Phosphorus in agricultural ditch soil and potential implications for water quality

E.J. Dunne, K.A. McKee, M.W. Clark, S. Grunwald, and K.R. Reddy

Abstract: Drainage ditches can transport water and nutrients within agricultural watersheds. Thus, it is important to consider ditch soil phosphorus (P) characteristics, as these can impact water quality. Objectives of this study were to determine (1) P characteristics of agricultural ditch soils in the Lake Okeechobee Basin, Florida; (2) what controls soil P; (3) relationships between different ditch soil P fractions; and (4) compare ditch soil characteristics with upland and wetland soil characteristics. Ditch soils had medium to low total P content (<600 mg kg^{-1} [<600 ppm]) with organic matter and soil metal content important for predicting soil total P. Degree P Saturation of soils suggests dairy and improved pasture soils could impact water quality. In general, ditch soil characteristics were more similar to upland soils rather than wetland soils. In-ditch management practices, such as the use of soil amendments and/or controlled drainage, could be useful to reduce P loss from ditch soils.

Key words: agriculture—ditches—phosphorus—soil—water quality

Drainage ditches are constructed linear water bodies which are often designed to remove surface water and lower water tables below plant rooting zones in agricultural fields (Janse and Puijenbroek 1998; Nguyen and Sukias 2002; Smith et al. 2006). While conducting water from fields to receiving water bodies, ditches often transport nutrients such as phosphorus (P) and other contaminants. During transport, some of the particulate P may settle to the ditch bottom or be transported further down the ditch. There are also dynamics between soluble reactive P (SRP) in ditch soil pore water and the overlying water, which can govern whether ditch soils act as a source or a sink for P.

There is little information on P storage and dynamics in agricultural drainage ditches. Within the United States, most of the research has focused in the mid-western (Smith et al. 2005, 2006) and eastern regions (Sallade and Sims 1997a, 1997b). Agricultural drainage ditch soils collected from row crops and cow grazing pasture can contain variable amounts of P ranging between 30 and 2,880 mg P kg^{-1} (30 and 2,880 ppm) (Sallade and Sims 1997a, 1997b; Nguyen and Sukias 2002) with P content in soils often influenced by surrounding land uses (Stuck et al. 2001). For example, a study in South Florida suggested that total P concentrations in ditch soils were significantly greater in ditches draining improved cow-calf grazing pasture (322 mg kg^{-1} [322 ppm]) relative to ditches draining semi-native cow-calf grazing pasture (149 mg kg^{-1} [149 ppm]) (Prein 2005).

Factors that influence whether ditch soils act as a source or a sink for P include the physicochemical characteristics of soils (Sallade and Sims 1997b; Axt and Walbridge 1999; Haggard et al. 1999; Nguyen and Sukias 2002), P concentration in soil relative to overlying water (Reddy et al. 1999), the duration and frequency of flooding (Yin and Shan 2001), water velocity, oxidation-reduction potential and ditch size (Stuck et al. 2001).

Within a watershed context, many agricultural soils have elevated P levels that can contribute P to receiving water bodies (Sims et al. 1998). In the past several years, many management practices have been adopted in the United States to reduce P loss from agriculture (Bottcher et al. 1995). For example, within the Okeechobee Basin, Florida, agricultural best management practices (BMPs) are implemented for over 30 years. As a result, P imports that include fertilizer and cattle feed supplements to the basin decreased from 2,380 t P yr^{-1} in 1995 (Boggess et al. 1995) to 1,717 t P yr^{-1} (Mock Roos Associates 2002). By land use, P imports to dairies decreased by about 61% between the years 1991 and 2002, imports to improved cow-calf grazing pasture decreased by 75% ($\sim$ 9 kg P ha^{-1} yr^{-1}) [$\sim$ 8.2 lb P ac^{-1} yr^{-1}]) and imports to unimproved cow-calf grazing pasture decreased by 80% (0.05 kg P ha^{-1} yr^{-1} [0.045 lb P ac^{-1} yr^{-1}]) (Mock Roos Associates 2002). Other BMPs used to reduce and mitigate P loss include buffer strips, improved nutrient and waste management systems, and the use of constructed and natural wetlands (Anderson and Flaig 1995). As BMPs continue to be implemented, it is expected that P loss to receiving waters will continue to reduce with time, which could lead to a set of environmental conditions, whereby P could flux from ditch soil to relatively low-P waters flowing through and over them. Thus, to ensure continued improvement of water quality in the Lake Okeechobee watershed, biogeochemical characteristics of ditch soils need to be incorporated into future BMPs.

