QUANTIFYING ECOSYSTEM SERVICES DERIVED FROM WETLAND CONSERVATION PRACTICES IN THE GLACIATED INTERIOR PLAINS: THE PROVISION OF WATER QUALITY (AND CARBON SEQUESTRATION) BENEFITS

FINAL REPORT to the U.S. Department of Agriculture Natural Resources Conservation Service, CEAP – Wetlands

Prepared by: Christopher Craft[1] (ccraft@indiana.edu), Siobhan Fennessy[2] and John Marton[1]

[1]School of Public and Environmental Affairs, Indiana University, Bloomington IN 47405
[2]Kenyon College, Gambier OH 43022

March 31, 2012

ACKNOWLEDGEMENTS. We thank CEAP - Wetland Science Coordinators, Dianne Eckles and William Effland, for supporting this study. We gratefully acknowledge the support of Chip O'Leary, Stephanie Frischie and the staff of The Nature Conservancy's Kankakee Sands Preserve (IN), the staffs of the Indiana Department of Natural Resources, LaSalle Fish and Wildlife Management Area and Willow Slough Fish and Wildlife Management Area, the Hamilton County (IN) Parks and Recreation Department Strawtown Koteewi Park for giving us access to sampling sites. We also thank Ellen Herbert, Anya Hopple, Bri Richards, Jacob Bannister, Nate Knowles, Laura Trice and Yanlong He for help with the collection, preparation and analysis of samples in Indiana and Claire Anderson, Cari Ficken, Jenny Howard, Pam Moriarity and Meg Murphy for help with sample collection and analysis in Ohio. In addition, many Ohio landowners were gracious enough to allow us to work on their farms for the better part of two years, and for that were are grateful.

TABLES Page

FIGURES

APPENDICES Page

MANUSCRIPTS

Hopple, A. and C. Craft. 2012. Managed disturbance enhances biodiversity of restored wetlands in the agricultural Midwest. *Ecological Engineering*. In press.

Marton, J.M., S.M. Fennessy and C.B. Craft. Water quality improvement potential and carbon sequestration of WRP and CRP wetland and riparian buffers in the Glaciated Interior Plains, Midwestern USA. *Ecological Applications*. In review.

Marton, J.M. S.M. Fennessy and C.B. Craft. Nutrient removal and carbon storage vary among USDA conservation practices: an example from Ohio. *Journal of Environmental Quality*. (In prep).

SUMMARY

We measured water quality improvement potential (denitrification, phosphorus (P) sorption) and carbon (C) sequestration in WRP-restored wetlands and CRP-restored riparian buffers and in natural wetlands and riparian areas of the Glaciated Interior Plains (GIP) of Indiana and Ohio. In Indiana, we sampled 10 WRP-restored wetlands and 10 natural wetlands and four CRP-restored riparian buffers and four natural riparian areas. In Ohio, we sampled six restored wetlands, five restored riparian buffers and five conserved (natural) riparian buffers.

Restored, conserved and natural riparian buffers exhibited greater ambient and potential denitrification than restored and natural depressional wetlands. Phosphorus sorption generally was greater in riparian buffers though natural wetlands high in soil organic matter sorbed the most P. Surprisingly riparian soils sequestered more C and stored more N and P than wetland soils.

From our findings, we produced a decision tree based on hydrologic connectivity, parent material and disturbance regime, to aid in the selection and placement of WRP/CRP restored and conserved (natural) riparian buffers and WRP restored wetlands on the landscape. Establishment of restored and conserved riparian buffers will provide the greatest levels of water quality improvement potential and C sequestration. Restored depressional wetlands on fine-textured soils provide intermediate levels of these services. Restored depressional wetlands on sandy soils and where disturbance (i.e. prescribed fire) is used to optimize other ecosystem services (biodiversity) provide the lowest levels of water quality improvement potential and C sequestration. For water quality improvement and C sequestration, future WRP and CRP efforts should focus on establishing riparian buffers. Establishment of restored wetlands provides these services at a lower level but affords other important services (e.g. biodiversity, habitat) that should not be overlooked when choosing sites for restoration and conservation.

INTRODUCTION

Wetlands are transitional ecosystems situated between upland and aquatic systems that provide a range of ecosystem services including carbon (C) sequestration, nutrient (nitrogen [N] and phosphorus [P]) retention and removal, biodiversity support, and water storage (Mitsch et al. 2001; Zedler 2003; Fennessy and Craft 2011). During the past 200 years, the Glaciated Interior Plains (GIP), also known as the Corn Belt, has experienced wetland losses of between 50 and 90% as a result of conversion to row-crop agriculture (Dahl 2000). Drainage of wetlands in the region has led to the expansion of highly productive agricultural land, but a loss in the delivery of ecosystem services, particularly water quality improvement functions (Zedler 2003; Fennessy and Craft 2011).

To offset these losses, the United States Department of Agriculture instituted programs such as the Wetland Reserve Program (WRP) and Conservation Reserve Program (CRP) to reintroduce ecosystem services to agricultural landscapes. These programs have assisted landowners in restoring and conserving over 2 million hectares through wetland and riparian restoration, creation, and enhancement (Fennessy and Craft 2011). In Indiana, there have been over 5700 ha of wetlands and 580 ha of riparian areas restored between 2001 and 2006. In Ohio 1160 and 428 ha of wetlands and riparian areas were restored under the WRP and CRP programs, respectively, during the same period. However, there has been little research on quantifying the effectiveness of these programs in reintroducing ecosystem services, particularly water quality improvement functions, in the GIP (Fennessy and Craft 2011). Furthermore, it is unclear if one practice provides greater levels of water quality improvement potential and C sequestration than other practices (i.e., wetland vs. riparian).

To address this knowledge gap, we compared ecosystem services associated with water quality improvement potential (denitrification, P sorption), C sequestration and nutrient (N, P) storage in soil between WRP-restored wetlands, natural wetlands, CRP-restored riparian buffers and natural riparian buffers in Indiana. We also evaluated three conservation practices in Ohio to determine which conservation practice (e.g., restored wetland, restored riparian, conserved riparian) provided the greatest water quality improvement functions, C sequestration and N & P storage. From this information, we developed a decision tree, based on hydrologic connectivity, parent material and disturbance regime, to aid in the selection and placement of WRP- and CRP-restored wetlands and CRP-riparian buffers on the landscape.

METHODS

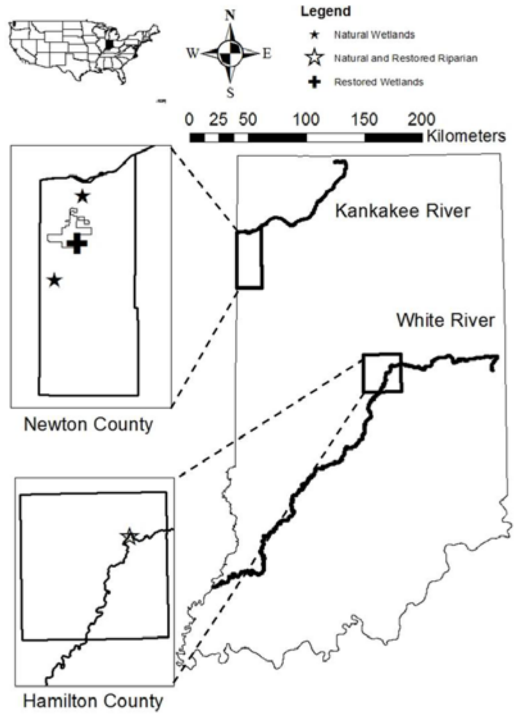
Site Description

We sampled 10 restored and 10 natural wetlands in northern Indiana, and 4 natural and 4 restored riparian buffers in central Indiana (Figure 1). We also sampled 5 agricultural fields adjacent to the restored wetlands and 2 agricultural fields adjacent to the restored riparian sites to characterize change in ecosystem services following restoration. Restored wetlands were located at Kankakee Sands Preserve, owned by The Nature Conservancy, and were restored under the Wetlands Reserve Program by filling in drainage ditches between 2000 and 2005 (C. O'Leary, personal communication). The WRP-restored wetlands are depressional, precipitation-fed systems and are surrounded by restored mesic prairie and row crop agriculture on a rotation of three years of corn and one year of soybean. Natural wetlands were located at the Willow Slough WS) Fish and Wildlife Area and the LaSalle Fish and Wildlife Area owned and managed by the Indiana Department of Natural Resources. The five natural wetlands at WS were depressional wetlands whereas, at LaSalle Fish and Wildlife Area, the five wetlands were floodplain forests.

