

Enhancing ecosystem restoration efficiency through spatial and temporal coordination

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Edited by Richard M. Cowling, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa, and approved April 2, 2015 (received for review December 11, 2014)

In many large ecosystems, conservation projects are selected by a diverse set of actors operating independently at spatial scales ranging from local to international. Although small-scale decision making can leverage local expert knowledge, it also may be an inefficient means of achieving large-scale objectives if piecemeal efforts are poorly coordinated. Here, we assess the value of coordinating efforts in both space and time to maximize the restoration of aquatic ecosystem connectivity. Habitat fragmentation is a leading driver of declining biodiversity and ecosystem services in rivers worldwide, and we simultaneously evaluate optimal barrier removal strategies for 661 tributary rivers of the Laurentian Great Lakes, which are fragmented by at least 6,692 dams and 232,068 road crossings. We find that coordinating barrier removals across the entire basin is nine times more efficient at reconnecting fish to headwater breeding grounds than optimizing independently for each watershed. Similarly, a one-time pulse of restoration investment is up to 10 times more efficient than annual allocations totaling the same amount. Despite widespread emphasis on dams as key barriers in river networks, improving road culvert passability is also essential for efficiently restoring connectivity to the Great Lakes. Our results highlight the dramatic economic and ecological advantages of coordinating efforts in both space and time during restoration of large ecosystems.

freshwater | conservation | connectivity | prioritization

Habitat loss and fragmentation are leading drivers of declining biodiversity and ecosystem services worldwide (1–3). Landscape corridors and dam removals are popular and effective strategies for mitigating fragmentation (4, 5). To implement these projects efficiently, societies around the world are developing regional and even continental-scale plans for restoring ecosystem connectivity (6). These plans set ecosystem-level conservation objectives and identify priority regions for investment, but individual project selection (e.g., a specific dam removal or habitat corridor) is generally dictated by opportunism and politics. When poorly coordinated, these piecemeal mitigation efforts may be an inefficient means of achieving ecosystem-level objectives. Transboundary coordination is known to increase the cost-effectiveness of nature reserve networks (7–9), but the benefits of coordination are likely to be even greater for connectivity efforts in rivers because the dendritic nature of drainage basins makes them highly susceptible to fragmentation (10–12). Migratory fishes, which support major fisheries and ecosystem processes, are particularly vulnerable to life cycle disruption by the millions of dams and road crossings that fragment the world's rivers (13, 14).

Here, we investigate the value of coordinating restoration efforts in space and time to maximize ecological connectivity between the Laurentian Great Lakes and their tributaries. The Great Lakes Basin (GLB) contains 21% of the world's surface freshwater and is home to more than 33.5 million people (15). High societal dependence on lake-derived ecosystem services includes US\$7 billion annually in economic activity related to recreational fishing (16). Historically, breeding migrations of dozens of native fish species

formed an important ecological link between the Great Lakes and their tributaries (17). Today, hundreds of thousands of dams and road culverts partially or fully block historical fish migration routes (18). There is growing investment in removing or modifying these structures, but project selection has been largely opportunistic and driven by local priorities.

Barrier removal projects to restore tributary connectivity are selected and funded by a diverse set of actors operating independently at different spatial scales across the GLB. Most road crossings are managed by counties or states, whereas impacts of dams are addressed at the watershed, state, federal, or even international level. Funding to restore connectivity is often disbursed as small, one-time investments, but large pulses of public investment are occasionally available, as within the \$1.2 billion Great Lakes Restoration Initiative (19). Although connectivity restoration efforts have been piecemeal, the GLB has a long history of collaborative management of shared resources, including binational treaties regarding fisheries, invasive species, and water quality (20). The success of these initiatives demonstrates that large-scale coordination is feasible and that large pulses of spending can be arranged when justified.

