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IMPLEMENTING INNOVATIVE DRAINAGE MANAGEMENT PRACTICES IN THE MISSISSIPPI RIVER BASIN TO ENHANCE NUTRIENT REDUCTIONS[1]

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ABSTRACT: In the Mississippi River Basin (MRB), practices that enhance drainage (e.g., channelization, tile drainage) are necessary management tools in order to maintain optimal agricultural production in modern farming systems. However, these practices facilitate, and may speed the delivery of excess nutrients and sediments to downstream water bodies via agricultural streams and ditches. These nonpoint sources contribute to elevated nutrient loading in the Gulf of Mexico, which has been linked to widespread hypoxia and associated ecological and economic problems. Research suggests agricultural drainage ditches are important links between farm fields and downstream ecosystems, and application of new management practices may play an important role in the mitigation of water quality impairments from agricultural watersheds. In this article, we describe how researchers and producers in the MRB are implementing and validating novel best management practices (BMPs) that if used in tandem could provide producers with continued cropping success combined with improved environmental protection. We discuss three BMPs — low-grade weirs, slotted inlet pipes, and the two-stage ditch. While these new BMPs have improved the quality of water leaving agricultural landscapes, they have been validated solely in isolation, at opposite ends of the MRB. These BMPs have similar function and would greatly benefit from stacked incorporation across the MRB to the benefit of the basin as a whole.

(KEY TERMS: best management practices; water conservation; sediment; runoff; surface water hydrology; biogeochemistry.)

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INTRODUCTION

The Mississippi River Basin (MRB) contains some of the most highly productive and intensively farmed areas in the world, including the Upper Midwest and the Mississippi Delta. Much of the region is dependent upon improved drainage practices (e.g., tile drainage, channelization) for reliable and economically viable production of agricultural commodities on fertile, but poorly drained soils (Fausey *et al.*, 1995). However, water containing excess nutrients from agricultural drainage contributes to impairment of surface waters, having impacts far beyond farm fields. In particular, runoff from agricultural fields to drainage ditches results in excess inorganic nitrogen

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(N) and phosphorus (P) transport and sediment delivery to downstream water bodies (Blann *et al.*, 2009). These nonpoint sources (NPS) of pollution not only influence local freshwaters like downstream lakes and rivers, but also fuel harmful algal blooms and subsequent die-offs that lead to hypoxic “dead zones,” such as those now occurring annually in the Gulf of Mexico (Turner and Rabalais, 2003).

Unfortunately, given their role in draining agricultural lands, ditches usually function as nutrient sources, rather than sinks, of NPS pollutants. In a study of 14 channelized streams, Laubel *et al.* (2003) found that erosion of unstable ditch banks contributed 48-59% of suspended sediments and 40-48% of P loads in small agricultural watersheds. These findings are consistent with other studies (e.g., Sharpley and Syers, 1979; Kronvang *et al.*, 2005; Walling *et al.*, 2008; Zaimes *et al.*, 2009) that found sediment and nutrient contributions from unstable, eroding channels varied from 1 to 87% of total watershed loads. Collectively, these findings and numerous other studies suggest that conventional drainage ditches must maintain their primary function as drainage-ways for excess soil-water, but new best management practices (BMPs) developed for these ditches could play an important and necessary role in the mitigation of downstream water quality impacts from agricultural land use.

In order to effectively manage surface water quality while allowing for agricultural productivity, science-based management to protect and enhance water quality while meeting drainage needs in all parts of the MRB will be essential for the future of agriculture. Many commonly used BMPs (e.g., constructed wetlands, riparian buffer strips, settling basins, and conservation tillage) have been useful in improving downstream water quality through the treatment of surface and subsurface runoff by creating zones of sediment deposition and enhancing biogeochemical transformation of pollutants. However, often their implementation has come at the expense of agricultural land, by taking land out of production, which has limited widespread implementation into current farming practices.

In this article, we describe a new generation of BMPs currently being tested, validated, and adopted in both the upper and lower portions of the MRB that are innovative in two ways: (1) each management practice seamlessly integrates into agricultural landscapes to maintain agronomic yields with minimal, if any, loss of land from production and (2) each management practice creates physical (i.e., hydrological) and biological (i.e., biogeochemical) conditions to enhance environmental stewardship, by reducing nutrient export from waterways, thus improving downstream water quality. Used in combination, we describe how these practices can improve water quality better than when used alone, and we demonstrate how the integration of conservation technologies can secure the sustainability of agricultural intensification.

