Two for One: Conservation of Aquatic Ecosystems With Buffers Protects Terrestrial Ecosystems

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Abstract

We evaluated how three widths of buffer zones on greater than or equal to 100-ha wetlands (240, 300, and 390 m) and rivers (10, 20, and 30 m) would help meet watershed conservation goals in the Upper Peninsula of Michigan, USA, and whether doing so also would protect each of the predominant types of terrestrial natural communities across the landscape. The use of buffer zones (even the narrowest widths assessed) around wetlands and riparian zones met or exceeded conservation targets in 75% of watersheds and greater than or equal to 85% of subwatersheds evaluated. Wetlands and riparian zones with buffers captured each of the predominant types of terrestrial natural community in Michigan’s Upper Peninsula, but not proportionately to their availability across the entire landscape. Our work demonstrates that a landscape-conservation approach focused on wetlands and riparian zones with buffers can conserve terrestrial, wetland, and riparian ecosystems across Michigan’s Upper Peninsula and may also be applicable in other areas where mapping of wetlands and rivers occurs.

Keywords: Michigan; wetlands; riparian zones; buffer zones

Introduction

The Laurentian Great Lakes (or simply Great Lakes) are a globally significant natural resource that contains one-fifth of the world’s and 84% of North America’s surface freshwater resources (U.S. Environmental Protection Agency and Government of Canada 1995; World Wildlife Fund Canada 2015; U.S. Environmental Protection Agency 2016). Historically, mineral extraction, forestry, agriculture, international shipping, and other factors contributed to environmental degradation in the Great Lakes region and impacted the way humans and wildlife can use aquatic resources in this region. In 2004, Environment Canada developed a framework to guide and prioritize the restoration of fish and wildlife habitat within the most severely degraded areas of the Great Lakes that aimed to ensure adequate habitat existed to sustain ecosystem functions and support viable wildlife populations.

The framework of Environment Canada (2004) set goals of conserving 10% of wetlands in all major watersheds and 6% of wetlands in subwatersheds and maintaining natural vegetation along 75% of the length of every river (Environment Canada 2004). Furthermore, to provide additional conservation benefits, including conservation of wildlife habitats and groundwater protection, Environment Canada (2004) recommended buffers of 240 m around wetlands and 30 m around rivers (Semlitsch and Jensen 2001; Rodgers and Schwi-kert 2002; Harper et al. 2008). Other research suggests the need for wider buffers (300–390 m) around wetlands for protection against nitrates, human disturbance to...
wildlife, erosion, core herpulture habitats, and nesting areas for other wildlife (Joyal et al. 2001; Semlitsch and Bodie 2003). Environment Canada (2004) recommended 30-m buffers around rivers to protect physical, chemical, and biological integrity of streams by contributing to sediment reduction and temperature regulation; 30-m buffers also confer benefits to macroinvertebrates and fish. Smaller buffers, however, can reduce sediment and herbicide loads in rivers (~10 m) and can protect against residential stormwater and nonpoint agricultural pollutants at approximately 20 m (Sweeney and Newbold 2014). In addition, buffer zones around wetlands and rivers have the potential to protect terrestrial ecosystems and wildlife habitats that occur in areas adjacent to wetlands and rivers (Environment Canada 2004; Hoekstra et al. 2005; Sabo et al. 2005).

The framework developed by Environment Canada informed some small-scale habitat restoration and rehabilitation, but there has been no assessment at larger scales (Environment Canada 2004). Furthermore, although there is potential for a framework for conservation of wetlands and rivers by using buffer zones to protect terrestrial ecosystems and wildlife habitats, little work documents explicitly the extent of protection to terrestrial ecosystems in this type of approach. We applied guidelines from the framework of Environment Canada (2004) to wetlands and rivers in the Upper Peninsula (UP) of Michigan, USA, to determine whether buffer zones around wetlands and rivers would 1) facilitate meeting wetland protection goals in watersheds (10%) and subwatersheds (6%), 2) result in 75% of all river lengths being naturally vegetated, and 3) result in protection of the full complement of terrestrial ecosystems (i.e., all natural community types; Table 1) being protected proportionately to their availability on the landscape. In addition, we assessed the Environment Canada recommendations of 240-m buffers for wetlands and 30-m buffers for rivers, but also evaluated other buffer distances as supported in the literature (300 and 390 m for wetlands and 10 and 20 m for rivers).