We used a return-on-investment framework to analyze potential efficiency gains from coordinating barrier removals at a range of spatial scales (county, tributary, state, lake, nation, or GLB-wide) and temporal scales (a single “pulse” of investment vs. the same amount allocated as a series of 2, 5, or 10 “trickle” investments). Return-on-investment approaches are known to outperform alternative strategies such as purely minimizing

Significance

Societies around the world make massive investments in ecosystem restoration projects to mitigate habitat loss, conserve biodiversity, and boost ecosystem services. We use a return-on-investment framework to assess the value of coordinating restoration efforts in space and time to maximize ecological connectivity between the Laurentian Great Lakes and their tributaries, which are fragmented by hundreds of thousands of dams and road crossings. We show that coordinating restoration efforts across the entire region is nine times more cost-effective than local-scale planning. Similarly, a single lump sum investment is up to 10 times more cost-effective than a series of annual allocations. These dramatic economic and ecological efficiencies provide ample incentive for coordinating conservation efforts across broad spatial and temporal scales.

Author contributions: T.M.N., M.C.F., M.W.D., P.J.D., J.R.O., and P.B.M. designed research; T.M.N., M.C.F., and J.R.O. performed research; M.C.F., M.W.D., and J.R.O. contributed new reagents/analytic tools; T.M.N., J.R.O., and P.B.M. analyzed data; and T.M.N., M.C.F., M.W.D., P.J.D., J.R.O., and P.B.M. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1423812112/-DCSupplemental.

Although our analyses focused on coordination for ecological objectives only, the political realities of infrastructure maintenance may also create opportunities for cost-efficient conservation investments. All infrastructure has a finite life span, and proper maintenance is costly in aggregate. Future investments in maintenance or replacement of dams and road crossings will come from many sources with various objectives, but ecological outcomes will generally be secondary to public use and safety issues. Thus, a promising conservation strategy is to leverage ongoing infrastructure maintenance activities by supporting low-cost, high-return add-ons to infrastructure projects that are already underway for other reasons (18, 25). In addition, using ecological restoration value as a tie-breaker in selection of infrastructure projects might enhance connectivity at no cost whatsoever.

We stress that large-scale coordination does not necessitate purely top-down, centralized planning. Self-organized or facilitated cooperation among local actors can represent a form of large-scale planning, but one that leverages the local resources and expertise that can be crucial for on-the-ground restoration success. In the GLB, numerous locally driven initiatives play essential roles in conservation efforts (24). Large-scale prioritization could complement local efforts by establishing overarching conservation targets and ensuring that individual projects align in ways that reconnect isolated habitats and populations (24, 26, 27). Moreover, we recognize that local-scale decision making is often rooted in unpredictable reductions in the economic or sociopolitical costs of a particular project. Such opportunities can be entirely worthwhile even if they were not prioritized when using standardized cost data.

Our model does not account for tributary habitat conditions, the spatial distribution of beneficiary species, or the likelihood of species invasions, all of which mediate the ecological benefits of barrier removals (28, 29). Unfortunately, these important management considerations have not been systematically mapped across the entire GLB, so they cannot be incorporated into current optimization models. However, previous work elsewhere suggests that, in some cases, project selection is less sensitive to the distribution of beneficiary species than to spatial variation in project costs (30). We also recognize that the decision to remove a specific barrier often involves multiple stakeholders with differing social and economic values and perspectives (31). Although socioeconomic factors often have enormous importance in individual project selection (32), this perspective is difficult to quantify systematically across the entire GLB for purposes of conservation planning. Nevertheless, our general findings on the relative efficiency of large-scale planning are likely to be robust to further consideration of the ecological costs and benefits of particular barrier removals due to statistical averaging of these costs and benefits over the enormous number of barriers in our analysis. Thus, it is unlikely that refining our estimates of removal costs, habitat gains, or other factors would alleviate the disparities in relative cost efficiency between large- and small-scale project selection, or pulsed and trickled funding patterns.

Given that most of the world's large freshwater and terrestrial ecosystems are heavily fragmented (13, 33), our finding that spatial and temporal coordination is critical for maximizing returns on societal investments in restoring connectivity is relevant in many conservation contexts. Moreover, the same concepts and mathematical tools could be applied proactively to minimize the impacts of new roads and dams (34–36). This is a critical conservation problem given estimates that the global road network will increase 60% in length between 2010 and 2050 (36). Similarly, our approach could be adapted to identify cases where it would be beneficial to retain existing barriers or construct new barriers to inhibit the spread of invasive species and pathogens (37). In the GLB, for example, more than 60 barriers have been constructed or modified to control the spread of invasive sea lampreys (38).