The natural and restored riparian buffers were located in the Strawtown Koteewi Park in Hamilton County, Indiana along the west fork of the White River. The CRP-restored riparian buffers were restored in 2006 by ceasing row crop agriculture and planting trees. The land adjacent to the restored riparian buffers is cultivated for corn during the growing season and left to fallow during winter. Natural riparian areas are located adjacent to the restored sites. Vegetation and soils of the restored/natural wetlands and riparian buffers are presented in table 1.

We also sampled six restored depressional wetlands, six restored riparian buffers, and six conserved riparian buffers in central Ohio (Figure 2). Wetlands and riparian buffers were restored under the WRP and CRP programs between 2000 and 2007. Conserved riparian buffers were natural systems and had not been previously farmed but were set aside as part of this conservation practice. Restored riparian buffers consisted of grass cover and also were planted with various *Quercus*, *Acer*, and *Populus* species. Vegetation and soils of the Ohio restored wetlands and restored/conserved riparian areas are presented in table 2. Four agricultural fields also were sampled adjacent to the conservation projects.

a.



b.

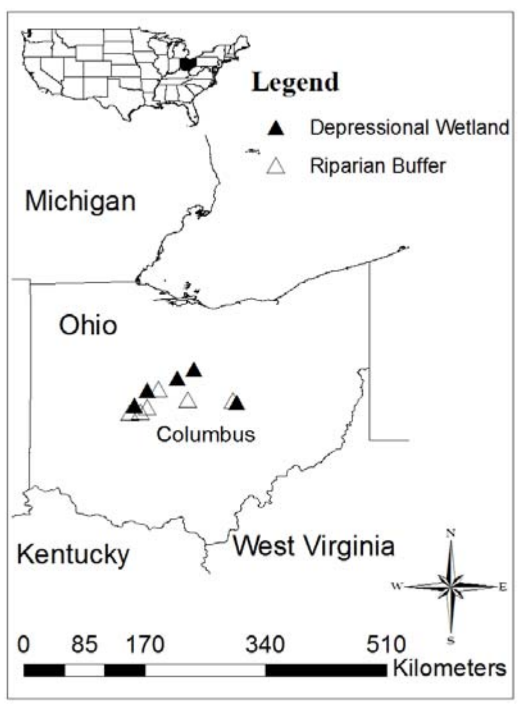


Figure 1. Location of study sites in (a) Indiana and (b) Ohio.

Table 1. Site characteristics (vegetation, soils) of WRP-restored wetlands, natural wetlands, CRP-restored riparian buffers and natural riparian buffers of Indiana.

	Vegetation	Soils
Wetland:		
Restored depressional	*Schoenoplectus pungens* (Vahl) Palla *Polygonum pennsylvanicum* L. *Eleocharis erythropoda* Steud., *Juncus brachycephalus* (Engelm.) Buchenau *Scirpus cyperinus* (L.) Kunth *Leersia oryzoides* (L.) Sw. *Phalaris arundinacea* L.	Mesic Typic Endoaquolls
Natural depressional	*Calamagrostis canadensis* (Michx.) P. Beauv. *Thelypteris palustris* Schott *Boehmeria cylindrica* (L.) Sw. *Polygonum* sp. *Scirpus cyperinus* (L.) Kunth	Terric Haplosaprists, Typic Humaquepts,
Natural floodplains	*Quercus palustris* Münchh, *Populus deltoides* Marshall *Fraxinus pennsylvanica* Marshall *Betula nigra* L. *Acer rubrum* L. *A. saccharinum* L.	Fluvaquentic Endoaquolls
Riparian:		
Restored	*Betula nigra* L. *Taxodium distichum* (L.) Rich.	Fluventic Eutrudepts
Natural	*Populus deltoides* Marshall *Fraxinus pennsylvanica* Marshall *Acer saccharinum* L. *Platanus occidentalis L.* *Celtis occidentalis L.*	Fluventic Eutrudepts

Soil Sampling and Analysis

In Indiana, replicate soil cores (n=4 per wetland), 8.5 cm diameter by 5 cm deep, were collected twice (2010, 2011) for measurement of denitrification. Ambient and potential denitrification was measured as described by Marton et al. (in review). Additional soil cores (n=4 per wetland, 0-15 cm) were collected in 2009 from each site for measurements of soil properties and C sequestration. Soils also were collected from five agricultural fields adjacent to the restored wetlands and from two fields adjacent to the restored riparian areas. Soils (0-5, 5-15 cm) were analyzed for pH, plant-available N (NO_3-N, NH_4-N) and P (PO_4-P), phosphorus sorption index (PSI), and soil moisture content. Dried soils were analyzed for total organic C, inorganic C, total N and total P. A detailed description of soil sampling handling, preparation and analysis are presented in Marton et al. (in review).

In Ohio, five soils cores (10 cm x 10 cm) were collected from each site in 2009 and 2010 for denitrification assays. Samples collected during the 2009 field season were taken to a depth of 10 cm and, in 2010, soils were collected in two increments (0-5 cm, 5-15 cm). Five additional

Table 2. Site characteristics (vegetation, soils) of WRP-restored wetlands, CRP-restored riparian buffers and CRP-conserved riparian buffers of Ohio.

	Vegetation	Soils
Restored depressional wetland	*Typha angustifolia* L. *Carex* sp. *Juncus effusus* L. *Phalaris arundinacea* L. *Potamogeton* sp.	Typic Argiaquolls, Typic Dystrudepts
Restored riparian	*Quercus spp*, *Acer sacchar*um Marsh. *Populus deltoides* Marshall	Oxyaqic & Aquultic Hapludalfs, Aeric Epiaqualfs, Fluvaquentic Endoaquolls
Conserved riparian	*Acer saccharinum* L. *Acer saccharum* Marsh. *Platanus occidentalis* L. *Aesculus* sp. *Fraxinus pennsylvanica* Marshall	Oxyaqic & Aquultic Hapludalfs, Aeric Epiaqualfs, Fluvaquentic Endoaquolls

cores soil cores (10 cm diameter by 15 cm deep) were collected from each site using a butyrate tube in 2009 for determination of bulk density, organic C, total N, total P, and P sorption. Samples also were collected from four agricultural fields adjacent to the sites. Samples (n=2 per site) were collected from fields adjacent to two of the restored wetlands and two of the restored riparian areas. Denitrification measurements were made on soils (0-10 cm) collected in 2009 and on surface (0-5 cm) soils collected in 2010, including the agricultural field soils. A detailed description of the methodologies is presented in Marton et al. (in review).