### Methods

Michigan’s UP covers approximately 42,610 km$^2$ between 45–48°N and 83–91°W. Lake Superior borders the north shore of the mainland, whereas lakes Michigan and Huron border the south shore. The UP is part of the Northern Lakes and Forests ecoregion, with glacial, nutrient-poor soils (U.S. Environmental Protection Agency 2007). Terrestrial ecosystem types are primarily coniferous boreal forest or northern hardwood associations (Henson et al. 2005), but wetlands (i.e., swamps, bogs, fens, and marshes) and oligotrophic lakes characteristic of northern latitudes are common.

We used the National Wetland Inventory, Michigan Trout Streams, and Michigan watersheds datasets for our analyses. For composition of terrestrial ecosystems, we used the 2006 National Land Cover Database, which has a pixel size of 30 × 30 m. We acquired all spatial datasets from the Michigan Geographic Data Library (https://gis.michigan.opendata.arcgis.com/, accessed May 2021) and completed all geoprocessing and spatial analysis by using ArcMap 10 (Environmental Systems Research Institute, Redlands, CA). From National Wetlands Inventory data, we selected wetland polygons of greater than or equal to 100 ha to generate the wetlands spatial data layer used in our analyses. Although smaller wetlands provide important functions, we did not include them in this analysis because of the difficulty in mapping small, forested wetlands. For the river portion of the analysis, we were interested in both the conservation of the river and the adjacent riparian zone (collectively referred to as riparian zones hereafter). For the riparian zone spatial data layer, we used the Michigan Trout Streams (produced in 2008) dataset with a bilateral 10-m buffer to represent the river and immediately adjacent vegetation. We used the Buffer tool in ArcMap to generate buffer zones around wetlands and riparian zones as follows: 1) wetlands with a 240-m buffer, 2) wetlands with a 300-m buffer, 3) wetlands with a 390-m buffer, 4)

| Land-cover class | Ecosystem–land-use classification |
|------------------|----------------------------------|
| Undefined or <100 ha | Undefined Land Use, North-central Interior Beech-Maple Forest, North-Central Interior and Appalachian Rich Swamp, Laurentian-Acadian Alkaline Conifer Hardwood Swamp, Central Tallgrass Prairie, North-Central Interior Oak Savanna, North-Central Interior Sand and Gravel Tallgrass Prairie, North-Central Oak Barren, Central Interior and Appalachian Shrub-Herbaceous Wetland System, Northern Great Lakes Coastal Marsh, and Introduced Upland Vegetation—Perennia Grassland and Forb Land |
| Natural classes (natural communities) | Laurentian-Acadian Northern Hardwood Forest, Laurentian-Acadian Northern Pine-(Oak) Forest, Laurentian-Acadian Pine-Hemlock-Hardwood Forest, Laurentian Pine-Oak Barren, Central Interior and Appalachian Floodplain System, Laurentian-Acadian Floodplain System, Laurentian-Acadian Swamp System, Boreal Aspen-Birch Forest, Boreal Jack Pine-Black Spruce Forest, Boreal White Spruce-Fir-Hardwood Forest, Boreal-Laurentian Conifer Acidic Swamp and Treed Poor Fen, Eastern Boreal Floodplain, Great Lakes Alvar, Great Lakes Dune, Great Lakes Coastal Marsh System, Laurentian-Acadian Freshwater Marsh, Harvested forest—Grass/Forb Regeneration, Open Water (fresh) |
| Urban and agricultural classes | Cultivated Cropland, Managed Tree Plantation, Pasture-Hay, Disturbed—Nonspecific, Developed—Open Space, Developed—Low Intensity, Developed—Medium Intensity, Developed—High Intensity |
riparian zones with a 10-m buffer, 5) riparian zones with a 20-m buffer, and 6) riparian zones with a 30-m buffer.

