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Nutrient Mitigation Efficiency in Agricultural Drainage Ditches: An Influence of Landscape Management

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Abstract Drainage systems are integral parts of agricultural landscapes and have the ability to intercept nutrient loading from runoff to surface water. This study investigated nutrient removal efficiency within replicated experimental agricultural drainage ditches during a simulated summer runoff event. Study objectives were to examine the influence of routine mowing of vegetated ditches on nutrient mitigation and to assess spatial transformation of nutrients along ditch length. Both mowed and unmowed ditch treatments decreased NO_3^--N by 79 % and 94 % and PO_4^{3-} by 95 % and 98 %, respectively, with no significant difference in reduction capacities between the two treatments. This suggests occasional ditch mowing as a management practice would not undermine nutrient mitigation capacity of vegetated drainage ditches.

Keywords Ditches · Nutrients · Flow rates · Runoff

Agriculture is a contributing source of surface water pollution by way of erosion and chemical runoff (US EPA 2012). As a result, increased emphasis has been placed on developing and implementing new, innovative best management practices (BMPs) to reduce surface water contamination from edge-of-field runoff containing nutrients, pesticides, bacteria and sediments (Cooper et al. 2004). Several BMP tools, such as, stiff grass hedges, cover crops, crop rotation, no-tillage, terracing, buffer zones, retention ponds, and constructed wetlands, are effective controls to reduce nonpoint source pollution from reaching receiving water bodies (Cooper et al. 2004; Kröger et al. 2007, 2008a, 2011; Moore et al. 2000, 2006, Needelman et al. 2007). Research now promotes the use of drainage systems as innovative and cost effective BMPs for reducing pollution from agricultural fields (Cooper et al. 2004; Kröger et al. 2008a). Traditionally, drainage systems are open-ditch (largely uncontrolled) systems solely used to convey surface runoff from production acreage into waterways (Cooper et al. 2004; Kröger et al. 2008a).

Over the years, there have been improvements and modifications to these drainage systems into different controlled types employing flashboard riser systems (Evans et al. 1995; Lalonde et al. 1996) and low-grade weir installations (Kröger et al. 2008b, 2011) to control water flow in drainage systems. According to Ayars et al. (2006), the transition from conventional uncontrolled drainage to controlled drainage in US agriculture was in response to rising environmental concerns (associated with conventional drainage contributing to nutrient losses) and to enhance better water management. For instance, during dry seasons or water stress periods, drainage is controlled by configuring risers to retain water and increase ground water levels. This helps to enhance soil moisture conditions (Evans et al. 1995; Kröger et al. 2008a). In addition to enhancing nutrient uptake by plants for increased crop production, risers are adjusted in controlled agricultural drainages to help minimize the amount of nutrients lost to receiving water from fields, thus allowing improved water quality in streams (Wesstrom et al. 2001). Controlled drainage ditches in North Carolina, have been employed as a BMP tool to prevent about 8,000,000 kg of nitrogen from

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reaching surface water annually (Evans et al. 1995). Unlike riser-controlled drainage systems, weir-controlled drainage systems can have low-grade weirs permanently installed and spatially arranged at different points in ditches. Weirs are designed to specifically increase water retention time within the ditches, increase sedimentation and lower flow velocity in order to reduce the loads of contaminants reaching the surface water (Kröger et al. 2008b). The weirs being spatially stratified within the ditches also help to uniformly lower the soil water table, thus allowing more nutrient uptake by crops (Kröger et al. 2008a).

Vegetation in drainage systems also encourages contaminant filtration, increases runoff retention time, reduces flow velocity and increases sedimentation, thereby creating more time for contaminant sorption by the plants (Brix 1994; Moore et al. 2006; Vymazal 2011). The capability of agriculture drainage systems in processing and transforming edge-of-field nutrient runoff continues to be investigated in the lower Mississippi Delta region. This study investigates nutrient transformation within replicated experimental agricultural drainage systems during a simulated summer storm runoff event. Specific objectives were to (1) compare transformation of nutrient runoff in mowed and unmowed experimental ditches to investigate the possible influence of routine mowing of vegetative agricultural drainage systems on nutrient mitigation; and (2) assess spatial transformation of nutrients in both mowed and unmowed experimental ditches to determine the necessary ditch length for effective mitigation of nutrient runoff, given recommended application rates and other underlying assumptions regarding rainfall and runoff variability. Current hypotheses state (1) nutrient filtration capability in unmowed ditch treatments would be significantly greater than treatments with mowed vegetation; (2) ditch nutrient concentrations would decrease from inflow to outflow in such a way to allow prediction of ditch length needed for a target nutrient outflow concentration.