RESULTS

Comparison of Natural and Restored Wetlands and Riparian Areas (Indiana)

Water quality improvement potential of natural wetlands was greater than in restored wetlands. Denitrification and phosphorus sorption (PSI) were greater in natural wetlands than in restored wetlands and agricultural fields (denitrification not measured) (Figures 2 and 3). There was no difference in PSI between agricultural fields and the 10 to 12 year old restored wetlands. In contrast to wetlands where PSI was greatest in natural soils, agricultural soils (5-15 cm depth) had greater PSI than restored and natural riparian soils (Figure 3). There was no difference in ambient and potential denitrification between natural and restored riparian soils (Figure 2). In both riparian buffers and wetlands, potential denitrification was three to five times greater than ambient denitrification.

Natural wetland soils contained higher percent organic C, total N and total P, and lower bulk density and pH than restored wetland and agricultural soils (Appendix 1 and 2). Natural wetland soils (0-5 cm) also had higher concentrations of plant-available NH_4-N and NO_3-N and lower concentrations of PO_4-P than restored wetland and agricultural soils (Appendix 2). The 10

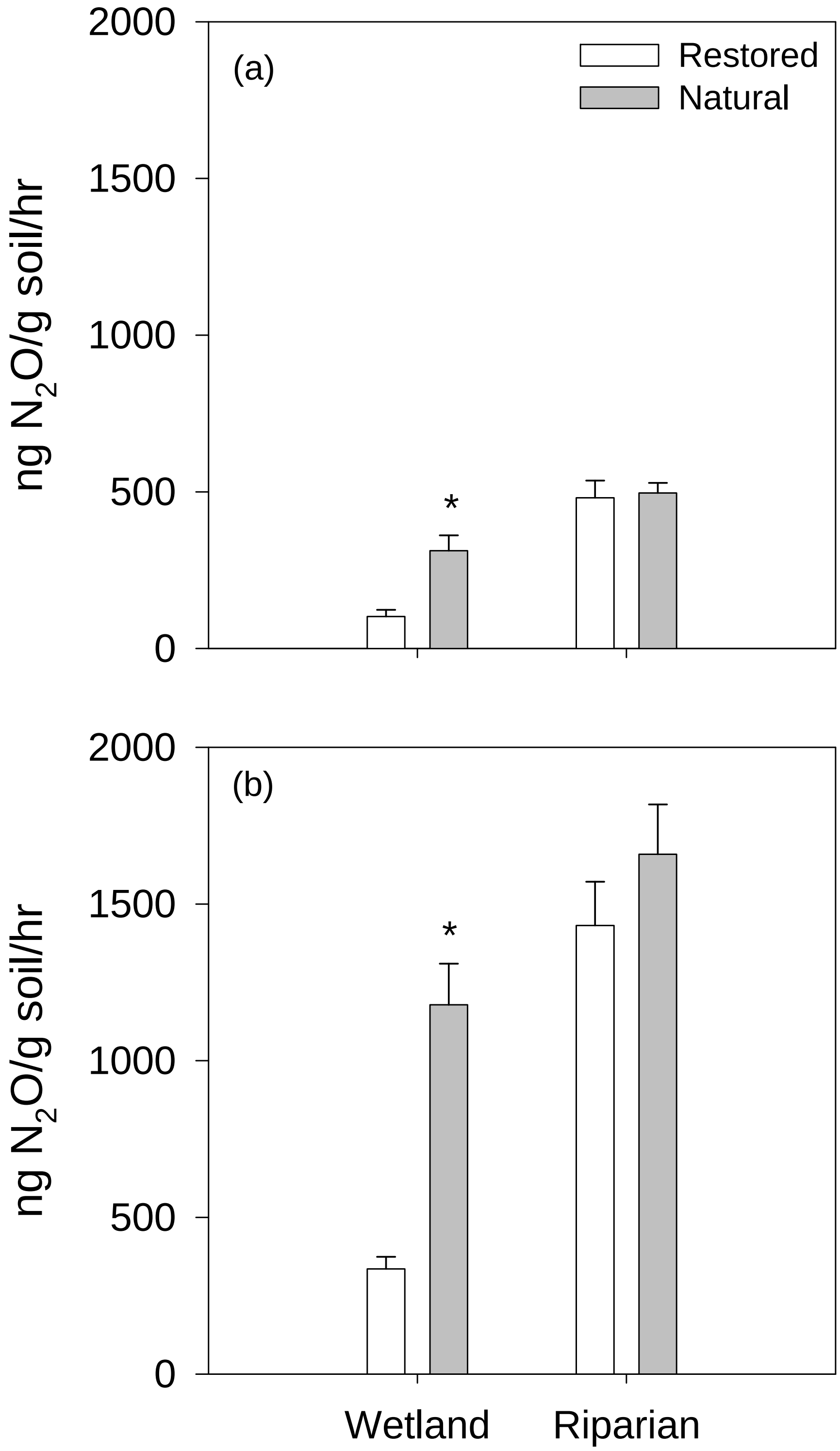


Figure 2. (a) Ambient and (b) potential denitrification in restored and natural wetlands and restored and natural riparian buffers of Indiana. Asterisks denote a significant difference in denitrification between the restored and natural wetlands according to Tukey's multiple comparison test ($p \leq 0.05$).