The aim of our study was to better understand P storage and P dynamics in three agricultural land uses within the Lake Okeechobee watershed. Objectives of this study were to (1) determine P characteristics of agricultural ditch soils in the Lake Okeechobee Basin, FL; (2) identify what controls soil P; (3) establish relationships between different ditch soil P fractions; and (4) compare ditch soil characteristics with upland and wetland soil characteristics. Further, we discuss how ditch soil characteristics might impact water quality, soil characteristics that may be useful indicators of potential P loss, and some management options that could be beneficial to mitigate potential P loss from ditch soils.

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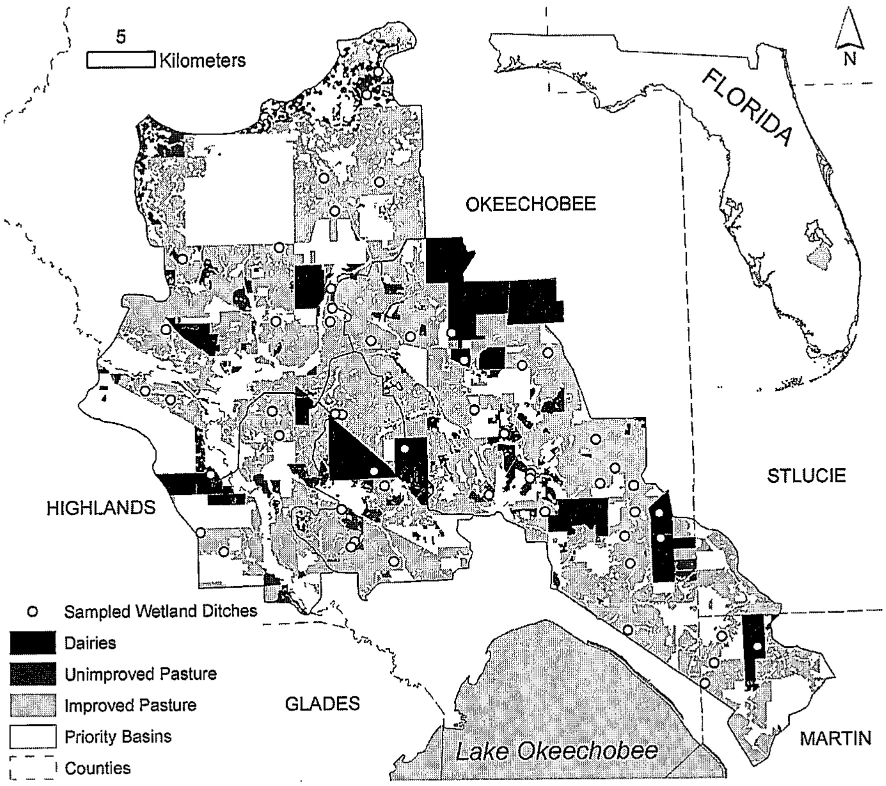
Materials and Methods

Site Description. All sample sites were located in the four priority basins of the Lake Okeechobee Basin (figure 1). These priority basins have contributed a disproportionate amount of P to Lake Okeechobee relative to their land area (Flaig and Reddy 1995). Based on 2003 land-use data (SFWMD 2003), 64% of the four priority basins were in agriculture (48% was in improved pasture, 7% was in dairy, and 6% was in unimproved pasture). All samples were collected from ditches that drained historically isolated wetlands in three different land uses (dairy, improved pasture, and unimproved pasture). Dairies were defined as any area pertaining to a commercial dairy. There was a range of land uses that pertained to dairies including ungrazed fields, fertilized hayfields, sprayfields, cow-calf grazing pastures, feeding pastures, and cow-barn areas. Improved pasture was defined as land which was cleared, tilled, reseeded with forage grasses, fertilized (FDOT 1999) and used for beef, cow-calf grazing. Unimproved pastures were cleared land, often with some trees and brush or native grasses, and were not fertilized (FDOT 1999) and used for beef cow-calf grazing.