From the watershed dataset we used the hydrologic unit codes to demarcate watersheds. We used major watercourses within watersheds to demarcate subwatersheds, with the assumption that this scale may be more feasible for regional conservation planning than subwatersheds demarcated at the level of U.S. Hydrologic Unit Code 12 level. To determine whether 10 and 6% watershed-cover goals were met for watersheds and subwatersheds, we used the Intersect tool in ArcMap to intersect each of the wetlands with buffer zones generated as described above with the watershed data layer. We then calculated the area of each watershed and subwatershed covered by wetlands to determine percent wetland cover.

For composition of terrestrial ecosystems within each wetland and riparian zone buffer, we merged the 37 ecosystem land-use classes (land-cover types) of the UP in the 2006 National Land Cover Database to 19 classes. We combined “introduced vegetation,” “agricultural,” and “disturbed” types into the “other” category and, because of uncertainty associated with remote sensing data, we also combined land-cover types that accounted for less than 100 ha of the UP landscape (11 types) into the other category (Table 1). We generated a summary of land-cover composition for the UP that we compared with land-cover composition of wetlands and riparian zones with buffers. To determine composition of terrestrial ecosystem types within each buffered wetland and riparian zone, we used the Extract by Mask tool in ArcMap with the buffered wetland and riparian zones and land-cover datasets. We used these data to calculate the percentage of river length, for all rivers in the UP, comprised of terrestrial ecosystem types and the percentage comprised of urbanized land-cover types (i.e., developed—open space, developed—low intensity, developed—medium intensity, developed—high intensity; Table 1) to assess imperviousness to urbanization. We summed the number of adjacent pixels (30 × 30 m pixels from the National Land Cover Database) that belonged to a natural community type vs. those that were urban or agricultural types (Table 1) and divided by the total number of pixels along the length of the river to determine the percentage naturally vegetated. We used the total length of all rivers because data resolution was not high enough to permit completing this analysis by individual rivers and streams. To determine how much of each watershed and subwatershed could be protected using this approach, we used the Intersect tool in ArcMap for watersheds and subwatersheds with each buffered wetland and riparian zone. For watersheds that spanned state boundaries, we used only the portions of those watersheds in Michigan’s UP for our analyses to match the extent of the other datasets used herein.

We used a \( \chi^2 \) goodness-of-fit test to compare land-cover composition of buffered wetlands and riparian zones to that of the UP to determine whether buffered wetlands and riparian zones were representative of the natural land cover of the UP. There were 18 terrestrial ecosystem types and water (we excluded the other category; Table 1); thus, we had 17 df. We made the following comparisons: 1) UP vs. wetlands with a 240-m buffer, 2) UP vs. wetlands with a 300-m buffer, 3) UP vs. wetlands with a 390-m buffer, 4) UP vs. riparian zones with a 10-m buffer, 5) UP vs. riparian zones with a 20-m buffer, and 6) UP vs. riparian zones with a 30-m buffer. Buffered wetlands and riparian zones were smaller in area than the UP and thus have lower absolute expected values of area by natural community type than the UP. To account for the difference in size, we calculated the expected area of each natural community type in each buffered wetlands and riparian zone, by multiplying the proportion of each natural community type in the UP by the total area of each buffered wetlands and riparian zone.

Results

Approximately 30.7% of Michigan’s UP is wetland and 1.5% is riparian zone, with the remainder comprising various upland types of land cover. Laurentian-Acadian Northern Hardwood Forest accounts for the largest portion of natural community types in the UP (37%), followed by Laurentian-Acadian Swamp System (17%), Boreal White Spruce-Fir-Hardwood Forest (10%), and Boreal Acidic Peatland System (8%; Figure 1). The other category accounted for approximately 7% of the landscape, and Laurentian-Acadian Northern Pine-(Oak) Forest, Laurentian Pine-Oak Barren, Central Interior and Appalachian Floodplain System, Eastern Boreal Floodplain, Great Lakes Alvar, Great Lakes Dune, Great Lakes Coastal Marsh System, Laurentian-Acadian Freshwater Marsh, Harvested Forest—Grass/Forb Regeneration, and Open Water each accounted for less than 1–5% of the land cover of the UP (Figure 1).