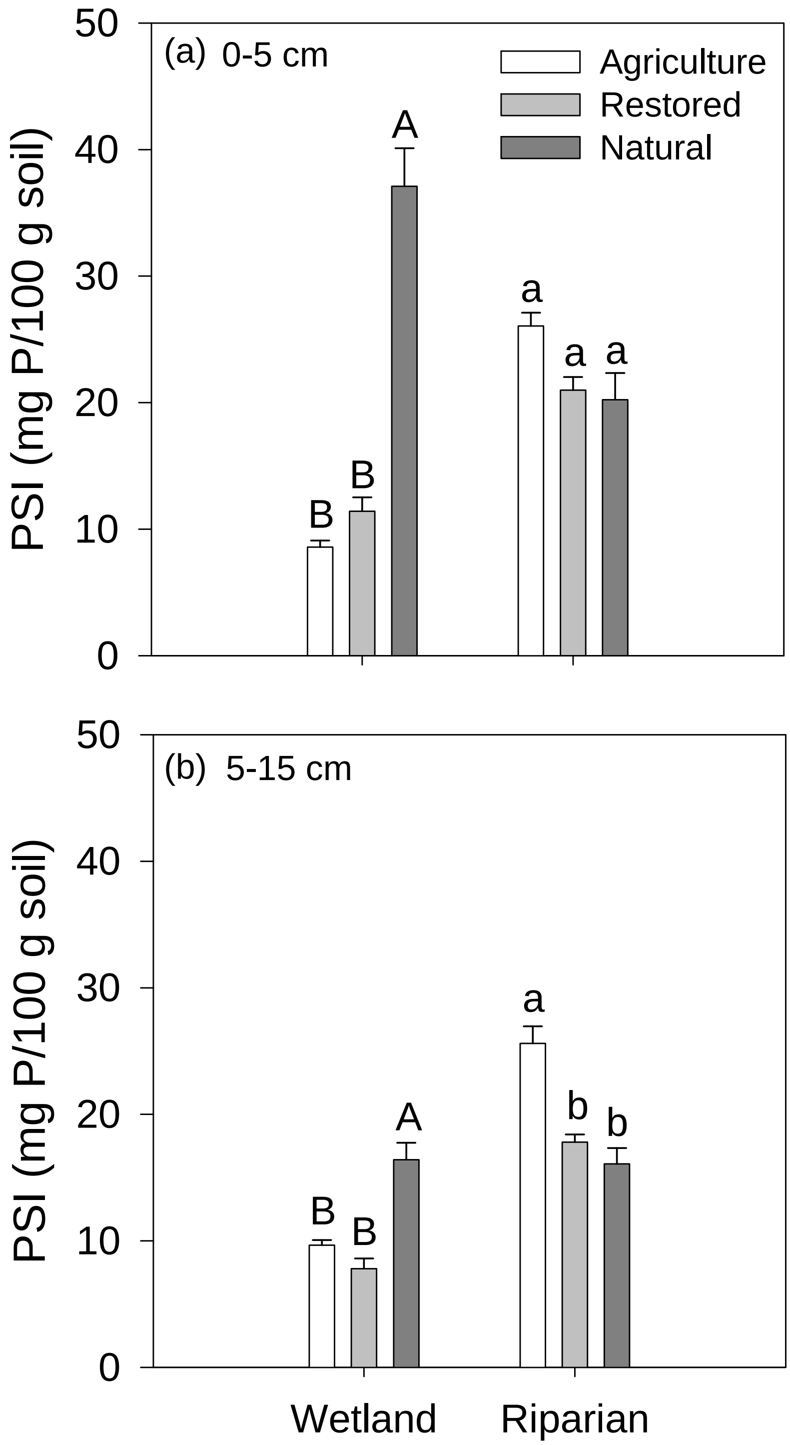


Figure 3. (a) Phosphorus sorption index in (a) surface and (b) subsurface soils of restored and natural wetlands and restored and natural riparian buffers of Indiana. For a given ecosystem (wetland, riparian), means separated by the same letter are not significantly different according to Tukey's multiple comparison test ($p \leq 0.05$).

to 12 year old restored wetlands had comparable bulk density, pH, and percent organic C relative to agricultural soils. Agricultural soils contained the most plant-available N and P in subsurface (5-15 cm) soils (Appendix 2). Natural wetlands had greater soil organic C (2,110 g/m^2) and N pools (210 g/m^2) than restored wetlands (1,350 g organic C/m^2, 110 g N/m^2). Agricultural soils also had the largest P pools (22 g P/m^2) (Figure 4).

Riparian soils had higher mineral content and contained more clay than wetland soils. Natural and restored riparian soils contained more silt, clay, organic matter, organic C, and total N than adjacent agricultural soils (Appendix 1). Plant-available NO_3-N and PO_4-P also were greater in natural and restored riparian soils than in agricultural soils (Appendix 2). Total organic C (0-5 cm) ranged from 2.2% (agricultural) to 4.8% (natural riparian) and inorganic C ranged from 0.22% (agricultural) to 0.91% (natural riparian) (Appendix 1). Organic C pools were comparable in natural (3,040 g/m^2) and restored riparian soils (3,810 g/m^2) and were two to two and a half times greater than in agricultural soils (1,510 g/m^2) (Figure 4). Total N pools followed a comparable trend ranging from 159 g N/m^2 (agricultural soils) to 206 g N/m^2 (natural ($p \leq 0.05$). riparian soils). There were no differences in total P pools among agricultural, restored riparian, and natural riparian soils.

Comparison of USDA Conservation Practices (Ohio)

Water quality improvement potential, PSI and denitrification, exhibited pronounced differences among the three practices. PSI (0-5 cm) was greater in the restored wetlands (40.3 mg P/100 g soil) than in conserved (18.7 mg P/100 g soil) and restored riparian (18.9 mg P/100 g soil) soils (Figure 5a). PSI was significantly correlated with organic C across the three practices (r=0.31, p = 0.02). In contrast to PSI which was greater in wetlands, denitrification (0-10 cm in 2009, 0-5 cm in 2010) was greater in the conserved (265 ng N_2O/g/hr) and restored (189 ng N_2O/g/hr) riparian buffers than in the restored wetlands (38 ng N_2O/g/hr). Across all sites, denitrification was greater in 2009 than in 2010 (Figure 5b).

Most soil properties did not differ among conservation practices. Soil pH, however, was greatest in conserved riparian buffers (7.4) and lowest in restored wetlands (6.7) (Appendix 3). Percent organic C (0-15 cm) also was greater in conserved riparian buffers than in restored wetlands and riparian buffers (Appendix 3). Soil properties also varied between surface and subsurface soils. Bulk density was lower in surface (1.0 g/cm^3) than subsurface (1.3 g/cm^3) soils whereas total N was greater in surface soils (Appendix 3). Percent organic C, inorganic C, and total P were comparable between surface and subsurface soils. Soil organic C, total N, and total P pools in (0-15 cm) were similar across the three NRCS practices (Figure 6) and ranged from 2,570-3,320 g organic C/m^2, 216-243 g N/m^2, and 60-71 g P/m^2, respectively. Organic C pools (0-15 cm), however, were lower relative to natural wetlands in the region (7,790 g organic C/m^2; 0-10 cm) reported by Fennessy et al. (2008).

Similar to our findings in Indiana, restored and conserved (natural) riparian buffers sequestered more C and stored more N than adjacent agricultural lands (0-5 cm) though only conserved riparian buffers contained significantly more C and N (Table 3). There was no difference in organic C and N pools between restored wetlands and agricultural lands in Ohio (Table 3) which is counter to our findings in Indiana where restored wetlands contained significantly less C and N than adjacent agricultural lands.