While many practices require a producer to remove land from production, slotted inlet pipes and low-grade weirs (explained in detail in the following sections) are BMPs that fit into fields without removing land from production and this factor alone may make them more desirable for implementation. The science behind these two practices is also intuitive, which can go far with pragmatic producers gaging the bottom line. Slotted inlet pipes and low-grade weirs fall into the broad class of controlled drainage systems, which allow the producer to manage the intensity of surface drainage from farm fields. Drainage can be tailored to meet the specific environmental conditions of the site, such as crop and soil type, and seasonal weather patterns (Wesström *et al.*, 2001). Controlled drainage significantly reduces edge-of-field outflow of N and P, primarily through reductions of outflow volumes (Evans *et al.*, 1995; Wesström *et al.*, 2001).

SLOTTED INLET PIPES

Slotted inlet pipes (Natural Resource Conservation Service [NRCS] practice code 410) are an innovative BMP for use in surface-drained acreage. Water leaving the field is directed through a conveyance device with a fixed elevation (Figure 1). This practice is typically coupled with pads (i.e., earthen levees, NRCS practice code 356) which prevent water from leaving the field except through this conveyance. In this way, slotted inlet pipes minimize erosion by preventing head cutting since water is not free to flow into the ditch except via the conveyance. This diversion also slows the velocity of runoff, encouraging sediment accumulation and retention. In this manner, pipes function very much like buffer strips, slowing outflow and holding back sediment, but without the loss of acreage. The resultant reductions in NPS pollution to downstream water bodies can be attributed not only to a reduction in the physical amount of sediment leaving the system, but also to biogeochemical processes which are microbially mediated by the sediment retained by the pipe.

Currently, there are caveats to slotted inlet pipes; while the theory suggests positive outcomes, few studies exist documenting the effectiveness of this fairly new practice. Kröger *et al.* (2013a) is one of the first published articles documenting research on slot-