Materials and Methods

The study site was located at Arkansas State University's (A-State) Agricultural Research Facility (35°50 32.92″ N, 90° 42′15.87″W) in Jonesboro, AR, USA and ditch assessments were conducted from June 12 through June 13, 2013. The current study was built on previous work from this facility using artificially constructed drainage ditch systems as described by Kröger et al. (2011). The A-State Agricultural Research Facility is located directly east of the university campus in Jonesboro, AR. It consists of eight drainage ditches, each with a mean width and length of 1.89 and 58.7 m, respectively, and a slope of 0.1 % along the length. A 0.38 hectare retention pond supplied by a groundwater well provided water to each of the eight drainage ditches via underground pipes connected to ditch inflows (Fig. 1).

Each ditch had an inflow structure with an adjustable valve to allow a constant flow rate in addition to an outflow structure. Four of the eight ditches were randomly selected to have concrete weirs spatially installed at 20 and 40 m along their length. The remaining four ditches remained conventional with no weirs. All ditches had mixed grass vegetation communities including *Typha latifolia* L. and *Carex* spp, but were dominated by *Typha latifolia* L. Two of each type of ditch treatments were randomly selected and mowed to assess influence of vegetation maintenance. Thus, four experimental drainage treatments were utilized for this study: (1) unmowed vegetated drainage ditches with weirs; (2) mowed vegetated drainage ditches with weirs; (3) unmowed vegetated drainage ditches without weirs; and (4) mowed vegetated

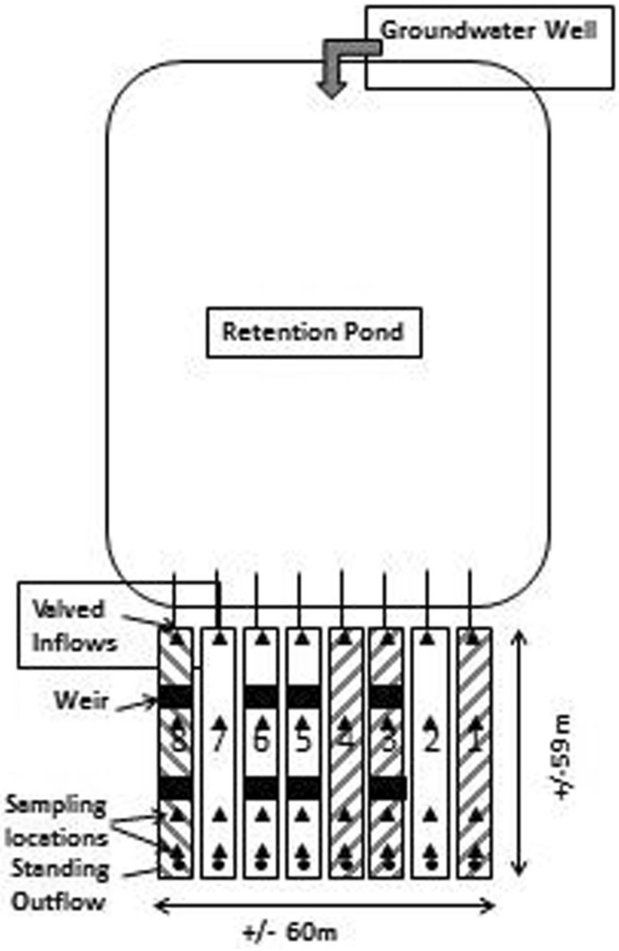

Fig. 1 Experimental drainage ditch design at Arkansas State University's Agricultural Research Facility with ditches 3, 5, 6 and 8 having weirs and ditches 1, 2, 4 and 7 as conventional systems with no weirs. Ditches highlighted in plain pattern were mowed (*cut*) and those highlighted in filled pattern were unmowed (*uncut*)

drainage ditches without weirs. Although the research facility had ditches with and without weirs, the current study made adjustments to remove the effect of weirs (by adjusting ditch flow rates accordingly) to better compare mowed and unmowed ditch treatments. A previous study on the site by Littlejohn (2012) demonstrated a significant reduction of added nutrient concentrations and loads in ditches with weirs due to increased retention time and ditch water volume. For this study, the influence of weirs was not assessed, and to shield the effect of weirs, equal retention time was maintained in all ditches.

