XVII^th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

CONTROLLED DRAINAGE TO IMPROVE EDGE-OF-FIELD WATER QUALITY IN SOUTHWEST MINNESOTA, USA

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CSBE100154 – Presented at ASABE's 9th International Drainage Symposium (IDS)

ABSTRACT Wet, poorly drained soils throughout the northern Cornbelt are often artificially drained to improve field conditions for timely 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, nitrogen and phosphorus loss, and grain yield from a conventional free-drainage (FD) compared to a controlled drainage (CD) system in Minnesota, USA. 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 22ha, respectively. The project used a paired design approach to statistically evaluate treatment effects. During the calibration period (2006-2007) each zone was managed the same. The treatment phase of the experiment began in 2008 with one zone managed in FD mode and the other managed in CD mode. During the two year treatment period (2008-2009) drain flow volume was reduced on average 63%, 141 to 52 mm. There was also evidence that annual nitrate-nitrogen, total phosphorus, and ortho-phosphorus loads were reduced by 61, 50, and 63%, respectively. However, the reasons for a 33% increase in flow weighted mean total phosphorus concentration under controlled drainage are unclear. The use of CD showed environmental benefits compared to FD but has not resulted in a consistent yield benefit at this site to date.

Keywords: Drainage, Controlled drainage, Water quality, Nitrogen, Phosphorus.

INTRODUCTION In order to improve productivity, extensive agricultural areas in the Midwest require drainage systems consisting of subsurface drainage (tile) and open ditches. In Minnesota, most agricultural producers improve the drainage on their land to improve trafficability, enhance field conditions for more timely planting and harvesting operations, and help decrease crop damage that can result from saturated soil and standing water. Agricultural drainage improvement can also help reduce year-to-year variability in crop yield, which helps reduce the risks associated with the production of abundant, high quality, affordable food. Farmers in the Minnesota River Basin grow crops on nearly 1.6 million hectares of poorly drained soils. These fields represent 41 percent of the state's cropland. Nearly 0.8 million hectares of these poorly drained soils are artificially drained.

Many of these artificially drained soils are adjacent to lakes and streams, areas that are environmentally sensitive and ecologically important. These drainage systems are also known to transport particulate and dissolved phosphorus, nitrate-nitrogen, and sediment to streams and rivers (Randall et al., 1997; Carpenter et al., 1998; Addiscott et al., 2000).

Current water quality impairments in the Minnesota River and many of its tributaries due to turbidity, excess nutrients, and fecal coliform impairments mean that there is an immediate and continuing need for practices and sustainable management systems that improve water quality while optimizing agricultural production and farm profitability. Although turbidity is not an inherent property of water, as is temperature or pH (Davies-Colley and Smith, 2001), the recognition of turbidity as an indicator of the environmental health of water bodies has increased over the past decade. Turbidity itself is not a major health concern, but high turbidity due to excess nutrients (nitrogen and phosphorus) may result in noxious and toxic algal growth, oxygen deficiency, and fish kills. Turbidity can also interfere with recreational uses of a water body, disinfection of surface water supplies used for drinking water, and provide attachment sites for heavy metals such as cadmium, mercury and lead, and many toxic organic contaminants such as polychlorinated biphenyls, and many pesticides (Davies-Colley and Smith, 2001).

There is a clear need to develop and implement management practices that allow the continued high agricultural productivity of these naturally poorly drained soils while reducing nitrogen and phosphorus losses to surface waters.

Controlled Drainage Today, the goal of drainage research is to improve drainage system design and function in order to meet production and environmental outcomes. Sustaining the high productivity of drained lands for food and fiber production and protecting the environment is a balancing act. In this field experiment controlled drainage (CD) is being evaluated as one technique to help reach this goal. Controlled drainage is the water management technique that allows the drainage system outlet to be set at any level between the ground surface and the drain depth for achieving soil-water conditions. Excess and deficit soil-water conditions in the soil profile can be managed to provide better plant growth conditions for crop production. Through the implementation of proper management practices and strategies, there also can be an environmental benefit.

In North Carolina, research on a total of 14 different soils showed that CD reduced drainage volume and nitrogen loss by 40 to 50% compared to conventional free-drainage (FD) (Skaggs et al., 2005). The loss of phosphorus to surface water was also reduced by 25 to 35%. The effect of CD on crop yields was strongly dependent on management. There was a 5% increase in crop yields when CD was effectively managed. Studies conducted in Ohio and Canada indicate that CD can have a similar effect of reducing nitrogen loss to surface waters as observed in studies in North Carolina (Skaggs et al., 2005).