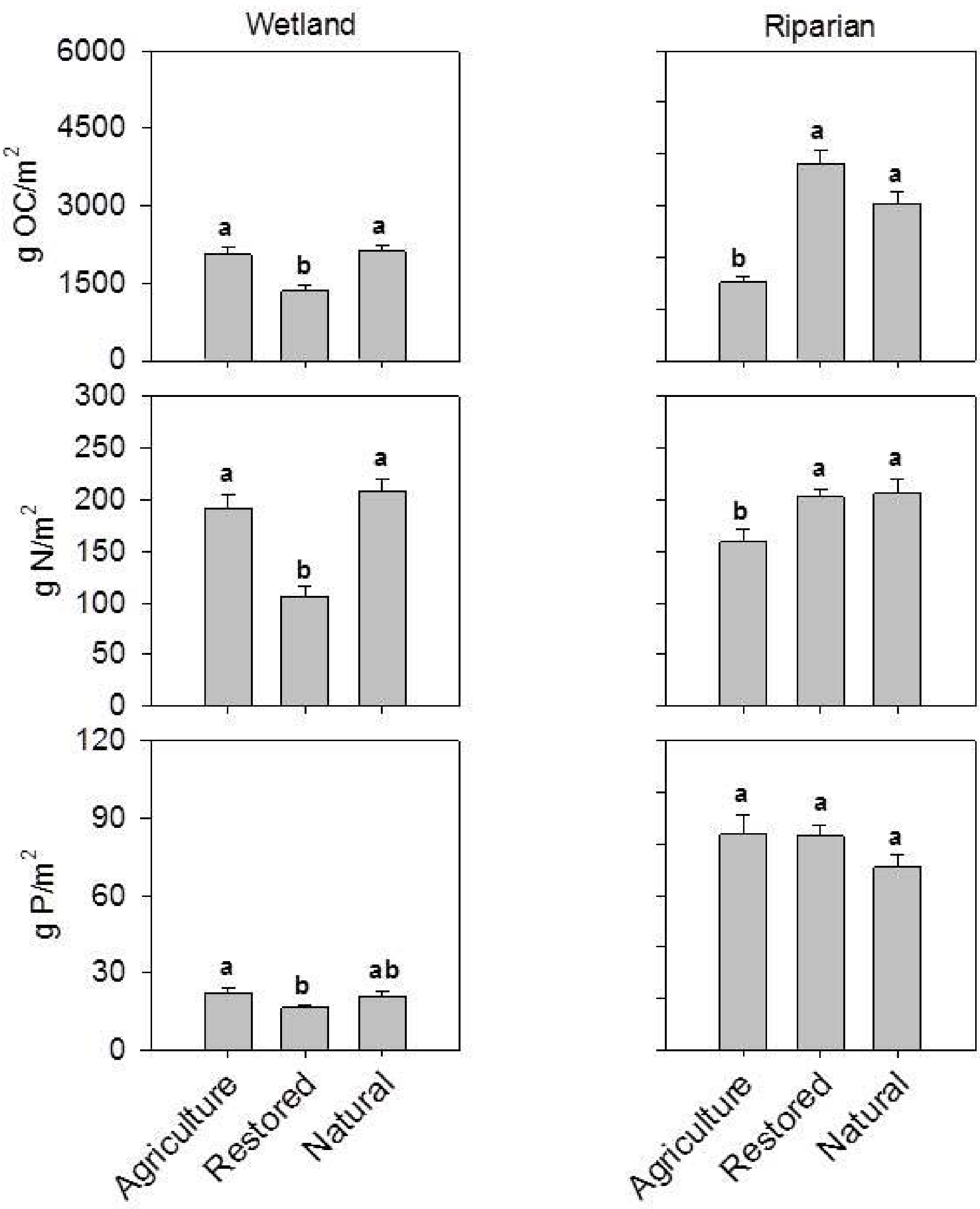


Figure 4. Carbon sequestration and N & P storage in soils (0-15 cm) of agricultural land, restored and natural wetlands and restored and natural riparian buffers of Indiana. For a given ecosystem (wetland, riparian), means separated by the same letter are not significantly different according to Tukey's multiple comparison test.

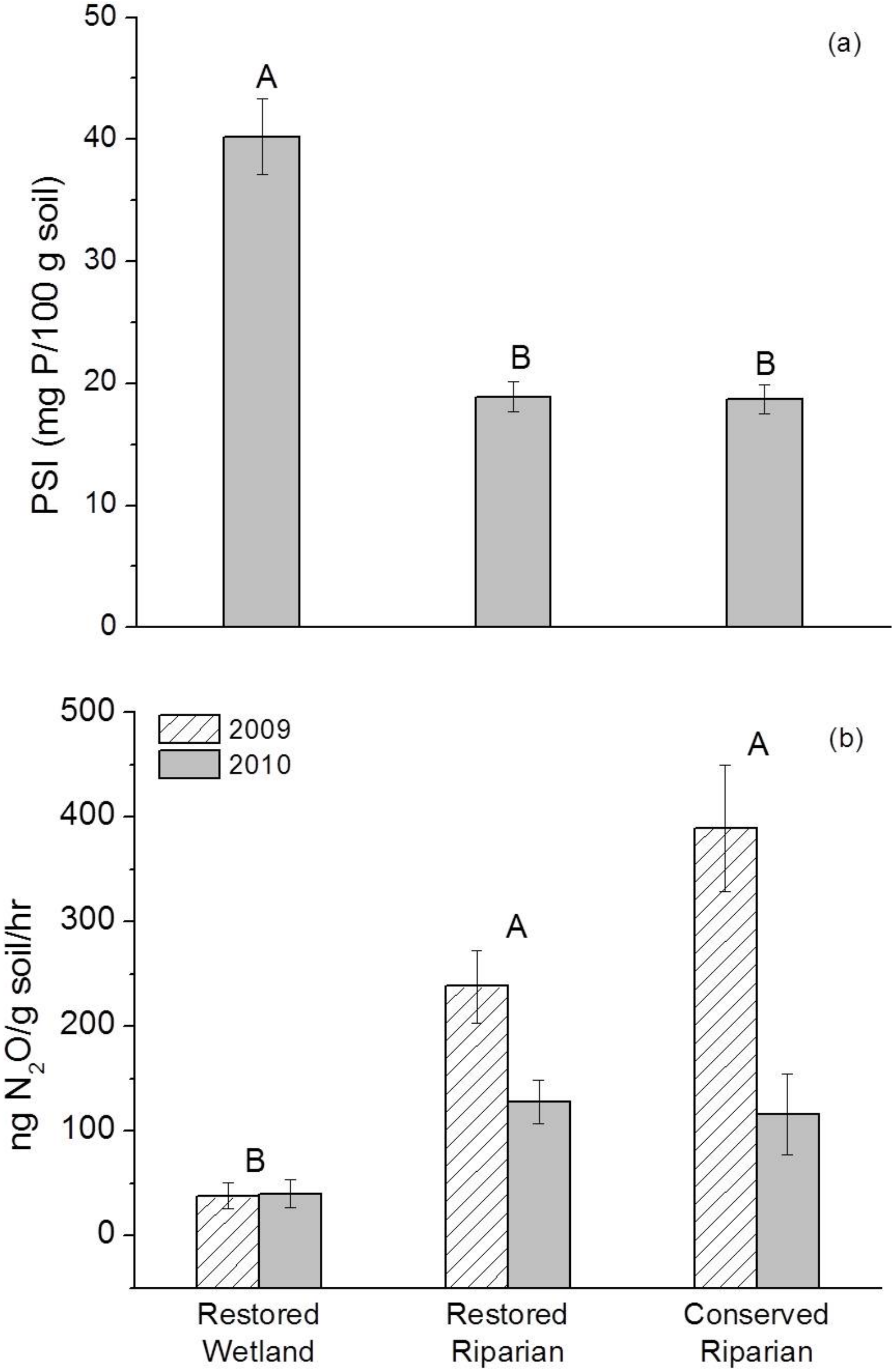


Figure 5. (a) Phosphorus sorption index and (b) denitrification in restored wetlands, restored riparian buffers and conserved riparian buffers in Ohio. Means separated by the same letter are not significantly different according to Tukey's multiple comparison test ($p \leq 0.05$).

