concentrations were assigned to each fifteen minute interval by using the concentration from one sample to the next. The fifteen minute nutrient yields were then summed for the corresponding flow periods in each respective year and used to determine flow weighted mean concentrations.

Data Analysis

The data was analyzed using a paired analysis approach as discussed in Clausen and Spooner, 1993. Statistical analysis of the data used analysis of variance (ANOVA) for regression of the paired observations of daily flow, yields, and flow weighted mean concentrations for DMRP, TP, ammonium-N, nitrate-N, and TN during the calibration and the treatment periods.

The smallest worthwhile detectable difference (d) was determined based on the calibration regression using the following relationship:

$$\frac{S_{xy}^2}{d^2} = \frac{n_1\, n_2}{n_1+n_2}\left\{\frac{1}{F\left(1+\frac{F}{n_1+n_2-2}\right)}\right\}$$

S_{yx}^2 = estimated residual variance about the regression
d^2 = square of the smallest worthwhile difference
n_1 *and* n_2 = numbers of observations in the calibration and treatment periods
F = table value (p=0.05) for the variance ratio at 1
$n_1 n_2 - 3df$

The purpose of this statistic was to determine whether a sufficient sample size has been taken to detect a given percent change from the mean.

Analysis of covariance (ANCOVA) was used to determine the significance of the overall model, intercepts, and slopes, by comparing the two regression equations to evaluate if there was a significant difference due to the influence of the treatment (controlled drainage). Daily flow, yields, and flow weighted mean concentrations for DMRP, TP, ammonium-N, nitrate-N, and TN was square root transformed and the distributions were tested for normality. Statistical analysis of the data was conducted using Statistical Analysis System, Inc. software (SAS, 2002).

It should be noted that regardless of year to year changes that were imposed on the control and treatment watersheds during the calibration and treatment phase (i.e. changes in crop and fertilizer use), it's not as important with a paired watershed design because the changes were imposed on both systems.

RESULTS AND DISCUSSION

Climate and Precipitation

The climate in Southern Minnesota is humid continental with hot summers and cold winters. Minnesota's location allows it to receive a wide variety of weather and each season (winter, spring, summer and fall) experiences its own set of unique characteristics. Precipitation data was taken at the study site for the four-year study period (2006-2009) during the frost free periods (April – October) and from the Marshall weather station during frozen periods (January – March and November – December) and then compared to the long-term annual average between 1975 and 2005 taken from the Marshall weather station (Table 2.1). The weather station is located approximately 32 kilometers from the research site. The average annual precipitation for 2006, 2007, 2008 and 2009 was 499.36, 685.04, 521.46 and 555.75 millimeters, respectively, while the long-term annual average was 700.39 millimeters. All four years had drier than normal precipitation. During the growing season (April through September) for 2006 the monthly average precipitation fluctuated from 40% above normal to 79% below normal, but from July through November precipitation was very low. During 2007, the monthly average precipitation was consistently below normal. During the early part of the growing season, April through July, precipitation ranged from 24% to 83% below normal. The average annual precipitation for 2008 was approximately 26% below normal while in 2009 it was approximately 21% below normal. Every month during the growing season for both 2008 and 2009 was below normal, except October of 2008 when it was 70% above normal and October of 2009 when it was 154% above normal. Dry conditions between 2006 and 2009 were extensive enough to potentially impact drainage system performance. The potential to store available soil water using CD practices was limited due to dry conditions. Dry conditions also would lead to reduced drain outflow under FD and CD due to a lack of excess water in the soil to drain.

Flow

The overall mean annual flow reduction during the treatment period was approximately 90% (Table 2.6). Based on ANOVA, regressions for treatment flow on control flow for the treatment period were significant ($F = 13.55$, $P = 0.0003$). The regression equations for the calibration period and the treatment period as well as the corresponding r-squared values are presented in Table 2.8. ANCOVA demonstrated there was an overall difference between calibration and treatment period regressions ($F = 7.76$, $P = 0.0055$) and their intercepts ($F = 77.16$, $P < 0.0001$), but not their slopes ($F = 2.38$, $P = 0.1458$) (Table 2.4). Although the slopes for each regression equation were not significantly different, a reduction of 48% was documented when comparing the slope of the calibration period to the treatment period. The effect of CD on flow is also visible by comparing cumulative flow curves for the control and treatment zones (Figure 2.4). The curves parallel each other but the cumulative flow for the treatment period is much lower than the control period.

Dry conditions between 2006 and 2009 likely resulted in lower flows than would be expected during normal or wet conditions. During the calibration period the mean annual flow from the control and treatment zones were 174 m^3 d^{-1} and 143 m^3 d^{-1}, whereas during the treatment period the mean annual flow from the control and treatment zones were 137 m^3 d^{-1} and 13 m^3 d^{-1}, respectively (Table 2.6). Figure 2.5 illustrates the monthly flow from the control and treatment zones during the treatment period. The only drainage outflow through the drainage system from the CD management zone during both 2008 and 2009 occurred in the spring before planting when the weir boards were removed. In April of 2009, more outflow occurred from the CD zone than the FD zone. This could be attributed to the fact that the after the weir boards were reinstalled after harvest in the fall of 2008 the site experienced above normal precipitation in October and during the winter season. This created optimal conditions for water storage in the field over the winter period, which caused the water table to rise until the weir boards were removed for spring field operations. Drainage system outflow from the FD management zone occurred continuously during 2008 and 2009 until the water table elevation dropped below the drain depth and flow ceased in August of 2008 and 2009.

Previous studies on CD have shown that drainage system discharge of water was reduced at the field’s edge, but the studies varied in the quantity of reduction.

Researchers in North Carolina reported numbers ranging from 13% to 50% (Evans et al., 1989; Evans et al., 1991; Gilliam et al., 1979; Jia et al., 2006), while researchers in Sweden reported values from 73% to 95% (Wesström et al., 2001; Wesström et al., 2004) and researchers in Canada reported ranges of 24% to 65% (Drury et al., 1996; Lalonde et al., 1996; Mejia and Madramootoo, 1998; Valero et al, 2007). Studies in North Carolina and Canada (Evans et al., 1991; Evans et al., 1995; Mitsch et al., 1999) believe that during dry periods outflow is reduced and may be even totally eliminated, but during wet periods there may be little to no effect on outflow and in some cases CD may even increase outflow.

Nitrogen

Yields

The overall mean annual yield reduction for NO_3N and TN during the treatment period was approximately 73% and 71%, respectively, while NH_4N showed a 100% increase (Table 2.6). Based on ANOVA, regressions for the treatment period were not significant for NH_4N ($F = 0.69$, $P = 0.4075$) but were significant for NO_3N ($F = 21.72$, $P < 0.0001$) and TN ($F = 25.09$, $P < 0.0001$). The regression equations for the calibration period and the treatment period as well as the corresponding r-squared values are presented in Table 2.8. Using ANCOVA for NH_4N, there was not an overall difference between calibration and treatment period regressions ($F = 0.98$, $P = 0.3233$), intercepts ($F = 1.10$, $P = 0.2962$) or slopes ($F = 1.37$, $P = 0.2463$); NO_3N did not show an overall difference between regressions ($F = 1.80$, $P = 0.1804$), they did however for intercepts ($F = 92.05$, $P < 0.0001$) but not slopes ($F = 1.37$, $P = 0.2463$); and TN showed the same trend as NO_3N with no overall difference between regressions ($F = 1.02$, $P = 0.3141$), but it did for intercepts ($F = 94.70$, $P < 0.0001$) and not slopes ($F = 2.41$, $P = 0.1469$) (Table 2.4). Even though reductions in the mean annual yield of all three parameters were documented; none of these parameters illustrated a significant difference in the slopes between the calibration and treatment period regression equations due to CD. If we compare the slopes of the calibration period to the treatment period, reductions of 25% and 19% are documented for NO_3N and TN, however, NH_4N illustrates an increase of 3300% (Table 2.8).

During the calibration period the NH_4N, NO_3N and TN yield from the control was 0.8, 46, and 44 kg N ha^{-1} while the treatment was 0.1, 21, and 21 kg N ha^{-1}, respectively (Table 2.6). During the treatment period the NH_4N, NO_3N and TN yield from the control was 0.1, 18, and 17 kg N ha^{-1} while the treatment was 0.2, 5.0 and 5.0 kg N ha^{-1}, respectively (Table 2.6). In both the calibration and treatment periods the TN results are less than the NO_3N amounts. Although the differences were small this result could be related to experimental and /or analytical error. The reduction in nitrogen yields indicate that loss of nitrogen under CD versus FD was mainly due to differences in water outflow between the two systems. More water flowed out of the FD system therefore carrying more nitrogen off the field.

Figure 2.5 illustrates the monthly NO_3N yields from the FD and CD zones during the treatment period. The only NO_3N that left the field in the CD zone was in the spring of 2008 and 2009 when the weir boards were removed for spring field operations. If we look at 2009 NO_3N yields, more NO_3N left the field under the CD zone as compared to the FD zone, with almost all the NO_3N leaving during the month of April. This, again, corresponds with the differences in outflow of water between the two systems.

All studies that published results on nutrient transport showed that total nitrogen (TN) was reduced at the field's edge. North Carolina studies found reductions in TN transport ranging from 30% to 46.5% (Evans et al., 1989; Evans et al., 1991; Evans et al., 1995; Evans and Skaggs, 2004; Gilliam and Skaggs, 1986; Kalita et al., 1992; Skaggs et al., 1994; Stone et al., 1992). In Canada they found reductions of 43% (Drury et al., 1996), while in Sweden they found reductions of 78% to 94% (Wesström et al., 2001). Some studies reported their results as nitrate-nitrogen instead of TN and found 94% (Mejia and Madramootoo, 1998) and 58% to 64% (Zucker and Brown, 1998) reductions in nitrate-nitrogen transport, respectively.

Flow Weighted Mean Concentrations

The overall annual flow weighted mean concentrations increased for NH_4N, NO_3N and TN when comparing FD to CD (Table 2.7). However, based on ANOVA, regressions for the treatment period were not significant for NH_4N (F = 1.23, P = 0.2721), NO_3N (F = 0.27, P = 0.6057) or TN (F = 0.13, P = 0.7218). The regression equations for the calibration period and the treatment period as well as the corresponding r-squared values are presented in Table 2.8. Using ANCOVA for NH_4N, there was an overall difference between calibration and treatment period regressions (F = 2.83, P = 0.0941), there was not for intercepts (F = 1.10, P = 0.2962) but there was for slopes (F = 1.37, P = 0.2463); NO_3N illustrated an overall difference between regressions (F = 3.08, P = 0.0796) and intercepts (F = 9.02, P = 0.0028) but not slopes (F = 0.67, P = 0.4503); and

TN did show an overall difference between regressions (F = 4.52, P = 0.0340), and intercepts (F = 8.88, P = 0.0030) but not slopes (F = 0.67, P = 0.4474) (Table 2.5). Even though increases in the mean annual flow weighted mean concentrations of all parameters were documented, only NH_4N illustrated a significant difference in the slopes between the calibration and treatment period regression equations due to CD. If we compare the slopes of the calibration period to the treatment period, reductions of 3625%, 74%, and 83% are documented for NH_4N, NO_3N and TN (Table 2.8).

Climate and agronomic practices more than likely affected the variability in nitrogen during the treatment period. The least amount of precipitation in the four year study period happened in 2009 and no water flowed out of the CD management zone during the growing season. The field also had liquid swine manure applied instead of commercial fertilizer. It should be noted that there were year to year differences in the agronomic practices for the entire 37 ha field, however, each zone was managed the same every year.

Studies in Iowa and Canada (Drury et al., 1996; Kalita et al., 1992, Kanwar and Kalita, 1990, Kanwar et al., 1993; Lalonde et al., 1996 and Mejia et al., 1998) showed that CD reduced the concentration of nitrate-nitrogen in subsurface drainage. Both Mejia et al., 1998 and Drury et al., 1996 found the CD samples to be below the EPA standard for drinking water of 10 mg/L while conventional samples were not. Mejia et al, 1998 reported reductions of 84% for the first year and 61% for the second year. Drury et al., 1996 reported a 25 % reduction. Lalonde et al., 1996 found that nitrate concentrations were reduced by approximately 76 % over 2 years at 2 water table depths (0.25m and 0.50 m).

