Trade-offs between prioritizing road-stream crossing upgrades based on connectivity restoration and erosion risk control

Running title: Prioritizing road-stream crossing for connectivity and erosion control

Hsien-Yung Lin[1*], Kelly F. Robinson[1], Lisa Walter[2]

[1]Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48824, USA; [2]Great Lakes Fishery Commission, Ann Arbor, MI 48105, USA

*Corresponding author: Hsien-Yung Lin, hylin0625@gmail.com

Acknowledgments

This research was funded by the Upper Midwest and Great Lakes Landscape Conservation Cooperative, F16AP00562 and also supported by the USDA National Institute of Food and Agriculture, Hatch project 1012487. We thank D. Shook and A. Beyer for conversations related to barrier removal planning in the Great Lakes. This is publication no. XXX of the Quantitative Fisheries Center.

Abstract

Prioritizing projects to improve cost-effectiveness has become a common practice in natural resources management, especially in selecting sites for river restoration work. Previous studies for prioritizing road-stream crossing upgrade projects either focused on restoring river connectivity or reducing sedimentation, even though crossings can affect connectivity and sedimentation simultaneously. In this study, we simulated site selection to maximize the improvement of connectivity restoration and sedimentation reduction of three prioritization schemes targeting: (1) river connectivity, (2) erosion risk, or (3) both objectives concurrently, and compared the results. Furthermore, we examined the relationships between the cost-effectiveness of prioritizations and watershed characteristics. We found significant differences among the effectiveness of prioritization objectives; thus, trade-offs should be taken into consideration when prioritizing crossings. The incorporation of spatial interdependency among crossings and weighting objectives could significantly change the cost-effectiveness. We also found that splitting the budget and using a portion to individually prioritize each objective could be more cost-effective than using the whole budget to achieve concurrent objectives. Watershed characteristics like size, connectivity- and sedimentation-related factors could be used to help identify effective management for both connectivity restoration and sedimentation control.

Keywords: decision support tools, connectivity, sedimentation, barrier removal, prioritization, road-stream crossing, river restoration, watershed management

Introduction

As one of the major features on human-modified landscapes, roads provide connections that improve the development of remote areas and the quality of human well-being (Forman et al., 2003). However, roads can negatively affect neighboring ecosystems by interrupting biological and hydrological connections (Forman & Alexander, 1998; Raiter, Possingham, Prober, & Hobbs, 2014). For example, road-stream crossings may hinder animal migration, alter hydrological characteristics and sedimentation processes, and degrade habitat quality in river ecosystems (Forman et al., 2003; Januchowski-Hartley et al., 2013). Therefore, the removal or upgrade of road-stream crossings to mitigate the negative effects of roads has become a key issue in river restoration and watershed management (McKay et al., 2016; Warrington et al., 2017).

Prioritization methods can help decision makers allocate resources for restoring watersheds by identifying a set of crossings that, once restored, results in the greatest benefit to the decision maker’s objective(s) for a given budget (Beechie, Pess, Roni, & Giannico, 2008; McKay et al., 2016). Scoring-and-ranking methods have been widely applied to prioritize crossings based on the expected improvement each removal or upgrade project could achieve for either river connectivity restoration (Taylor, Love, Grey, & Knoche, 2002) or sedimentation control (Witmer et al., 2009). These methods can incorporate multiple objectives, are easily understood by managers and stakeholders, and are transparent (i.e., explicitly list all relevant variables, weightings, and how to calculate scores and rank priorities). The spatial interdependence among crossings is a critical consideration for connectivity restoration (Kemp & O'Hanley, 2010). For example, the removal/construction of one road-stream crossing could change the cumulative passability of all upstream crossings in the same river network. However, most scoring-and-ranking methods cannot account for spatial interdependence, and those that attempt to do so (e.g., Martin & Apse, 2013; Nunn & Cowx, 2012) have not been evaluated for performance, compared to other prioritization methods. In contrast, optimization approaches incorporate the spatial interdependence among barriers (King & O'Hanley, 2016), and can help reveal how management scales influence the cost-effectiveness of connectivity restoration projects (Milt et al., 2017; Neeson et al., 2015). Decision support tools have been developed to reduce the requirements for mathematical and programming expertise for applying optimization models to prioritize dams and crossings for connectivity restoration (e.g., OptiPass, O'Hanley, 2015; Fishwerks, Moody et al., 2017).

Previous research has focused on either (1) restoring river connectivity (e.g., scoring-and-ranking: Taylor et al., 2002; optimization: Neeson et al., 2015) or (2) reducing sedimentation (e.g., scoring-and-ranking: Witmer et al., 2009; optimization: Madej, Eschenbach, Diaz, Teasley, & Baker, 2006), but road-stream crossings can affect both factors simultaneously. From reviewing publications on the Web of Science database with keywords "road-stream crossing" and "prioritize" or "restoration", we observed a recent increase of studies in peer-reviewed journals focusing on connectivity since 2009 while more publications addressed sedimentation prior to 2009 (Appendix Fig. 1 and Table 1). The separation of connectivity restoration and sedimentation control was also observed in government protocols for prioritizing crossings in the United States (e.g., connectivity: Clarkin et al., 2003; Hotchkiss & Frei, 2007; Stream Simulation Working Group, 2008; sedimentation: Nonpoint Source Approved and Pending Watershed Plans, Michigan, USA) depending on the primary goal of the management plan. Nevertheless, some protocols prioritize crossings by combining both connectivity and erosion condition with scoring-and-ranking methods (joint method: Great Lakes Road Stream Crossing Inventory Instructions 2011 in North America; Reducing the Impact of Road Crossings on Aquatic Habitat in Coastal Waterways NSW 2005 in Australia). Although the effects of crossings on river connectivity and sedimentation are recognized in watershed restoration plans in Europe (Lindström-Jönsson, Christoffersson, Hallgren, & Ärlebrandt, 2014) and Australia (Rutherfurd, Jerie, & Marsh, 2000), studies and prioritization methods have largely been developed and conducted in North America (Appendix Table 1). Therefore, we see value in better connecting the problem, both connectivity loss and sedimentation caused by road crossings, and the solution by evaluating the performance and unveiling the trade-offs among different prioritization methods.