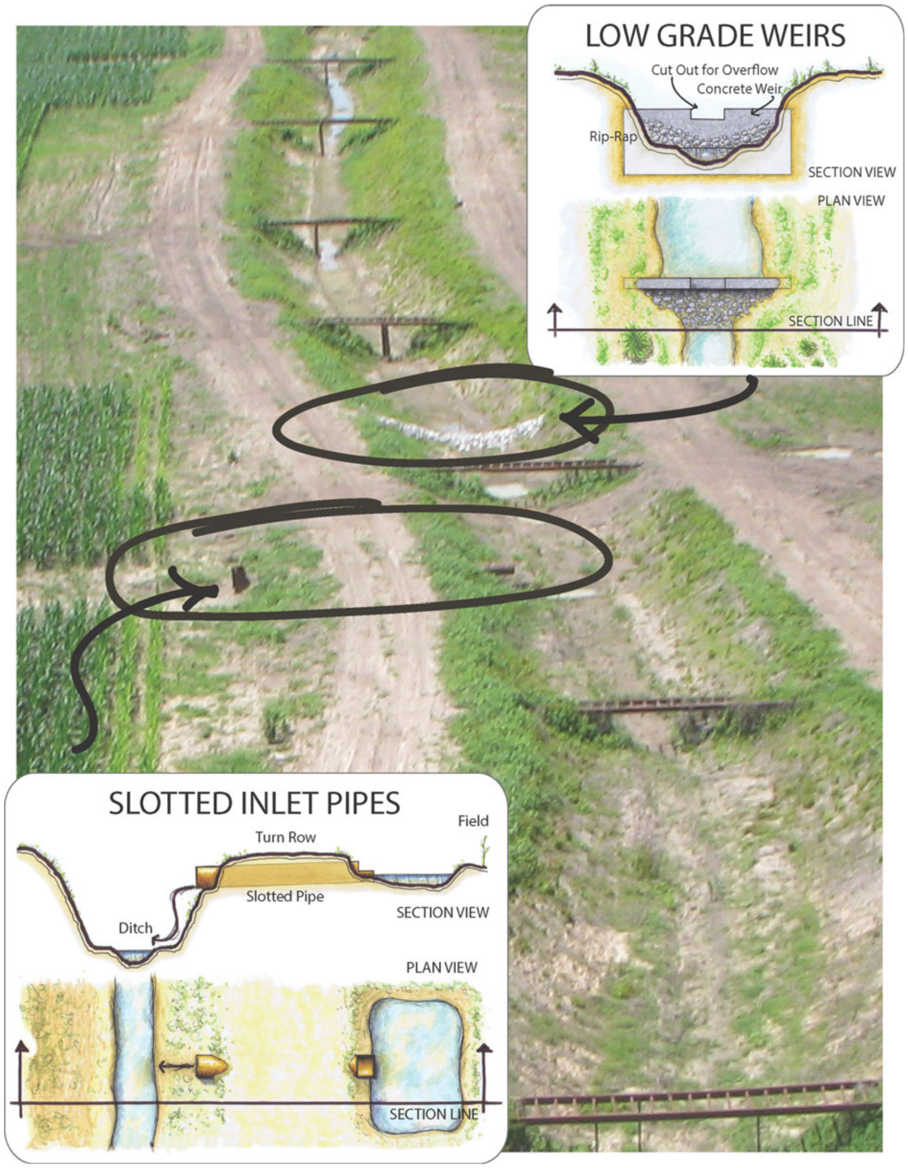

FIGURE 1. Illustration of Slotted Inlet Pipes and Low-Grade Weirs Installed in an Agricultural Landscape.

ted inlet pipes as a BMP which showed that pipes held between 3.32 and 18.86 kg of P per pipe in a limited replicated study. Phosphorus retention should be a function of pipe catchment area, pipe retention area, and soil type (Kröger *et al.*, 2013a), but the relative importance of these factors and the direct translation to P reduction needs to be further investigated, in addition to any N removal that might also be associated with the practice.

Just as critical to implementation of the practice is the maintenance associated with the practice to ensure maintained effectiveness in water quality improvement. Kröger *et al.* (2013a) noted that the maintenance schedule for pipes required them to be periodically cleared of accumulated sediment and significant differences in accumulation rates occurred 235 days after installation (Kröger *et al.*, 2013a). Figure 2 shows a conceptualized model of how sediment accumulation should vary over time and with regular maintenance of pipes. Since publishing their original article, the Kröger *et al.* (2013a) dataset has been extended further which shows a clear stabilization of accumulation rate over time (Figure 3) with an average time to reach maximum P accumulation at 396 days post-installation. A Wilcoxon-Mann-Whitney U-test confirmed a significant difference between rate of sediment accumulation between $T_{0\text{-}396}$ and $T_{396\text{-}794}$ ($U = 113$, $p = 0.019$), with rates of 0.67 and 0.44 mm/day, respectively. These data suggest maintenance may improve functionality of slotted inlet pipes.

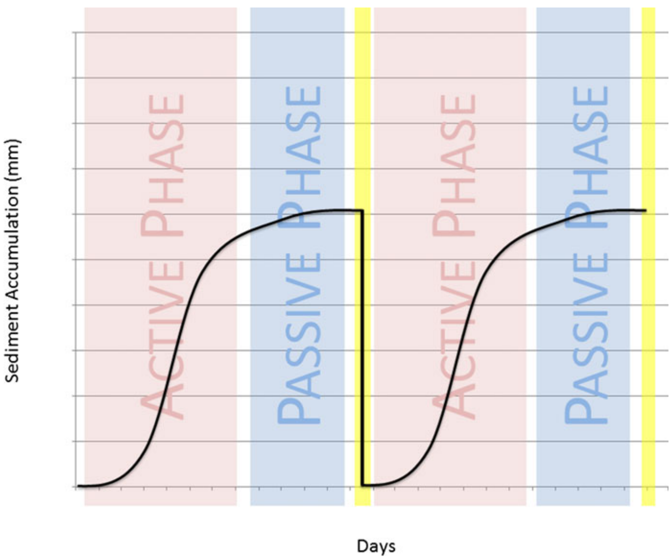

FIGURE 2. Conceptualized Model of Rate of Sediment Accumulation over Time. During the active phase, sediment accumulation increases exponentially until pipe capacity limits accumulation and the rate of accumulation stabilizes; at this point the passive phase beings. Kröger *et al.* (2013a) proposed a "cleaning out" phase (shown in yellow) which serves to reset the system and force a new active phase.

