Published November 21, 2019

Agricultural & Environmental Letters

Commentary

Multipurpose Oxbows as a Nitrate Export Reduction Practice in the Agricultural Midwest

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Core Ideas

- Oxbows reduce nitrate export from agricultural fields to adjacent rivers and streams.
- Oxbows are important habitat for wildlife, including the endangered Topeka shiner.
- Oxbows have largely disappeared from midwestern landscapes modified for agriculture.
- Restoring multipurpose oxbows provides multiple benefits in the agricultural Midwest.

Abstract: Nutrient export from the agricultural US Midwest influences streams and rivers and contributes to the development of hypoxia in the Gulf of Mexico. Oxbows are natural waterbodies formed when a river cuts off a meander loop as it migrates within its floodplain. Creation of *multipurpose oxbows* by restoration of former oxbows can potentially reduce export of nitrate-nitrogen (nitrate) from agricultural land as well as provide important habitat for many species, including the endangered Topeka shiner. Recent studies of nitrate export reduction by oxbows in Iowa are encouraging, demonstrating a 45% reduction in nitrate export of water entering oxbows from subsurface tiles compared with water discharged to the adjacent stream. Oxbow restorations are as effective as several other nutrient reduction practices, are relatively inexpensive, last for decades if not centuries, remove little or no land from agricultural production, and provide significant ecosystem services. Multipurpose oxbows are a promising new best management practice for reducing nitrate export from agricultural lands.

Nutrient export from the agricultural US Midwest influences streams and rivers and contributes to the development of hypoxia in the Gulf of Mexico (Turner et al., 2008). Gulf hypoxia is caused by nitrate exported from row crop agricultural fields via the Mississippi River. One path for nitrate export is leaching from soil and transport to streams through groundwater discharge and subsurface tile drainage systems. Watersheds with tile systems are highly susceptible to increased nitrate losses to streams and rivers, and conservation practices are needed mitigate these losses (Jaynes et al., 2001; Schilling et al., 2012; Tomer et al., 2013).

Oxbows are natural waterbodies formed when a river cuts off a meander loop as it migrates within its floodplain (Wohlman and Leopold, 1957). While natural oxbows are among the most biologically diverse aquatic systems in the world (Ward, 1998), in agricultural regions, practices such as stream channelization and removal of riparian vegetation, along with increased drainage from tiles and ditches, profoundly changed natural stream hydrology (e.g., Schumm et al., 1984). Oxbows in agricultural areas tend to be isolated from the main channel and rapidly accumulate sediment and organic material from overbank flooding, as they transition to terrestrial habitat (Constantine et al., 2010). Oxbow restoration reverses this process by removing the fill material and restoring hydrologic connection and aquatic habitat (Kenney, 2018).

Wetlands are effective in reducing downstream export of nutrients such as nitrate from agricultural lands (Crumpton et al., 2008). Due to their proximity to streams, oxbows, whether naturally occurring or restored, are a type of wetland that is ideally suited to process nitrate-rich water exiting agricultural fields via natural pathways or artificial tile systems. Thus, restoration of former oxbows (Zambory et al., 2019), particularly where they can intercept

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Agric. Environ. Lett. 4:190035 (2019)
doi:10.2134/ael2019.09.0035

Received 20 Sept. 2019.
Accepted 31 Oct. 2019.
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Abbreviations: BMP, best management practice; SGCN, Species of Greatest Conservation Need.

tile drainage, has great potential as a nitrate export reduction practice in the agricultural Midwest.

Oxbows are key components of floodplain habitat diversity (Ward, 1998; Amoros and Bornette, 2002; Tockner and Stanford, 2002) and are important habitats for many species in the agricultural Midwest, including several fish Species of Greatest Conservation Need (SGCN; Iowa Department of Natural Resources, 2015) such as the federally endangered Topeka shiner (*Notropis topeka*) (Bakevich et al., 2013; Simpson et al., 2019). To date, oxbow restoration in midwestern agricultural areas has primarily focused on creating habitat for the Topeka shiner. The US Fish and Wildlife Service and The Nature Conservancy have completed over 100 such restorations in Iowa (Kenney, 2018), and a similar restoration program is underway in Minnesota (Utrup, 2015). Most of the Iowa restorations have been located in the North Raccoon River and Boone River watersheds where remnant Topeka shiner populations occur (Fig. 1).

Nitrate Export Reduction

Several studies have shown that oxbows can be effective at reducing nitrate export if runoff or tile drainage is diverted to and through these systems. García-García et al. (2009) reported that the mean nitrate retention efficiency was 72.3% for two oxbows in Spain. Fink and Mitsch (2007) measured annual nitrate retention to be 48 ± 3% in a constructed oxbow in Ohio receiving streamflow diversions. Harrison et al. (2014) reported the percentage retention of nitrate loads delivered to two oxbows in Maryland during storm events ranged from 23 to 87%. Nitrate removal rates ranging from 53 to 98% were estimated for a floodplain diversion wetland in Illinois (Kadlec, 2010).