The removal/upgrade of a road-stream crossing may both improve river connectivity and reduce sedimentation in a watershed regardless of the prioritization objectives or methods. However, there is a lack of understanding regarding how focusing on one objective (e.g., sedimentation control) influences the accomplishment of a second objective (e.g., connectivity restoration). Furthermore, the effectiveness of joint methods on both objectives has not been evaluated.

Our primary goal was to examine the trade-offs between road-stream crossing upgrade prioritizations with different objectives. Specifically, we examined predicted benefits to connectivity restoration and sedimentation reduction after upgrading crossings prioritized by (1) their effects on river connectivity, (2) erosion risk, or (3) both connectivity and erosion risk (joint method) given the same budget. Two types of joint method were used to assess the influence of incorporating effects of downstream crossings (i.e., spatial interdependence) and changing objective weights. We further examined the relationship between prioritization efficiency and watershed characteristics including size and features related to connectivity or erosion conditions. We hypothesized that the joint method would produce a landscape benefit for both connectivity and sedimentation control somewhere between the predicted benefit of either single objective. In addition, incorporating the spatial interdependence among crossings might improve the efficiency of prioritizations, especially for connectivity restoration. We also expected higher efficiency of connectivity restoration or sedimentation reduction when more weights are assigned to either objective. Lastly, while prioritization plans for large watersheds might have higher cost-effectiveness than for small watersheds (Milt et al., 2017; Neeson et al., 2015), watershed characteristics such as the number of dams or erosion condition could also influence the outcome of prioritization plans regardless of objectives used.

Watersheds around Lake Michigan were used as a case study because improving lake-stream connectivity and reducing sedimentation into waterways are critical goals in watershed management plans throughout the Laurentian Great Lakes region (Neeson et al., 2015; Seilheimer, Zimmerman, Stueve, & Perry, 2013). These watersheds also support valuable forestry and agricultural activities, but have been experiencing increased urbanization, a shift which can diminish tributary water quality by increasing sediment and nutrient loading (Seilheimer et al., 2013).

Material and methods

Lake Michigan case study and data acquisition

Lake Michigan, the second largest lake among the five Laurentian Great Lakes, has a drainage area of approximately 44,922 square miles, composed of 32% agriculture, 29% forest, 20% wetlands, and 7% urban land cover (Christiansen, Walker, & Hunt, 2014). The streams around Lake Michigan provide critical spawning habitats for over 40 ecologically and economically important migratory fish species in the lake, such as Walleye (*Sander vitreus*), Lake Sturgeon (*Acipenser fulvescens*), Northern Pike (*Esox lucius*), and Salmonids (Salmonidae) (Moody et al., 2017). However, dams and road-stream crossings have reduced the amount of accessible upstream habitats for fish and other aquatic organisms (Neeson et al., 2015).

We acquired road-stream crossing and sedimentation data from two publicly available decision support tools for this region. The location, upgrade cost, fish passability, size of upstream habitat above barriers (road-stream crossing, dam, and waterfall), and watershed boundaries were downloaded from the Fishwerks website (https://greatlakesconnectivity.org/). Although the upgrade costs in Fishwerks are calculated primarily for restoring connectivity, the data also include some estimates relevant to road-stream crossing upgrade projects for sedimentation control, such as the cost for road surfacing, excavating, and upgrading culverts to bridges (Neeson et al., 2015). Estimated annual erosion data were downloaded from the High Impact Targeting website (http://www.iwr.msu.edu/hit2/), in which the estimates are calculated by RUSLE (Revised Universal Soil Loss Equation, Renard, Foster, Weesies, McCool, & Yoder, 1996) to produce 30-meter resolution raster data (tons/900 m^2/year). We extracted erosion estimates at the location of crossings from raster layers to represent the relative erosion scores at sites with QGIS 3.0.0 (QGIS Development Team, 2018).

Road-stream crossing prioritization

Four methods were used to compare the effectiveness of prioritizations (Table 1), in which integer linear programming (ILP) was used to prioritize crossings and the scoring-and-ranking method was used to combine two objectives for the joint method. First, we prioritized road-stream crossings to maximize the cumulative accessible habitat for fishes moving from Lake Michigan ("connectivity prioritization" hereafter). Cumulative passability was calculated as the product of the passability rating (between 0: impassable and 1: fully passable) of a particular barrier (e.g., dam, crossing, or waterfall) and all downstream barriers. Then, the length of river segment (i.e., habitat) above this barrier was multiplied by the cumulative passability to produce a value describing the cumulative accessible habitat. The Fishwerks tool identifies passability ratings for fish with strong, moderate, and weak swimming ability (Moody et al., 2017). Because our primary intent is not to address the influence of fish with different swimming abilities, the passability ratings for moderate swimmers were chosen here to represent a general scenario. We used OptiPass v. 1.1 (O'Hanley, 2015) to select a set of crossings that maximized the summed cumulative accessible habitat value for a given budget.

Our second method was to minimize sedimentation from road-stream crossings. Road-stream crossings were selected based on their erosion scores, assuming that crossings with greater erosion scores contribute more sediment to tributaries, and thus should be a high priority for upgrade ("erosion prioritization" hereafter).

Finally, scoring-and-ranking methods were used to represent two types of joint methods that considered both connectivity and erosion status. The first type of joint method was derived from protocols in North America and Australia (joint method, as in Great Lakes Road Stream Crossing Inventory Instructions 2011 and Reducing the Impact of Road Crossings on Aquatic Habitat in Coastal Waterways NSW 2005), in which only the passability of individual crossings was considered. For this method (“joint prioritization” hereafter), all erosion scores and passability ratings of crossings across the Lake Michigan basin were standardized to percent scales between 100 (priority value: greatest value of erosion and lowest value of passability) and 0 (least priority value: lowest value of erosion and greatest value of passability). Subsequently, we weighted both standardized values by 0.5 and summed them together for every crossing to produce a final rank. The second type of joint method (“joint D prioritization” hereafter) was derived from the prioritization used in the United Kingdom (Nunn & Cowx, 2012), which considers the effect of downstream crossings. In this comparison, the crossing that produces the greatest improvement in cumulative passability after upgrade was the highest priority (O’Hanley, 2015). The standardized percent scale of cumulative passability improvement was summed with the standardized erosion score for every crossing. Three weighting systems were applied on joint D prioritization: 0.25 on erosion score and 0.75 on cumulative passability ("joint D S25" hereafter), 0.5 on both ("joint D S50" hereafter), and 0.75 on erosion score and 0.25 on cumulative passability ("joint D S75" hereafter). The prioritizr package (Hanson et al., 2017) in R (R Core Team, 2017) using Gurobi solver (Gurobi Optimization, Inc., 2016) was used to select sets of road-stream crossings that produced the greatest total erosion scores (for erosion prioritization) or combined rank value (for joint and joint D prioritization) for a given budget.