Soils of the Lake Okeechobee Basin are mainly Alaquods formed in sandy marine sediments (Graetz and Nair 1995) which have a naturally low native P content (Hodges et al. 1967). Immokalee (sandy, siliceous, hyperthermic Arenic Alaquod) and Myakka (sandy, siliceous, hyperthermic Aeric Alaquod) are the most common soil series occurring in upland areas. Soils in wetlands of the study area are dominated by Aquepts and Aquents and to a lesser extent, Aquolls and Aqualfs (USDA NRCS 1995; Lewis et al. 2001).

Drainage has been improved for producing grass, with extensive ditching of fields and wetlands to convey storm water runoff towards Lake Okeechobee (Haan 1995). Ditching densities in the landscape increase with land-use intensity from unimproved pastures to improved pastures to intensively managed pastures (dairies) to row crops (Heatwole 1986). The National Wetland Inventory (NWI) suggests that 18% of the area consists of wetlands (McKee 2005) with 59% being mostly small (typically less than 2 ha [4.9 ac]), depressional, nonriparian wetlands. It has been estimated that 45% of these wetlands in the four priority basins are ditched and drained (SFWMD et al. 2004).

Figure 1
Map of ditch soil sampling locations with surrounding land use within the four priority basins of the Lake Okeechobee Basin, Florida.



During field sampling, ditches were classified into three classes: major, intermediate and minor. Major ditches were wide (more than 1 m [39.4 in]) and deep (more than 40 cm [15.7 in]). Minor ditches were unmaintained, shallow (less than 15 cm [5.9 in] deep), and narrow (less than 1 m [39.4 in]), while intermediate ditches were somewhere in between major and minor ditches.

Soil Sampling. All soils were collected between April and November 2003. Ditch soils were collected from ditches that drained small, (~ 1 ha [2.47 ac]) historically isolated wetlands within pastures. Some wetlands were connected to more than one ditch. The outlet ditches from wetlands were identified by evidence of water flowing from the wetland or a topography change indicating outward flow. Three soil cores (0 to 10 cm [0 to 3.9 in]) were collected randomly from each ditch within 10 m (32.8 ft) of the wetland. Soil cores were collected by hammering a polycarbonate tube (10 cm [3.9 in] internal diameter × 0.3 cm [0.1 in] wall depth × 60 cm [23.6 in] in length), to a soil depth of 15 cm (5.9 in). The top 10 cm of soil cores were extruded, sectioned at 10 cm (3.9 in) and placed into a zip-closure plastic bag. In the wetland, eight soil cores were collected at random, whereas in the upland, three soil cores were collected at random between 3 and 20 meters (9.8 and 65.6 ft) from the wetland. All wetland and upland soils were extruded and section as mentioned previously. All samples were stored on ice until return to the laboratory, where samples were refrigerated at 4°C (39.2°F) until they were prepared for analysis.

Soil Analyses. Composite soil samples were manually homogenized. Roots larger than 2 mm (0.08 in) in diameter and live vegetation were removed. Soil pH was measured using a 1:2 soil to water ratio (20 g [0.7 oz] of field-moist soil to 40 mL [1.35 fl oz] of distilled, deionized water). Water content was determined as the difference between wet and dry weights of an oven-dried (70°C [158°F] for three days) sample. Bulk density was calculated on a dry-weight basis using the known volume of soil cores. A subsample of each homogenized soil was air-dried for three weeks. Air-dried samples were machine-ground and passed through a #100 mesh (0.15 mm [0.006 in] openings)

Table 2

Soil metal characteristics of ditch soils collected within the four priority basins of the Okeechobee Basin, Florida.