Recent studies of nitrate export reduction by oxbows in Iowa are encouraging. In a 2-yr study of a restored oxbow in north-central Iowa that was constructed for habitat and was configured to receive flow and nutrients from subsurface field tiles, nitrate concentrations and loads into the oxbow were dominated by tile drainage inputs compared with groundwater seepage (Schilling et al., 2017). Nitrate concentrations were highest in tile drainage water (9–17 mg L^{-1}) and lowest in downgradient groundwater (0.2 mg L^{-1}), and results indicated that the restored oxbow reduced the influx of nitrate by an average of approximately 45% for the 2-yr study. A second study conducted at the same central Iowa site, but using a continuously reading nitrate sensor, developed a budget for the oxbow to estimate annual and monthly load reductions (Schilling et al., 2018b). Based on a daily mass balance, the oxbow retained 42.3 kg of nitrate, or 0.21 g N m^{-2} d^{-1}, and the retention efficiency was 35.4%. Removal efficiencies in late summer and fall were much higher than late spring and early summer.

Another 2-yr study compared nitrate retention in a restored oxbow to an unrestored oxbow in north-central Iowa. The restored oxbow reduced nitrate mass approximately 54% compared with the incoming flows from a field tile. In the unrestored oxbow, flow from a field tile quickly flowed through a channel in the sediment-filled oxbow and little nitrate reduction was observed (Kalkhoff et al., 2016).

In an eastern Iowa restoration where the oxbow was configured to receive inputs from groundwater seepage and overbank flooding (Schilling et al., 2018a), nitrate loading

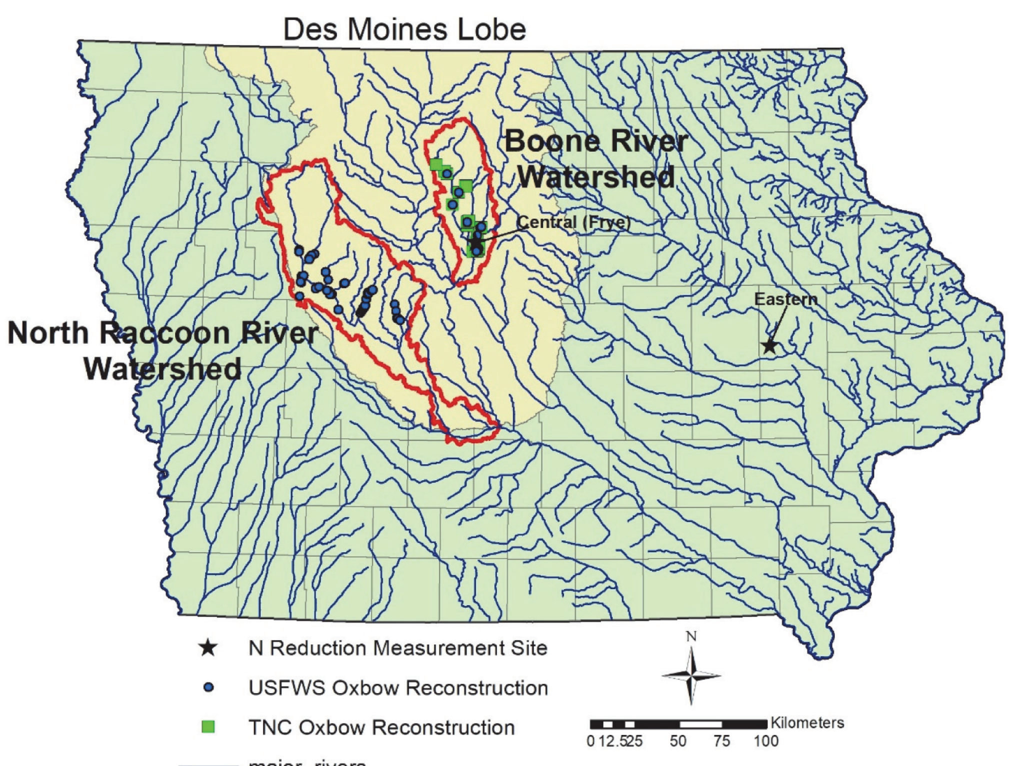

Fig. 1. Location of restored oxbows in Iowa. TNC, The Nature Conservancy; USFWS, US Fish and Wildlife Service.

into the oxbow was dominated by flood pulses. Following a spring flood event, an in situ sensor measured nitrate concentrations decreasing in the oxbow from 5.4 to 0.7 mg L^{-1} over a 21-d period. Retention efficiency was estimated to be 0.30 g N m^{-2} d^{-1}, or a 74.2% reduction efficiency of the nitrate delivered into the oxbow from the event.