Wetlands (>100 ha) comprised primarily Laurentian-Acadian Swamp System (45%), Boreal-Laurentian Conifer Acidic Swamp and Treed Poor Fen (Boreal Acidic Peatland; 16%), and Open Water (14%). Addition of a 240-m buffer to wetlands changed land-cover composition to 34% Laurentian-Acadian Swamp System, 17% Laurentian-Acadian Northern Hardwood Forest, 14% Boreal Acidic Peatland, and 10% Boreal White Spruce-Fir-Hardwood Forest (Figure 1). Wetlands with a 300-m buffer were dominated by Laurentian-Acadian Swamp System (32%), Laurentian-Acadian Northern Hardwood Forest (18%), Boreal Acidic Peatland (13%), and 10% Boreal White Spruce-Fir-Hardwood Forest (Figure 1). The addition of a 390-m buffer resulted in a wetland landscape dominated by Laurentian-Acadian Swamp System (31%), Laurentian-Acadian Northern Hardwood Forest (20%), Boreal Acidic Peatland (13%), and Boreal White Spruce-Fir-Hardwood Forest (10%). Although the buffered wetlands captured the predominant terrestrial ecosystem types of the UP, results from all \( \chi^2 \) analyses showed that land-cover composition of the UP was different from land-cover composition of all buffered wetlands, regardless of buffer width (Table 2).

Riparian zones comprised primarily Laurentian-Acadian Northern Hardwood Forest (27%), Laurentian-Acadian Swamp System (20%), and Boreal Acidic Peatland (17%
Figure 1. Land-cover composition of the entire landscape of the Upper Peninsula of Michigan, USA, and buffered wetlands and rivers based on the 2006 National Land Cover Database and National Wetlands Inventory. “Other” includes disturbed, nonnative vegetation communities, and areas for which spatial accuracy was too low to confidently classify as distinct community types. Natural communities representing less than 1% of the UP land cover (i.e., Laurentian-Acadian Northern Pine-(Oak) Forest, Laurentian Pine-Oak Barren, Central Interior and Appalachian Floodplain System, Eastern Boreal Floodplain, Great Lakes Alvar, Great Lakes Dune, Great Lakes Coastal Marsh System, Laurentian-Acadian Freshwater Marsh) are not shown.

Table 2. The $\chi^2$ statistics for each cell computed as $\chi^2 = (\text{observed} - \text{expected})^2/\text{(expected)}$ for the area of each natural community in the Upper Peninsula of Michigan, USA, as determined from the 2006 National Land Cover Database, in each feature class of current or theoretical conservation areas (e.g., stewardship areas, random areas, wetlands, etc.) relative to its expected value on the landscape, and the sum of these values by column represents the overall $\chi^2$ test statistic ($df = 17$, critical value $= 28.869$ at $\alpha = 0.05$).
Generally, riparian zones in the UP exceeded conservation recommendations of 75% natural vegetation (Environment Canada 2004). In addition, the approach we assessed met recommendations for conservation of 10% of wetlands at the watershed level and 6% of wetlands at the subwatershed level (Environment Canada 2004). Natural vegetation occurred along most of the length of rivers in the UP with buffer zones—only approximately 3% of the total length of all rivers comprised croplands or regenerating forests and only approximately 2% comprised developed land-cover types (Table 2). Open Water accounted for an additional approximately 3% of the land cover along rivers. The remaining landscape comprised terrestrial ecosystem types and approximately 2% of the total landscape comprised floodplain systems, while the remaining 90% of land cover was forested (Table 2).

**Discussion**

The approach to conservation planning we assessed met recommendations for conservation of 10% of wetlands at the watershed level and 6% of wetlands at the subwatershed level (Environment Canada 2004). Generally, riparian zones in the UP exceeded conservation recommendations of 75% natural vegetation (Environment Canada 2004). In addition, the approach we
assessed—buffering wetlands and rivers to conserve wetland and terrestrial ecosystems—captured the predominant natural communities, both terrestrial (upland) and wetland, of the UP. These results demonstrate the efficacy of the Environment Canada guidelines in meeting watershed- and subwatershed-level conservation goals for wetland and riparian zones as well as providing protection for the full complement of terrestrial ecosystem types across the landscape; however, terrestrial ecosystem types were represented disproportionately to their availability on the landscape. Representation of wetland communities (e.g., Laurentian-Acadian Swamp System) was higher in buffers than on the landscape, whereas representation of upland types of plant communities (e.g., Laurentian-Acadian Northern Hardwood Forest) was typically lower in buffers than across the landscape.