Land use	n	Fe_{HCl} (mg kg^{-1})	Al_{HCl} (mg kg^{-1})	Ca_{HCl} (mg kg^{-1})	Mg_{HCl} (mg kg^{-1})	Fe_{ox} (mg kg^{-1})	Al_{ox} (mg kg^{-1})
Dairy	7	1920a ±627	285a ±65	502 ±181	674 ±270	674a ±252	399a ±114
Improved	48	989a ±149	167a ±26	446 ±71	270 ±52	382b ±59	239b ±35
Unimproved	5	671a ±495	152a ±114	754 ±635	156 ±96	233a ±115	680a ±573

Notes: Soils were collected between April and November 2003. Values represent means ± one standard error. Values with similar letters indicate that there was not a significant difference between the different concentrations of Fe and Al in 1 *M* HCl and ammonium oxalate extractions, whereas those with different letters indicate that extracting solution was a significant factor at the $p < 0.05$ level.

pasture were wetter for longer periods and/or had greater OM due to in-ditch vegetation, as they were often not maintained and grazed at a lower intensity.

Soil metal content values were much less than those reported for previous agricultural ditch soil studies (table 2). For surface ditch soils (0 to 5 cm; 0 to 2 in) collected from row crop fields in Delaware, Sallade and Sims (1997a) report mean values of 1,380 and 1,306 mg kg^{-1} (1,380 and 1,360 ppm) for total Al and Fe oxides, respectively. Nguyen and Sukias (2002) collected ditch soils (0 to 15 cm [0 to 5.9 in] in depth) from a pastoral catchment in New Zealand and also reported much higher mean values for Al and Fe ranging between 3,680 to 8,080 mg kg^{-1} (3,680 to 8,080 ppm) and 2,030 to 1,080 mg kg^{-1} (2,030 to 1,080 ppm), respectively. Thus, in comparison, ditch soils in our study area (Okeechobee Basin) have limited ability to retain P by sorbing P to Fe and Al oxides. Table 2 also shows that the ammonium oxalate solution extracted greater amounts of Fe relative to 1 *M* HCl solution; whereas the reverse was true for Al. We hypothesize that the ammonium oxalate solution is extracting organically bound Fe, and the HCl solution is not as ammonium oxalate can extract both inorganic and organic forms (Wang et al. 1986). As Al content was similar between ditch soils, irrespective of extracting procedure, it indicates that most Al is bound to inorganic P forms. Fe and Mg content of dairy ditch soils were slightly higher than improved and unimproved ditch soil (table 2). Although this difference was not significant, it suggests that these soil components increase with degree of impact (Sims et al. 1998; Josan et al. 2005).

Variability in ditch soil metal content (Fe, Al, Mg, and Ca) was high in unimproved pasture ditch soils (sometimes as high as 85% of the mean) (table 2), which may be due to the low number of samples collected. Comparing unimproved and dairy ditch soil metal content (table 2) indicated that metal content variability somewhat decreased with increasing degree of land use impact. For wetland soils, it was found that with an increasing degree of impact, variability of soil parameters also decreased (Bruland and Richardson 2005).

Ditch Soil Phosphorus. Land use was a significant factor regulating total P content of ditch soils ($p = 0.045$). Although ditch soils collected from dairies had slightly higher P concentrations in all P fractions measured (table 1), this was not significant. Reddy et al. (1998a) found that surface soils (0 to 15 cm) (0 to 5.9 in) of a drainage ditch near a dairy in Okeechobee Basin had total P concentrations of about 221 mg kg^{-1} (221 ppm) upstream and 1,590 mg kg^{-1} (1,590 ppm) downstream of the dairy. Also within the Lake Okeechobee Basin, Prein (2005) reports greater soil total phosphorus (TP) in ditches of improved pasture (322 mg kg^{-1} [322 ppm]); whereas ditch soil TP in unimproved pasture was very similar to the TP observed in unimproved pasture of this study (table 1).