We performed all prioritizations (connectivity, erosion, joint, joint D S25, joint D S50, and joint D S75) across the entire Lake Michigan basin to examine the trade-offs among objectives, prioritization methods, and objective weights. Subsequently, we conducted prioritizations for individual watersheds within the basin to explore the relationship between watershed characteristics and cost-effectiveness. Based on data downloaded from Fishwerks, watersheds with fewer than 20 crossing records (*n* = 328), or those with an impassable dam near the river mouth (e.g., Manistique and Menominee watersheds; *n* = 18) were excluded from individual analysis, because we focused specifically on connectivity for lake-stream migratory fish. Only road-stream crossings could be selected for prioritization, but the effect of dams was included when calculating watershed connectivity. For example, although upgrading crossings upstream of impassable dams might reduce overall sedimentation, it could not improve the connectivity between upstream tributaries and Lake Michigan. Overall, 44 watersheds were analyzed individually, with numbers of barriers in a watershed ranging from 22 – 4463 (Appendix Fig. 2).

The effectiveness was defined as the predicted improvement in connectivity (i.e., the increase of accessibility-weighted habitat) and sedimentation reduction (i.e., the decrease of total erosion scores) if the suite of selected crossings were to be upgraded. We assumed that the selected crossings would become fully passable for aquatic species and reduce the erosion value to 0. First, we prioritized road-stream crossings throughout the entire Lake Michigan basin, given a range of budgets between 1-100 million US dollars (USD) to compare the cost-effectiveness (i.e., effectiveness per 1 million USD) among prioritizations with different methods (Table 1). For comparison purposes, we split the budget into two parts and allocated them sequentially to connectivity and erosion prioritizations (i.e., 0:10, 1:9, 2:8, 3:7, …, 9:1, 10:0) to produce a type of Pareto front curve on which both objectives were optimized. We compared the performances of joint and joint D prioritizations with different weightings with the budget splitting curve given a 100 million USD budget.

Second, we calculated the effectiveness of a 1 million USD budget for 44 individual watersheds by examining the relationship between cost and four different watershed characteristics: (1) planning scale (watershed size: the number of barriers in a watershed), (2) the proportion of impassable dams among all barriers, (3) average erosion scores, and (4) maximum erosion scores. We only considered the effect of dams because one waterfall was found among 20,249 barriers in the 44 selected watersheds. The correlation between cost-effectiveness and each watershed characteristic was calculated with Kendall tests because most data were not normally distributed. Subsequently, we separated the 44 watersheds into groups based on the first and third quartile of values for each characteristic. Eight groups were analyzed, which included watersheds with a high (>300, $n = 11$) or low (<100, $n = 18$) number of barriers, a high (> 0.04, $n = 12$) or low (< 0.03, $n = 24$) proportion of impassable dams, high (> 0.08, $n = 13$) or low (< 0.04, $n = 17$) average erosion scores, and high (> 0.08, $n = 15$) or low (< 0.04, $n = 14$) maximum erosion scores. Kruskal-Wallis tests and pairwise Wilcoxon tests were applied to examine the differences in cost-effectiveness when prioritizing crossings with different methods in watershed groups. All statistical analyses were conducted in R 3.4.2 (R Core Team, 2017).

Results

Trade-offs among prioritizations across the entire lake basin

While larger budgets produced greater connectivity restoration and sedimentation reduction (Appendix Fig. 3), the cost-effectiveness of connectivity restoration and sedimentation reduction varied substantially among prioritizations with different methods (Fig. 1). Prioritizing crossings based on connectivity produced the greatest cost-effectiveness for connectivity restoration, followed by joint D prioritization with greater weight on connectivity (joint D S25). The joint D S50, joint D S75, joint, and erosion prioritizations resulted in lower cost-effectiveness for connectivity restoration (Fig. 1a, overall $p < 0.005$). Similarly, the cost-effectiveness of sedimentation reduction was greatest in erosion prioritization, followed by joint D and joint prioritizations, then connectivity prioritization (Fig. 1b, overall $p < 0.005$). Although joint and joint D prioritizations led to increases in connectivity and sedimentation reduction, these schemes resulted in a greater return on sedimentation reduction than on connectivity (Figs. 1, 2 and Appendix Fig. 3). Joint D prioritizations, regardless of weightings, performed significantly better at optimizing both connectivity and sedimentation control than joint prioritization (Fig. 2). Nevertheless, both joint methods had lower cost-effectiveness than budget splitting, especially for connectivity restoration. Because the joint prioritization performed poorly in achieving both connectivity restoration and sedimentation reduction (Fig. 2), this prioritization was not included in the following results for individual watersheds.

Trade-offs among prioritizations for individual watersheds

For 44 selected watersheds, connectivity prioritization yielded significantly greater cost-effectiveness for connectivity restoration than joint D and erosion prioritizations ($p < 0.005$). Whereas no significant difference was observed among three joint D prioritizations with different weightings, the cost-effectiveness of connectivity restoration was significantly lower ($p < 0.05$) for erosion prioritization than all other prioritizations. In contrast, only connectivity prioritization displayed significantly lower cost-effectiveness for sedimentation reduction than all other prioritizations ($p < 0.005$), whereas no significant difference was found among erosion and three joint D prioritizations.

The relationship between watershed characteristics and cost-effectiveness

Planning scale (watershed size)

The total number of barriers in a watershed was a significant factor influencing cost-effectiveness in most cases (Appendix Table 2). The cost-effectiveness of connectivity restoration was positively correlated with the number of barriers ($r = 0.31$) for connectivity prioritization but negatively correlated for erosion prioritization ($r = -0.35$). The cost-effectiveness of sedimentation reduction showed positive correlations ($r = 0.63$ for erosion, 0.58 for joint D) with the total number of barriers in the watershed.