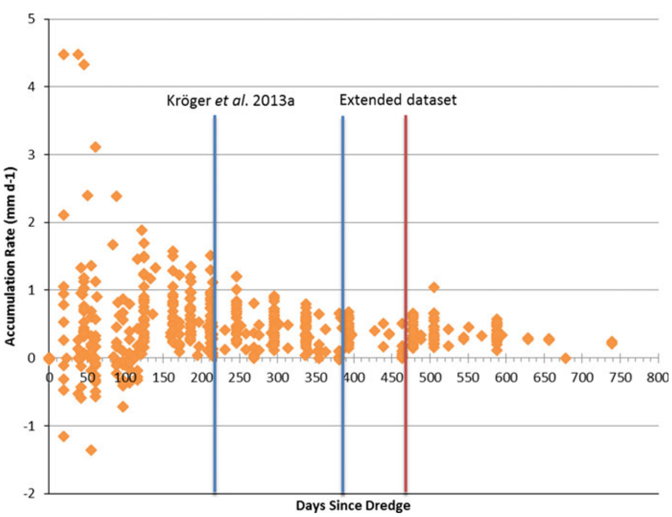

FIGURE 3. Rate over Sediment Accumulation over Time, Corrected for Dredging. Blue lines indicate the average time taken to reach maximum sediment accumulation in the original study and the extended dataset. The red line indicates the median time taken to reach maximum sediment accumulation in the extended dataset.

LOW-GRADE WEIRS

Another BMP being advocated is low-grade weirs (NRCS practice code 410 and 587, Figure 1), which are small impoundments placed within drainage ditches at strategic intervals, dependent on the slope and length of a ditch channel, to retain a certain volume of water (Kröger *et al.*, 2011). Weirs typically occupy between 5 and 20% of bankfull height and are adjusted based on drainage ditch slope. Weirs can be utilized across varying ecosystems under a multitude of conditions because they can be used with any agricultural commodity and do not require specially sourced materials. Often low-grade weirs are installed with additional modifications to the landscape which include increasing the drainage ditch size and altering the profile from incised v-channels to ditches with tailed slopes (2:1 or 3:1) with a wider U-shaped channel bottom. This drainage modification creates a raised berm on either side of the channel that allows channelization of runoff through grade stabilization structures (such as slotted inlet pipes) and provides enhanced drainage due to the larger volume capacity of the ditch. With a larger drainage ditch, low-grade weirs serve to retain variable volumes of water within the system that typically acts like an ephemeral conduit of drainage runoff.

Functionally, low-grade weirs retain drainage such that the ditch operates like linear wetland, providing improved hydrological and biogeochemical conditions for water quality improvement. Hydrologically, weirs slow runoff velocities and create multiple locations within a single drainage system for sediment to accumulate. Gilliam and Skaggs (1986) noted that controlled drainage had the potential to alter both hydrologic characteristics and nutrient efflux. Earlier field studies on low-grade weirs have noted frustrations with alternation of ditches from source to sink depending on rainfall patterns (Kröger *et al.*, 2008b) and seasonal effects (Littlejohn *et al.*, 2014), which complicated the clarity of research findings. However, it is reasonable to hypothesize that weirs should produce results similar to those of other controlled drainage methods because the mechanism is similar — to retain and hold water.

Weirs can be used to manage for retention of both N and P. Usborne *et al.* (2013) evaluated eight weirs for sediment and P accumulation one year post-installation and reported that one-year-old weirs had significantly greater sediment accumulation (54 cm *vs*. 13 cm, respectively) when compared to reference ditches. They also noted that weirs led to a reduction in the ephemeral nature of drainage ditch systems, which was considered beneficial for P retention. Kröger *et al.* (2014) found that weirs could push a system towards denitrification at fairly significant rates, with an overall mean net denitrification rate of 2,215 μg of N/m^2/h. In their study, no significant differences were seen between ditches with and without weirs, indicating that if conditions conducive for denitrification are present (e.g., unconsolidated sediments, continuous inundation), then the microbially mediated process can and will occur. Additional studies have demonstrated the potential of weirs to significantly reduce outflow concentrations and loads of N and P; Kröger *et al.* (2011) obtained significant decreases in nitrate (NO_3^-) concentration between inflow and outflow in a system with weirs, with reductions of 79% in a simulated, high-concentration runoff event. Littlejohn *et al.* (2014) reported median NO_3^- load reductions of 25%, with a 14% reduction in dissolved P in a field-scale evaluation of storm event runoff.