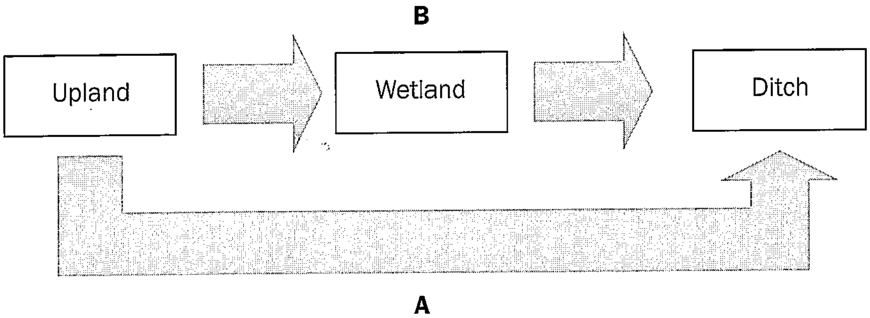
Unimproved pasture ditch soils had significantly lower total P content, water-extractable phosphorus (WEP), Mehlich 1 P and 1 *M* HCl P than ditch soils from both dairy and improved pasture ($p < 0.05$). The 1 *M* HCl (inorganic P) from dairy ditch soils was about twice the 1 *M* HCl P in improved pasture ditch soil, which had about twice the amount in unimproved pastures ditch soil (table 1). Ditch soils in dairies had the greatest proportion (25%) and unimproved pasture ditch soils had the least amount of soil P stored as inorganic P (17%). Inorganic P, as a percentage of total P, is a useful quantitative indicator of how P-impacted a particular soil can be, as when soils are P impacted, inorganic P fractions typically increase (Reddy et al. 1998). Using such indices to rank a ditch soil's potential to impact water quality may be useful to water quality managers.

Soil WEP fraction decreased with decreasing land use intensity. Dairy ditch soils had 7% of soil total P stored as WEP compared to unimproved pasture ditch soils (4% as WEP). For soils to release P to overlying water, there must be a P concentration gradient from soil pore water to the overlying water (Reddy et al. 1999; Smith et al. 2005). We hypothesize that ditch soils in dairy and improved pasture have a greater potential to release P relative to unimproved pasture ditch soils. In a watershed where BMPs are implemented for over 30 years, we also hypothesize that P concentrations in water entering ditches will decrease in the future. Thus, during ditch flow events, the prevalent direction of P movement may be from ditch soil (historically loaded) to overlying water (low P waters due to present BMPs). A useful parameter to assess this (although not measured in this study) would be equilibrium P concentration (EPC). These could be determined using standard sequential P sorption isotherms (Richardson and Vaithiyanathan 1995; Reddy et al. 1998a) and/or using soil-water core studies (Reddy et al. 1995). The benefit of determining EPC is that the concentration at which ditch soils release or retain P could be determined. Water SRP concentrations above the EPC would suggest ditch soils retain P, whereas if concentrations were below the EPC, ditch soils would potentially release P.

There was little evidence of land use impact on plant-available P (Mehlich 1 P), HCl P as measured using ICP, and ammonium oxalate P, suggesting that these P fractions may not be useful indicators of P impacts. On average, 13% of soil total P was plant-available. The HCl extracted P measured by ICP and phosphorus oxalate (P_{ox}), represented 42% and 43% of ditch soil total P. Both HCl P fractions and P_{ox} covaried best ($r = 0.78$, 0.75, and 0.72 for HCl P measured using AA, HCl P measured using ICP, and P_{ox}, respectively) with soil total P content. The 1 *M* HCl P was greater in ditch soil solution extracts when extracts were measured for P using ICP, relative to

Figure 3

Schematic of phosphorus transport between uplands, ditches and wetlands. Arrows indicate P transport between (A) uplands, wetland, and ditches and (B) uplands and ditches.