In watersheds with large numbers of barriers, connectivity prioritization produced the greatest cost-effectiveness in connectivity restoration but the lowest cost-effectiveness in sedimentation reduction (Figs. 3a and 3c). Joint D prioritizations yielded greater cost-effectiveness in connectivity restoration than erosion prioritization in watersheds with large numbers of barriers (Fig. 3a) but not in watersheds with fewer barriers (Fig. 3c). The differences in the cost-effectiveness among prioritizations became smaller (Fig. 3b) or even insignificant (Fig. 3d) for watersheds with fewer barriers.

Proportion of impassable dams

No significant relationship was found between the proportion of impassable dams and connectivity prioritization (Appendix Table 2). The proportion of impassable dams was negatively associated with the cost-effectiveness of connectivity restoration (r = -0.37 and -0.24) and positively associated with the cost-effectiveness of sedimentation reduction (r = 0.38 and 0.36) under erosion and joint D prioritization. Connectivity prioritization produced the greatest cost-effectiveness in connectivity restoration, followed by joint D S25, regardless of the proportion of impassable dams (Figs. 4a and 4b). For sedimentation reduction, lower cost-effectiveness was only observed for connectivity prioritization in watersheds with a high proportion of impassable dams (Figs. 4c and 4d).

Average erosion scores

Greater cost-effectiveness of sedimentation reduction was recorded in watersheds with greater average erosion scores regardless of prioritization methods (Appendix Table 2). In contrast, the cost-effectiveness of connectivity restoration was negatively associated with the average erosion scores across methods. The differences in the cost-effectiveness of connectivity restoration among prioritizations increased in watersheds with lower average erosion scores (Figs. 5a, 5b), however, the differences in sedimentation reduction among prioritizations decreased (Figs. 5c, 5d). No significant difference was found among joint D and erosion prioritizations for sedimentation reduction across erosion scores (Figs. 5c and 5d).

Maximum erosion scores

Strong and positive correlations were found between the maximum erosion score in watersheds and the cost-effectiveness of sedimentation reduction, especially under erosion and joint D prioritizations (*r* = 0.82, 0.79, Appendix Table 2). However, negative relationships were found between the erosion score and the cost-effectiveness of connectivity restoration, except for connectivity prioritization (Appendix Table 2). Connectivity prioritization yielded the highest cost-effectiveness in connectivity restoration and the lowest cost-effectiveness in sedimentation reduction regardless of erosion scores (Fig. 6). Using joint D prioritizations to improve the cost-effectiveness was more significant for connectivity restoration (Figs. 6a, 6b) than sedimentation reduction (Figs. 6c, 6d). The differences among prioritization methods were lower in watersheds with lower maximum erosion scores (Figs. 6b, 6d) compared to watersheds with higher scores (Figs. 6a, 6c).

Discussion

Significant differences were found among prioritization methods based on connectivity, sedimentation reduction, or both objectives across a range of budgets and watershed characteristics in the Lake Michigan basin. As expected, simulated prioritizations targeting river connectivity and erosion risk produced the greatest effectiveness for connectivity restoration and sedimentation reduction, respectively. Although the removal/upgrade of one road-stream crossing may improve the connectivity and mitigate the sedimentation at the restored site, the benefit to the non-target objective was relatively marginal, especially at a large scale (i.e., Lake Michigan basin and watersheds with > 300 barriers).

Differences in Restoring Connectivity and Reducing Sedimentation

The fundamental differences among prioritization outcomes might result from the difference between (1) the spatial distribution of “sedimentation reduction-” and “connectivity-” important crossings, and (2) the structure of optimization algorithms. The location and passability of crossings are key factors influencing watershed connectivity (Kemp & O’Hanley, 2010). Therefore, crossings that were prioritized for connectivity restoration for migratory fish were generally located lower in the watershed. In contrast, the amount of sedimentation at a crossing depends on local rainfall, soil type, landscape characteristics (slope length, steepness, and land-cover), and erosion control practice (Renard et al., 1996), and thus, these high priority crossings have a more scattered distribution. These differences might be more evident at large scales because larger scales contain more spatial heterogeneity among crossings, leading to fewer crossings simultaneously being a priority for both objectives. Our results indicated that incorporating the effect of downstream crossings and weightings into scoring-and-ranking could significantly improve cost-effectiveness for both objectives. Although this method might reduce the trade-offs between restoring connectivity and reducing sedimentation, the improvement that occurred in connectivity was usually more limited than for sedimentation reduction.

The ability to account for dynamic connectivity during the prioritization process is the key to finding the optimal solution for connectivity restoration (O'Hanley, 2015). The difference between the prioritizr package and OptiPass is that the algorithm in prioritizr selects crossings only based on the fixed rank we produced before selection, whereas the algorithm in OptiPass recalculates the cumulative passability for all crossings after each crossing was selected. Failing to consider this dynamic could result in less effective outcomes even if connectivity-related factors, such as passability or the effect of downstream barriers, are incorporated using scoring-and-ranking methods. However, existing optimization models that incorporate dynamics among barriers generally lack the functionality of incorporating non-connectivity related targets into prioritization. Developing optimization methods that can prioritize crossings for connectivity and non-connectivity related targets would benefit watershed restoration planners.

Management implications

Our simulated prioritization in watersheds around Lake Michigan provided some management guidelines. First, when planning road-stream crossing prioritization in small watersheds or watersheds with few barriers, prioritizing crossings to maximize river connectivity might be preferable to the erosion or joint prioritization methods because it could provide the best outcome in connectivity restoration and a fair outcome in sedimentation reduction. This is because (1) the proportions of road-stream crossings that were considered as priorities for both connectivity and sedimentation control among all crossings were greater in watersheds with fewer barriers, and (2) the simulated connectivity restoration was very sensitive to the spatial interdependence among crossings while the effectiveness of sedimentation reduction was not. Second, impassable dams in the watershed should be taken into consideration even when those dams will not be prioritized for removal. Greater connectivity could be achieved regardless of prioritization objectives in watersheds with fewer impassable dams. Third, the prioritization method used in this study for sedimentation control was more sensitive to watershed characteristics than the method for connectivity restoration. For example, while prioritization plans for large watersheds generally resulted in higher cost-effectiveness of connectivity restoration than prioritization plans for small watersheds (*r* = 0.31), the positive correlation between watershed size and the cost-effectiveness of sediment reduction was even stronger (*r* = 0.63) than the correlation for connectivity restoration. Lastly, although joint D prioritization performed better than joint prioritization in achieving both objectives, optimizing each connectivity and non-connectivity related objective separately could produce a greater outcome than combining different objectives into a single objective, as in scoring-and-ranking methods. We also acknowledge that while the joint methods perform relatively poorly at improving connectivity for migratory fish, the removal of mid- and upstream barriers with low passability might benefit resident fish species (King, O'Hanley, Newbold, Kemp, & Diebel, 2017).