Phosphorus

Yields

The overall mean annual yield reduction for DMRP and TP during the treatment period was approximately 80% and 60% (Table 2.6). However, based on ANOVA, regressions for the treatment period were significant for DMRP ($F = 18.03$, $P < 0.0001$) but were not for TP ($F = 1.53$, $P = 0.2169$). The regression equations for the calibration period and the treatment period as well as the corresponding r-squared values are presented in Table 2.8. Using ANCOVA for DMRP, there was not an overall difference between calibration and treatment period regressions ($F = 1.66$, $P = 0.1986$), but there was for intercepts ($F = 7.24$, $P = 0.0073$) and slopes ($F = 8.39$, $P = 0.0109$). TP showed the same trend with no overall difference between calibration and treatment period regressions ($F = 1.23$, $P = 0.2686$), but there was for intercepts ($F = 4.71$, $P = 0.0304$) and slopes ($F = 3.48$, $P = 0.0754$) (Table 2.4). Reductions in the mean annual yield of DMRP and TP were documented and the slopes between the calibration and treatment period regression equations were significantly different due to CD. If we compare the slopes of the calibration period to the treatment period a reduction of 68% was documented for TP, however, DMRP illustrates an increase of 183% (Table 2.8).

During the calibration period the DMRP and TP yields were 0.6 and 0.5 kg ha^{-1} from the control and 0.4 and 0.3 kg ha^{-1} from the treatment (Table 2.6). During the treatment period the DMRP and TP yield from the control was 0.1 and 0.1 kg ha^{-1} while the treatment was 0.02 and 0.04 kg ha^{-1} (Table 2.6). As stated above, this demonstrates a 80% and 60% reduction in DMRP and TP yields. These results indicate that reduced loss of DMRP and TP under CD versus FD was due to differences in water outflow between the two systems.

Figure 2.5 illustrates the monthly DMRP and TP yields from the FD and CD zones during the treatment period. The only DMRP and TP that left the field in the CD zone were in the spring of 2008 and 2009 when the weir boards were removed for spring field operations. If we look specifically at 2009 DMRP and TP yields, more DMRP and TP left the field under the CD zone as compared to the FD zone, with almost all leaving during the month of April. This, again, corresponds with the differences in outflow of water between the two systems.

Many studies showed reductions for TP ranging from 16% to 85% (Evans et al., 1989; Evans et al, 1991; Evans et al., 1995; Skaggs et al., 1994; Stone et al, 1992; Wesström et al., 2001; and Zucker and Brown, 1998). Our study showed very large reductions and again we attribute this to below normal annual precipitation during the four year study period. If precipitation had been more normal we may not have seen quite as large of a reduction in the DMRP and TP yields or we may have even seen increases. A few studies in North Carolina and Canada found increases in TP (Evans et al., 1995; Thomas et al., 1992; and Valero et al., 2007). The North Carolina studies believe this was caused by high amounts of surface runoff because they have surface and subsurface flow contributing to drainage where in Minnesota drainage mainly consists of subsurface flow. The Canada study (Valero et al., 2007) found increases of 89% and

98%, respectively, for TP and total dissolved phosphorus (TDP) loads. They concluded that the presence of a shallow water table and the resulting anoxic conditions were most likely responsible for the increases in P solubility. Compared to conventional drainage plots, TP loads from CD were increased in spring and fall, but were reduced during the summer. The decrease in the summer months was due to the decrease in drainage outflow.

Generally, phosphorus is adsorbed to soil particles and associated more with surface runoff than subsurface drainage because of its low mobility in soil. The CD technique is performed on relatively flat landscapes where you wouldn't expect to see much surface runoff. Also, the forms of phosphorus can be different when comparing surface runoff to subsurface drainage. Subsurface drainage water typically has more dissolved forms of phosphorus, such as DMRP or TDP, which is most readily available for plant uptake.

Flow Weighted Mean Concentrations

The overall annual flow weighted mean concentrations increased for DMRP and TP when comparing FD to CD. Based on ANOVA, regressions for the treatment period were significant for DMRP (F = 3.18, P = 0.0760) but were not for TP (F = 1.24, P = 0.2667). The regression equations for the calibration period and the treatment period as well as the corresponding r-squared values are presented in Table 2.8. Using ANCOVA for DMRP, there was not an overall difference between calibration and treatment period regressions (F = 0.97, P = 0.3263), but there was for intercepts (F = 3.39, P = 0.0661) and slopes (F = 6.40, P = 0.0314); and TP did show an overall difference between regressions (F = 3.80, P = 0.0517), but not for intercepts (F = 0.12, P = 0.7344) or slopes

(F = 2.31, P = 0.1574) (Table 2.5). Even though increases in the mean annual flow weighted mean concentrations of DMRP and TP were documented, only DMRP illustrated a significant difference in the slopes between the calibration and treatment period regression equations due to the treatment of CD. If we compare the slopes of the calibration period to the treatment period a reduction of 170% was documented for TP, however, DMRP illustrates an increase of 230% (Table 2.8). Soil type, climate, and agronomic practices more than likely affected the variability in phosphorus during the treatment period.

Studies that published results for phosphorus were inconsistent and there was no common trend found (Evans et al., 1991; Evans et al., 1995; Gilliam and Skaggs, 1986; and Thomas et al., 1992). Some studies demonstrated increases while others demonstrated decreases. However, all studies that found decreases believe they were due to the reductions in outflow of drainage water. More research is needed on phosphorus because of the complexity associated with phosphorus sorption and solubility. At the present time additional measurements and modeling are being conducted in order to determine the processes and mechanisms controlling phosphorus release from this CD system.

CONCLUSION

This research study used a paired watershed design specifically as it was prescribed in Clausen and Spooner, 1993 to analyze the effectiveness of the CD technique. Due to the large number of data points being zero during the treatment period because no flow occurred out of the field in the treatment zone, it really effected the regression equations and caused low r-squared values. This suggests that the paired watershed approach may not be the best analysis to use for our paired watershed study.

Overall, the use of CD showed environmental benefits compared to FD. Results from this field study show large reductions in flow, DMRP, TP, NH_4N, NO_3N and TN yields at the field's edge. The reductions were primarily due to reductions in drainage water outflow. The benefit of CD on mitigating nutrient loss to surface waters if implemented in Minnesota looks very promising but we experienced below average precipitation during the entire study period. The short duration of this study indicates more research is needed to understand how the CD system will function during normal and above normal years of precipitation, the mechanisms for phosphorus yield and concentration reductions, and to observe whether we will continue to document a consistent reduction in all of the above parameters.

Table 2.1. Average monthly and annual precipitation measured at the study site during the frost free periods (April – October) and taken from the Marshall weather station during the frozen periods (January – March and November – December) from 2006 to 2009 and the Marshall weather station.

Month	2006	2007	2008	2009	Marshall (1975-2005)
	-----------------	-----------------	-mm-	-----------------	-----------------
January	10.67	2.54	1.27	28.70	21.66
February	5.59	53.34	0.51	25.91	15.08
March	44.45	73.66	57.40	37.08	49.26
April	79.76	49.53	41.40	22.61	65.63
May	40.64	62.99	82.80	51.05	83.13
June	140.97	61.98	55.12	57.40	100.99
July	38.10	15.75	51.56	45.21	92.85
August	48.01	156.97	25.40	61.21	90.58
September	16.26	52.58	62.48	60.45	70.58
October	9.65	134.62	79.25	118.11	46.53
November	11.68	2.03	36.32	5.08	43.84
December	53.59	19.05	27.94	42.93	20.25
Total	499.36	685.04	521.46	555.75	700.39

Table 2.2. Summary of the agricultural activities in the paired watersheds.

	Calibration Period		Treatment Period	
	Control	Treatment	Control	Treatment
Crop Planted	2006 – Corn 2007 – Corn		2008 – Soybeans 2009 – Corn	
Fertilizer	2006 – 174 kg ha^{-1} N 67 kg ha^{-1} P_2O_5 67 kg ha^{-1} K_2O 2007 – 179 kg ha^{-1} N 67 kg ha^{-1} P_2O_5 67 kg ha^{-1} K_2O		2008 – Not Fertilized 2009* – 150 kg ha^{-1} N 99 kg ha^{-1} P_2O_5 143 kg ha^{-1} K_2O	

* liquid swine manure: 37,416 L ha^{-1}; 5.0 kg N 1000 L^{-1}, 2.6 kg P 1000 L^{-1}, 3.8 kg K 1000 L^{-1}

Table 2.3. Summary of the management for the paired watersheds during the calibration and treatment periods.

	Calibration Period		Treatment Period	
	Control	Treatment	Control	Treatment
Drainage	2006 – Free	2006 – Free	2008 – Free	2008 – Controlled
	2007 – Controlled	2007 – Controlled	2009 – Free	2009 – Controlled
Weir Height	2006 – NA	2006 – NA	2008 – NA	2008 – 0.6 meters
(below surface)	2007 – 0.6 meter	2007 – 0.6 meters	2009 – NA	2009 – 0.6 meters

Table 2.4. ANCOVA for comparing calibration and treatment period regressions for flow, dissolved molybdate reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate-nitrogen and total nitrogen yields.

Variable		F	P
Flow ($m^3\ d^{-1}$)	Overall	7.76	0.0055*
	Intercept	77.16	<0.0001*
	Slope	2.38	0.1458
Yields (kg ha^{-1})			
DMRP	Overall	1.66	0.1986
	Intercept	7.24	0.0073*
	Slope	8.39	0.0109*
TP	Overall	1.23	0.2686
	Intercept	4.71	0.0304*
	Slope	3.48	0.0754*
NH_4N	Overall	0.98	0.3233
	Intercept	1.10	0.2962
	Slope	1.37	0.2463
NO_3N	Overall	1.80	0.1804
	Intercept	92.05	<0.0001*
	Slope	1.83	0.2061
TN	Overall	1.02	0.3141
	Intercept	94.70	<0.0001*
	Slope	2.41	0.1469

* Indicates significance at p = 0.10

Table 2.5. ANCOVA for comparing calibration and treatment period regressions for dissolved molybdate reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate-nitrogen and total nitrogen flow weighted mean concentrations.

Variable		F	P
DMRP ($\mu g\ L^{-1}$)	Overall	0.97	0.3263
	Intercept	3.39	0.0661*
	Slope	6.40	0.0314*
TP ($\mu g\ L^{-1}$)	Overall	3.80	0.0517*
	Intercept	0.12	0.7344
	Slope	2.31	0.1574
NH_4N ($mg\ L^{-1}$)	Overall	2.83	0.0941*
	Intercept	2.53	0.1131
	Slope	4.54	0.0364*
NO_3N ($mg\ L^{-1}$)	Overall	3.08	0.0796*
	Intercept	9.02	0.0028*
	Slope	0.67	0.4503
TN ($mg\ L^{-1}$)	Overall	4.52	0.0340*
	Intercept	8.88	0.0030*
	Slope	0.67	0.4474

* Indicates significance at p = 0.10

Table 2.6. Mean annual† flow and yields for dissolved molybdate reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate-nitrogen and total nitrogen for the paired watersheds during the calibration and treatment periods.

	Calibration Period		Treatment Period	
Variable	Control	Treatment	Control	Treatment
Flow ($m^3\ d^{-1}$)	174	143	137	13
<u>Yields ($kg\ ha^{-1}$)</u>				
DMRP	0.6	0.4	0.1	0.02
TP	0.5	0.3	0.1	0.04
NH_4N	0.8	0.1	0.1	0.2
NO_3N	46	21	18	5.0
TN	44	21	17	5.0

† For monitoring during frost free periods and when there was measured flow.

Table 2.7. Flow weighted mean concentrations for dissolved molybdate reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate-nitrogen and total nitrogen for the paired watersheds during the calibration and treatment periods.

	Calibration Period		Treatment Period	
Variable	Control	Treatment	Control	Treatment
DMRP ($\mu g\ L^{-1}$)	110	154	37	53
TP ($\mu g\ L^{-1}$)	129	190	102	143
NH_4N ($mg\ L^{-1}$)	1	0.4	0.2	1
NO_3N ($mg\ L^{-1}$)	8	8	8	19
TN ($mg\ L^{-1}$)	8	7	9	19

Table 2.8. Regression equations and r-squared values of flow, dissolved molybdate reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate-nitrogen and total nitrogen yields and flow weighted mean concentrations as well as the percent change in slope for the paired watersheds during the calibration and treatment periods.