Large differences in climate, soils, and farming practices make it difficult to predict the performance of CD for Minnesota conditions. 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 of analysis for precipitation, drain flow, nitrogen and phosphorus load, and grain yield data from 2006-2009. The objective of this study was to quantify differences between yield, drain flow, and nitrogen and phosphorus loads through subsurface drainage from conventional free-drainage and controlled drainage practices.

METHODS This section describes the main experimental components of this research project. The project was designed on infrastructure developed during fall 2005 at the Hick's family farm near Tracy, MN. A paired design approach was used to evaluate the effect of water table management on crop performance, drain flow volume, and nitrogen and phosphorus loss from the two management zones. The design consisted of two treatments, FD and CD, and two periods of study, calibration from 2006–2007 and treatment from 2008–2009.

Description of research site The site was established on a previously undrained 37 ha field that consisted mainly of Millington loam, a poorly drained soil with moderate permeability. Tile drains were installed 1.2 m deep and spaced 15 m apart in fall 2005. The field was divided into two management zones, the west management zone being 22 ha and the east management zone being 15 ha (Figure 1). Each zone was outleted into manually operated water table management structures (AgriDrain, Adair, IA) equipped with two stilling wells each; one to measure drain flow rate and one to collect water samples for determination of drainage water quality.

The management zones were grid soil sampled (48 total geo-referenced locations) following small grain harvest in order to track soil nutrient status and to interpret crop response (Figure 1). Soil samples were analyzed for available phosphorus and potassium, organic matter, and pH. Composite soil samples at each geo-referenced location were collected from the 0-10, 10-20, 20-30, and 30-60 cm depths. These depths were chosen to assess nutrient levels before liquid swine manure injection following soybean harvest in 2008.

Prior to drainage, the field was planted to soybeans in 2004 and small grains in 2005. In 2006 and 2007 the field was planted to corn (*Zea mays* L.) and fertilized with 174 kg N/ha and 179 kg N/ha, respectively. Phosphorus was broadcast and incorporated in fall as diammonium phosphate at a rate of 67 kg P/ha in both years. Nitrogen in the form of urea was spring applied and incorporated before planting. In 2008 the field was planted to soybeans (*Glycine max* (L.) Merr.). Following soybean, liquid swine manure was injected in fall 2008 at a rate of 56,173 L/ha. A manure sample was collected prior to application and analyzed for nutrient content. The manure supplied 138 kg P/ha and 189 kg N/ha in available nutrients for the following corn crop.

Figure 1. Drainage system layout showing east, controlled drainage, and west, conventional free-drainage zones and 48 geo-referenced sampling locations.

Drainage System Management Water table management structures allow the management zones to be managed in undrained (water table near the soil surface), FD (water table at the drain depth), or CD modes (water table maintained at a predetermined depth). During the calibration period beginning April 3, 2006, the field was managed under FD with the drain depth at 1.2 m. On November 16, 2006, after harvest, weir boards were installed in the water table management structures to raise the water table to within 0.15 m of the soil surface. Beginning on May 2, 2007, the second year of calibration, both management zones were managed under CD mode. This was done to limit drainage outflow from the management zones and to reduce the delivery of nutrients to ditches and streams during the nongrowing season. The weir boards were removed on April 17, 2007 to allow drainage to occur prior to spring planting. The weir boards were reinstalled in the structures on May 8, 2007 at approximately 0.6 m below the soil surface to create a potential to store water for crop use during the growing season. The treatment period began in 2008 with the east management zone in FD mode and the west management zone in CD mode. In order to accommodate spring operations, weir logs were removed on May 15, 2008. The late date was due to a wet spring and the field was planted to soybeans so it did not need to be drained as early. On May 23, 2008 the logs were reinstalled in the west zone at approximately 0.6 m below the soil surface for the growing season. For the west zone, during the nongrowing season the logs were 0.15 m below the soil surface. In 2009 the weir logs were removed from the west zone on April 9 and reinstalled on May 11 at approximately 0.6 m below the soil surface for the growing season.