Almost universally across our study area, buffers of greater than or equal to 240 m around wetlands achieved watershed and subwatershed conservation goals for wetland cover. In almost all watersheds and subwatersheds, even the smallest buffer width that we assessed was able to meet or exceed conservation recommendations of Environment Canada (2004). Buffer zone widths that we assessed represent only general recommendations for this region (i.e., 240, 300, and 390 m), and different buffer widths may be better for achieving conservation goals in other areas (e.g., Vuori and Joensuu 1996; Environment Canada 2004). In addition, given that even the narrowest buffer width that we assessed for wetlands (240 m) exceeded conservation recommendations for watersheds and subwatersheds, it is possible that narrower buffer widths than those that we assessed would meet conservation goals in our study area. For rivers, buffer zones that we assessed also met conservation goals (i.e., to maintain natural vegetation along ≥75% of river length). Although using narrower buffers can conserve some ecological processes, many benefits will go unrealized until riparian buffer zones are greater than or equal to 30 m wide (Environment Canada 2004). For example, buffers greater than or equal to 30 m wide help reduce sediment and pollutant loads, regulate water temperatures, provide nesting and other core habitat for many taxa of wildlife, protect wildlife from human disturbance, and prevent erosion (Joyal et al. 2001; Semlitsch and Jensen 2001; Rodgers and Schwikert 2002; Semlitsch and Bodie 2003; Environment Canada 2004; Sweeney and Newbold 2014).

The use of this approach captured the full complement of terrestrial ecosystem types on the landscape, but did not proportionately represent them relative to their availability on the entire UP landscape. Underrepresentation of some terrestrial ecosystem types occurred using this approach, whereas overrepresentation occurred for others. Underrepresentation and overrepresentation of specific types of ecosystems may not be a practical concern in this approach, however, because large proportions of terrestrial ecosystems would gain protection under our approach. Furthermore, differences between representation of terrestrial ecosystems on the landscape vs. in our approach may be relatively minor at landscape scales. For example, Laurentian-Acadian Northern Hardwoods Forests and Laurentian-Acadian Swamp Systems were reversed in order of prevalence in wetlands with buffer zones compared with their availability across the UP, which may reflect the fact that the latter are a type of wetland and the former are an upland land-cover class. These communities have similar species composition and community attributes (Gawler 2007, 2009). Nevertheless, there may be functional differences in wetland vs. upland habitat types that may warrant further consideration at finer scales, including different roles in nutrient cycling and storage, provision of habitat for different species of wildlife, and different roles in flood mitigation and erosion control (Environment Canada 2004; Hawes and Smith 2005).

Using buffer zones around wetlands and riparian zones may be practical in conservation planning to account for the interdependence of aquatic and terrestrial ecosystems. The approach that we evaluated underrepresented the proportion of many forest types on the landscape and overrepresented several floodplain, swamp, and peatland land-cover types, as well as bodies of water. Buffers around riparian zones tended to be more similar, in terms of composition of terrestrial ecosystem types, to the UP landscape than were wetlands with buffer zones and therefore may be a better single candidate for conservation planning than wetlands if the only goal is to represent the terrestrial ecosystem types. Although there are limitations to a wetland-only approach, wetland conservation in this type of approach benefits landscape connectivity (Shafer 1995), because wetlands may be important stepping stones between protected areas for dispersing species (Amezaga et al. 2002). Riparian zones, however, provide similar benefits to wildlife by maintaining connectivity across the landscape (Fausch et al. 2002; Hilty and Merenlender 2004) and may be more practical from a mapping perspective because rivers and riparian zones can readily be generated from digital elevation models. Although our approach did not result in perfect representation of the landscape, it represented all types of terrestrial ecosystems and thus ecosystem functions could be protected via application of this approach across the landscape. Furthermore, some over- or underrepresentation of specific types of land-cover classes in our analyses, as determined using the χ² test, may not be biologically significant and may instead reflect the large number of categories we included in our analyses (n = 18 categories). Combining similar types of land-cover classes for the χ² test may have indicated better overall representation of land-cover classes; however, we were interested in examining how well our approach would work for each natural community examined. Combining similar natural community types would have prevented us from identifying potential differences in representation of each natural community on the landscape vs. in our approach, which may have been less informative to conservation planners. Concerns over conservation of specific types of forest and wetland communities may warrant additional and complementa-
ny focus in conservation plans based on wetlands and riparian zones. Implementation of buffers identified in this study may occur through public and private landowners, including through existing incentive programs that help achieve conservation goals associated with the Farm Bill and other natural resources conservation programs and regulations, including filter strip enrollment (e.g., Loftus and Kraft 2003) and Wetlands Reserve Program, Wildlife Habitat Incentives Program, etc. (Gray and Teels 2006).