Overall, research on newly restored oxbows suggests that these systems are capable of reducing nitrate concentrations and loads delivered via tile drainage, groundwater seepage, and overbank flooding. However, restored oxbows configured to receive inputs from tile drainage receive considerably more nitrate than oxbows fed only by groundwater discharge or from an occasional flood pulse. Nitrate input to an oxbow fed by tile drainage ranged from 100 to 450 kg yr^{-1} (Schilling et al., 2017, 2018b), whereas an oxbow constructed to receive inputs from groundwater and flooding only intercepted 15 kg of nitrate during a flood pulse (Schilling et al., 2018a). Thus, oxbows fed by tile drainage provide a greater opportunity to reduce the nitrate load from agriculture to downstream river systems.

Habitat and Conservation Benefits

In the agricultural Midwest, oxbows are important habitats for endangered Topeka shiners and other fish SGCN (Bakevich et al., 2013; Simpson et al., 2019), as well as waterfowl (LaGrange and Dinsmore, 1989). A recent study of 98 oxbows and 111 nearby streams in the current Topeka shiner range in Iowa and Minnesota reported 49 fish species in oxbows and 58 fish species in streams (Simpson, 2018). Eight fish SGCN were found in oxbows. Topeka shiners were found in 40% of the oxbows but in only 36% of the streams. Five species were found in oxbows but were not found in streams. Of the 64 restored and 34 unrestored oxbows sampled, restored oxbows harbored populations of Topeka shiners more frequently than unrestored oxbows, and populations in the restored oxbows tended to be more abundant (Simpson et al., 2019). Coincident with the period of accelerating oxbow restoration, the distributional status of Topeka shiners in Iowa has recently reversed a previously declining trend, suggesting that oxbow restoration is contributing to the species' improving status (Pierce et al., 2019).

Multipurpose Oxbows as a Nitrate Export Reduction and Conservation Practice

We propose the term *multipurpose oxbow* to describe oxbows restored for both nitrate export reduction and creation of habitat for conservation. Multipurpose oxbows have the potential to simultaneously provide two important, yet distinct, ecological services, with benefits ranging from lessening hypoxia in the Gulf of Mexico to conservation of an endangered species. Restored oxbows provide effective nitrate export reduction from tile drainage before tile water is discharged to streams and also provide important habitat for SGCN, including the endangered Topeka shiner. Because of these dual benefits, restored oxbows are now considered a new best management practice (BMP) in agricultural regions. As an example of this new acceptance, oxbow restorations that intercept tile drainage before entry to streams are now recognized as an official nutrient reduction practice by the Iowa Nutrient Research Center (INRC, 2019).

It is important to note that the efficacy of multipurpose oxbows as a nutrient removal practice is restricted to those restorations where the oxbow receives tile water drainage. Although oxbow restorations that do not receive tile drainage are still effective processors of nitrate entering oxbows by other pathways (Schilling et al., 2018a), they do not receive enough nitrate mass to provide significant nutrient reduction benefits at a local or regional scale.

We acknowledge that the dual function of multipurpose oxbows may prevent them from achieving maximum nitrate reduction benefits. For maximum nitrate reduction, oxbows would need to be built similar to constructed wetlands that receive water from tile drainage (Crumpton et al., 2008; Drake et al., 2018). These constructed wetlands are often dominated by emergent wetland vegetation and have long water residence times and are often located higher in drainage networks than where oxbows naturally occur. "Oxbows" restored in such a way would likely go dry frequently, with resulting mortality of all fish present. In a recent study by Fischer et al. (2018) of 12 oxbows continuously monitored for 6 mo, two oxbows never contained fish and were among three oxbows that were dry for long periods. It is possible that oxbows designed and placed solely for maximum nitrate reduction could become a trap for endangered Topeka shiners and other species when they go dry. Thus, multipurpose oxbows represent a balance between nitrate export reduction and conservation benefits.