Water Quality and Quantity Monitoring Two instrument shelters were located near the water level control structures and contain the equipment for measuring water level data and water sample collection from each of the management zones. Each shelter contains two ISCO water samplers (Model #3700) and a Campbell Scientific Inc., datalogger (CR-10X) used to collect and store stage height (water level) data. 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. The USDA-ARS has a Texas Electronics Inc. rain gauge in the field that collects precipitation at 10 minute intervals. A combination of grab and storm activated composite and discrete samples were collected for each management zone. Storm sampling was initiated by a 1.5 cm rise in stage and samples (1 L) were collected every 283 m^3. Samples were analyzed for nitrate-nitrogen, ammonium-nitrogen, total nitrogen, total phosphorus, and ortho-phosphorus. Water table position was manually measured, on a weekly basis, at observation wells located midway between the drain lines in the field to monitor the position of the water table.

RESULTS AND DISCUSSION

Precipitation Precipitation data for the study period (2006-2009) was compared to the long-term annual average between 1978 and 2005 taken from the Tracy weather station (Table 1). The weather station is located approximately 6.4 km from the experimental site. The total annual precipitation for 2006 to 2009 was 620, 620, 510, and 610 mm, respectively, while the long-term annual average was 705mm. All four years had drier than normal precipitation. During the growing season (April through September) for 2006 the monthly total precipitation fluctuated above and below normal (data not shown). During the fall of 2006 there were three consecutive months, September through November, that were below normal. During 2007, the monthly precipitation was consistently below normal. During the early part of the growing season, April through July, precipitation ranged from 19 to 80% below normal. The annual precipitation for 2008 was approximately 28% below normal. Every month, except for April, the growing season had below normal rainfall. Growing season precipitation was 28% below normal for 2009. Dry conditions between 2006 and 2009 were extensive enough to potentially impact crop yield and 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.

Table 1. Water quantity and quality results from east, conventional free-drainage (FD), and west, controlled drainage (CD), zones for the period 2006–2009.

Variable	2006	2007	2008		2009	
			west	east	west	east
Precipitation (mm)	620	620	510		610	
Drainage (mm)	147	51	64	201	39	81
Nitrate-nitrogen (kg/ha)	47	4	8	22	1.7	2.4
Nitrate concentration (mg/L)	11	10	13	11	7	4
Total phosphorus (kg/ha)	0.28	0.07	0.03	0.13	0.03	0.04
Total Phosphorus concentration (μg/L)	77	210	49	69	137	55
Ortho-phosphorus (kg/ha)	-	0.05	0.02	0.08	0.01	0.01
Ortho Phosphorus concentration (mg/L)	-	205	28	38	34	19

Table 2. Soil chemical property data from east, conventional free-drainage (FD), and west, controlled drainage (CD), zones following 2008 growing season.

Variable	EAST			WEST		
	Mean	Min.	Max.	Mean	Min.	Max.
0-10 cm						
pH	7.6	7.4	7.8	7.7	7.6	7.8
OM (%)	4.7	3.4	5.4	4.9	3.1	6.1
Bray P1 (mg/kg)	21	11	39	17	2	42
Olsen P (mg/kg)	11	5	22	10	4	28
Available K (mg/kg)	256	181	332	270	156	386
Zinc (ppm)	1.4	1.1	1.7	1.5	0.9	2.1

Soil The field is dominated by one soil, Millington loam. The majority of the field tested in the low to medium categories based on the Olsen soil phosphorus test. Mean soil test phosphorus (Olsen-P) level for the east zone (FD) was 11 mg/kg and 10 mg/kg for the west zone (CD) (Table 2). This result is likely due to a combination of historical fertilizer management practices and to reduced phosphorus availability at the relatively high soil pH values found in the two zones. Given that, on average, soil phosphorus testing indicated low to medium concentrations of plant available soil phosphorus, fine soil texture, and no history of manure applications, the environmental risk associated with phosphorus loss from this site would be expected to be low. Based on soil test results for available potassium, there was sufficient potassium for corn and soybean production in this field (Table 2). Soil test results for zinc showed that zinc was not a limiting nutrient based on University thresholds (Table 2). Historically, zinc was part of the producer's fertilizer management plan although no recent applications of zinc have been made.