	Calibration Period		Treatment Period		Change
Variable	Regression Equation	R^2	Regression Equation	R^2	%
Flow	y = 6.177 + 0.476x	0.81	y = 1.250 + 0.247x	0.31	-48
Yields					
DMRP	y = 0.026 + 0.081x	0.29	y = 0.001 + 0.230x	0.18	183
TP	y = 0.021 + 0.197x	0.44	y = 0.005 + 0.064x	0.01	-68
NH_4N	y = 0.004 + 0.006x	0.02	y = 0.012 + 0.204x	0.00	3300
NO_3N	y = 0.128 + 0.325x	0.80	y = 0.028 + 0.245x	0.50	-25
TN	y = 0.120 + 0.343x	0.82	y = 0.016 + 0.279x	0.59	-19
Flow Weighted Mean Concentrations					
DMRP	y = 6.452 + 0.044x	0.18	y = 0.465 + 0.145x	0.01	230
TP	y = 5.988 + 0.078x	0.21	y = 2.170 - 0.055x	0.05	-170
NH_4N	y = 0.017 + 0.004x	0.00	y = 0.133 - 0.141x	0.00	-3625
NO_3N	y = 1.308 + 0.115x	0.24	y = 0.702 + 0.030x	0.01	-74
TN	y = 1.279 + 0.122x	0.26	y = 0.699 + 0.021x	0.00	-83

Figure 2.1. Location of study site in southwest Minnesota. St. Paul is shown for reference.

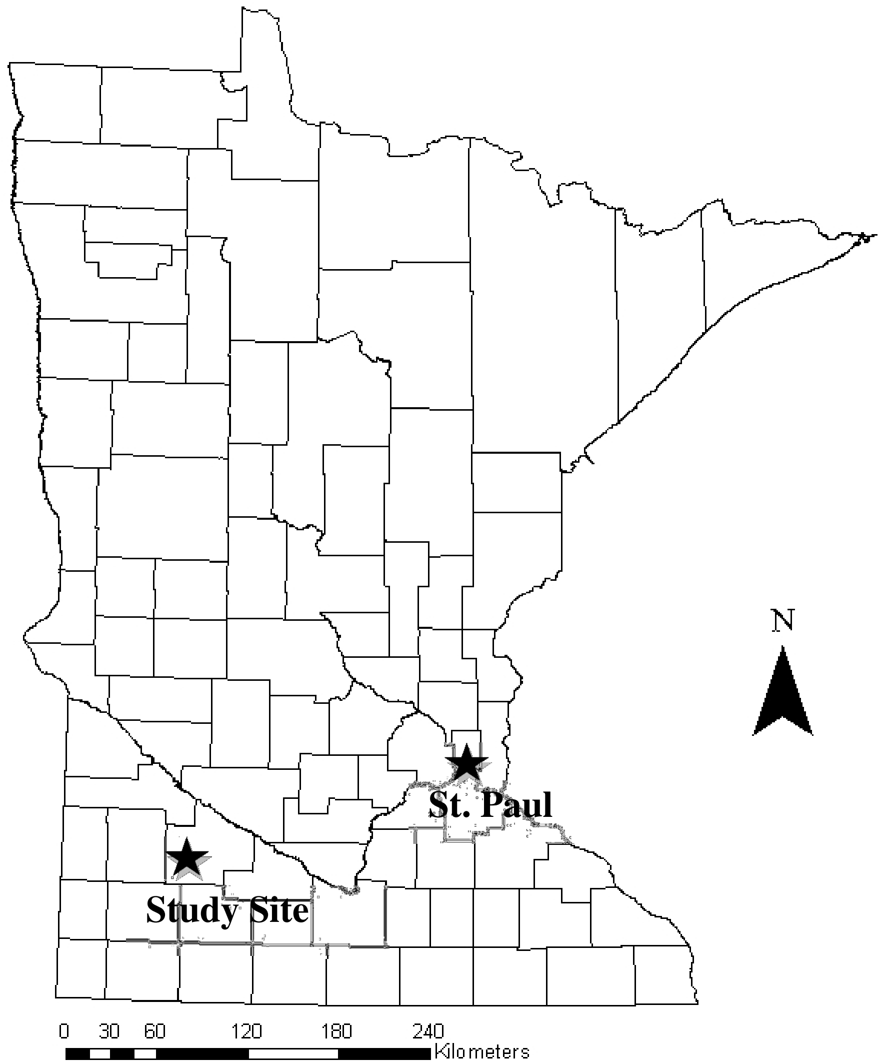


Figure 2.2. Soil series boundaries within the field.

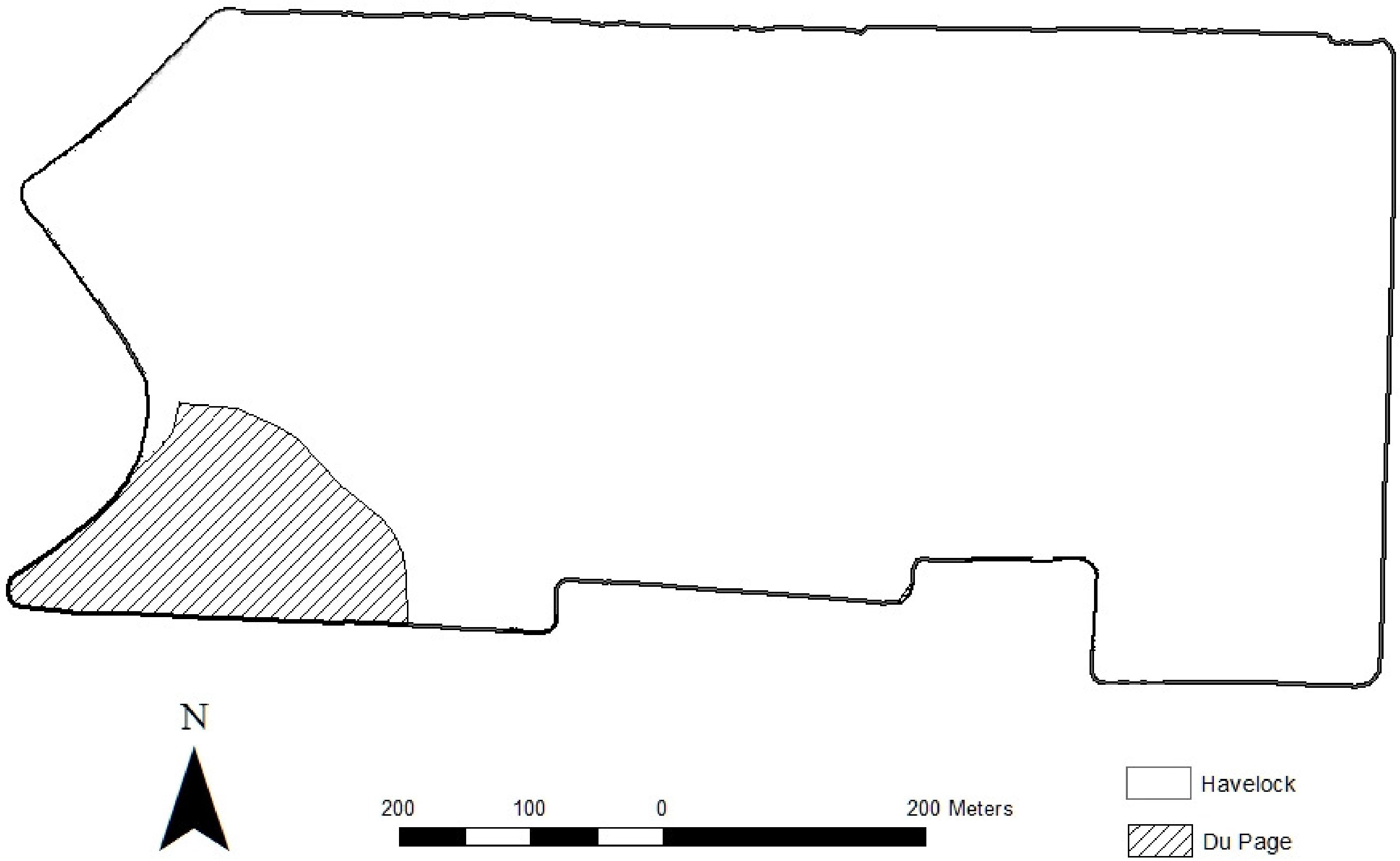


Figure 2.3. Layout of study site.

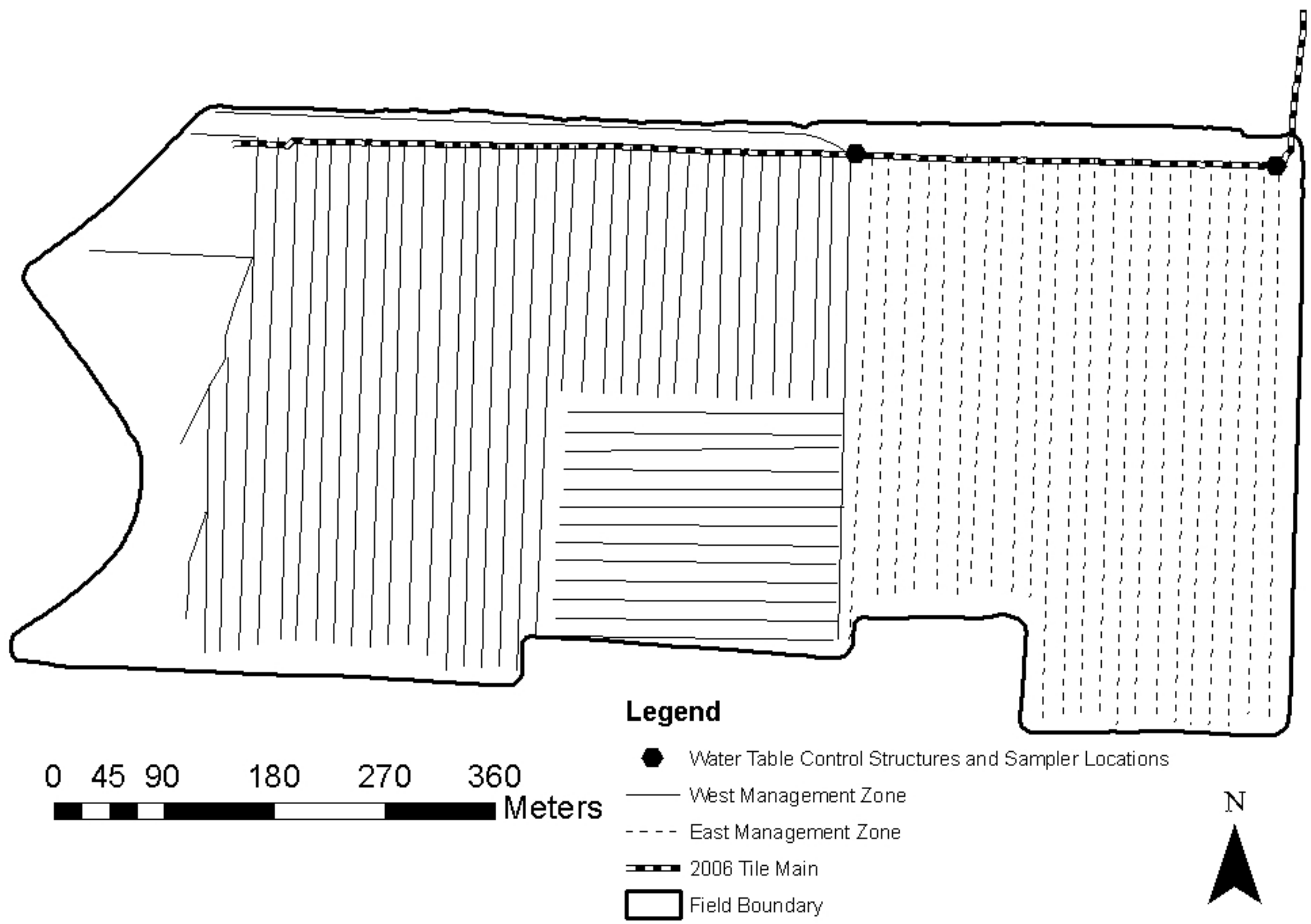


Figure 2.4. Cumulative volume from the control and treatment zones.