Flow rates into each ditch were calibrated at the inflow pipe utilizing volume measurements for standard times using a graduated bucket and a stopwatch. The flow rate for each ditch was adjusted accordingly, such that a four hour hydraulic retention time was established simultaneously in all ditches. A 4-h retention time was chosen because it would allow three system turnovers (3 full "flushes') within a 12 h day. Flow rates for each ditch treatment are provided in Table 1. Given the formula; retention time = Volume/flow rate, weirs in ditches increased ditch volume, hence the reason for higher flow rates in ditches with weirs compared to ditches without weirs. This helped to shield the effect of weirs. A runoff event was simulated as a nutrient pulse through the eight drainage systems on June 12, 2013. Each ditch was amended with potassium phosphate dibasic (K_2HPO_4) and sodium nitrate ($NaNO_3$) crystalline/certified ACS), Fisher Chemical, Fishers Scientific®, USA (each with assay percent purity range $\geq$ 99.0 %) as a pulse exposure. The concentration amended was typical of a potential runoff concentration leaving a 32 ha agricultural field during a 0.64 cm storm event. This is a commonly used scenario on various agriculture runoff studies conducted in the lower Mississippi River Valley (Cooper et al. 2004; Kröger et al. 2011). Each simulated pulse was achieved using eight, 190-L polyethylene mixing chambers (one for each ditch) filled with groundwater from the retention pond and appropriately measured nutrient mixture specific for each ditch. The slurry was thoroughly mixed in the chambers and then delivered to the ditches as a simultaneous pulse exposure. Mean nutrient concentrations in the mixing chambers prior to ditch amendments were 14.55 ± 0.71 and 22.20 ± 0.59 mg/L NO_3^--N, and PO_4^{3-}, respectively. The targeted nutrient concentration of ditch water was 5 mg/L for both nitrate and phosphate. This targeted concentration accounted for both standing water, as well as water that would be amended during the exposure.

Prior to nutrient exposure, grab samples of water were collected from all sampling locations in each of the eight ditches (Fig. 1) and from nutrient mixing chambers using 250 mL polyethylene cups. Samples were analyzed for background nutrient concentrations in ditches, as well as confirmation of concentration in mixing chambers. Immediately following the pulse exposure, water samples were collected in 250 mL polyethylene cups every 15 min for 2 h from all sampling points (with the exception of the inflow), then at every hour up to 10 h and again at 24 h post-nutrient application. Samples were collected from ditch inflows at 1, 2, 4, 6, 8, 10 and 24 h post-application. Sampling points for the study were established at the inflow (runoff injection point = 0 m), 20 m, 40 m and the outflow of all ditches. The 20 m and 40 m designation corresponded to weir downstream locations in the ditch systems. All samples were transported on ice from the field to the United States Departments of Agriculture (USDA) Sedimentation Laboratory, Oxford MS for nutrient analysis. Collected water samples were analyzed for NO_3^--N, NO_2^--N and dissolved inorganic orthophosphate (DIP) on a Lachat Quick Chem FIA + 8000 Series analyzer, utilizing standard methods (APHA 1998). Limits of detection were 0.0015, 0.0015 and 0.001 mg L^{-1} for NO_3^--N, NO_2^--N and PO_4^{3-}, respectively. Accuracy checks with

Table 1 Flow characteristics of the eight treatment drainage ditches evaluated during the study period

Ditch number	Ditch type	Ditch treatment	Depth (m)	Flow rate at inflow pipe (Ls^{-1})
1	Non-weir	Unmowed	0.10	0.52
2	Non-weir	Mowed	0.11	0.20
3	Weir	Unmowed	0.25	1.25
4	Non-weir	Unmowed	0.15	0.17
5	Weir	Mowed	0.20	1.28
6	Weir	Mowed	0.22	0.82
7	Non-weir	Mowed	0.17	0.18
8	Weir	Unmowed	0.14	0.23
	Weir average ± SE			0.90 ± 0.25^{a}
	Non-weir average ± SE			$0.27 \pm 0.08^{b*}$
	Mowed			0.61 ± 0.26
	Unmowed			0.55 ± 0.25

Different letters indicate significant differences; * indicate $p \leq 0.05$

known standard nutrient concentration and a blank deionized water control were analyzed with each run, one check for every ten samples (with >99 % accuracy). Duplicate analyses were also conducted on at least 10 % of samples in each batch.