In addition to objectives used in optimization models, socio-economic and political factors often influence the prioritization of watershed management actions and reduce the applicability of "optimized" solutions (McKay et al., 2016; Patterson, Smith, & Bellamy, 2013). Resource availability, construction logistics, and landowner's permission are all critical factors that influence where and when to implement management actions in the Lake Michigan basin (Shook, D. [Grand Traverse Band of Ottawa and Chippewa Indians] and Beyer, A. [Conservation Resource Alliance], personal communication) and previous studies (Fleeger & Becker, 2008; Koontz & Newig, 2014; Patterson et al., 2013). These factors are often highly contextual and difficult to quantify or integrate into prioritization exercises (Langford & Shaw, 2014; McKay et al., 2016). Furthermore, decision makers and stakeholders might hold competing objectives. Applying a structured decision making framework is suggested to help address socio-economic issues and stakeholders' interests before running optimization models (Gregory et al., 2012; ; Lin, Robinson, Jones, & Walter, 2019).

Model assumptions and limitations

We acknowledge that local inventories of road-stream crossings are available in some watersheds (e.g., http://www.northernmichiganstreams.org/rsxinfo.asp) and these inventories likely provide greater accuracy compared to the regional database that estimated local parameters from remote sensing data with lower resolution. However, the differences in collected information (e.g., the cost, upstream habitat, or passability data are not always available in local inventories), field survey methods and protocols among inventories and watersheds make it difficult to combine local databases for basin-wide analysis. Furthermore, while most road-stream inventories only record the erosion estimate directly at each crossing, the erosion risk in the surrounding area might also provide important information for prioritizing upgrades considering the long-term and large-scale sedimentation input. Nevertheless, the accuracy and quality of input data could influence the performance of prioritization models.

In addition to connectivity restoration, the spatial interdependency among crossings might also influence the priority of sedimentation control projects. For example, controlling sedimentation at upstream crossings may reduce the amount of cumulative sediments at downstream crossings. Although this downstream effect has not been incorporated in the current study nor in previous studies (Madej et al., 2006; Witmer et al., 2009), the influence of sedimentation might be limited in a few nearby downstream crossings, and this effect declines with distance. Further studies on sediment transportation will be required to improve the effectiveness of crossing prioritization.

Conclusions

This study quantified the differences in the effectiveness among different prioritizations that target sedimentation control, river connectivity, and both. While different spatial distributions of sedimentation- and connectivity-related factors and the structure of optimization algorithms make it difficult to find a win-win solution, watershed characteristics could be used to provide a general direction. Watershed and natural resources managers, stakeholders, and decision makers should express their preferences, optimize objectives that interest them the most, and explicitly discuss trade-offs among objectives. By evaluating decision support tools using management relevant objectives, these studies could ultimately improve the usefulness of these tools (Lin, Robinson, Milt, & Walter, 2019).

Data Availability Statement

The data that support the findings of this study are openly available in online databases Fishwerks (https://greatlakesconnectivity.org/) and High Impact Targeting (http://www.iwr.msu.edu/hit2/).

Reference

Beechie, T., Pess, G., Roni, P., & Giannico, G. (2008). Setting river restoration priorities: a review of approaches and a general protocol for identifying and prioritizing actions. *North American Journal of Fisheries Management*, *28*(3), 891–905. https://doi.org/10.1577/M06-174.1

Christiansen, D. E., Walker, J. F., & Hunt, R. J. (2014). *Basin-scale simulation of current and potential climate changed hydrologic conditions in the Lake Michigan basin, United States*. U.S. Geological Survey Scientific Investigations Report 2014–5175. https://doi.org/http://dx.doi.org/10.3133/sir20145175

Clarkin, K., Connor, A., Furniss, M., Gubernick, B., Love, L., Moynan, K., & Wilson Musser, S. (2003). *National inventory and assessment procedure for identifying barriers to aquatic organism passage at road-stream crossings*. San Dimas, CA, USA.

Fleeger, W. E., & Becker, M. L. (2008). Creating and sustaining community capacity for ecosystem-based management: Is local government the key? *Journal of Environmental Management*, *88*(4), 1396–1405. https://doi.org/10.1016/J.JENVMAN.2007.07.018

Forman, R. T., Sperling, T. D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V. H., … Winter, T. C. (2003). *Road ecology : science and solutions*. Washington, DC.: Island Press. Retrieved from http://catalog.lib.msu.edu/record=b3992792~S39a

Forman, R. T. T., & Alexander, L. E. (1998). Roads and their major ecological effects.

Annual Review of Ecology and Systematics, *29*(1), 207–231. https://doi.org/10.1146/annurev.ecolsys.29.1.207

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., & Ohlson, D. (2012). *Structured decision making*. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781444398557

Hanson, J., Schuster, R., Morrell, N., Strimas-Mackey, M., Watts, M., Arcese, P., Bennett, J., Possingham, H. (2017). prioritizr: systematic conservation prioritization in R, Version 3.0.3.

Hotchkiss, R. H., & Frei, C. M. (2007). *Design for fish passage at roadway-stream crossings: synthesis report*. McLean, Virginia, USA.

Januchowski-Hartley, S. R., McIntyre, P. B., Diebel, M., Doran, P. J., Infante, D. M., Joseph, C., & Allan, J. D. (2013). Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. *Frontiers in Ecology and the Environment*, *11*(4), 211–217. https://doi.org/10.1890/120168

Kemp, P. S., & O'Hanley, J. R. (2010). Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. *Fisheries Management and Ecology*, *17*(4), 297–322. https://doi.org/10.1111/j.1365-2400.2010.00751.x

King, S., & O'Hanley, J. R. (2016). Optimal fish passage barrier removal-revisited. *River Research and Applications*, *32*(3), 418–428. https://doi.org/10.1002/rra.2859

King, S., O’Hanley, J. R., Newbold, L. R., Kemp, P. S., & Diebel, M. W. (2017). A toolkit for optimizing fish passage barrier mitigation actions. *Journal of Applied Ecology*, *54*(2), 599–611. https://doi.org/10.1111/1365-2664.12706