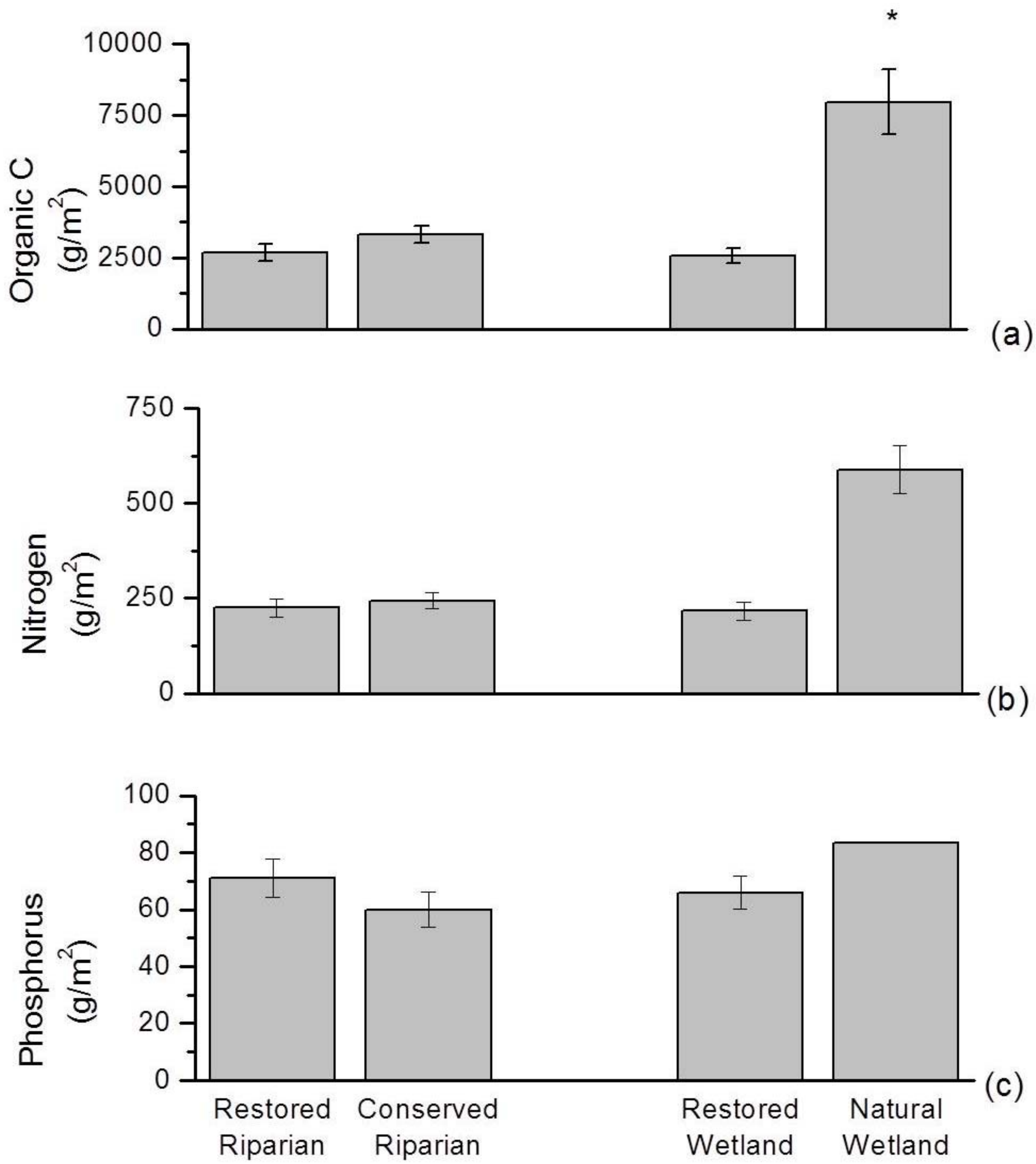


Figure 6. Carbon sequestration and N & P storage in soils (0-15 cm) of restored wetlands, restored riparian buffers and conserved riparian buffers of Ohio. The asterisk indicates a significant difference in organic C pools between restored wetlands and natural wetlands measured by Fennessy et al. (2008) based on Student's t-Test ($\alpha = 0.05$).

Table 3. Mean organic C, N and P pools (g/m^2, 0-5 cm) in agricultural lands, restored depressional wetlands, restored riparian buffers and conserved riparian buffers of Ohio.

	Organic C	Nitrogen	Phosphorus
Wetland			
Agricultural land	1198	111	28
Restored wetland	1437	128	33
Riparian			
Agricultural land	1108 **a**	110 **a**	31
Restored riparian	1717 **a,b**	145 **a,b**	42
Conserved riparian	2553 **b**	187 **b**	40

* For the riparian sites, means separated by the same letter are not significantly different according to Tukey's multiple comparison test ($p \leq 0.05$).

DISCUSSION

Comparison of Natural and Restored Wetlands and Riparian Areas (Indiana)

Restored and natural riparian buffers provided greater N removal compared to restored and natural wetlands (Figure 2). Restored riparian soils generally sorbed more P than restored wetlands (Figure 3). Phosphorus sorption was greatest in natural wetlands (Figure 3) that contained high percent soil organic C. Soil texture explains some of the observed variation in denitrification and PSI between the wetlands and riparian buffers. PSI was positively correlated with soil organic C in wetlands and adjacent agricultural soils ($r=0.82$, $p<0.01$) and riparian buffers ($r=0.36$, $p<0.05$). Soil texture also explains the high levels of ambient and potential denitrification in measured in the riparian buffers that contain more clay relative to wetlands. Riparian soils contained three to four times more clay (approximately 7.5%) than wetland soils (less than 2%) (Appendix 1). Higher denitrification associated with finer textured soils has been observed in other ecosystems (Groffman and Tiedje 1989a, b; Ullah and Faulkner 2006). Fine-textured soils have a higher water-holding capacity relative to sandier soils, and therefore may be more supportive of anaerobic conditions and thus denitrification.

Surprisingly, restored and natural riparian soils sequestered more organic C and generally stored more N than restored wetlands (Figure 4). It is thought that in the restored wetlands, prescribed fire and more aerobic soil conditions slowed C and N build-up. Riparian soils also contained P pools that were five times larger than in wetlands (Figure 4) and that is attributed to greater riverine inputs of sediment and higher clay content that provides sites for P sorption (Tisdale et al. 1985).

Comparison of USDA Conservation Practices (Ohio)

Our measurements of water quality improvement potential, denitrification and PSI, were similar to our findings in Indiana. For example, denitrification was similar between restored and conserved riparian buffers (Figure 5b), suggesting that restoration was successful in restoring N removal via denitrification within three to five years following restoration. Furthermore, riparian buffers exhibited greater denitrification than restored wetlands. Phosphorus sorption, however, was two times greater in restored wetlands than in riparian buffers (Figure 5a). Many studies have shown that P sorption in soils can reduce P loading to adjacent waters (Bridgham et al. 2001, Bruland et al. 2003, Hogan et al. 2004, Bruland and Richardson 2006). In our study, PSI was two times greater in restored wetlands than in restored and conserved riparian buffers. Correlation analyses revealed that percent organic C explained between 32% (wetland) and 58% (riparian) of the variation in PSI.

Whereas soil organic C concentrations differed between the different practices (Appendix 3), no differences were observed in surface (0-15 cm) soil organic C, total N, or total P pools (Figure 6), suggesting that restored riparian buffers achieve comparable nutrient pools to their natural counterparts within 3-7 years. However, natural depressional wetlands in Ohio measured by Fennessy et al. (2008) had organic C (7,970 g organic C/m^2), total N (590 g N/m^2), and total P (83 g P/m^2) pools (0-10 cm) that were one (P) to three (organic C) times greater than our five year old restored wetlands. The amount of C stored in natural wetland soils is even greater considering that Fennessy et al. (2008) measured the top 10 cm of soil, whereas we measured it in the top 15 cm.

Synthesis of Indiana and Ohio Findings

In both Indiana and Ohio, restored riparian buffers exhibited greater C and N storage than in adjacent agricultural land (Figure 4, Table 3), suggesting that this conservation practice produces measurable benefits when agricultural lands are restored to riparian buffers. Restoring wetlands on agricultural lands for C and N storage yielded mixed results. In Ohio, restored wetlands contained comparable to slightly greater organic C and N pools than agricultural land (Table 3). However, in Indiana, restored wetlands contained less organic C and N than adjacent agricultural land that we attribute to the use of prescribed fire by the Nature Conservancy to enhance plant biodiversity of the site.

Our data from Indiana and Ohio are unique in that they compare water quality improvement potential and C sequestration between multiple NRCS restoration and conservation practices (i.e. restored riparian buffers, restored wetlands (Hossler and Bouchard 2010; Fennessy and Craft 2011; Hossler et al. 2011) or CRP wetlands and riparian buffers. As outlined by Zedler (2003) and Fennessy and Craft (2011), restoring wetlands, particularly in agricultural landscapes, reintroduces ecosystem services such as water quality improvement functions, flood abatement, C sequestration, and biodiversity support. However, not all wetlands provide the same ecosystem services and there often are trade-offs in which services are restored or optimized. For example, Aronson and Galatowitsch (2008) found lower wetland plant diversity in restored wetlands of the prairie pothole region relative to natural wetlands. On the other hand, Rewa (2007) reported comparable diversity of amphibians, birds, and invertebrates between restored and natural depressional wetlands. We measured lower water quality improvement functions and C pools in restored wetlands than in natural wetlands. However, on the same sites, (Hopple and Craft, in press) measured comparable species richness in the same restored wetlands than natural wetlands that was attributed to management activities (i.e. prescribed fire) used by The Nature Conservancy on the sites. Thus, it is important to recognize that there are trade-offs as optimizing one ecosystem service (biodiversity) is likely to occur at the expense of another service (C sequestration).