Statistical analyses were performed using Minitab® Statistical Software (version 16, Minitab Inc., USA). Two sample *t* tests were performed to check for differences in flow rates between ditches with weirs and without weirs and between mowed and unmowed ditch treatments. Multivariate analysis (MANOVA) was performed to assess if any differences existed in the outflow nutrient concentrations between mowed and unmowed ditch treatments. Paired *t* tests were performed to check if differences existed between influent and effluent nutrient concentrations. Data were checked for normality and homogeneity of variance. Pearson linear correlation was used to assess any relationship between nutrient concentrations and nutrient spatial transport. Where correlation existed, ordinary least-square linear regression analysis were conducted by fitting the curve with ditch water nutrient concentration (y) versus sampling distances along ditch length from the injection point to the ditch outflow (x). Only maximum concentrations observed at each sampling point, irrespective of time, were used in the analyses (this justifiable rationale was adopted from Cooper et al. (2004) since the maximum concentration at any location had occurred within the 4 h of flow from inflow to outflow). Alpha was set to 0.05 for all tests.

Results and Discussion

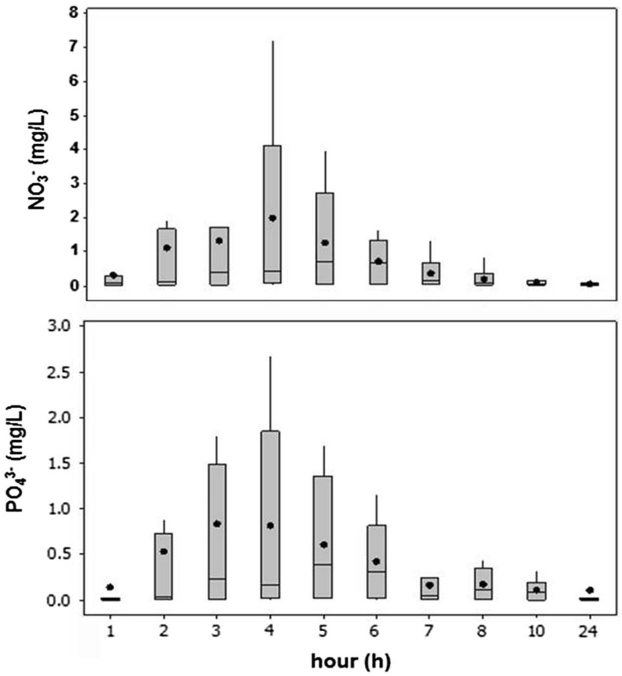

Fig. 2 *Boxplot* of hourly nutrient concentration trend in the ditch outflows depicting the nutrient concentration peaked upon 4 h of ditch dosage. The symbol *filled circle* represent the mean nutrient concentrations

Flow rates were significantly higher in ditches with weirs than without weirs ($T = -2.42; p = 0.05$), but were similar between mowed and unmowed ditch treatments ($T = 0.16$; $p = 0.88$) (Table 1). Outflow nutrient concentrations (NO_3^--N, and PO_4^{3-}) peaked after 4 h of exposure in agreement with the intended 4 h retention time (Fig. 2); however, overall nutrient concentrations decreased from inflow to outflow in all ditch treatments. Upon 4 h of exposure was no significant difference observed (Pillai's Trace = 0.23, $F = 0.40; p = 0.77$) in outflow NO_3^--N and PO_4^{3-}concentrations between mowed and unmowed ditch treatments (Fig. 3). The mean NO_3^--N concentration in mowed ditches was 2.99 ± 1.70 mg/L, while that of unmowed ditches was 1.00 ± 0.60 mg/L. Similarly, the mean PO_4^{3-} concentration in mowed ditches was 1.21 ± 0.66 mg/L while that of unmowed ditches was 0.45 ± 0.35 mg/L. On average, NO_2^--N concentrations in ditch treatments were very low with no significant difference observed (Pillai's Trace = 0.23, $F = 0.40; p = 0.77$) in the mean concentrations between mowed and unmowed ditches. Mean NO_2^--N concentration in mowed ditches was 0.03 ± 0.01 mg/L and that of unmowed ditches was 0.01 ± 0.01 mg/L.