Weirs have also been found to significantly alter dynamic processes within the ditch in favorable ways. Usborne *et al.* (2013) reported an increase in hydroperiod due to weirs with significantly greater water depths in ditches with weirs (28 cm) than ditches without weirs (6 cm). Kröger *et al.* (2013b) also noted weirs provided an average water depth eight times greater than reference ditches. Littlejohn (2012) used replicated experiments with constructed drainage ditches under a regulated flow regime and found that weirs significantly increased hydraulic residence time from 48 to 249 min; increased residence time is associated with elevated biogeochemical processing. Kröger *et al.* (2008a) compared vegetated and nonvegetated ditches with weirs against vegetated and nonvegetated ditches without weirs and reported significantly longer time to peak (T_p) (i.e., the time elapsed from the beginning of a storm event until peak water height within the ditch) and time to base (T_b) (i.e., the time elapsed from the beginning of the storm event until water heights return to base-flow level within the ditch) in ditches with weirs when compared to ditches without weirs. All ditches in the study were approximately 33 m in length. For nonvegetated ditches, the average increase in time was over three hours. Insufficient samples were collected to directly compare average times for vegetated ditches, but minimum and maximum T_p and T_b were significantly higher for ditches with weirs.

These alterations to hydrology trap sediment and reduce loads via physical arrest and resultant biogeochemical processes, but a concern for producers has been that by slowing and trapping outflow water, the risks of backflow and flooding would increase. Prince Czarnecki *et al.* (2014) found that this risk was not present, and that weirs increased T_b by over 23 h without increasing peak heights in study ditches (ranging from 600 to 2,200 m in length), which means that the water does not rise higher or faster when weirs are present, though they do take longer to drain.

Finally, Kröger *et al.* (2013b) reported that weirs decreased the time for drainage ditches to reach their peak capacity for sediment retention with weirs in their study, on average collecting 102 m^3 of sediment annually. These rates suggest that just like slotted inlet pipes, maintenance of ditches outfitted with weirs is required to remove sediment build-up and optimize sediment capture. Kröger *et al.* (2014) also found that the denitrification potential of weirs decreased with age — again suggesting that maintenance may be necessary that can "reset" the system. Previous authors (Usborne *et al.*, 2013; Littlejohn *et al.*, 2014) have advocated for increased research on the long-term effects of weirs which can yield information about how an appropriate maintenance plan would prolong the effectiveness of these BMPs and keep them functioning optimally for longer time periods.

TWO-STAGE DITCHES

The two-stage ditch is a drainage management approach that is gaining popularity as a farming practice and conservation BMP because it provides a more sustainable method for drainage maintenance while potentially reducing nutrient and sediment export. Historically, streams and ditches have been maintained through routine channelization (i.e., dipping) to achieve and maintain a trapezoidal-shaped system (Figures 4A and 4B); this provides tile outlet depths with 2 ft, or more, of freeboard. Conventional trapezoidal ditches often require regular maintenance to restore and maintain drainage capacity when aggraded sediment impairs drainage function or where unstable ditch banks impact adjacent fields.

The two-stage ditch (Figures 4C and 4D) is a more sustainable and physically stable design that was developed based on observations of natural stream systems and ditches that function without ongoing human intervention. In low-gradient landscapes, natural streams typically have a main channel that conveys the most frequent low flows, but surface water spills out onto vegetated floodplains (i.e., the "2nd stage") during larger storm events, which slows water velocities, and reduces bank shear stress resulting in improved bank stability and fewer bank failures. The two-stage ditch approach mimics natural streams by providing space within the ditch bottom for a main channel, in addition to floodplain benches that provide stability and reduce the need for costly maintenance while simultaneously minimizing the ecological disturbance caused by routine ditch clean-outs.

Since the two-stage ditch design concept is relatively new, long-term datasets are lacking to assess the evolution of the post-construction channel form. However, in a study of seven two-stages in Indiana,