Optimization models can also be expanded to account for risk of infrastructure failure or habitat loss under climate change (39). In each of these contexts, our results on restoring aquatic connectivity, and previous work on transboundary coordination in nature reserve networks (7–9), illustrate the benefits of coordinating investments in both space and time. These dramatic economic and ecological efficiencies provide ample incentive for coordinating restoration efforts across broad spatial and temporal scales.

Methods

Optimization Model. We developed a mathematical optimization model that, for a given budget, identifies the portfolio of barrier removal projects that provides the greatest net increase in accessibility-weighted tributary habitat available to migratory fishes. Barrier passability is defined conceptually as the proportion of fish able to pass through or over a barrier while migrating upstream (11). We define the cumulative passability of a barrier as the product of that barrier's passability and the passability of all downstream barriers. Cumulative passability thus represents the probability that a fish can migrate between the Great Lakes and the tributary channel immediately upstream of a barrier. This is equivalent to the definition of "accessibility" in ref. 11. In calculating cumulative passability, we treat successive passage events as independent, which is typical in fish passage prioritization analyses (12). It is not our intent to address performance differences among individual fish based on swimming ability. For the strongest individuals, our passability ratings would be underestimates, or if fatigue leads to diminishing swimming ability with each barrier passed, then our cumulative passability ratings would be overestimates.

Our model extends that of ref. 11 to account for differences in barrier passability ratings and upstream habitat length for multiple species. Specifically, we consider a set of fish guilds, where a guild represents a group of species exhibiting similar swimming abilities and thus having similar likelihood of being capable of passing a particular barrier.

In this study, we only consider projects that restore full passability to a barrier location. We also assume that each barrier has only a single proximate downstream barrier. Our formulation thus omits braided channels, deltas, and artificial connections via drainage channels. This modest simplification is essential for model tractability and captures the large majority of tributary network patterns in our study area.

Given the following decision variables:

$$x_j = \begin{cases} 1 & \text{if artificial barrier } j \text{ is removed (i.e., restored to full passability)} \\ 0 & \text{otherwise} \end{cases}$$

our mathematical formulation of the fish passage barrier removal problem is as follows:

$$\max \sum_{j \in J} \sum_{g \in G} h_{jg} \alpha_{jg} \quad [1]$$

s.t.

$$\alpha_{jg} = \prod_{k \in D_j} (p_{kg}^0 + p_{kg} x_k) \quad \forall j \in J, g \in G \quad [2]$$

$$\sum_{j \in J^{Art}} \sum_{r \in R} c_j x_j \leq b_r \quad \forall r \in R \quad [3]$$

$$x_j \in \{0, 1\} \quad \forall j \in J^{Art} \quad [4]$$

Here, G is the set of all fish guilds, indexed by g ; J is the set of all natural and artificial barriers, indexed by j ; J^{Art} is the subset of artificial barriers; D_j is the set of all barriers downstream from and including j ; R is the set of planning regions, indexed by r ; h_{jg} is the net amount of habitat for guild g between barrier j and its immediate upstream barriers or the range limit for guild g , in stream kilometers; p_{kg}^0 is the initial passability for guild g at barrier j ; p_{jg} is the increase in passability for guild g given mitigation of barrier j ; c_j is the cost of mitigating barrier j , in US dollars; b_r is the available budget for region r , in US dollars; and α_{jg} is the cumulative passability (i.e., accessibility) of barrier j for guild g .

The objective function [1] maximizes total accessibility-weighted habitat upstream of each barrier $h_{jg} \alpha_{jg}$, over all barriers $j \in J$ and guilds $g \in G$. We weighted all guilds equally for the analyses in this paper. Eqs. 2 give the cumulative passability α_{jg} of barrier j for guild g . The passability for guild g at any intervening barrier k in set D_j is simply equal to the initial passability p_{kg}^0 for guild g plus the potential increase in passability $p_{kg} x_k$ for guild g given mitigation of barrier k . Multiplying the passability of all barriers in D_j yields

the cumulative passability of barrier j for guild g . Inequalities [3] specify that the sum of the project costs within a given planning region r cannot exceed the available budget b_r allocated to that region. We modeled budget allocations b_r as proportional to the number of barriers in a region (results in Figs. 2–4) or proportional to human population (results in *SI Methods*). Leftover funds were not carried over to other planning regions or time periods. Last, constraints [4] specify that all barrier mitigation decision variables must be binary.