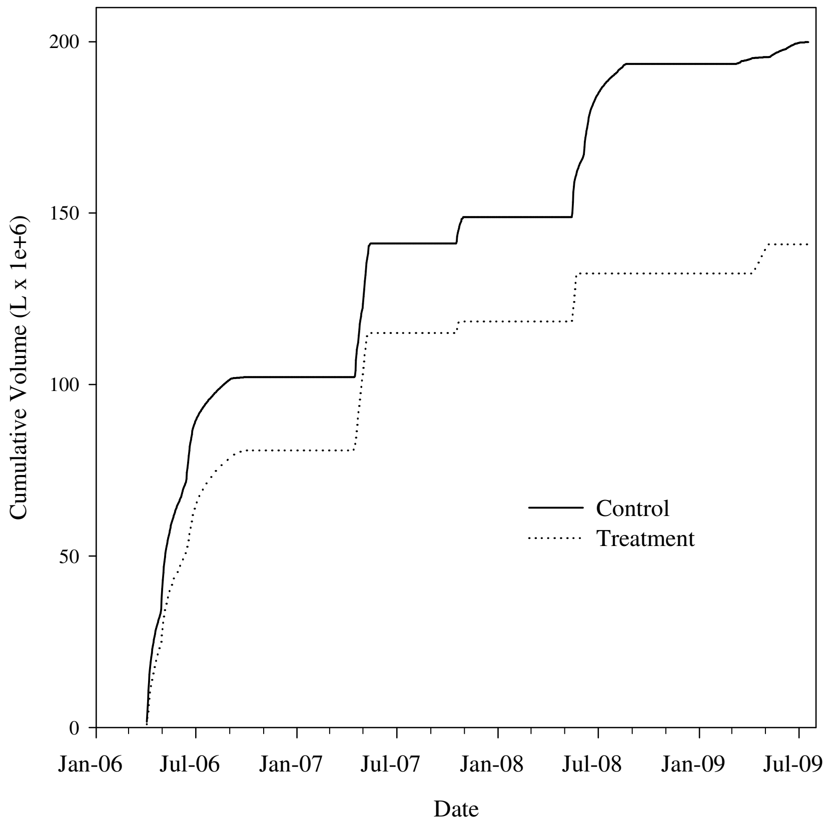
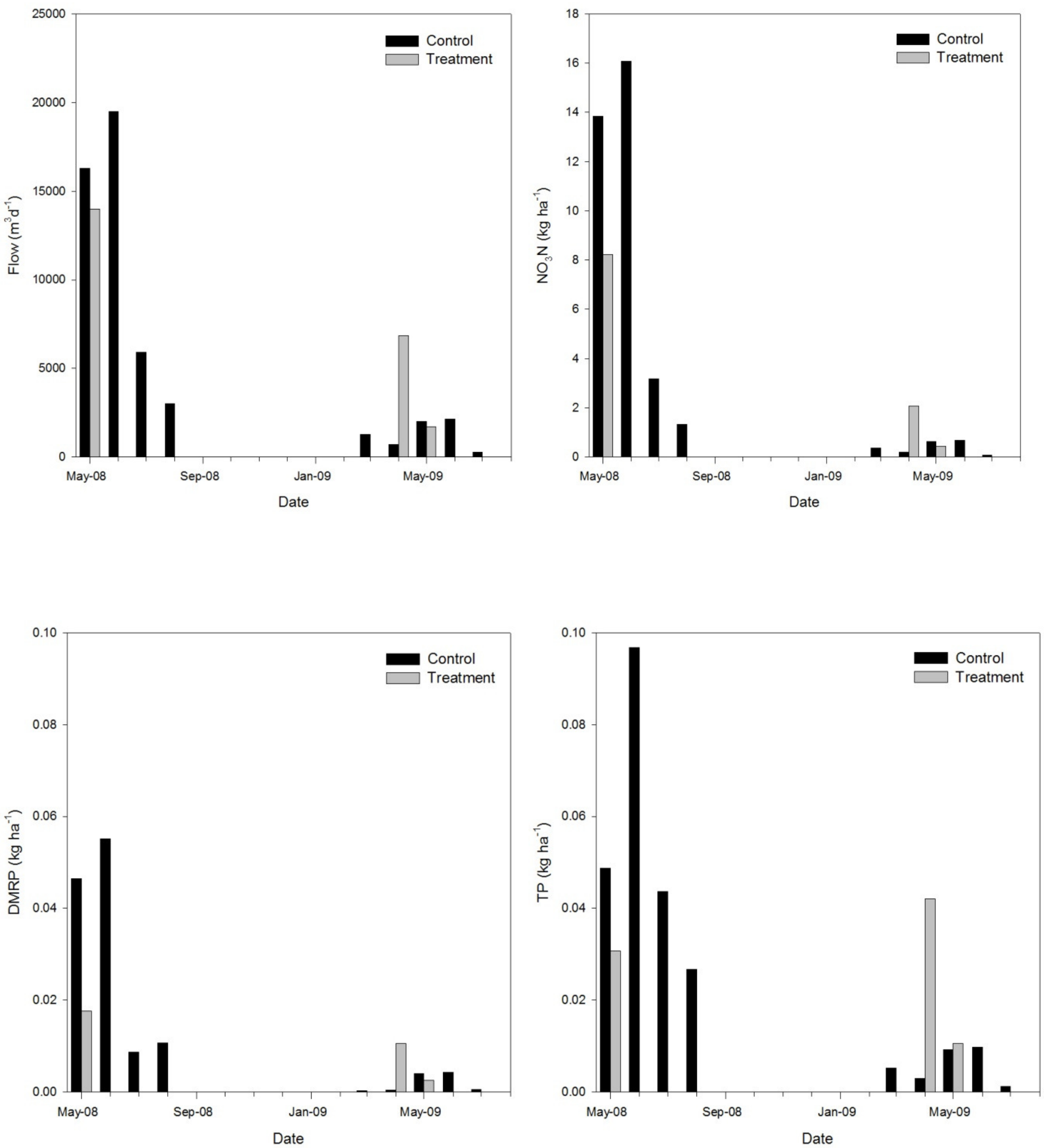


Figure 2.5. Monthly flow, nitrate-nitrogen, dissolved molybdate reactive phosphorus, and total phosphorus yields for the treatment period (2008-2009).



CHAPTER 3. Soil Physical and Hydraulic Properties of an Undrained, Cultivated Row Crop Field Compared to an Undrained Remnant Prairie in Southwest Minnesota

OVERVIEW

Tallgrass prairies once covered one-third of Minnesota in a zone extending from the northwest to the south and southeast. Through the introduction of mechanized agriculture in the mid-1800's, these grasslands became one of the richest, most productive agricultural regions in the world. Although annual soil tillage may be beneficial and in some cases necessary for seedbed preparation, tillage-pan alleviation, and residue management, however, it has altered soil properties. This study was conducted to compare soil physical and hydraulic properties between an undrained, cultivated, row crop field and an adjacent undrained remnant prairie; both which developed under similar soil forming processes. Forty-eight undisturbed soil cores (0 - 1.27 m depth) were collected from the undrained cultivated field and 12 were collected from the prairie site and analyzed by horizon. The soil types were Havelock and Nishna in the prairie site and Havelock in the undrained cultivated field. Bulk density in the surface horizon was found to be significantly lower for the soils under prairie vegetation (1.11 Mg m^{-3} and 1.14 Mg m^{-3} for Havelock and Nishna, respectively) compared with the soil in the row crop field (1.30 Mg m^{-3}); while bulk density in the subsurface horizons 1 and 2 of the prairie Havelock (1.12, and 1.10 Mg m^{-3}, respectively) was significantly lower than those for the prairie Nishna (1.32 and 1.23 Mg m^{-3}, respectively) and row crop Havelock soil (1.30 and 1.32 Mg m^{-3}, respectively). Total porosity in the surface horizon for both soils in the native prairie was significantly higher (0.58% and 0.57%, respectively) than that in

the row crop Havelock soil (0.51%); whereas in the subsurface horizon 1 and 2, total porosity was greater for the Havelock soil (0.58% and 0.58%, respectively) than for Nishna (0.50% and 0.54%, respectively) and row crop Havelock (0.51% and 0.50%, respectively). There was a decrease in the volumetric water content at field capacity and an increase in volumetric water content at which the soil is at the wilting point for the row crop Havelock compared with the prairie soils at the surface horizon. These results suggest that there was a reduction in the amount of available water for plant uptake in the row crop Havelock compared with the prairie soils. Because a large percentage of Minnesota's land base is under cultivation, it is useful to evaluate changes in soil physical properties and relate them to past and future management practices.

INTRODUCTION

Approximately 162 million ha of prairie existed prior to European settlement (Samson and Knopf, 1994). Since the introduction of mechanized agriculture in the late 1800's survey's suggest that the area of native prairie has declined by as much as 99.9% with overgrazing and recreation adding additional stress to remnant prairies (Samson and Knopf, 1994). Remnant prairie fragments are rare, however they offer great opportunities to observe what the landscape might be like had it not been altered. Remnant prairies can also provide soil physical, chemical, and biological property data to help understand the effects of land use change as well as provide index values for soil properties in ecosystem restoration efforts (Brye and Moreno, 2006; Brye and Pirani, 2005).

Continuous annual tillage is a practice commonly used by farmers for seedbed preparation, tillage-pan alleviation, and residue management. Tillage is generally not beneficial for maintaining or improving soil quality because it promotes the loss of soil organic matter, disrupts root processes, affects water infiltration and hydraulic conductivity, and untimely cultivation, especially under wet conditions can result in increased bulk density due to soil compaction (Brye, 2003; Brye and Pirani, 2005; Chan and Mead, 1989; McVay et al, 2006; Mudgal et al., 2010; Scott and Wood. 1989). Wetting and drying cycles, settling, and reconsolidation of soil after tillage changes the shape of the soil water retention curve and modifies the conductivity – water content relationship (Schwartz et al., 2003). Tillage has also been shown to affect the volume of macropores in the soil by reducing and disrupting them, which can have a large impact on the hydrology and soil-air-water relations of the cropping areas (Brye, 2003; Cassel and Nelson, 1985; Chan and Mead, 1989).

Perennial vegetation has been shown to increase soil porosity, which can influence soil hydraulic properties (Fuentes et al., 2004; Mudgal et al., 2010). Soil under perennial vegetation is not disrupted by tillage and therefore allows for better soil bulk density and hydraulic properties over the long term (Fuentes et al., 2004; Mudgal et al., 2010). Soil hydraulic properties are temporally variable and can be affected by soil structure (Fuentes et al., 2004; Mudgal et al., 2010), biological plants and organisms (Mudgal et al., 2010), shrink-swell cracks in clay rich soils (Mudgal et al., 2010), and agricultural activities (Anderson et al., 1990; Bharati et al., 2002; Brye, 2003; Brye and Moreno, 2006; Brye and Pirani, 2005; Cassel and Nelson, 1985; Fuentes et al., 2004; Mallants et al., 1996;

Mudgal et al., 2010; Oquist et al., 2006; Schwartz et al., 2003; Scott and Wood. 1989; Seobi et al., 2005; Sperber et al., 2003; Udawatta et al., 2008). Conversion of native prairies to cropland will, over time, result in changes in soil physical and hydraulic properties, root activities, the development of biopores, and a decrease in aggregate stability (Schwartz et al., 2003).

Soil physical and hydraulic properties are important indicators of the overall quality of the soil and the potential for agricultural production. Soil hydraulic properties can influence infiltration and soil water movement through the profile (Kucharik et al., 2006). Differences in these properties can affect the amount and timing of plant-available soil water, and the potential for surface runoff and erosion (Sperber et al., 2003). Saturated hydraulic conductivity (K_s) has been thought to be one of the most valuable hydraulic properties in deducing soil physical properties for applied purposes (Wang et al., 1985). According to Wang et al., 1985, soil compaction, plant root characteristics (i.e. soil aggregation and root biopore formation), and the increased or decreased tortuosity of soil pores would be reflected in changes in K_s because it is strongly influenced by pore size distribution and pore continuity (Sperber et al., 2003).