Future iterations of this or similar approaches may benefit from beginning with small pilot areas to document biodiversity and associated ecological processes at a fine scale before scaling up to the landscape. The size of even the smallest wetland buffers we used may be larger than what is practical at the landscape scale and further work is needed to understand optimum buffer widths across different scales of conservation planning. The addition of algorithms and other decision-support tools (e.g., McConnell and Burger 2011) to assist in cost–benefit analyses (sensu Linke et al. 2008) could fine-tune areas to target for conservation. Furthermore, the most appropriate buffer width at a specific site depends on many other considerations such as soil texture, vegetation species, and slope (Liu et al. 2008). Although a 10-m buffer may help trap sediment, nitrates, and phosphorus and contribute to erosion control on relatively flat topography, the same buffer will not be as effective on steep slopes (Hawes and Smith 2005; Liu et al. 2008). Wider buffers (15–70 m) may prevent pesticides from entering water bodies, provide wildlife habitat, and provide shade and woody debris for streams (Hawes and Smith 2005). Where agricultural and stormwater runoff are especially concerning, combining buffers with other strategies may reduce entry of phosphorus and other contaminants into water bodies (Hawes and Smith 2005). Thus, application of our methods should be considered in the context of local conditions to ensure the best chances of meeting site-specific conservation goals.

As the world changes, no single approach can solve every problem facing conservation planners, but waiting for the perfect plan is not a viable option (Rodrigues et al. 2010). An approach to landscape conservation planning that integrates aquatic and terrestrial ecosystems can simultaneously support ecosystem and biodiversity conservation goals (Chan et al. 2006; Goldman et al. 2008). Our approach provides evidence that conservation of aquatic ecosystems can conserve the full complement of terrestrial ecosystem types, while providing protection to aquatic ecosystems, in essence providing “two-for-one” benefits. The general approach that we used may be practical to ensure that the full complement of terrestrial and aquatic ecosystems gets captured in a conservation plan and may be useful in other areas where wetlands and rivers are, or can easily be, mapped. Benefits associated with this type of approach merit further inquiry at additional spatial scales and in other types of ecosystems.

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References

Amezaga JM, Santamaria L, Green AJ. 2002. Biotic wetland connectivity – supporting a new approach for wetland policy. Acta Oecologica 23:213–222.

Chan KMA, Shaw MR, Cameron DR, Underwood EC, Daily GC. 2006. Conservation planning for ecosystem services. PLoS Biology 4:2138–2152.

Environment Canada. 2004. How much habitat is enough?: a framework for guiding habitat rehabilitation in Great Lakes areas of concern. 2nd edition. Downsview, Ontario, Canada: Environment Canada.

Fausch KD, Torgersen CE, Baxter CV, Li HW. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483–498.

Gawler SC. 2007. Ecological system comprehensive report: Laurentian-Acadian Swamp Systems. Available: https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.723021/Laurentian-Acadian_Alkaline_Fen (May 2021).

Gawler SC. 2009. Ecological system comprehensive report: Laurentian-Acadian Northern Hardwoods Forests. Available: https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.723040/Laurentian-Acadian_Northern_Hardwood_Forest (May 2021).