Note that the above model is nonlinear. An exact linear formulation of the problem was devised by introducing a series of probability chains (40) to evaluate cumulative passability terms [2]. A probability chain is a newly proposed technique from the operations research field for linearizing certain classes of high-order polynomial terms such as [2]. See *SI Methods* for linearization methods and an example return-on-investment analysis using a small fish passage barrier network.

Data and Submodels. Here, we describe data and submodels for the calculation of project costs, passability, and upstream habitat for each of the 238,760 potential barriers in our analysis. For these calculations, we derived geomorphic and road network covariates from widely available spatial datasets using ArcGIS 10.2 (41). We obtained road surface type (paved or gravel/dirt) and road class (interstate highway, regional highway, or local road), where available, from the US Census Bureau's TIGER roads layer (42) and Land Information Ontario's Ontario Road Network (43). We estimated road width by assuming that interstate highways are six lanes wide, regional highways are four lanes wide, and local roads are two lanes wide, and that these three road classes have widths of 25.6 m (84 ft), 18.3 m (60 ft), and 11 m (36 ft), respectively. The stream polylines are a merged dataset derived from the US Geological Survey's National Hydrography Dataset (44) and the Canadian National Hydro Network (45). To ensure all stream network polylines were strictly dendritic, we manually removed braided and artificial channels and then used the Check Network Topology tool in FLOWS, version 9.3 (46), using ArcGIS 10.2. We calculated upstream drainage area at each barrier using a 30×30 -m digital elevation model (47).

Our database of 238,760 structures is a subset of the 276,027 dams and road crossings reported in ref. 18. Our dataset is smaller because we omit barriers on very small drainages that drain directly to the Great Lakes. These smallest drainages were omitted because most barrier removal projects focus on larger tributaries that host spawning migrations of a wider range of species. Although the source barrier dataset is the most comprehensive available for the GLB, it also omits natural barriers (e.g., waterfalls) and dams and road crossings that have not been mapped in federal or state databases. These additional barriers may reduce realized habitat gains relative to those reported here. These data gaps are likely to be systematic, however, such that our core findings on the relative efficiencies of planning at different spatial and temporal scales still hold.

Project Cost. For each of the 238,760 structures in our analysis, we used data on completed project costs (for dams) or estimates of material, labor, and personnel costs (for road crossings) to predict the cost of restoring full passability at a structure. Specifically, we model the cost of removing a dam or the cost of replacing a road-crossing structure with a “fish-friendly” culvert or bridge.

To estimate dam removal costs, we used data from 108 completed dam removal projects in the GLB compiled by American Rivers, a nonprofit organization. Completed projects spanned the period 1965–2013, with 95 of 108 dam removals completed after 1990. To represent historical project costs in 2012 US dollars, we used the Consumer Price Index, an index of inflation published by the US Bureau of Labor Statistics (48). After converting historical project costs to 2012 US dollars, we created a statistical model to predict the cost of removing a dam based on characteristics of that dam. Because our aim was to apply this model to the majority of the 6,692 dams in our dataset, we used as model covariates only those that were widely available for the majority of the dams in the GLB. Dam height was the most consistently available attribute, available for ~75% of dams in our database. Although dam age, purpose and ownership are often important determinants of removal cost, this information is available for only a small subset of the dams in the GLB. Furthermore, we focused solely on infrastructure costs; we did not consider costs associated with removing or mitigating contaminated impounded sediments (4, 29), or the ecological and economic costs of suppressing species invasions into the newly accessible habitat. Accounting for these additional costs could potentially alter the balance of road crossings and dams in optimal project portfolios.