Yield Yield data from the management zones was collected by the farmer cooperator using the GreenStar™ Combine Yield Mapping System from John Deere. Raw yield map data were processed and filtered using USDA-ARS Yield Editor software. Researchers have reported that between 10% and 50% of yield data observations must be removed by filtering procedures. Raw yield map data from 2006 was lost due to a computer malfunction, however, the farmer was able to provide yield data for the whole field based on grain scale receipts. The mean corn grain yield for 2006, when the field was managed under FD was 12.1 Mg/ha. The raw yield map data from 2007, when both zones were managed in CD mode, were processed for the east and west management zone. The mean corn grain yields for the east and west zones were 9.9 Mg/ha and 10.1 Mg/ha, respectively. Although there was almost no difference in yield between the two management zones in 2007, there was about a 1.9 Mg/ha yield reduction from 2006 to 2007. This can be explained in part by the dry conditions preceding and during the growing season in 2007 and the result of growing corn following corn. Soybean was grown in 2008, and for the first time the east zone was managed in FD mode and the west zone managed in CD mode. Late planting due to a wetter than average April, combined with pest pressure resulted in poor soybean yields in 2008. The FD management zone yielded 1.5 Mg/ha and CD management zone yielded 1.3 Mg/ha. Late planting, drought, variety selection, insect pressure (soybean aphid) and pathogen pressure (soybean cyst nematode) combined to negatively impact soybean yields. Corn was grown in 2009 and although the growing season was not ideal because of cool, dry conditions, yields were exceptional with a difference of 1.4 Mg/ha between the two management zones. The FD management zone yielded 12.7 Mg/ha and CD management zone yielded 14.1 Mg/ha.

Drainage/Hydrology Dry conditions between 2006 and 2009 likely resulted in lower flows than would be expected during normal or wet conditions. During the calibration period 147 mm of water drained from the field while in FD mode in 2006 whereas 51mm of water drained from the field in 2007 while managed in CD mode (Table 2). The treatment period began in 2008 and continued through 2009. The only drain flow through the drainage system from the CD management zone during both years occurred in the spring before planting when the weir boards were removed. Drainage system outflow from the FD management zone occurred continuously during 2008 until the water table elevation dropped below the drain depth and flow ceased on August 22. Drain flow was reduced by 68% under CD compared to FD. Previous studies on CD have shown that drainage system discharge of water was reduced at the field's edge (Lalonde et al., 1996; Skaggs et al., 1995). Only 39 mm of water was discharged through the drainage system under CD during 2009. This reflects the lack of soil water recharge from the previous fall and dry conditions during spring. Drainage system outflow from the FD management zone occurred continuously during 2009, however, the flow level was below the detection limit of the monitoring equipment and therefore no flow was recorded.

Nitrogen During 2006, the first year of the calibration period, the nitrate-nitrogen (NO_3-N) load from both management zones, when managed in FD mode, was 47 kg N/ha (Table 1). During 2007, the second year of calibration, the NO_3-N load from both management zones, when managed in CD mode, was 4 kg N/ha (Table 1). In 2006, the flow weighted mean NO_3-N concentration was 11 mg/L while in 2007 it was 10 mg/L. For 2008, the annual NO_3-N load from the west management zone under CD was 65% lower than from the east management zone under FD, 8 kg N/ha compared to 22 kg N/ha, respectively. Previous studies have documented this same result (Evans et al., 1995; Kalita et al., 1992). The flow weighted mean NO_3-N concentrations from the west and east management zones were 13 and 11 mg/L, respectively. These results indicate that reduced loss of NO_3-N under CD versus FD was mainly due to differences in drain flow between the two systems. More NO_3-N was transported along with drainage water from the FD system. During 2009, the annual NO_3-N load from the zone managed under CD was 1.7 kg N/ha compared to 2.4 kg N/ha under FD. The flow weighted mean NO_3-N concentrations from the FD and CD management zones were 4 and 7 mg/L, respectively. These results indicate that reduced loss of nitrate-nitrogen under controlled drainage versus conventional drainage was mainly due to differences in water outflow between the two systems. More nitrate-nitrogen was transported along with drainage water from the conventional system.