Choosing Conservation Practices to Optimize Water Quality Improvement and C Sequestration

To aid in the selection of a particular USDA conservation practice and to place them in appropriate locations on the landscape, we used our data to construct a decision tree based on hydrologic connectivity, parent material and disturbance regime (Figure 7). For the services we measured (water quality improvement, C sequestration), restored and conserved riparian buffers afforded the greatest benefits. These ecosystems, with their strong hydrologic connections and fin(er) textured soils provided the highest denitrification and high levels of P sorption and C sequestration. Restored depressional wetlands, because of their limited hydrologic connectivity, provide less water quality improvement potential though the fin(er) textured soils provide high levels of P sorption. Depressional wetlands with sandy soils and that are managed for other ecosystem services such as biodiversity, provided the lowest levels of water quality improvement potential and C sequestration of the USDA conservation practices we sampled.

Our findings of differences in water quality improvement potential and C sequestration among restored wetland and riparian areas can help improve policies pertaining to wetland and riparian restoration by providing greater insight into the provisioning of ecosystem services

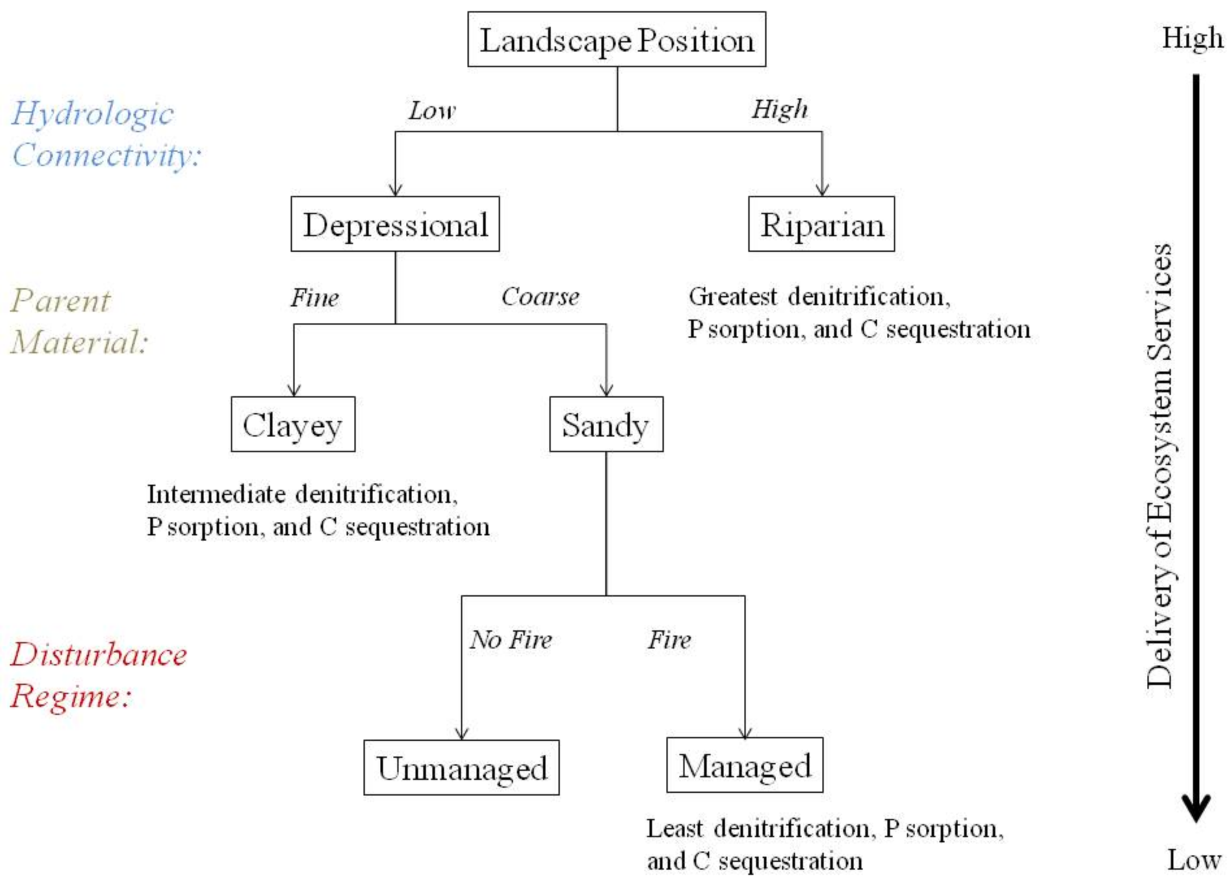


Figure 7. Decision tree, based on hydrologic connectivity, parent material and disturbance regime, to aid in the placement of USDA conservation practices in the Glaciated Interior Plains.

among different conservation practices. Future USDA efforts to restore lands in agricultural landscapes for water quality improvement should focus on areas with high hydrologic connectivity, finer-textured soils and limited anthropogenic disturbance (i.e. prescribed fire).

REFERENCES

Aronson M, S Galatowitsch (2008). Long-term vegetation development of restored prairie pothole wetlands. Wetlands 28(4): 883-895.

Dahl, T. 2000. Status and trends of wetlands in the conterminous United States 1986 to 1997. U.S. Department of the Interior; Fish and Wildlife Service. Washington, D.C.**:** 82.

Fennessy, S.M. and C.B. Craft 2011. Agricultural conservation practices increase wetland ecosystem services in the Glaciated Interior Plains. *Ecological Applications* 21(3 Supplement): S49-S64.

Fennessy, S.M, A. Rokosch, J. Mack. 2008. Patterns of plant decomposition and nutrient cycling in natural and created wetlands. *Wetlands* 28(2): 300-310.

Groffman, P.M. and J.M. Tiedje. 1989. Denitrification in north temperate forest soils: relationships between denitrification and environmental factors at the landscape scale. *Soil Biology and Biochemistry* 21: 621-626.

Groffman, P.M. and J.M. Tiedje. 1989. Denitrification in north temperate forest soils: spatial and temporal patterns at the landscape and seasonal scales. *Soil Biol. Biochem.* 21: 613-620.

Hopple A, C Craft (In press). Managed Disturbance Enhances Biodiversity of Restored Wetlands in the Agricultural Midwest. Ecological Engineering.

Hossler, K. and V. Bouchard. 2010. Soil development and establishment of carbon-based properties in created freshwater marshes. *Ecological Applications* 20: 539-553.

Hossler, K., V. Bouchard, M. Fennessy, S. Frey, E. Anamaet and E. Herbert. 2011. No-net-loss not met for nutrient function in freshwater marshes: recommendations for wetland mitigation policies. *Ecosphere* 2(7): doi:10.1890/ES1811-00009.00001.

Mitsch, W., J. Day, J. Gilliam, P. Groffman, D. Hey, G. Randall and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi river basin: strategies to counter a persistent ecological problem. *BioScience* 51(5): 373-388.

Rewa C (2007). Fish and wildlife benefits associated with wetland establishment practices. USDA-ARS/UNL Faculty Paper 488.

Tisdale, S., W. Nelson and J. Beaton. 1985. Soil and Fertilizer Phosphorus. *In*. Soil Fertility and Fertilizers. New York, NY, Macmillan Publishing Company.

Ullah, S. and S. Faulkner. 2006. Denitrification potential of different land-use types in an agricultural watershed, lower Mississippi valley. *Ecological Engineering* 28: 131-140.

Zedler, J.B. 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. *Frontiers in Ecology and the Environment* 1(2): 65-72.

Appendix 1. Bulk soil properties (means ±1 SE) of agricultural land, restored and natural wetlands and restored and natural riparian buffers in Indiana. Note: sand, silt and clay percentages in *italics* were calculated without percent organic matter.