Goldman RL, Tallis H, Kareiva P, Daily GC. 2008. Field evidence that ecosystem service projects support biodiversity and diversify options. Proceedings of the National Academy of Sciences of the United States of America 105:9445–9448.

Gray RL, Teels BM. 2006. Wildlife and fish conservation through the Farm Bill. Wildlife Society Bulletin 34:906–913.

Harper EB, Rittenhouse TAG, Semlitsch RD. 2008. Demographic consequences of terrestrial habitat loss for pool-breeding amphibians: predicting extinction risks associated with inadequate size of buffer zones. Conservation Biology 22:1205–1215.

Hawes E, Smith M. 2005. Riparian buffer zones: functions and recommended widths. Eightmile River Wild and Scenic Study Committee 15. Available: http://
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eightmileriver.org/appendicies/09c3_Riparian%20Buffer%20Science_YALE.pdf (May 2021).

Henson BL, Brodribb KE, Riley JL. 2005. Great Lakes blueprint for terrestrial biodiversity. Toronto, Ontario, Canada: Nature Conservancy of Canada.

Hilty JA, Merenlender AM. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. Conservation Biology 18:126–135.

Hoekstra JM, Boucher TM, Rickets TH, Roberts C. 2005. Confronting a biome in crisis: global disparities of habitat loss and protection. Ecology Letters 8:23–29.

Hunter M Jr, Dinerstein E, Hoekstra J, Lindemayer D. 2010. A call to action for conserving biological diversity in the face of climate change. Conservation Biology 24:1169–1171.

Joyal LA, McCollough M, Hunter ML. 2001. Landscape ecology approaches to wetland species conservation: a case study of two turtle species in southern Maine. Conservation Biology 15:1755–1762.

Linke S, Norris RH, Pressey RL. 2008. Irreplaceability of river networks: towards catchment-based conservation planning. Journal of Applied Ecology 45:1486–1495.

Liu X, Zhang X, Zhang M. 2008. Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis. Journal of Environmental Quality 37:1667–1674.

Loftus TT, Kraft SE. 2003. Enrolling conservation buffers in the CRP. Land Use Policy 20:73–84.

McConnell M, Burger LW. 2011. Precision conservation: a geospatial decision support tool for optimizing conservation and profitability in agricultural landscapes. Journal of Soil and Water Conservation 66:347–354.

Rodgers JA Jr, Schwikert ST. 2002. Buffer-zone distances to protect foraging and loafing waterbirds from disturbance by personal watercraft and outboard-powered boats. Conservation Biology 16:216–224.

Rodrigues ASL, Andelman SJ, Bakarr MI, Boitani L, Brooks TM, Cowling RM, Fishpool LDC, da Fonseca GAB, Gaston KJ, Hoffmann M, Long JS, Marquet PA, Pilgrim JD, Pressey RL, Schipper J, Sechrest W, Stuart SN, Underhill LG, Waller RW, Watts MEJ, Yan X. 2004. Effectiveness of the global protected area network in representing species diversity. Nature 428:640–643.

Sabo JL, Sponseller R, Dixon M, Gade M, Harms T, Heffernan J, Jani A, Katz G, Soykan C, Watts J, Welte J. 2005. Riparian zones increase regional species richness by harboring different, not more, species. Ecology 86:56–52.

Semlitsch RD, Bodie JR. 2003. Biological criteria for buffer zones around wetlands and riparian and transition zones. Conservation Biology 17:1219–1228.

U.S. Environmental Protection Agency and Government of Canada. 1995. The Great Lakes: an environmental atlas and resource book. 3rd edition. Chicago, Illinois: Great Lakes National Program Office.

U.S. Environmental Protection Agency. 2007. Level III and IV ecoregions of the continental United States. Arlington, Virginia: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency. 2016. Great Lakes facts and figures. Available: https://www.epa.gov/greatlakes/facts-and-figures-about-great-lakes (May 2021).

Vuori K, Jonsuu I. 1996. Impact of forest drainage on the macroinvertebrates of a small boreal headwater stream: do buffer zones protect lotic biodiversity? Biological Conservation 77:87–95.

World Wildlife Fund Canada. 2015. Great Lakes Watershed Report. Toronto, Ontario, Canada: World Wildlife Fund Canada.