The soil moisture retention curve is another hydraulic property that can reveal a lot about a soil especially under different management practices, vegetation, and locations on the landscape. The soil moisture retention curve describes the relationship between soil-water potentials and water content. As water content decreases and pressure increases, water is held in the soil by incrementally smaller pores (McVay et al, 2006). If this concept is applied, water potential refers to the amount of energy necessary for water to be removed from the soil by plant roots. The optimum range of water content for plant growth has generally been from field capacity to the permanent wilting point. This curve is generally determined in the laboratory on disturbed soil samples (Letey, 1985), which allow for differing relationships in the field versus the laboratory. The use of intact, undisturbed soil cores preserves the existing soil and pore structure allowing researchers to adequately evaluate the land use or management practice being used in the field (Brye, 2003).

Many studies have compared sites under row crop and cultivation to native prairies, restored prairies, CRP lands, pastures, and agricultural and agroforestry buffer strips to determine the effect the varying degrees of annual tillage (conventional tillage, conservation tillage and no-till) and crop rotations have on soil physical and hydraulic properties (Anderson et al., 1990; Bharati et al., 2002; Brye, 2003; Brye and Moreno, 2006; Brye and Pirani, 2005; Cassel and Nelson, 1985; Chan and Mead, 1989; Fuentes et al., 2004; Kucharik et al., 2006; McVay et al, 2006; Mudgal et al., 2010; Schwartz et al., 2003; Scott and Wood. 1989; Seobi et al., 2005; Sperber et al., 2003; Udawatta et al., 2008; Wang et al., 1985). Of all these studies, only two did not find significant differences between the two management practices (Brye, 2003; Schwartz et al., 2003), while the others found varying ranges in differences nevertheless differences were still found, with prairies, buffers, and pastures exhibiting improved physical and hydraulic properties than the cultivated and row crop sites.

In this study, we investigated the difference in soil physical and hydraulic properties between an undrained, remnant prairie and an adjacent undrained, row crop field that is annually cultivated. This area was chosen because the soils were developed under similar soil-forming processes, therefore, any differences observed in the soil physical and hydraulic properties could be attributed to the different management practices. This study differs from the majority of the research reported in the literature as it evaluates differences in soil physical properties throughout the entire soil profile as opposed to 0-10 cm, which is the depth usually studied by others. This study also evaluates undisturbed soil cores by horizon. All studies reviewed analyzed the soil using specified depth increments. Lastly, many studies determine the physical and hydrologic properties using disturbed soil samples, which do not give an accurate representation of the conditions present in the field. Our study used undisturbed soil samples.

MATERIALS AND METHODS

Study Area

The study was conducted at the Hicks Family Farm located within Redwood County in Southwest Minnesota (Figure 3.1). The climate in Southern Minnesota is humid continental with hot summers and cold winters. Minnesota's location allows it to receive a wide variety of weather and each season (winter, spring, summer and fall) experiences its own set of unique characteristics. There are three types of soil located in the study area, a Havelock clay loam (mesic Cumulic Endoaquolls), a Nishna silty clay loam (mesic Cumulic Vertic Endoaquolls), and a Du Page loam (mesic Cumulic Hapludolls), which were all formed in calcareous alluvium (Figure 3.2 and 3.4). The study focused on the Havelock and Nishna soils because most of the samples were collected on these soil types. Havelock and Nishna soils are nearly level and located on flood plains and are poorly and very poorly drained soils, respectively.

The research was conducted on two fields, an undrained remnant prairie and an undrained, cultivated, row crop field, located within 0.86 km of each other (Figure 3.3). The row crop site was 37 ha in size, and planted to corn (*Zea mays* L.) in 2006, 2007, and 2009, and soybean (*Glycine max* L.) Merr.) in 2008. Prior to the experiment soybean was planted in 2004 and spring wheat (*Triticum aestivum* L.) in 2005. The row crop field was split into two different management zones, east and west. Prior to 2005 the undrained, cultivated field had never been drained and was split into two different zones as there was also a water table management (controlled drainage) experiment being conducted at the field site. The soil sampling locations for the row crop field were all located in the Havelock soil type. The remnant prairie site, 53.4 ha in size, has never been cultivated, and the vegetation is harvested once or twice a year. Vegetation on the remnant prairie site consisted of a mix of grasses dominated by big bluestem (*Andropogon gerardii* Vitman), Indiangrass [*Sorghastrum nutans* (L.) Nash], switchgrass (*Panicum virgatum* L.), and numerous unidentified forbs. A smaller area, 3.6 ha in size and located in the southeast corner of the remnant prairie was selected for soil characterization and analysis. The smaller area was chosen because it contained the Havelock and Nishna soil types, which were the same and similar to the soil types in the row crop field.

Sample Collection and Analysis

Soil sampling was conducted at both sites using a 0.81 ha grid spacing for the row crop field and a 0.40 ha grid spacing for the remnant prairie, which was determined using the Farm Site Mate (Farm Works Software, Hamilton, IN) program installed on a handheld PDA-GPS device. Forty-eight soil sampling locations were determined for the row crop field, 30 in the west management zone and 18 in the east management zone, and 12 soil sampling locations were determined for the remnant prairie (Figure 3.2 and 3.4). Three soil cores were collected at each sampling location in the autumn of 2005 from the row crop field and in the autumn of 2007 from the remnant prairie. Intact, uncompacted soil cores were collected using a tractor mounted hydraulic probe to a depth of 1.27 m (Giddings Mfr, CO). The soil cores were then stored in plastic liners and refrigerated until analysis. During the time of collection soil cores were examined and confirmed to be uncompacted.

The analysis conducted on the soil cores were soil texture, soil moisture retention, vertical saturated hydraulic conductivity (K_s), bulk density, and porosity. The average depths of the soil horizons for each field are presented in Table 3.1. Soil texture was determined using the feel method when describing the undisturbed soil cores. Analysis for soil moisture retention, K_s, bulk density, and porosity were all conducted on undisturbed samples. Soil moisture was characterized with three replicate samples at 0 kPa and two replicate samples at -10, -30, and -100 kPa matric potentials. Moisture contents for -500 and -1500 kPa matric potentials were determined by extrapolation using regression analysis. Saturated hydraulic conductivity was measured using three replicate samples from each horizon. Bulk density determination followed the core method (Blake, 1965), while total porosity (ϕ) was calculated using the following relationship:

$$\phi = \left(1 - \frac{\rho_b}{\rho_s}\right) \qquad [3.1]$$

where ρ_b is the soil bulk density and ρ_s is the particle density (assumed to be 2.65 g cm^{-3}). A detailed description for each of the soil analysis listed above can be found in Rolf, 2005.

Statistical Analysis

Data analysis compared the soil physical and hydraulic properties by field, soil type and horizon and the interactions between them. Bulk density, porosity and K_s were analyzed by analysis of variance (Proc Glimmix, SAS Institute 2002) to distinguish significant effects of field, soil type, and horizon. Volumetric water content (θ_v) was analyzed using regression analysis by comparing the slopes and intercepts for the natural log of θ_v as a function of the natural log of pressure (Proc Glimmix, SAS Institute 2002). Statistical significance was determined at the $P < 0.05$ level for all comparisons.

RESULTS AND DISCUSSION

Soil Horizons

The average depths and horizonation for the undrained, cultivated row crop field were different than for the remnant prairie (Table 3.1). The row crop field consisted of Apk, Ak1, Ak2 and Ak3 horizons while the remnant prairie consisted of Ak1, Ak2, and Ak3 horizons. The “k” indicates there is an accumulation of carbonates, which was present throughout the entire soil profile for both fields, and “p” indicates disturbance of the surface layer by mechanical means, pasturing or similar uses. The remnant prairie did not have the Apk horizon present because it has never been disturbed by tillage or pasturing. The Havelock and Nishna soils consisted of very thick, dark surface horizons and over the sampling depth (0 – 1.27 m depth) the B and C horizons were never reached.

When making comparisons between the row crop field and the remnant prairie it was difficult to compare the Ak1 horizon to the Ak1 horizon, as they were not the same horizon. In order to accurately compare each horizon they were relabeled surface, subsurface 1, subsurface 2, and subsurface 3 (Table 3.1).

Soil Bulk Density

Soil bulk density was significantly different between the row crop fields and the remnant prairie soils; in addition, there were also significant differences in bulk density at different horizons within a soil type, which led to a significant soil type by horizon interaction (Table 3.2). Bulk density was significantly lower for the Havelock soil in the Remnant prairie compared to the east and west zones of the row crop field for all soil horizons (Table 3.2). This suggests disruption of root processes and compaction due to tillage in the row crop field and enhanced soil structure, soil aeration, and ease of root penetration through the entire Havelock soil profile of the remnant prairie. Native plants have dense and deep roots, which help to create the lower bulk densities throughout the soil horizons as was observed in this study and by others (Mudgal et al., 2010, Oquist et al., 2006, and Udawatta et al., 2008). The Nishna soil in the remnant prairie showed an interesting behavior in bulk density, as the bulk density was significantly lower in the surface horizon and not significantly different in the deeper subsurface horizons compared with the soils in the row crop field (Table 3.2). This is most likely attributed to the native prairie plants in the surface horizon and the higher clay content documented in the soil descriptions in the lower horizons of the Nishna soil type. A study by Mudgal et al., 2010 also found bulk density to be dominated by clay content in the deeper depths.

For the soils in the row crop field, the bulk density was significantly different only at the deepest subsurface horizon; however, the reasons for this result are unclear but could be related to textural differences at depth (Table 3.2).

Although there were some significant differences in bulk density by soil horizon, the trends observed were not consistent. For example, bulk density tended to increase with depth only in the east row crop for the Havelock and Nishna soil under the remnant prairie vegetation (Table 3.2). The reasons for this are not known, but could be attributed to the fact that these soil types have thick A horizons and during sampling the B or C horizons were never reached.

Total Porosity

Because total porosity is an inverse function of bulk density (as shown in equation 3.1), the results observed for total porosity were, in the majority of cases, the opposite as those observed for bulk density (Table 3.3). Total porosity was significantly higher in the remnant prairie under the Havelock soil as compared to east and west zones of the row crop field for all soil horizons (Table 3.3). Whereas, the Nishna soil in the native prairie was significantly higher as compared to field east and field west for the surface horizon, but not for the subsurface horizons (Table 3.3). There were no significant differences in total porosity between soils in the row crop field (Table 3.3). Total porosity tended to decrease with increasing depth only for the Nishna under the native prairie (Table 3.3). Tillage and agricultural activities have been reported to decrease total porosity of soils, while native prairie grass have been reported to increase pore volume (Brye and Moreno, 2006, Mudgal et al., 2010, and Seobi et al., 2005).

Saturated Hydraulic Conductivity

The least square means for saturated hydraulic conductivity (K_s) are presented in Table 3.4. There were no significant differences found between the row crop field and the remnant prairie for all horizons except the subsurface 2 horizon. The subsurface 2 horizon had the largest variability with means ranging from 68.05 to 812.12 cm d^{-1}.

When comparing the east and west management zones of the row crop field there were no significant differences found between the different zones or the horizons. Comparing the different soil types in the remnant prairie showed no significant difference in K_s until the subsurface 2 horizon. This horizon showed significantly lower K_s for the Havelock soil type. The Havelock soil in the remnant prairie and the row crop field were not significantly different until the subsurface 2 horizon, in which the K_s for the Havelock soil in the remnant prairie was significantly lower from the east zone but not the west zone. This is most likely attributed to differences in clay content in the deeper horizons. Unfortunately a textural analysis was not performed for this study, however, it may have been helpful to explain some of these differences.

When comparing K_s by soil horizon across both fields and soil types the general trend showed K_s to increase as you moved down the soil profile. In the row crop field significant differences were found in the west zone for the subsurface 3 horizon and in the east for the subsurface 2 horizon, however significant differences were not detectable in the remnant prairie under either soil type (Havelock or Nishna). This trend has also been documented in studies by Oquist et al., 2006, and Schwartz et al., 2003. Differences are most likely attributed to the presence of macropores created by root channels, shrink-swell processes and soil fauna. Also, all the soils analyzed are located in floodplains and numerous sand seams and shell fragments were documented throughout the soil profile.