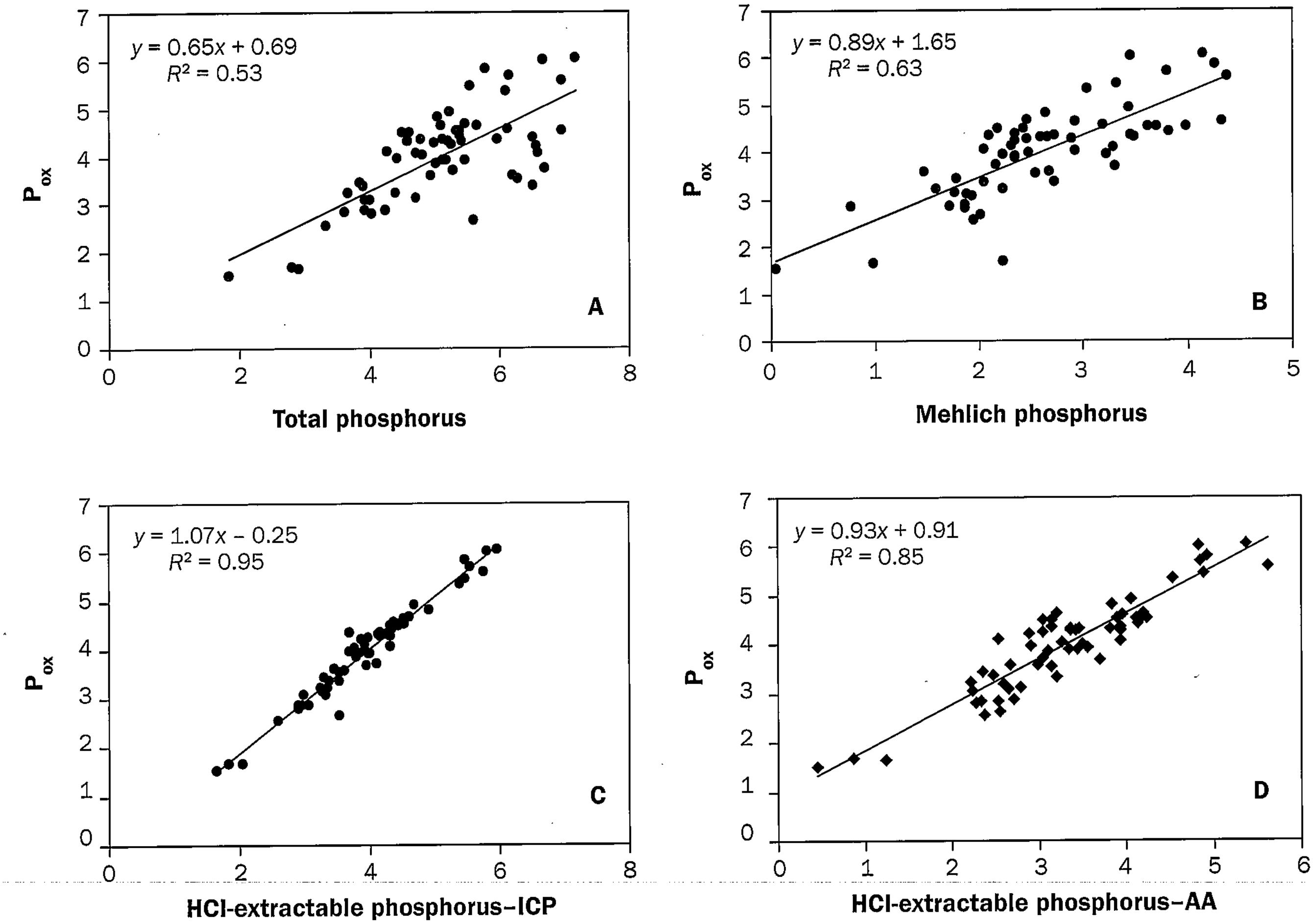


values of unimproved pasture ditch soils were less than the 25% threshold value (14%). To rank agricultural ditch soils for their potential to release and or retain P, it is important to incorporate an index like DPS with other site soil characteristics including adjacent land use, hydrological, physical, chemical and biological characteristics of ditches.