To predict dam removal costs using dam height, we fit a simple linear regression model ($R^2 = 0.30$) to relate dam removal costs, in 2012 US dollars, to the \log_{10} of dam height, in meters:

$$\log_{10}(\text{cost}) = 4.74 + 0.94 \times \log_{10}(\text{height}).$$

We then used this equation to predict dam removal costs for each of the 4,897 dams in our dataset with recorded field-measured height data. For the 1,795 dams for which we had no height information, we assumed that the median dam removal cost (US\$173,032.50) was applicable in lieu of height data. To test whether this assumption affected our results, we compared the value of the objective function calculated using the median dam removal cost to the values of the objective when replacing these cost estimates with one of eight different values in the range \$113,000 (representative of a dam 2.13 m tall) to \$261,000 (representative of a dam 5.22 m tall). The differences in objective function values were less than 1% in all cases, except for the first scenario (setting the removal cost of these 1,795 dams to \$113,000), which was 1.3% different from the results in Fig. 2.

Dams for which we had no height data are very unlikely to be large dams with a removal cost greater than \$261,000. Our database includes height data for all GLB dams within the US National Inventory of Dams, which is stated to include all dams that are equal to or greater than 6 ft (1.83 m) in height and 50 acre-feet (61.7 ML) in storage, as well as all dams that are equal to or greater than 25 ft (7.62 m) in height and exceed 15 acre-feet (18.5 ML) in storage.

For each of the 232,068 road crossings in our analysis, we used data on material and personnel costs to estimate the total cost of replacing the road-crossing structure with a fish-friendly culvert or bridge. The main drivers of project costs are stream width, road width, road fill depth, and road surface. Details are presented in *SI Methods*.

Upstream Habitat. For each of the 238,760 structures in our analysis, we estimated the amount of habitat upstream of that structure by measuring the net tributary length (h_{jg} in the model) between each structure and its nearest set of upstream structures. For this calculation, we used RivEX (49) and ArcGIS 10.2 (41) to sum the distance of all upstream polylines up to the closest set of upstream structures or the river source.

We chose to use tributary length as a measure of habitat because it is a simple metric that integrates restoration benefit across the community of native beneficiary species, whose preferred habitat is patchy and spatially variable across the GLB. Analyses aimed at generating restoration plans for particular species or groups of species are possible using our model by replacing tributary length with more specific estimates of the amount and quality of each habitat type. In each case, the set of priority barriers identified will depend on the set of species chosen and the weightings assigned to those species.

Structure Passability. We assumed that all dams in our analysis had zero passability and that removing a dam would restore full passability. Although a small subset of dams may in reality be partially passable to certain fishes (due to low height or having a fish passage structure), passability data for dams are not consistently available across the GLB. Fish passage structures are absent from most dams in the GLB, and even where present, salmonid-inspired passage structures may not work well for the weak leapers that dominate the native migratory fish assemblage (50).

For road crossings, we assumed that all intersections with streams of Strahler order >4 were likely to be bridges (22) and therefore fully passable to migratory fishes (~7.4% of the road crossings in our analysis). For structures over streams with a Strahler order ≤ 4 , we used structure-specific passability estimates from ref. 22. In brief, field-surveyed data from 2,235 culverts across nine watersheds in the GLB were used to create a statistical model linking culvert passability to geographic information system (GIS)-derived landscape geomorphic covariates. In this model, the passability of a culvert is the product of two independent dimensions, culvert outlet drop and culvert outlet water velocity, each of which is estimated independently using a boosted regression tree model. The predictive power of these models as measured by the area under the receiver operating characteristic curve ranged from 0.64 to 0.69, suggesting reasonable ability to predict passability of road crossings from GIS-derived landscape covariates.

ACKNOWLEDGMENTS. We thank S. Januchowski-Hartley for developing initial barrier maps and passability estimates, and S. Carpenter, M. Guyette, M. Herbert, M. Khoury, and B. Lalasz for helpful comments on the project. Funding was provided by the Upper Midwest and Great Lakes Landscape Conservation Cooperative, The Nature Conservancy's Great Lakes Project, the University of Wisconsin, the David and Lucille Packard Foundation, the University of Michigan Water Center, and the US Fish and Wildlife Service. The findings and conclusions of this article are those of the authors and do not necessarily represent the view of the US Fish and Wildlife Service.

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