Overall, significant differences were more difficult to detect for K_s than for other soil properties as the variability was quite large. Large variability in K_s was documented by Fuentes et al., 2004, Mallants et al., 1996, Mudgal et al., 2010, Schwartz et al., 2003, Seobi et al., 2005, and Sperber et al., 2003 as well. Many studies (Cassel and Nelson, 1985; Fuentes et al., 2004; Mallants et al., 1996; Mudgal et al., 2010; Schwartz et al., 2003; Scott and Wood, 1989; Seobi et al., 2005; Sperber et al., 2003; Udawatta et al., 2008; Wang et al., 1985) found higher K_s values under native prairie sites as compared to cultivated and row crop sites, as well as K_s to decrease with depth, which is in contrast to the results reported from this study. The researchers attributed these trends to better soil structure, well-preserved pore networks, enhanced macropore flow, roots, organic matter additions, and an increase in bulk density. Differences in the top depths were more likely attributed to the soil structure variations caused by the management and macropores while differences for the lower depths were due to variations in clay content.

Soil Moisture Retention Curves

The pressures used in this study represent pressures required to bring soil from saturation to permanent wilting point. Although volumetric water content (θ_v) is a non-linear function of pressure, the relationship between these two soil properties will become linear by taking the logarithm of both terms. Linear transformations allow for easier interpretations about the relationship between changes in θ_v as a function of changes in pressure when comparing different soil types, or soils under different management systems, or between other treatments that can affect the θ_v. By linearizing this relationship, the slope of the regression indicates how much water drains from or is stored in the soil by applying a given pressure.

In this study, it was observed that the slopes for the regression line that explained the change in θ_v as a function of pressure were significantly different in the surface of remnant prairie soils than in the surface of row crop soils (Figure 3.5 and Table 3.5). This indicates that water will drain from the remnant prairie easier than from soils in the row crop site. As a result, plants can remove water from the surface of the prairie soils by applying lower pressure than from the surface of the row crop soils. In addition, the data suggests that there was an increase in the θ_v which represents the wilting point for row crop soils (Figure 3.5). The implication of this result is a decrease in the total amount of water that can be available for plant uptake when prairie soils are compared with row crop soils. The differences in slopes between soils in the prairie and row crop fields were not significant at the lower horizons, though there were significant differences in the θ_v when the soils are at field capacity between the different soils (Table 3.5). This is a direct result of greater total porosity between those soils, which allows for greater water storage (Table 3.3).

Mudgal et al., 2010 looked at the differences in water content at various pressures ranging from 0 to -1500 kPa in a native prairie and cultivated row crop field in 10 cm increments at depths ranging from 0 to 60 cm. They reported the native prairie site exhibited larger water contents than the field site in pressures less than -20 kPa for all depths except the 30-40 cm range. Pressures higher than -33 kPa showed higher water contents in the prairie site for the 0-10 and 50-60 cm ranges while the other depths showed higher water contents for the field site. The researchers attributed these results to differences in management practices near the surface with higher root density in the prairie, which improved soil structure, but the deeper depths were more dependent on clay content. Brye, 2003 showed very similar results with the native prairie having higher water content for each change in water potential. However, this study reported that land use had no effect on the water content at the permanent wilting point.

CONCLUSION

The remnant prairie site exhibited lower bulk density and higher total porosities for the Havelock soil type in all horizons and the Nishna soil type in the surface horizon as compared to the field site. Bulk density did not increase with depth, which we attributed to the thick A horizon and never reaching the B or C horizon during sampling. The K_s was highly variable and no significant differences were found between the remnant prairie and the row crop field site, however K_s increased with depth. The soil moisture retention curves generally showed the remnant prairie, especially the Havelock soil type, to have higher water contents for all pressures as compared to the field site, which could be translated to high water availability to plants grown on those soils than compared with plants grown on undrained, cultivated row crop soils. These results will help to better understand the effects of different management practices on soil physical and hydraulic properties, especially if the future agricultural landscape changes to more bioenergy perennial crops.

Table 3.1. Average depths (cm) of the soil horizons for each field.

	Field		Native Prairie		
	Horizon	Havelock	Horizon	Havelock	Nishna
Surface	Apk	27	Ak1	42	42
Subsurface 1	Ak1	68	Ak2	86	98
Subsurface 2	Ak2	119	Ak3	127	127
Subsurface 3	Ak3	127	---	---	---

Table 3.2. Least square means of bulk density (Mg m^{-3}) for each field, soil type and horizon.

	Field						Native Prairie					
Horizon	Havelock East			Havelock West			Havelock			Nishna		
Surface	1.30	b†	A	1.29	a	A	1.11	a	B	1.14	b	B
Subsurface 1	1.30	b	A	1.26	a	A	1.12	a	B	1.32	a	A
Subsurface 2	1.32	ab	A	1.24	a	A	1.10	a	B	1.23	ab	A
Subsurface 3	1.36	a	A	1.27	a	B	---			---		

† Means followed by the same lower case letter within the column or upper case letter within the row are not significantly different (P<0.05).

Table 3.3. Least square means of total porosity (%) for each field, soil type and horizon.

	Field						Native Prairie					
Horizon	Havelock East			Havelock West			Havelock			Nishna		
Surface	0.51	a†	B	0.51	a	B	0.58	a	A	0.57	a	A
Subsurface 1	0.51	a	B	0.52	a	B	0.58	a	A	0.50	b	B
Subsurface 2	0.50	a	B	0.53	a	B	0.58	a	A	0.54	ab	B
Subsurface 3	0.49	a	A	0.52	a	A	---			---		

† Means followed by the same lower case letter within the column or upper case letter within the row are not significantly different (P<0.05).

Table 3.4. Least square means of saturated hydraulic conductivity (K_s) (cm d^{-1}) for each field, type and horizon.

	Field						Native Prairie					
Horizon	Havelock East			Havelock West			Havelock			Nishna		
Surface	134.40	b†	A	121.06	b	A	101.45	a	A	306.48	a	A
Subsurface 1	418.41	ab	A	270.82	b	A	517.42	a	A	246.01	a	A
Subsurface 2	812.12	a	A	675.23	ab	AB	68.05	a	B	747.51	a	AB
Subsurface 3	566.83	ab	A	820.29	a	A	---			---		

† Means followed by the same lower case letter within the column or upper case letter within the row are not significantly different (P<0.05).

Table 3.5. Least square means for regression equation parameters for the effects of applied pressure on the soil moisture content for each field, soil type and horizon.

	Field						Native Prairie					
Horizon	Havelock East			Havelock West			Havelock			Nishna		
						Intercept						
Surface	-1.007	b†	B	-1.012	b	B	-1.060	a	A	-1.005	b	B
Subsurface 1	-1.217	a	A	-1.139	a	B	-1.065	a	C	-1.175	a	AB
Subsurface 2	-1.214	a	A	-1.129	a	B	-0.959	b	C	-1.161	a	AB
Subsurface 3	-1.222	a	A	-1.164	a	A	---			---		
	Field						Native Prairie					
Horizon	Havelock East			Havelock West			Havelock			Nishna		
						Slope						
Surface	-0.075	c	B	-0.074	b	B	-0.127	a	A	-0.107	a	A
Subsurface 1	-0.121	a	A	-0.105	a	B	-0.126	a	A	-0.115	a	AB
Subsurface 2	-0.106	b	A	-0.099	a	A	-0.092	b	A	-0.117	a	A
Subsurface 3	-0.101	b	A	-0.094	a	A	---			---		

† Means followed by the same lower case letter within the column or upper case letter within the row are not significantly different(P<0.05).

Figure 3.1. Location of study site in southwest Minnesota. St. Paul is shown for reference.

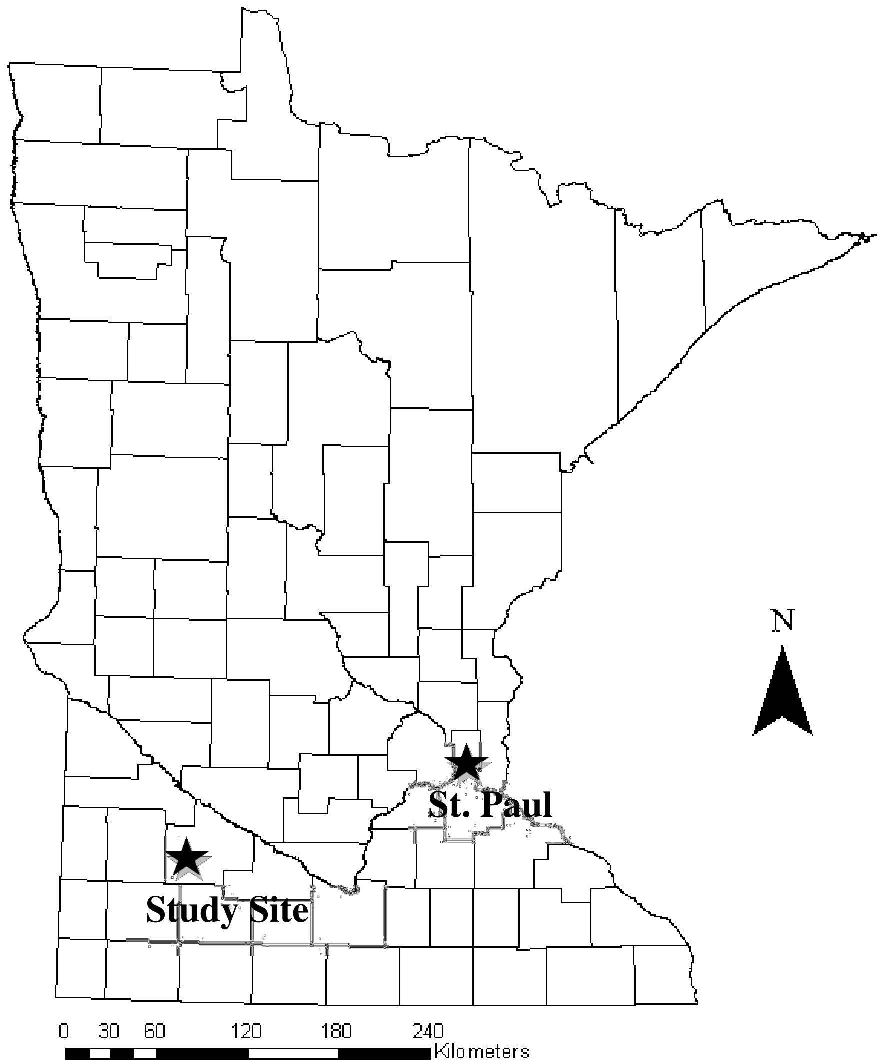


Figure 3.2. Soil series boundaries and location of soil borings within the row crop field site.

Figure 3.3. Location of the row crop field and remnant prairie site.