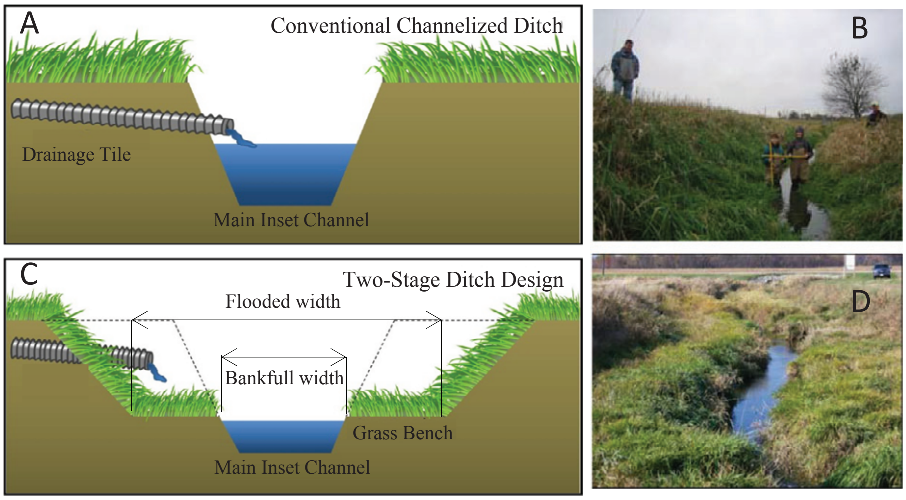

FIGURE 4. (A) Typical Cross Section of a Conventional Channelized Ditch and (B) Field Example of Shatto Ditch, Indiana in 2007. (C) Cross section of a two-stage ditch with floodplain benches that will inundate during storm flow or through forced inundation events when paired with instream controlled drainage with (D) field example of Shatto Ditch (Indiana) in 2008 after a 600-m two-stage implementation.

Michigan, and Ohio that ranged in age from three to eleven years, D'Ambrosio *et al.* (2015) found only minor, insignificant changes to channel form through time. Furthermore, key studies of naturally formed two-stage ditches suggest that the practice is sustainable over much longer time horizons. In a study of the Spoon River (Illinois), Landwehr and Rhoads (2003) found that by 1940, floodplain benches had formed naturally by fluvial processes within the ditch bottom that was originally constructed in 1925. They used a sequence of aerial photographs to confirm the presence of the stable, alternating floodplain bars for at least 60 years thereafter. Jayakaran and Ward (2007) studied 13 sites in Ohio which had established a two-stage geometry following their initial construction as trapezoidal ditches. While they could not ascertain how quickly the floodplain benches formed, drainage maintenance records suggest that no maintenance activities had been performed on the sites for 20-75 years.

In addition to the physical benefits provided by the two-stage ditch, the practice also provides water quality benefits. When surface water spills out onto vegetated floodplain benches during storms or seasonally elevated flows (e.g., spring runoff), these constructed floodplains provide increased bioreactive surface area and extended water residence times which promote improved nutrient and sediment removal. Several two-stage ditches in the MRB have been monitored for their sediment export and nutrient (both N and P) removal capacity. For example, monitoring of a 600-m two-stage demonstration project at Shatto Ditch (Indiana) (Figures 4B and 4D) showed that microbially mediated sediment denitrification in the two-stage reach increased N removal by as much as 350% compared to an upstream control reach (Roley *et al.*, 2012). In addition, in a study of multiple two-stage reaches in Indiana, Michigan, and Ohio, Davis *et al.* (2015) found that continuously monitored water-column turbidity was also significantly lower in reaches with two stages, suggesting that floodplains promote settling of particles, which may result in a net reduction in particle-associated total P. Furthermore, Davis *et al.* (2015) also found a significant decline in water column dissolved reactive P in the two-stage reaches compared to upstream trapezoidal reaches.

The two-stage ditch has potential to be economically beneficial to farmers, especially in the long term. In some cases, the reduction in maintenance costs for a two-stage ditch may more than offset the minimal loss of productive land due to the construction of a wider ditch. Kramer (2011) conducted an economic analysis of trapezoidal and two-stage channels that considered initial construction costs, maintenance frequency, maintenance costs, and the opportunity costs of land taken out of production and his results suggest that when interest rates are low and the maintenance frequency and costs for the trapezoidal ditch are high, the two-stage ditch is an economically preferable management approach for the farming operation. In terms of assessing the water quality and associated economic benefits to society, Roley *et al.* (2014, unpublished data) compared the N removal costs of several common BMPs, including cover crops, wetlands, and two-stage ditches over 10- and 50-year time horizons. In the 10-year time horizon, the two-stage ditch practice had the highest cost per unit N reduction due to high initial implementation costs relative to wetlands and cover crops. However, over the 50-year time horizon, the two-stage practice had N removal costs that were less than cover crops, but more than wetlands. In all cases, the cost of implementation for any of the conservation BMPs was less than the cost of N pollution to society.