After 4 h of exposure, nutrient concentrations in the ditch outflow of all treatments were significantly reduced ($p < 0.001$ for NO_3^--N; $p < 0.001$ for PO_4^{3-}) beyond the initial concentration dosages at the injection points (Fig. 3). Percent nutrient reduction in ditch treatments with unmowed vegetation on average were 93.55 % ± 4.24 % and 97.74 % ± 1.79 % of initial NO_3^--N and PO_4^{3-}concentrations, respectively. Similarly and on average, 78.80 ± 12.9 % and 94.81 ± 2.83 % reduction of initial NO_3^--N and PO_4^{3-}concentrations, respectively, were observed in ditch treatments with mowed vegetation. Studies that have examined nutrient mitigation in drainage ditches reported varying percentage decreases in nutrient concentrations depending on different conditions and landscape system attributes. Kröger et al. (2007) reported NO_3^--N concentration reduction between 34.5 % and 100 % in agricultural drainage ditches draining cotton fields in Lafayette County, Mississippi, during growing seasons. The study highlighted variation in percent reductions was a result of variable hydrological conditions experienced during the growing period between April and September 2005, post-fertilizer application. Kröger et al. (2011) reported 97 % and 79 % NO_3^--N concentration reduction in ditches with weirs and

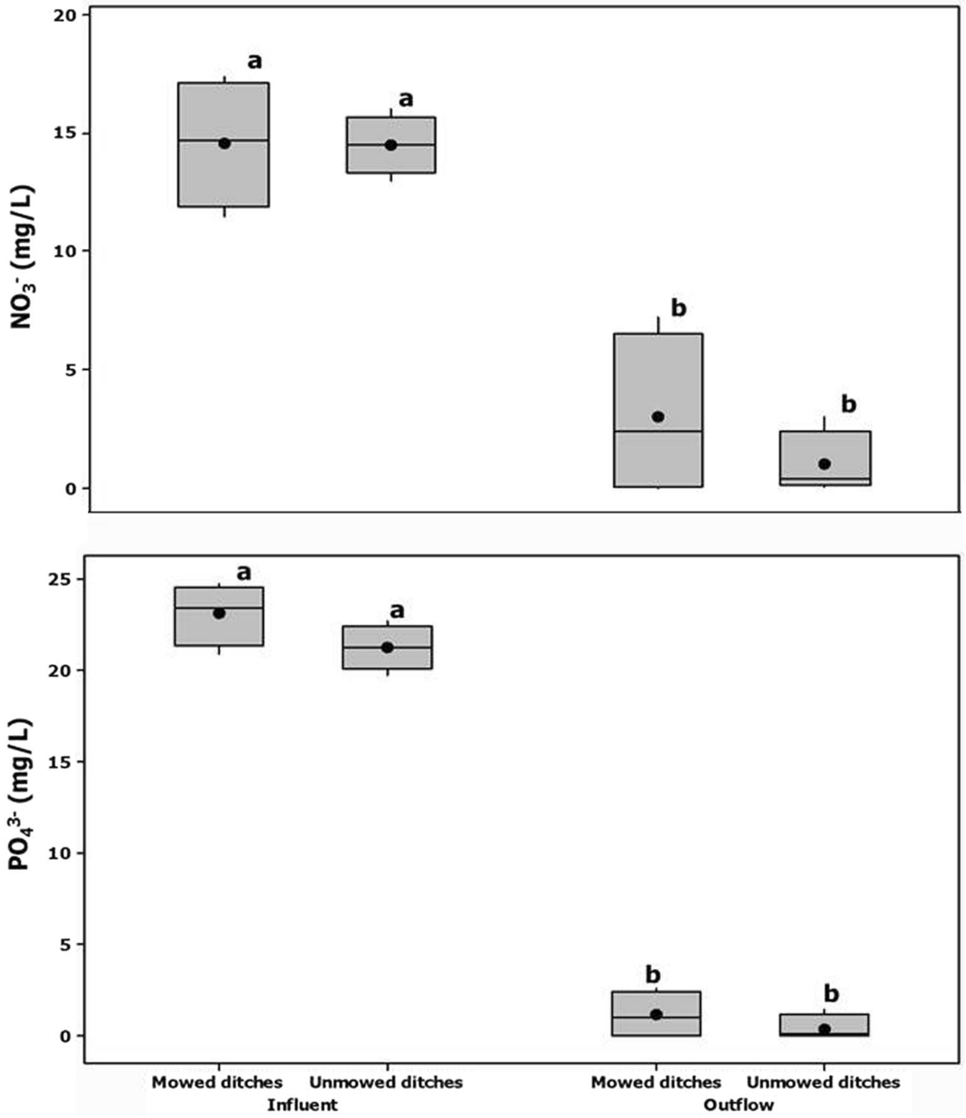

Fig. 3 95 % confidence estimates for the influent and effluent nitrate and dissolved orthophosphate concentrations between ditch treatments. *Different letters* indicate significant differences ($p < 0.001$)

risers, respectively, post-split fertilizer application. The same study also reported a significant decrease of 70 % and 80 % in PO_4^{3-} concentrations in ditches with weirs and risers, respectively. Other studies upon agricultural drainage systems have additionally reported reduction in nutrient loadings and concentrations attributed to ditch structural designs and attributes (Marttila and Kløve 2009; Moore et al. 2013; Fu et al. 2014).