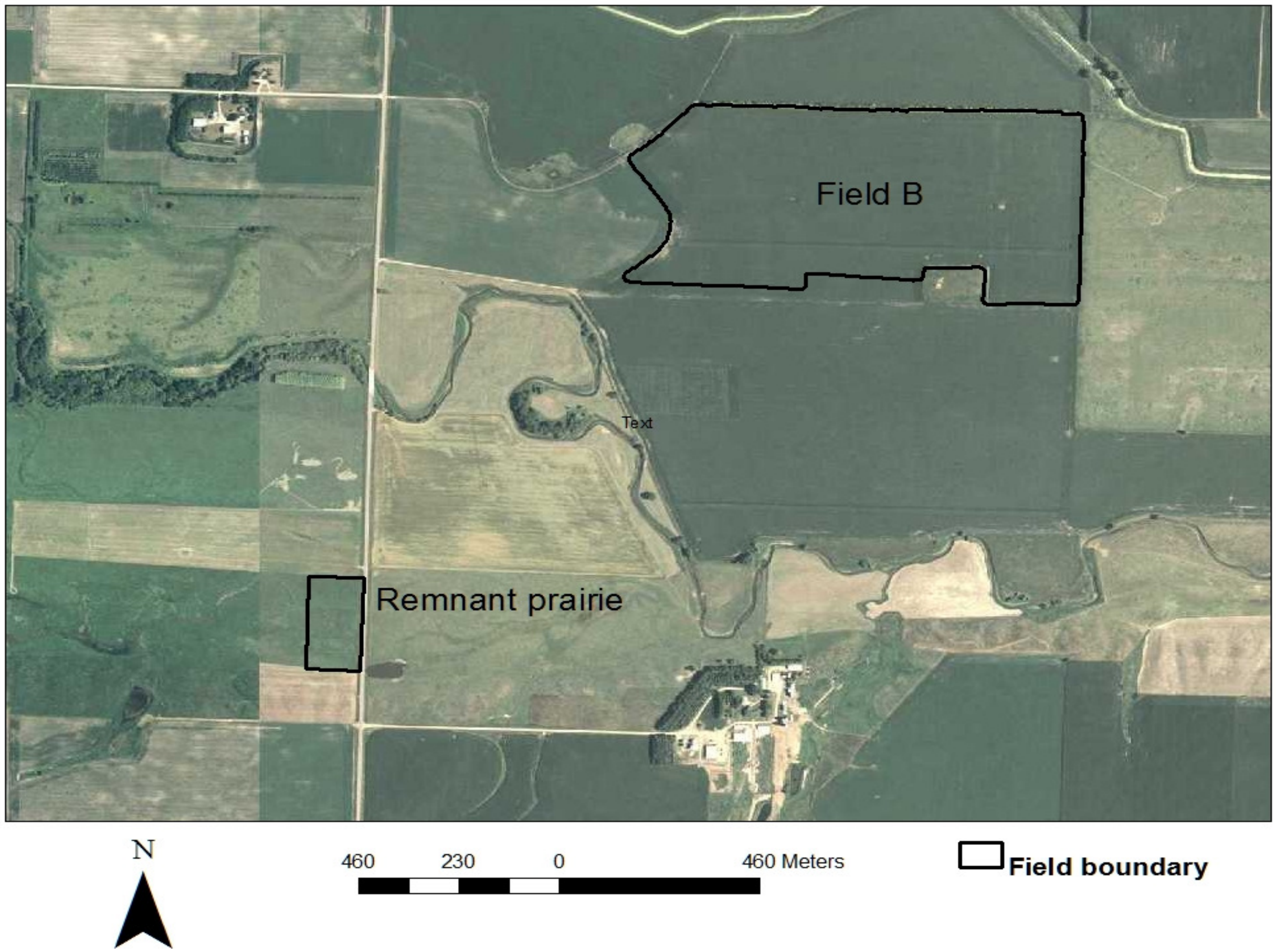


Figure 3.4. Soil series boundaries and location of soil borings within the remnant prairie site.

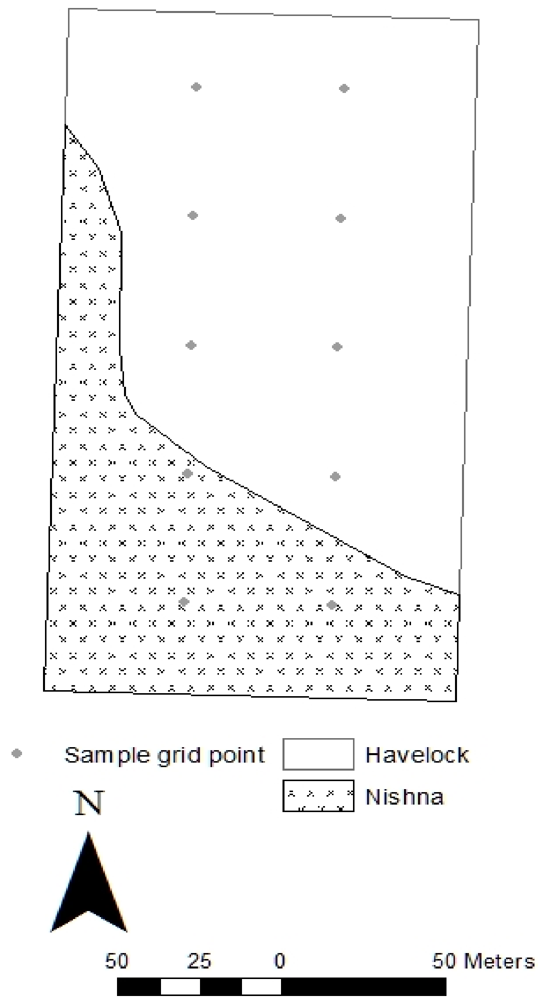
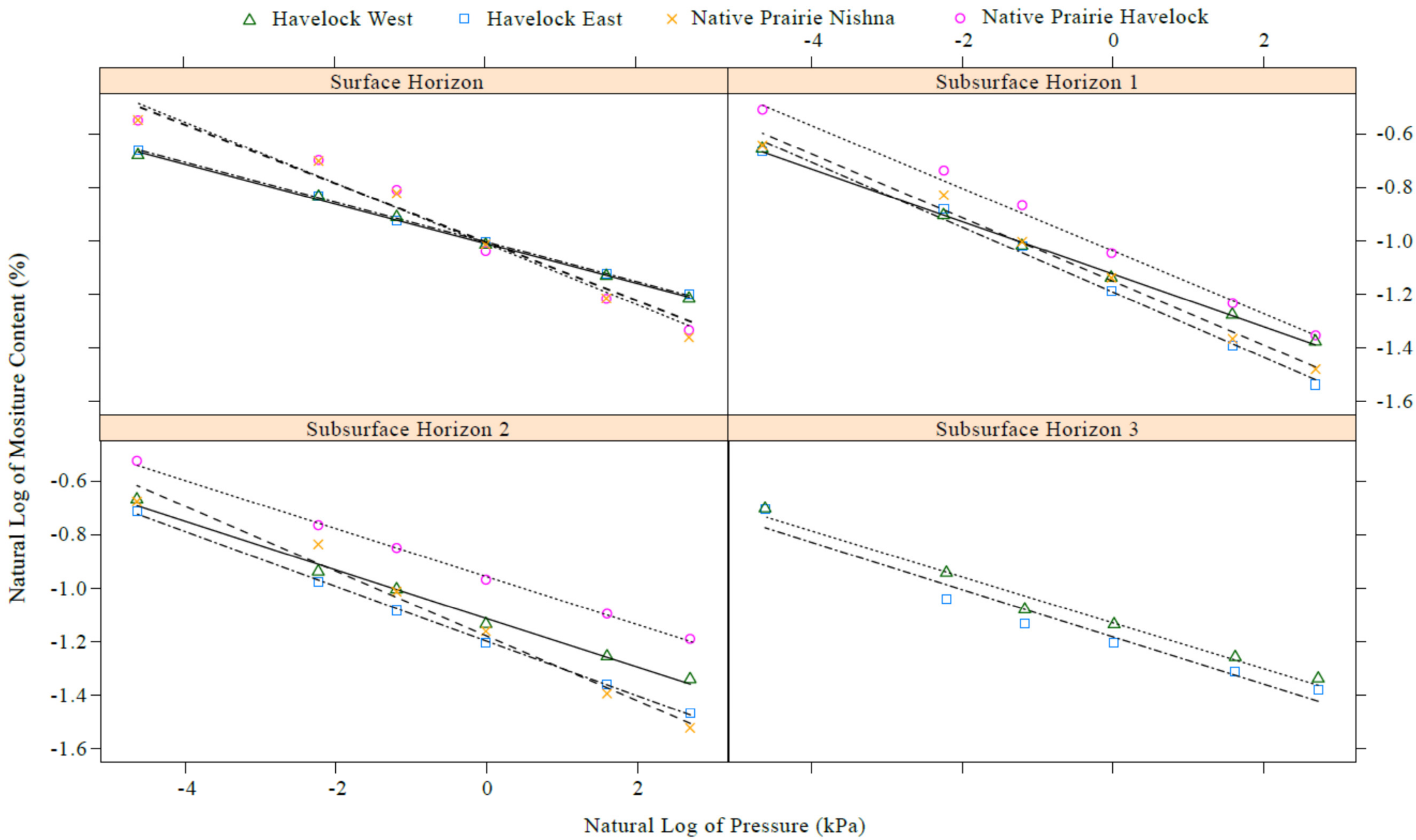


Figure 3.5. Regression line for the natural log of volumetric water content (θ_v) as a function of the natural log of pressure for each field, soil type and horizon.



REFERENCES

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. *Journal of Soil and Water Conservation*. 45:117-121.

Appelboom, T.W., and Fouss, J.L. 2006. Methods for removing nitrate nitrogen from agricultural drainage waters: A review and assessment. ASABE Meeting Presentation. Paper No. 062328.

Addiscott, T.M., D. Brockie, J.A. Catt, D.G. Christian, N.N. Mirza, and K.R. Howse. 2000. Phosphate losses through field drains in a heavy cultivated soil. *Journal of Environmental Quality.* 29:522-532.

Bharati, L., K.H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. *Agroforestry Systems.* 56:249-257.

Blake, G.R. 1965. Bulk Density. P 374-390. *In* C.*A. Black (ed.) Methods of soil analysis. Part 1. Agron. Monogr*. 9. ASA and SSSA, Madison, WI.

Brye, K.R. 2003. Long-term effects of cultivation on particle size and water-retention characteristics determined using wetting curves. *Soil Science.* 168:459-468.

Brye, K.R. and L. Moreno. 2006. Vegetation removal effects on soil quality in a native tallgrass prairie fragment in east-central Arkansas. *Natural Areas Journal.* 26:94-100.

Brye, K.R. and A.L. Pirani. 2005. Native soil quality and the effects of tillage in the Grand Prairie region of eastern Arkansas. *American Midland Naturalist.* 154:28-41.

Bucks, D., and T. Spofford. 2005. Upgrading America's underground drainage network. *Agricultural Research.USDA.*

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecology Applications.* 8:559-568.

Cassel, D.K., and L.A. Nelson. 1985. Spatial and temporal variability of soil physical properties of Norfolk loamy sand as affected by tillage. *Soil and Tillage Research.* 5:5-17.

Chan, K.Y., and J.A Mead. 1989. Water movement and macroporosity of an Australian alfisol under different tillage and pasture conditions. *Soil and Tillage Research.* 14:31-310.

Clausen, J.C. and J. Spooner. 1993. Paired watershed study design. United States Environmental Protection Agency. 841-F-93-009

CVision Corporation. 2006. Benefits and costs of a subsurface agricultural drainage water management system. [cited 1/16/2012]. Available from http://www.admcoalition.com/complete_analysis.pdf

David, M.B., and L.E. Gentry. 1999. Anthropogenic inputs of nitrogen and phosphorus and riverine export for Illinois, USA. *Journal of Environmental Quality.* 29 :494-508.

David, M.B., L.E. Gentry, K.M. Starks, and R.A. Cooke. 2003. Stream transport of herbicides and metabolites in a tile-drained agricultural watershed. *Journal of Environmental Quality.* 32:1790-1801.

Deal, S.C., J.W. Gilliam, R.W. Skaggs, and K.D. Konyha. 1986. Prediction of nitrogen and phosphorus losses as related to agricultural drainage system design. *Agriculture, Ecosystems & Environment.* 18(1):37-51.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agronomy Journal.* 94(1):153-171.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya, and T.W. Welacky. 1996. Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss. *Journal of Environmental Quality.* 25:317-324.

El-Sadek, A., J. Feyen, R.W. Skaggs, and J. Berlamont. 2002. Economics of nitrate losses from drained agricltural land. *Journal of Environmental Engineering.* 128(4):376-383.

Evans, R.O., J.W. Gilliam, and R.W. Skaggs. 1991. Controlled drainage management guidelines for improving water quality. *AG-443. North Carolina Agricultural Extension Service.* 16 pp.

Evans, R.O., J.W. Gilliam, and R.W. Skaggs. 1989. Effects of agricultural water table management on drainage water quality. *Water Resources Research Institute of the University of North Carolina* 237(1).

Evans, R.O., J.E. Parsons, K.C. Stone, and W.B. Wells. 1992. Water table management on a watershed scale. *Journal of Soil and Water Conservation. 47(1):58-64*.

Evans, R.O., and Skaggs, R.W. 2004. Development of controlled drainage as a BMP in North Carolina. Sacramento, California USA Ed.

Evans, R.O., and R.W. Skaggs. 1989. Design guidelines for water table management systems on coastal plain soils. *Applied Engineering in Agriculture.* 5(4):539-548.