Biogeochemical Relationships between Different Landscape Units. Figure 2 suggests that the total P content in the surrounding upland soils were similar to, or slightly less than, ditch soil P. Ditch soils possessed similar total P and ammonium oxalate P to upland soils. They also had similar bulk density and Fe content (1 *M* HCl) to wetland soils (table 3). Stuck et al. (2001) found that P concentrations in ditch soils of the Everglades Agricultural Area, Florida, were similar to adjacent fields. At the landscape-scale, ditches could receive P directly from uplands during runoff events (figure 3a). Also, a landscape continuum of P transport

Figure 4

Relationships between available phosphorus (P_{ox}) and (A) total phosphorus, (B) Mehlich phosphorus, (C) HCl-extractable phosphorus measured using ICP, and (D) HCl-extractable phosphorus measured using an autoanalyzer (AA) of ditch soils (*n* = 60).



Note: Values are log-transformed concentrations (mg kg^{-1}) (ppm).

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Effect of ditch dredging on the fate of nutrients in deep drainage ditches of the Midwestern United States

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Abstract: Dredging of drainage ditches is necessary to ensure that agricultural fields are drained adequately. This study compared the potential impacts of dredging on water quality. Using a fluvarium (stream simulator), bed material collected from drainage ditches prior to dredging was better able to remove NO_3-N, NH_4-N, and soluble P from water than material collected from the bed of the ditches after dredging. Water column NH_4-N concentrations were reduced to 0 mg L^{-1} (0 ppm) earlier in pre-dredged bed material. Nutrient uptake rates were greater for the ditch bed materials collected prior to dredging. Dredging decreased the specific surface area of ditch bed sediments and removed some of the biota responsible for nutrient uptake by the bed sediments in these ditches. Resource managers should perform maintenance tasks, including ditch dredging, when nutrient loads are expected to be low, thus minimizing the potential water quality impacts.

Key words: ammonium—drainage ditch—dredging—phosphorus—nitrate—water quality

The soils of the Midwestern United States are some of the most potentially productive in the world. Nizeyimana et al. (2001) estimated that Iowa, Illinois and Indiana contain the greatest amount of potentially highly productive soils in the United States (figure 1a). The combination of the slowly permeable glacial till soils (most commonly alfisols and mollisols), and the humid environment require agricultural producers to artificially drain many of these soils. This drainage allows for trafficability and for crops to germinate and grow when otherwise, the soil conditions would be too wet. The greatest density of subsurface drainage occurs in the Midwestern United States (figure 1b), which coincides with the general region with the most potentially productive soils in the nation.

In this region, drainage water from fields is typically conveyed through a network of tile lines, generally located approximately 0.6 to 1.0 m (2.0 to 3.3 ft) below the soil surface, to managed drainage ditches. The ditches then convey the water to natural streams or rivers. One necessary management strategy in these systems, which is typically performed when it is perceived that drainage water is not efficiently removed from adjacent agricultural fields, is dredging. Dredging can occur as often as every 5 years or as infrequently as every 50 years. Typically, a local government entity such as a Country Drainage Board or the local Soil and Water Conservation District is responsible for planning and coordinating ditch maintenance and dredging.

Bed materials (i.e. sediments) are known to act as sources or sinks for phosphorus (P) and ammonium (NH_4-N) in the water column, especially in lower order stream networks (first, second, or third order streams) (McDowell and Sharpley 2003; Malecki et al. 2004; Storey et al. 2004; Merseburger et al. 2005; Zhou et al. 2005; Bernot et al. 2006). When wastewater treatment plant effluent with unregulated levels of soluble phosphorus (SP) in discharge was conveyed into streams, elevated SP concentrations in stream water and sediments were observed as far as 30 km (18.6 mi) downstream (Haggard

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