Koontz, T. M., & Newig, J. (2014). From planning to implementation: top-down and bottom-up approaches for collaborative watershed management. *Policy Studies Journal*, *42*(3), 416–442. https://doi.org/10.1111/psj.12067

Langford, T. E. L., & Shaw, P. J. (2014). Socio-economic, commercial and political factors in river recovery and restoration: has ecology taken a back seat? *Freshwater Reviews*, *7*(2), 121–138. https://doi.org/10.1608/FRJ-7.2.787

Lin, H., Robinson, K. F., Jones, M. L., Walter, L. (2019). Using structured decision making to overcome scale mismatch challenges in barrier removal for watershed restoration. *Fisheries, 44*(11), 545–550. https://doi.org/10.1002/fsh.10342

Lin, H., Robinson, K. F., Milt, A., Walter, L. (2019). The application of web-based decision support tools and the value of local information in prioritizing barrier removal, a case study in northwest lower Michigan, USA. *Journal of Great Lakes Research, 45*(2), 360-370. https://doi.org/10.1016/j.jglr.2019.01.008

Lindström-Jönsson, E., Christoffersson, P., Hallgren, P., & Ärlebrandt, K. (2014). *Ecologically adapted stream crossings for forest roads − a guide (for planning and construction)*. Swedish Forest Agency. Retrieved from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=REMIBAR_Manual_EN.pdf

Madej, M. A., Eschenbach, E. A., Diaz, C., Teasley, R., & Baker, K. (2006). Optimization strategies for sediment reduction practices on roads in steep, forested terrain. *Earth Surface Processes and Landforms*, *31*(13), 1643–1656. https://doi.org/10.1002/esp.1436

Martin, E. H., & Apse, C. D. (2013). *Chesapeake fish passage prioritization: an assessment of dams in the Chesapeake Bay watershed*. The Nature Conservancy, Eastern Division Conservation Science. Retrieved from http://easternbrooktrout.org/resources/science-publications/chesapeake-fish-passage-prioritization-an-assessment-of-dams-in-the-chesapeake-bay-watershed

McKay, S. K., Cooper, A. R., Diebel, M. W., Elkins, D., Oldford, G., Roghair, C., & Wieferich, D. (2016). Informing watershed connectivity barrier prioritization decisions: a synthesis. *River Research and Applications*, *33*, 847–862. https://doi.org/10.1002/rra.3021

Milt, A. W., Doran, P. J., Ferris, M. C., Moody, A. T., Neeson, T. M., & McIntyre, P. B. (2017). Local-scale benefits of river connectivity restoration planning beyond jurisdictional boundaries. *River Research and Applications*, *33*(5), 788–795. https://doi.org/10.1002/rra.3135

Moody, A. T., Neeson, T. M., Wangen, S., Dischler, J., Diebel, M. W., Milt, A., … McIntyre,

P. B. (2017). Pet project or best project? online decision support tools for prioritizing barrier removals in the Great Lakes and beyond. *Fisheries*, *42*(1), 57–65. https://doi.org/10.1080/03632415.2016.1263195

Neeson, T. M., Ferris, M. C., Diebel, M. W., Doran, P. J., O'Hanley, J. R., & McIntyre, P. B. (2015). Enhancing ecosystem restoration efficiency through spatial and temporal coordination. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(19), 6236–41. https://doi.org/10.1073/pnas.1423812112

Nunn, A. D., & Cowx, I. G. (2012). Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys. *Ambio*, *41*(4), 402–409.

O'Hanley, J. R. (2015). *OptiPass: The migratory fish passage optimization tool, version 1.1 user manual.* Ecotelligence LLC, Portland, OR, USA.

Patterson, J. J., Smith, C., & Bellamy, J. (2013). Understanding enabling capacities for managing the 'wicked problem' of nonpoint source water pollution in catchments: A conceptual framework. *Journal of Environmental Management*, *128*, 441–452. https://doi.org/10.1016/J.JENVMAN.2013.05.033

Raiter, K. G., Possingham, H. P., Prober, S. M., & Hobbs, R. J. (2014). Under the radar: mitigating enigmatic ecological impacts. *Trends in Ecology & Evolution*, *29*(11), 635–644. https://doi.org/10.1016/J.TREE.2014.09.003

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1996). *Predicting soil erosion* *by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. USDA, Agriculture Handbook Number 703.

Rutherfurd, I. D., Jerie, K., & Marsh, N. (2000). *A rehabilitation manual for Australian streams VOLUME 1*. Land and Water Resources Research and Development Corporation and Cooperative Research Centre for Catchment Hydrology, Monash University, Canberra. Retrieved from www.lwrrdc.gov.au

Seilheimer, T. S., Zimmerman, P. L., Stueve, K. M., & Perry, C. H. (2013). Landscape-scale modeling of water quality in Lake Superior and Lake Michigan watersheds: How useful are forest-based indicators? *Journal of Great Lakes Research*, *39*, 211–223. https://doi.org/10.1016/j.jglr.2013.03.012

Stream Simulation Working Group. (2008). *Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings*. US Department of Agriculture Forest Service San Dimas Technology and Development Center. Retrieved from https://www.fs.fed.us/eng/pubs/pdf/StreamSimulation/hi_res/ FullDoc.pdf

Taylor, R. N., Love, M., Grey, T. D., & Knoche, A. L. (2002). *Final report: Trinity County culvert inventory and fish passage evaluation*. Trinity County Planning Department, Natural Resources Division, Hayfork, California. Retrieved from https://www.researchgate.net/publication/228987516_Final_Report_Trinity_County_Culvert_Inventory_and_Fish_Passage_Evaluation

Warrington, B. M., Aust, W. M., Barrett, S. M., Ford, W. M., Dolloff, C. A., Schilling, E. B., … Bolding, M. C. (2017). Forestry best management practices relationships with aquatic and riparian fauna: a review. *Forests*, *8*(9), 331. https://doi.org/10.3390/f8090331

Witmer, P. L., Stewart, P. M., & Metcalf, C. K. (2009). Development and use of a sedimentation risk index for unpaved road-stream crossings in the Choctawhatchee watershed. *JAWRA Journal of the American Water Resources Association*, *45*(3), 734–747. https://doi.org/10.1111/j.1752-1688.2009.00319.x

Data citaion

[dataset] Moody, A. T., Neeson, T. M., Wangen, S., Dischler, J., Diebel, M. W., Milt, A., Herbert, M., Khoury, M., Yacobson, E., Doran, P. J., Ferris, M. C., O'Hanley, J. R., & McIntyre, P. B. (2015). Fishwerks. https://greatlakesconnectivity.org/

[dataset] O’Neil, G., Salveta, T., Hanselman, T., Lindeman, L., & Switzer, J. (2009). High Impact Targeting. http://www.iwr.msu.edu/hit2/

Tables

Table 1. Prioritization methods and evaluation metrics for simulated road-stream crossing upgrades in Lake Michigan tributaries.