Phosphorus During 2006, the first year of calibration, the total phosphorus (TP) load from both management zones, when managed in FD mode, was 0.28 kg P/ha (Table 2). During 2007, the second year of calibration, the TP load from both management zones, when managed in CD mode, was 0.07 kg P/ha (Table 2). In 2006, the flow weighted mean TP concentration was 77 μg/L while in 2007 it was 210 μg/L. This corresponds to an increase of 73%. Research by Ponnamperuma (1972) and Sanchez-Valero et al., (2007) have shown phosphorus concentrations to increase under reducing conditions caused by flooded or anoxic conditions similar to those found under CD conditions. 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. For 2007, TP loads and flow weighted mean concentrations were calculated using the west management zone due to sediment settling out in the corrugated plastic tubing between the west and east management zone rendering negative numbers for the east. In 2008, the annual TP load from west management zone under CD was 77% lower than from the east management zone under FD, 0.03 kg P/ha compared to 0.13 kg P/ha, respectively. The flow weighted mean TP concentrations from the FD and CD management zones were 69 and 49 μg P/L, respectively. Ortho-phosphorus (OP; dissolved reactive phosphorus) made up 55% to 57% of the annual TP load. The OP load from the east management zone under FD was 0.08 kg P/ha while the load from the west management zone under CD was 0.02 kg P/ha. The flow weighted mean OP concentrations from the FD and CD management zones were 38 and 28 μg P/L, respectively. These results indicate that reduced loss of total phosphorus and ortho-phosphorus under CD versus FD was due to differences in drain flow between the two systems and for ortho-phosphorus a reduction in concentration. During 2009, the annual TP load from the zone managed under CD was 0.03 kg P/ha compared to 0.04 from the zone managed under FD. The annual OP load from the both zones was 0.01 kg P/ha. The flow weighted mean TP concentration from the CD and FD management zones was 137 μg/L and 55 μg/L, respectively. The flow weighted mean OP concentration from the CD and FD management zones was 34 μg/L and 19 μg/L, respectively.

It is unclear what the cause of the variability and higher than expected total phosphorus concentration is from. There are several causal factors which have been ruled out including: coarse textured soil, high soil test phosphorus concentrations, and a long history of manure application. Other plausible reasons for the high total phosphorus concentrations are the installation of the drainage system which disturbed and mixed the soil which could result in soil enriched with phosphorus to be relocated in close proximity to the buried drain pipe. The drainage system was installed in the fall of 2005 and higher than expect total phosphorus concentrations are still being observed. The source of phosphorus could partially be attributed to dissolution of phosphorus from natural soil minerals (i.e. rocks). The glacial parent material suggests that dissolution of phosphorus from soil minerals would not likely be a significant contributor to phosphorus transport from soils at this site. However, the soils at the site have not undergone mineralogical investigation by x-ray diffraction methods to support this hypothesis. Another potential source of phosphorus is that which is stored along with soil organic matter. No organic matter fractionation has been carried out on soils from the site, although the average soil organic matter content ranged from 3.1 to 6.1 % (Table 2). Preferential flow pathways could transport phosphorus to the drain pipe. Soil cracking and earthworm burrows have been observed at the site. Sediment deposition in the drain pipe from installation of the drainage system and possibly preferential transport of soil particles could contribute to situations where deposited sediments act as a source and sink of phosphorus. There are no surface intakes in either zone. Finally, the source of phosphorus could be due to reductive dissolution of phosphorus coupled with microbial reduction. It is well know that increased phosphorus mobility due to dissolution, release of phosphorus into the soil solution, of Fe(III)-phosphate minerals or Fe-oxides with adsorbed phosphorus in soils increases under reduced conditions associated with seasonal flooding and/or water logging of soils. This process has also been coupled with soil organic matter and dissolved organic matter. The very nature of controlled drainage may result in conditions which promote reductive dissolution of phosphorus. The practice of controlled drainage results in elevated variable water table elevations throughout the year; within six inches of the soil surface during the non-growing season, and within two feet of the soil surface during the growing season. Some have argued that the bulk soil does not become reduced long enough or to the extent necessary to cause reducing conditions in the soil that would increase phosphorus mobility. However, it is highly probable that zones exist within the soil, within aggregates, that would favor conditions where reductive dissolution of phosphorus may occur. Clearly the issues surrounding phosphorus and controlled drainage require additional investigation.

CONCLUSION Preliminary results from this field study showed the potential benefit of CD on mitigating nutrient loss to surface waters if implemented in Minnesota. The reduction was primarily due to reductions in drainage water flow rather than reductions for nitrogen and total phosphorus concentration. For ortho-phosphorus there also appeared to be a reduction in concentration. The short duration of this study and limited yield impacts indicated further study is required to determine if CD will result in a consistent agronomic benefit compared to FD.

Acknowledgements. We thank the Minnesota Agricultural Fertilizer and Research & Education Council for their financial support of this project. We also thank Mark Coulter, Lynn Lendt, and Sarah Olson for their support of this project through field data collection and sample analysis. Finally, we sincerely thank Brian Hicks and family for cooperating with us and allowing us to conduct this research on their farm.

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