Design Features, Life Expectancy, Performance, and Cost

Under our definition, multipurpose oxbows include routing tile water into the oxbow. Oxbows recommended for restoration have nearly completely filled in with sediment and no longer have the storage capacity to retain tile water. Zambory et al. (2019) developed a GIS procedure to locate potential oxbow restoration sites and found several hundred potential sites in the Boone River watershed alone. Restoration deepens the oxbow down to the current adjacent streambed elevation to ensure connection to groundwater, allowing the oxbow to hold ample water to sustain fish populations year-round. Although current oxbow restoration designs are based on the historic footprint of the stream channel and not the number of drained acres discharging into it, to be multipurpose we suggest that oxbows be designed to fall within the CREP wetland sizing of 0.5 to 2% of the drainage area. Oxbows needing to be sized larger than 0.2 ha (0.5 acres) to meet the 0.5 to 2% sizing recommendation could be broken into multiple cells so no cell exceeds 0.2 ha (0.5 acres). Oxbow banks sloped 3:1 or gentler are preferred to prevent siltation of the oxbow after restoration. A narrow connection to the adjacent stream on the downstream end to allow connection with the stream during typical 1.5- to 2-yr flood events is suggested. Avoiding potential restoration sites near outer cutbank curves in the adjacent stream where natural meander of the stream will eventually encroach into the oxbow is recommended. We also suggest avoiding areas where flow from the adjacent stream could be directed into the upstream end of the oxbow and potentially fill it with sediment. Kenney (2018) stated that the best oxbows for conservation are <0.2 ha (<1/2 acre) in size, have a depth approximately equal to the depth of the adjacent stream channel, and have <50% tree canopy cover.

Kenney (2018) reported that in follow-up monitoring of previously restored sites, an average of approximately 7.6 cm (3 inches) of silt settled in the oxbows after 17 yr. This equates to a sedimentation rate of approximately 0.44 cm yr^{-1}. With the average depth of approximately 2 m, life expectancy would be approximately 400 yr. We emphasize that this is an estimate only as the oxbow depths, sedimentation rates, and flooding frequency will vary among sites, but there is no doubt that current oxbow restorations will last many decades, if not centuries. Furthermore, it is reasonable to expect nitrate reduction rates to improve as organic sediments are slowly redeposited over time.

Multipurpose oxbows can process tile drainage delivered from a typical agricultural field of 8 to 32 ha (20–80 acres), which is similar to areas treated by a bioreactor or saturated buffer. The nitrate retention of the central Iowa oxbow (42 ± 6%) (Schilling et al., 2017, 2018b) is comparable to other BMPs designed for reducing nitrate in tile drainage water. Estimated nitrate reductions for other tile drainage BMPs include bioreactors (43 ± 21%), drainage water management (33 ± 32%), wetlands (52%), and saturated buffers (50 ± 13%) (INRS, 2017). Compared with bioreactors that are installed belowground to treat tile drainage water, achieving similar nitrate retention efficiency with oxbows offers several advantages, including important habitat. Jones et al. (2015) reported that landowners were especially intrigued by the practice because water quality and wildlife responses are measurable and potential sites are typically found on marginal land unsuited for crop production. Because the oxbows are multipurpose, there is also potential for receiving financial support from multiple funding groups.

At the north-central Iowa site, restoration cost was approximately $8,000 for excavation and removal of approximately 920 m^3 of sediment to construct a 0.1-ha (1/4-acre) oxbow (Schilling et al., 2017). At the eastern Iowa site, excavation cost was about $28,000 for removal of approximately 2500 m^3 of floodplain alluvium (Schilling et al., 2018b). The difference in cost was mainly due to transportation of excavated material out of the floodplain. In the north-central Iowa case, the excavated material was spread on an adjacent field located outside the floodplain, whereas in the case of the eastern Iowa site located in a county park, the material was transported to a remote location at substantially greater cost. In comparison, woodchip bioreactors cost approximately $10,000 to build and then treat high-nitrate tile water from about 10 to 40 ha (Jones and Kult, 2016), and construction costs of large nutrient removal wetlands can exceed $400,000 to treat nitrate loads from up to 500 ha (Christianson et al., 2013). Multipurpose oxbows have a similar restoration cost and treat a similar area as bioreactors, and as it is an edge-of-field practice, no impacts on crop yields are anticipated. In addition, multipurpose oxbow restorations would require little to no maintenance, in contrast with other edge-of-field practices.

Conclusions

Multipurpose oxbows restored for the dual benefits of creating habitat for SGCN and reducing nitrate loads from tile drainage provide ecosystem services to floodplains and offer opportunities to achieve environmental benefits in agricultural watersheds. The practice represents a new approach that may be added to the portfolio of BMPs working toward reducing nitrate export from agricultural regions to downstream rivers and ultimately the Gulf of Mexico.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

This project was supported in part by the Natural Resources Conservation Service, US Department of Agriculture (Award No. 69-6114-14-008), the Sand County Foundation, and the Iowa Nutrient Research Center (Award No. C6-72746-68). We thank Steve Kalkhoff for comments that improved the manuscript. We are grateful to many landowners and conservation groups for their continued support for oxbow restorations. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the US Fish and Wildlife Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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