Prioritization Methods	**Evaluation Metric**
Connectivity prioritization: Maximizing accessibility-weighted habitat for species moving upstream from Lake Michigan	The increase in total accessibility-weighted habitat
Erosion prioritization: Minimizing the total erosion score	The reduction of the total erosion score
Joint prioritization: Minimizing the total erosion score while maximizing the overall passability (with weight 0.5 on both erosion scores and passability)	The reduction of the total erosion score and the increase in total accessibility-weighted habitat
Joint D prioritization: Minimizing the total erosion score while maximizing the overall downstream cumulative passability (with weight 0.25 on erosion scores and 0.75 on cumulative passability: joint D S25; 0.5 on both: joint D S50; 0.75 on erosion scores and 0.25 on cumulative passability: joint D S25)	The reduction of the total erosion score and the increase in total accessibility-weighted habitat

Figure legends

Fig. 1. Cost-effectiveness (CE) of connectivity restoration (a) and sedimentation reduction (b) among prioritization methods for the Lake Michigan basin. Significant differences were found among most groups except between joint D S25 and joint D S50 in panel (a) and between joint and joint D S50, between joint D S50 and joint D S75, and between joint D S75 and erosion in panel (b).

Fig. 2. The curve of sequential budget splitting for connectivity and erosion prioritization (circles) and the effectiveness of joint (square) and joint D prioritizations with different weightings (triangles) given a total 100 USD million budget.

Fig. 3. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with a high (> 300; $n = 11$) or low (< 100; $n = 18$) number of barriers. Horizontal lines on the bottom of each plot represent significant ($p < 0.05$, solid) differences between objectives.

Fig. 4. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with a high (> 0.04; $n = 12$) or low (< 0.03; $n = 24$) proportion of impassable dams among all barriers. Horizontal lines on the bottom of each plot represent significant ($p < 0.05$, solid) or near significant ($0.05 < p < 0.1$, dotted) differences between objectives.

Fig. 5. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with high (> 0.08; *n* = 13) or low (< 0.04; *n* = 17) average erosion scores. Horizontal lines on the bottom of each plot represent significant (*p* < 0.05, solid) or near significant (0.05 < *p* < 0.1, dotted) differences between objectives.

Fig. 6. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with high (> 1.6; *n* = 15) or low (< 0.5; *n* = 14) maximum erosion scores. Horizontal lines on the bottom of each plot represent significant (*p* < 0.05, solid) or near significant (0.05 < *p* < 0.1, dotted) differences between objectives.

Trade-offs between prioritizing road-stream crossing upgrades based on connectivity restoration and erosion risk control

Hsien-Yung Lin[1*], Kelly F. Robinson[1], Lisa Walter[2]

[1]Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48824, USA; [2]Great Lakes Fishery Commission, Ann Arbor, MI 48105, USA

*Corresponding author: hylin0625@gmail.com

Appendix

Table 1. Articles published in peer-reviewed journals on ISI Web of Science between 1996 (January) and 2018 (June) using keywords "road stream crossing" with "restoration" or "prioritize".

Primary focus	Year	Description
Connectivity	2018	Fitzpatrick KB, Neeson TM. Aligning dam removals and road culvert upgrades boosts conservation return-on-investment. Ecological Modelling. 368: 198-204
	2018	Nathan LR, Smith AA, Welsh AB, Vokoun JC. Are culvert assessment scores an indicator of Brook Trout *Salvelinus fontinalis* population fragmentation? Ecological Indicators. 84: 208-217
	2017	King S, O'Hanley JR, Newbold LR, Kemp PS, Diebel MW. A toolkit for optimizing fish passage barrier mitigation actions. Journal of Applied Ecology. 54: 599-611
	2017	Moody AT, Neeson TM, Wangen S, Dischler J, Diebel MW, Milt A, Herbert M, Khoury M, Yacobson E, Doran PJ, Ferris MC, O'Hanley JR, McIntyre PB. Pet Project or Best Project? Online Decision Support Tools for Prioritizing Barrier Removals in the Great Lakes and Beyond. Fisheries. 42: 57-65.
	2016	Maitland BM, Poesch M, Anderson AE. Prioritising culvert removals to restore habitat for at-risk salmonids in the boreal forest. Fisheries Management and Ecology. 23: 489-502
	2015	Chelgren ND, Dunham JB. Connectivity and conditional models of access and abundance of species in stream networks. Ecological Applications. 25: 1357-1372
	2015	Diebel MW, Fedora M, Cogswell S, O'Hanley JR. Effects of Road Crossings on