	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Organic C (%)	Inorganic C (%)	Total N (%)	Total P (µg/g)
Wetland 0-5 cm								
Agriculture	86±0.5[b] *91±0.5*	7±0.5[a] *7±0.5*	2±0.2[a] *2±0.2*	4.8±0.20[b]	2.4±0.10[b]	0±0	0.22±0.01[b]	270±11[b]
Restored	91±0.6[a] *92±0.6*	6±0.6[ab] *6±0.6*	2±0.2[a] *2±0.2*	4.4±0.52[b]	2.2±0.26[b]	0±0	0.18±0.02[c]	230±17[b]
Natural	80±1.1[c] *95±1.3*	4±0.9[bc] *5±1.1*	0.6±0.2[b] *0.7±0.2*	15±0.81[a]	10±1.1[a]	0±0	0.88±0.10[a]	620±46[a]
5-15 cm								
Agriculture	--	--	--	4.5±0.20[a]	2.3±0.09[a]	0±0	0.21±0.01[a]	240±19[b]
Restored	--	--	--	2.6±0.31[b]	1.3±0.15[b]	0±0	0.10±0.01[b]	160±14[c]
Natural	--	--	--	5.8±0.56[a]	2.90±0.28[a]	0±0	0.30±0.02[a]	330±26[a]

	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Organic C (%)	Inorganic C (%)	Total N (%)	Total P (µg/g)
Riparian 0-5 cm								
Agriculture	78±1[a] *82±1.1*	2±0.2[c] *2±0.2*	15±0.8[a] *16±0.8*	4.4±0.29[b]	2.2±0.15[b]	0.33±0.08	0.23±0.01[b]	1050±51
Restored	72±1[b] *80±1.1*	8±0.4[a] *9±0.4*	10±7[b] *11±7.8*	9.7±0.13[a]	4.5±0.13[a]	0.45±0.10	0.27±0.01[ab]	1010±29
Natural	78±1[a] *87±1.1*	7±0.4[b] *8±0.4*	5±0.5[c] *6±0.6*	10±0.47[a]	4.8±0.28[a]	0.31±0.19	0.30±0.01[a]	1010±29
5-15 cm								
Agriculture	--	--	--	3.2±0.13[b]	1.6±0.07[b]	0.22±0.04	0.17±0.01[b]	940±41
Restored	--	--	--	8.0±0.34[a]	4.0±0.17[a]	0.40±0.11	0.20±0.01[b]	860±26
Natural	--	--	--	7.7±0.54[a]	3.8±0.27[a]	0.91±0.39	0.28±0.01[a]	950±32

Separate analyses were conducted for each system (wetland, riparian) and depth (0-5 cm, 5-15 cm). Values with different letters are significantly different based on Tukey's multiple comparison test (α = 0.05).

Appendix 2. Field-moist soil properties (mean ± 1 SE) of agricultural land, restored and natural wetlands and restored and natural riparian buffers of Indiana.

	pH	Soil Moisture (%)	Bulk Density (g/cm^3)	NH_4-N (µg/g)	NO_3-N (µg/g)	PO_4-P (µg/g)
Wetland **0-5 cm**						
Agriculture	7.0 ± 0.1^{a}	19 ± 1.1^{c}	1.13 ± 0.04^{a}	2 ± 0.3^{b}	3 ± 1^{a}	6 ± 0.8^{a}
Restored	6.8 ± 0.1^{a}	36 ± 1.8^{b}	1.05 ± 0.04^{a}	2 ± 0.8^{b}	1 ± 0.1^{b}	0.4 ± 0.05^{b}
Natural	5.6 ± 0.1^{b}	64 ± 2.1^{a}	0.42 ± 0.04^{b}	12 ± 3^{a}	9 ± 3^{a}	0.1 ± 0.02^{c}
5-15 cm						
Agriculture	6.8 ± 0.2^{a}	21 ± 1.0^{b}	1.23 ± 0.02^{b}	34 ± 18^{a}	12 ± 4^{a}	4 ± 0.6^{a}
Restored	6.8 ± 0.1^{a}	24 ± 1.5^{b}	1.40 ± 0.03^{a}	0.2 ± 0.1^{b}	1 ± 0.2^{c}	0.3 ± 0.1^{b}
Natural	5.7 ± 0.1^{b}	37 ± 1.6^{a}	0.97 ± 0.04^{c}	1 ± 0.2^{a}	4 ± 0.6^{b}	0.1 ± 0.01^{c}
Riparian **0-5 cm**						
Agriculture	7.3 ± 0.02^{c}	26 ± 0.8^{ab}	1.0 ± 0.05^{b}	1 ± 0.1	1 ± 0.2^{b}	4 ± 2^{b}
Restored	7.7 ± 0.05^{a}	23 ± 1.0^{b}	1.3 ± 0.04^{a}	1 ± 0.1	26 ± 2^{a}	8 ± 1^{a}
Natural	7.5 ± 0.04^{b}	34 ± 3.0^{a}	1.0 ± 0.07^{b}	2 ± 0.3	30 ± 4^{a}	11 ± 1^{a}

	pH	Soil Moisture (%)	Bulk Density (g/cm^3)	NH_4-N (µg/g)	NO_3-N (µg/g)	PO_4-P (µg/g)
5-15 cm						
Agriculture	7.4±0.02^c	22±1.6^a	1.2±0.04^a	1±0.6^a	2±0.5^b	2±1^c
Restored	7.8±0.05^a	22±1.7^a	1.2±0.06^a	0.8±0.1^a	15±2^a	4±1^b
Natural	7.6±0.04^b	29±2.8^a	0.95±0.06^b	1±0.1^a	17±3^a	11±1^a

Separate analyses were conducted for each system (wetland, riparian) and depth (0-5 cm, 5-15 cm). Values with different letters are significantly different based on Tukey's multiple comparison test ($\alpha = 0.05$).

Appendix 3. Bulk soil properties (Mean ± 1 SE) by NRCS practice - restored wetland, restored riparian buffer and conserved riparian buffer – and adjacent agricultural lands of Ohio.

	pH	Bulk Density (g/cm^3)	Organic C (%)	CO_3-C (%)	Total N (%)	Total P (µg/g)
0-5 cm						
Restored Wetland	6.7±0.1	1.0±0.08	3.4±0.5	0.03±0.2	0.29±0.05	683±61
Restored Riparian	7.2±0.2	1.1±0.03	3.2±0.3	0±0	0.28±0.02	739±47
Conserved Riparian	7.4±0.1	1.0±0.05	4.6±0.4	0.02±0.02	0.34±0.02	747±52
Agricultural Land (adj. to wetlands)	6.8±0.3	0.9±0.16	2.8±0.5	0±0	0.26±0.04	645±125
Agricultural Land (adj. to riparian)	6.7±0.6	1.06±0.22	2.4±0.2	0±0	0.24+0.02	687±62
5-15 cm						
Restored Wetland	--	1.3±0.04	2.9±0.4	0.03±0.1	0.24±0.03	754±64
Restored Riparian	--	1.4±0.04	2.5±0.3	0.10±0.1	0.22±0.02	670±49
Conserved Riparian	--	1.2±0.07	3.3±0.3	0±0	0.25±0.02	683±57
Mean (0-15 cm)						
Restored Wetland	6.7±0.1^{b}	1.2±0.05	3.1±0.3^{b}	0.03±0.1	0.26±0.03	722±45
Restored Riparian	7.2±0.2^{ab}	1.2±0.04	2.9±0.2^{b}	0.04±0.04	0.25±0.02	703±34
Conserved Riparian	7.4±0.1^{a}	1.1±0.05	4.0±0.2^{a}	0.003±0.02	0.30±0.02	718±38

Different letters indicate significant differences based on Tukey's multiple comparison test ($\alpha = 0.05$).