STACKING BEST MANAGEMENT PRACTICES IN ORDER TO MAXIMIZE WATER QUALITY BENEFITS IN THE MISSISSIPPI RIVER BASIN

Ongoing research suggests that water quality improvements are possible in intensely managed agricultural landscapes, but it will require the implementation of a combination of innovative conservation BMPs to achieve significant improvements (Kröger *et al.*, 2012b). In practice, when implemented in isolation, individual BMPs alone may not have the capacity to make a significant improvement in water quality, especially if nutrient loads are excessively high. Controlled surface drainage approaches (i.e., slotted inlet pipes, low-grade weirs) and the two-stage ditch are independent options for water quality improvement of agricultural runoff, but they are not necessarily alternative or "competing" BMPs to be implemented at the exclusion of other practices. In fact, they are complementary and could be implemented simultaneously, in a "stacked" BMP configuration which could potentially maximize the strengths of each individual BMP.

Previous research (Prince Czarnecki *et al.*, 2014, unpublished data) has shown that combining two BMPs (low-grade weirs and buffer strips) yielded greater nutrient reductions than using a single BMP alone. A recent effort to improve water quality at Shatto Ditch is using a combined BMP approach by adding winter cover crops on at least 1,200 acres of cropland to the 600-m two-stage ditch in the Shatto watershed. Although Davis *et al.* (2015) had previously found no detectable decreases in NO_3^- concentrations in high-nutrient stream water from short reaches (<600 m) of two-stage ditch, the combination of cover crops and two-stage ditch in Shatto watershed is predicted to reduce NO_3^- inputs to a point where a two-stage ditch would be more effective at reducing NO_3^- loading to downstream ecosystems.

Mississippi River Basin practices can be implemented in tandem to produce nutrient reductions. Roley *et al.* (2012) examined how the natural variability in the duration and frequency of flooding in the Shatto two-stage ditch influenced sediment denitrification and suggested that coupling the two-stage ditch with controlled drainage would be beneficial in ensuring prolonged periods of floodplain inundation. For example, in a dry year when floodplains were inundated only 29 days of the year, only 12% of annual N removal was attributed to two-stage floodplains. In contrast, in a wetter year, the two-stage floodplains were inundated for 132 days, contributing to 47% of the annual N removal due to extended inundation and higher denitrification rates. In a stacked system, the two-stage ditch would reduce nutrients and sediments during floodplain inundation in periods of high flow (e.g., winter and spring), while low-grade weirs would enhance conditions for biogeochemically mediated reactions during periods of low-flow (e.g., summer). To date, there has only been one previous study of instream controlled drainage paired with an upstream two-stage ditch. Usborne (2012) evaluated a series of spatially distributed low-grade weirs along a reach of a two-stage ditch in the Harris Bayou (Mississippi) and found that increased water depth due to ponding behind weirs increased hydraulic residence time, reduced the frequency of wetting-drying cycles, and retained more total P without increasing the pool of bioavailable P.

The two-stage ditch increases the bioreactive surface area for nutrient and sediment retention, while instream controlled drainage controls the duration and frequency of floodplain inundation; in combination, the two practices combined could extend the efficacy of the two-stage ditch beyond isolated storm flows, expanding the potential benefits of improved water quality. We anticipate that the utility of this system could be expanded for water conservation and reuse purposes in regions that are vulnerable to water shortages during specific times of the year. Finally, the addition of the two practices minimizes the additional retirement of land from agricultural production compared to other more well-known conservation practices (Kröger *et al.*, 2012a).

CONCLUSIONS

As we progress into the 21st Century, conservation strategies will have to become increasingly more efficient within agricultural landscapes that are intensifying production. Conservation practices will have to utilize available landscape features, while at the same time enhancing hydrological and biogeochemical processing to improve water quality leaving these systems. Innovative BMPs associated with drainage management such as slotted inlet pipes, low-grade weirs, and two-stage ditches are all gaining popularity in agricultural landscapes; they are cost-effective, mimic processes in natural systems, and require minimal loss of land from production. Research reviewed and highlighted in this article demonstrates the capacity of each of these practices individually to reduce nutrients in drained agricultural systems. However, as we learn more about individual practices, we begin to understand how each can be integrated such that you have multiple BMPs stacked within the agricultural landscape (e.g., slotted pipe draining into a two-stage ditch, with low-grade weirs) that would lead to enhanced water quality. Stacking of practices begs further research to understanding the true impact of the practices, with research questions focusing around additive, multiplicative, or cumulative functions.

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