Evans, R.O., R.W. Skaggs, and J.W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. *Journal of Irrigation & Drainage Engineering.* 121(4):271-276.

Fausey, N.R., L.C. Brown, H.W. Belcher, and R.S. Kanwar. 1995. Drainage and water quality in Great Lakes and cornbelt states. *Journal of Irrigation & Drainage Engineering.* 121(4):283-288.

Fenelon, J.M., and R.C. Moore. 1998. Transport of agrichemicals to ground and surface water in a small Central Indiana watershed. *Journal of Environmental Quality*. 27:884–894.

Fisher, M.J., N.R. Fausey, S.E. Subler, L.C. Brown, and P.M. Bierman. 1999. Water table management, nitrogen dynamics, and yields of corn and soybean. *Soil Science Society of America Journal.* 63(6):1786-1795.

Fuentes, J.P., M. Flury, and D.F. Bezdicek. 2004. Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no-till. *Soil Science Society of America Journal.* 68:1679-1688.

Gilliam, J.W., J.L. Baker, and K.R. Reddy. 1999. Water quality effects of drainage in humid regions. p. 801-830. *In* R.W. Skaggs and J. van Schilfgaarde (eds.). Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Gilliam, J.W., and R.W. Skaggs. 1986. Controlled agricultural drainage to maintain water quality. *Journal of Irrigation & Drainage Engineering.* 112(3):254-263.

Gilliam, J.W., R.W. Skaggs, and S.B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. *Journal of Environmental Quality.* 8(1):137-142.

Gilliam, J.W., R.W. Skaggs, and S.B. Weed. 1978. An evaluation of the potential for using drainage control to reduce nitrate loss from agricultural fields to surface waters. *Water Resources Research Institute of the University of North Carolina. Report No. 128.* 108 pp.

Jamieson, R.C., R.J. Gordon, K.E. Sharples, G.W. Stratton, and A. Madani. 2002. Movement and persistence of fecal bacteria in agricultural soils and subsurface drainage water: A review. *Canadian Biosystems Engr.* 44:1.1-1.9.

Jaynes, D.B., J.L. Hatfield, and D.W. Meek. 1999. Water quality in Walnut Creek watershed: Herbicides and nitrate in surface waters. *Journal of Environmental Quality.* 28:45-59.

Jia, Z., R.O. Evans, and J.T. Smith. 2006. Effect of controlled drainage and vegetative buffers on drainage water quality from wastewater irrigated fields. *Journal of Irrigation and Drainage Engineering.* 132(2):159-170.

Kalita, P.K., R.S. Kanwar, and S.W. Melvin. 1992. *Subirrigation and Controlled Drainage: Management Tools for Reducing Environmental Impact of Non-Point Source Pollution.*

Kanwar, R.S., and P.K. Kalita. 1990. *Water Quality Benefits from Water Table Management and Subirrigation.* Bangkok, Thailand Ed.

Kanwar, R.S., S.W. Melvin, and P.K. Kalita. 1993. Dual-Pipe subirrigation system for productivity and water quality benefits. *Trans. 15th Cong. on Irrig. and Drain. IC (R76-R103):*1017-1031.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, K.M. Oates and W. Pask. 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. *Journal of Environmental Quality.* 20:264-270.

Kladivko, E.J., J. Rrochulska, R.R. Turco, G.E. Van Scoyoc, and J.D. Eigel. 1999. Pesticide and nitrate transport into subsurface tile drains of different spacings. *Journal of Environmental Quality.* 28:997-1004.

Kucharik, C.J., N.J. Fayram, and K.N. Cahill. 2006. A paired study of prairie carbon stocks, fluxes, and phenology: comparing the world's oldest prairie restoration with an adjacent remnant. *Global Change Biology.* 12:122-139.

Lalonde, V., C.A. Madramootoo, L. Trenholm, and R.S. Broughton. 1996. Effects of controlled drainage on nitrate concentrations in subsurface drain discharge. *Agricultural Water Management.* 29(2):187-199.

Letey, J. 1985. Relationship between soil physical properties and crop production. *Advances in Soil Science.* 1:277-294.

Luo, W., R.W. Skaggs, and G.M. Chescheir III. 2000. DRAINMOD Modifications for cold conditions. *Transactions of the American Society of Agricultural Engineers.* 43(6):1569-1582.

Luo, W., G.R. Sands, M. Youssef, J.S. Strock, I. Song, and D. Canelon. 2010. Modeling the impact of alternative drainage practices in the northern Corn-belt with DRAINMOD-NII. *Agricultural Water Management.* 97:389-398.

Madramootoo, C.A., G.T. Dodds, A. Popadopoulos. 1993. Agronomic and environmental benefits of water table management. *Journal of Irrigation and Drainage Engineering.* 119(6):1052-1065.

Magner, J.A., G.A. Payne, and L.J. Steffen. 2004. Drainage effects on stream nitrate-N and hydrology in South-Central Minnesota (USA). *Environmental Monitoring and Assessment.* 91:183-198.

Mallants, D., B.P. Mohanty, D. Jacques, and J. Feyen. 1996. Spatial variability of hydraulic properties in a multi-layered soil profile. *Soil Science.* 161:167-181.

McVay, K.A., J.A. Budde, K. Fabrizzi, M.M. Mikha, C.W. Rice, A.J. Schlegel, D.E. Peterson, D.W. Sweeney, and C. Thompson. 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. *Soil Science Society of America Journal.* 70:434-438.

Mejia, M.N., and C.A. Madramootoo. 1998. Improved water quality through water table management in eastern Canada. *Journal of Irrigation & Drainage Engineering.* 124(2):116-122.

Mejia, M.N., C.A. Madramootoo, and R.S. Broughton. 2000. Influence of water table management on corn and soybean yields. *Agricultural Water Management.* 46(1):73-89.

Mitsch, W.J., J.W. Day Jr., J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang. 1999. Reducing nitrate loads, especially nitrate-nitrogen, to surface water, ground water, and the Gulf of Mexico: Topic 5 report for the integrated assessment on hypoxia in the Gulf of Mexico. *NOAA Coastal Ocean Program Decision Analysis Series No. 19. NOAA Coastal Ocean Program, Silver Spring, MD.*111 pp.

Mudgal, A., S.H. Anderson, C. Baffaut, N.R. Kitchen, and E.J. Sadler. 2010. Effects of long-term soil and crop management on soil hydraulic properties for claypan soils. *Journal of Soil and Water Conservation.* 65:393-403.

Ng, H.Y.F., C.S. Tan, C.F. Drury, and J.D. Gaynor. 2002. Controlled drainage and subirrigation influences tile nitrate loss and corn yields in a sandy loam soil in Southwestern Ontario. *Agriculture, Ecosystems & Environment.* 90(1):81-88.

Oquist, K.A., J.S. Strock, and D.J. Mulla. 2006. Influence of alternative and conventional management practices on soil physical and hydraulic properties. *Vadose Zone Journal.* 5:356-364.

Randall, G.W., and M.J. Goss. 2001. Nitrate losses to surface water through subsurface, tile drainage. p. 95-122. *In* R.F. Follett and J.L. Hatfield (Eds.). Nitrogen in the environment: Sources, Problems, and Management. Elsevier Sci. B.V., Amsterdam.

Rolf, K.A. 2005. Evaluation of alternative versus conventional farming systems impacts on subsurface drainage flow and water quality. M.S. Thesis, University of Minnesota.

SAS Institute Inc. 2002. JMP: Statistics and Graphics Guide, Version 5. SAS Institute Inc., Cary, NC.

Samson, F. and F. Knopf. 1994. Prairie conservation in North America. *Bioscience.* 44:418-421.

Sands, G.R. 2001. Agricultural Drainage: Soil Water Concepts. *University of Minnesota Extension Publication Number 07644*1.

Sands, G.R., I., Song, L.M. Busman, and B.J. Hansen. 2008. The effects of drainage depth and intensity on nitrate loads in the Northern Cornbelt. *Transactions of the ASABE.* 51(3): 937-946.

Schwartz, R.C., S.R. Evett, and P.W. Unger. 2003. Soil hydraulic properties of cropland compared with re-established and native grassland. *Geoderma.* 116:47-60.

Scott, C.A., L.D. Geohring, and M.F. Walter. 1998. Water quality impacts of tile drains in shallow, sloping structured soils as affected by manure application. *Applied Engineering in Agriculture.* 14:599-603.

Scott, H.D., and L.S. Wood. 1989. Impact of crop production on the physical status of a typic albaqualf. *Soil Science Society of America Journal.* 53:1819-1825.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an albaqualf. *Soil Science Society of America Journal.* 69:893-901.

Shirmohammadi, A., C.R. Camp, and D.L. Thomas. 1992. Water table management for field-sized areas in the Atlantic coastal plain. *Journal of Soil and Water Conservation.* 47(1):52-57.

Shirmohammadi, A., R.D. Wenberg, W.F. Ritter, and F.S. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic states. *Journal of Irrigation & Drainage Engineering.* 121(4):302-306.

Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1995. Predicting effects of water table management on loss of nitrogen from poorly drained soils. *European Journal of Agronomy.* 44:441-451.

Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1994. Hydrologic and water quality impacts of agricultural drainage. *Critical Reviews in Environmental Science and Technology.* 24(1):1-32.

Skaggs, R.W., and G.M. Chescheir III. 2002. Effects of subsurface drain depth on nitrogen losses from drained lands. *Transactions of the American Society of Agricultural Engineers.* 46(2):237-244.

Skaggs, R.W., and J.W. Gilliam. 1981. Effect of drainage system design and operation on nitrate transport. *Transactions of the American Society of Agricultural Engineers.* 24(4):929-934.

Sperber, T.D., J.M. Wraith, and B.E. Olson. 2003. Soil physical properties associated with the invasive spotted knapweed and native grasses are similar. *Plant and Soil.* 252:241-249.

Stone, K.C., R.C. Sommers, G.H. Williams, and D.E. Hawkins. 1992. Water table management in the eastern coastal plain. *Journal of Soil and Water Conservation.* 47(1):47-51.

Tan, C.S., C.F. Drury, J.D. Gaynor, T.W. Welacky, and W.D. Reynolds. 2002. Effect of tillage and water table control on evapotranspiration, surface runoff, tile drainage and soil water content under maize on a clay loam soil. *Agricultural Water Management.* 54(3):173-188.

Thomas, D.L., P.G. Hunt, and J.W. Gilliam. 1992. Water table management for water quality improvement. *Journal of Soil and Water Conservation.* 47(1):65-70.

Thorp, K.R., D.B. Janes, and R.W. Malone. 2008. Simulating the long-term performance of drainage water management across the Midwestern United States. *Transactions of the ASABE.* 51(3): 961-976.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008. Influence of Prairie restoration on CT-measured soil pore characteristics. *Journal of Environmental Quality.* 37:219-228.

Valero, C.S., C.S. Madramootoo, N. Stämpfli. 2007. Water table management impacts on phosphorus loads in tile drainage. *Agricultural Water Management.* 89:71-80.

Wang, C., J.A. McKeague and K.D. Switzer-Howse. 1985. Saturated hydraulic conductivity as an indicator of structural degradation in clayey soils of Ottawa area Canada. *Soil and tillage Research.* 5:19-31.

Wesström, I., G. Ekbohm, H. Linnér, and I. Messing. 2004. Application of recession analysis on subsurface outflow from controlled drainage. *Sacramento, California. USA. Ed.*

Wesström, I., G. Ekbohm, H. Linnér, and I. Messing. 2003. The effects of controlled drainage on subsurface outflow from level agricultural fields. *Hydrological Processes.* 17(8):1525-1538.

Wesström, I., I. Messing, H. Linnér, and J. Lindström. 2001. Controlled drainage — effects on drain outflow and water quality. *Agricultural Water Management.* 47(2):85-100.

Wilson, B.N. History of drainage research at the University of Minnesota. 2004 [cited 2/26/2008]. Available from http://www.bbe.umn.edu/history/drainage/index.htm.

Zucker, L.A., and L.C. Brown. 1998. Agricultural drainage: Water quality impacts and subsurface drainage studies in the Midwest. *Ohio State University Extension Bulletin No. 871*. 40 pp.