Generally, vegetation in systems offers 20 %–50 % of nutrient removal efficiency via biotic sorption and by providing surfaces and substrate for microbial transformation (Brix and Schlerup 1989). A lack of difference in nutrient reduction capacities between mowed and unmowed ditch treatments in the current study suggests occasional ditch mowing as a management practice during the growing season would not undermine the nutrient mitigation capacity of vegetated drainage systems. Rather, it may offer a benefit to flow constriction management option, in addition to nutrient mitigation control. According to Needelman et al. (2007), ditch vegetation maintenance and selective woody vegetation cleanout in agricultural ditches helps prevent flow constraints and flooding during storm events and can improve water management for agricultural production. In addition to flow management, trimming of ditch vegetation may also furnish an opportunity for sustainable vegetation regrowth, productivity and establishment (Brix and Schlerup 1989), thus providing ditch treatments with additional plant surface areas for biotic sorption and transformation of nutrients (Kröger et al. 2009a; Moore et al. 2010).

In the current study, although nutrient concentrations decreased significantly from inflow to outflow, there was no correlation observed between sampling distances (along ditch length from the injection point to the ditch outflow) and nutrient concentrations in all treatments (except in ditch # 4). In the case of ditch treatment # 4 where correlation was observed between sampling distances and nutrient concentrations, a regression analysis could not be fitted because data violated other assumptions and transformations to validate ordinary least-square linear regression analysis. Data were again fitted using a weighted least squares method which revealed the inappropriateness of the regression model ($p = 0.17$). This is somewhat surprising in that Kröger et al.(2007) reported an alternating positive and negative relationship between nutrient concentrations and their longitudinal transport along ditch length during dormant seasons with periods of very high and low hydrological discharge. However, Kröger et al. (2007) particularly emphasized the obvious decrease or increase of nutrient concentrations along ditch lengths as being dependent on water volume and discharge. The same study also highlighted a period of temporary homogenized nutrient concentrations along ditch lengths during a period of consistent water volume and discharge rates. In agreement with Kröger et al. (2007), a lack of correlation between nutrient concentrations and ditch length may have been due to uniform flow rates within ditch treatments in this study. Kovacic et al. (2000) reported in their study that nutrient removal efficiency in wetland treatments was more a function of wetland size (i.e., area not length), hydrological flow, nutrient hydraulic loading, and retention time. Kröger et al. (2009b) highlighted that any ditch attributes that enhance chemical retention time would provide more opportunity for chemical mitigation through microbial transformation, sediment adsorption and macrophyte assimilation.

Although conventional BMPs have thus far emphasized reduced farm tillage, grassed waterways, and having riparian buffer strips adjacent to receiving streams that drain agricultural catchments (Lemke et al. 2011), this study is in agreement with other research (Moore et al. 2000; Kröger et al. 2007, 2009b), recommending greater emphasis being placed on understanding and manipulating landscape features that enhance nutrient retention and mitigation in receiving agriculture drainage ditches that provide primary contact with runoff during transfer to these streams. While scientists encourage and advocate the use of vegetation within agricultural ditches for ecological functions, many farmers have the perception that ditch vegetation may obstruct flow and limit the primary hydrological function of drainage ditches (Kröger et al. 2009b). The outcome of the current study demonstrated mowing vegetated ditches (instead of complete vegetation removal or dredging) during the growing season as a management practice could help maintain a balance between the hydrological and ecological benefits of drainage ditches. This was attributed to the mowed ditches in the current study having similar nutrient removal efficiency as unmowed ditches, thus offering a beneficial flow constriction management option in addition to a mitigation control benefit. Demonstration and replications of the outcome from this study on actual fields, coupled with educating landowners and farmers on the benefits of keeping ditches vegetated, may facilitate their voluntary adoption of this cost effective BMP.

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