		Habitat Connectivity for Stream-Resident Fish. River Research and Applications. 31: 1251-1261
	2015	Evans NT, Riley CW, Lamberti GA. Culvert Replacement Enhances Connectivity of Stream Fish Communities in a Michigan Drainage Network. Transactions of the American Fisheries Society. 144: 967-976
	2014	David BO, Tonkin JD, Taipeti KW, Hokianga HT. Learning the ropes: mussel spat ropes improve fish and shrimp passage through culverts. Journal of Applied Ecology. 51: 214-223
	2014	Januchowski-Hartley SR, Diebel M, Doran PJ, McIntyre PB. Predicting road culvert passability for migratory fishes. Diversity and Distributions. 20: 1414-1424
	2014	Mahlum S, Kehler D, Cote D, Wiersma YF, Stanfield L. Assessing the biological relevance of aquatic connectivity to stream fish communities. Canadian Journal of Fisheries and Aquatic Sciences. 71: 1852-1863
	2013	Cooney PB, Kwak TJ. Spatial Extent and Dynamics of Dam Impacts on Tropical Island Freshwater Fish Assemblages. BioScience. 63: 176-190
	2013	McKay SK, Schramski JR, Conyngham JN, Fischenich JC. Assessing upstream fish passage connectivity with network analysis. Ecological Applications. 23: 1396-1409
	2013	Perkin JS, Gido KB, Al-Ta'ani O, Scoglio C. Simulating fish dispersal in stream networks fragmented by multiple road crossings. Ecological Modelling. 257: 44-56
	2012	Anderson GB, Freeman MC, Freeman BJ, Straight CA, Hagler MM, Peterson JT. Dealing With Uncertainty When Assessing Fish Passage Through Culvert Road Crossings. Environmental Management. 50: 462-477
	2011	Foster HR, Keller TA. Flow in culverts as a potential mechanism of stream fragmentation for native and nonindigenous crayfish species. Journal of the North American Benthological Society. 30: 1129-1137
	2010	Price DM, Quinn T, Barnard RJ. Fish Passage Effectiveness of Recently Constructed Road Crossing Culverts in the Puget Sound Region of Washington State. North American Journal of Fisheries Management. 30: 1110-1125
	2009	Planton P, Marcus WA. Railroads, roads and lateral disconnection in the river landscapes of the continental United States. Geomorphology. 112: 212-227
	2009	Poplar-Jeffers IO, Petty JT, Anderson JT, Kite SJ, Strager MP, Fortney RH. Culvert Replacement and Stream Habitat Restoration: Implications from Brook Trout Management in an Appalachian Watershed, USA. Restoration Ecology. 17: 404-413
	2006	Blakely TJ, Harding JS, Mcintosh AR, Winterbourn MJ. Barriers to the recovery of aquatic insect communities in urban streams. Freshwater Biology. 51: 1634-1645
Sedimentation	2017	Massey W, Biron PM, Choné G. Impacts of river bank stabilization using riprap on

		fish habitat in two contrasting environments. Earth Surface Processes and Landforms. 42: 635-646
	2016	Thomaz EL, Peretto GT. Hydrogeomorphic connectivity on roads crossing in rural headwaters and its effect on stream dynamics. Science of The Total Environment. 550: 547-555
	2014	Burdett S, Hulley M, Smith A. Applying the Soil Water Assessment Tool to 5th Canadian Division Support Base Gagetown. Water Quality Research Journal of Canada. 49: 372-385
	2010	Johnson PA, Sheeder Sa, Newlin JT. Waterway transitions at US bridges. Water and Environment Journal. 24: 274-281
	2009	Witmer PL, Stewart PM, Metcalf. Development and Use of a Sedimentation Risk Index for Unpaved Road-Stream Crossings in the Choctawhatchee Watershed. Journal of The American Water Resources Association. 45: 734-747
	2006	Madej MA, Eschenbach EA, Diaz C, Teasley R, Baker K. Optimization strategies for sediment reduction practices on roads in steep, forested terrain. Earth Surface Process and Landforms. 31: 1643-1656
	2002	Gregory KJ, Chin A. Urban stream channel hazards. Area. 34: 312-321
	2002	Johnson PA, Hey RD, Brown ER, Rosgen DL. Stream restoration in the vicinity of bridges. Journal of The American Water Resources Association. 38: 55-67
	2001	Chin A, Gregory KJ. Urbanization and Adjustment of Ephemeral Stream Channels. Annals of the Association of American Geographers. 91-595-608
	2001	Madej MA. Erosion and sediment delivery following removal of forest roads. Earth Surface Process and Landforms. 26: 175-190
	1996	Myers TJ, Swanson S. Long-Term Aquatic Habitat Restoration: Mahogany Creek, Nevada, as a Case Study. Journal of The American Water Resources Association. 32: 241-252
Both, but not for prioritizing crossings		**Studies on other river rehabilitation projects**
	2017	Canto-Perello J, Martinez-Leon J, Curiel-Esparza J, Martin-Utrillas M. Consensus in prioritizing river rehabilitation projects through the integration of social, economic and landscape indicators. Ecological Indicators. 72: 659-666
	2014	Sterling Sm, Garroway K, Guan Y, Ambrose SM, Home P, Kennedy GW. A new watershed assessment framework for Nova Scotia: A high-level, integrated approach for regions without a dense network of monitoring stations. Journal of Hydrology. 519: 2596-2612
	2013	Nichols RA, Ketcheson GL. A Two-Decade Watershed Approach to Stream Restoration Log Jam Design and Stream Recovery Monitoring: Finney Creek,

	Washington. Journal of The American Water Resources Association. 49: 1367-1384
2010	Merten EC, Finlay J, Johnson L, Newman R, Stefan H, Vondracek B. Environmental controls of wood entrapment in upper Midwestern streams. Hydrological Processes. 25: 593-602
	Monitoring/assessment studies on restored crossings
2017	Olson JC, Marcarelli AM, Timm AL, Eggert SL, Kolka RK. Evaluating the Effects of Culvert Designs on Ecosystem Processes in Northern Wisconsin Streams. River Research and Applications. 33: 777-787
2015	Deboer JA, Holtgren JM, Ogren SA, Snyder EB. Movement and Habitat Use by Mottled Sculpin After Restoration of a Sand-Dominated 1st-Order Stream. American Midland Naturalist. 173: 335-345
2015	Ogren SA, Huckins CJ. Culvert replacements: improvement of stream biotic integrity? Restoration Ecology. 23: 821-828
2014	Favaro C, Moore JW, Reynolds JD, Beakes MP. Potential loss and rehabilitation of stream longitudinal connectivity: fish populations in urban streams with culverts. Canadian Journal of Fisheries and Aquatic Sciences. 71: 1805-1816

Table 2. The correlation between the cost-effectiveness of connectivity restoration or sedimentation reduction and four types of watershed characteristics.

	Prioritization method		
	Connectivity	**Joint D**	**Erosion**
Watershed characteristics: planning scale			
Connectivity restoration	r = 0.31*	r = -0.12, p = 0.24	r = -0.35*
Sedimentation reduction	r = 0.024, p = 0.82	r = 0.58*	r = 0.63*
Watershed characteristics: proportion of impassable dams			
Connectivity restoration	r = 0.0091, p = 0.93	r = -0.24*	r = -0.37*
Sedimentation reduction	r = 0.079, p = 0.47	r = 0.36*	r = 0.38*

Watershed characteristics: average erosion scores			
Connectivity restoration	r = -0.31*	r = -0.35*	r = -0.22*
Sedimentation reduction	r = 0.41*	r = 0.42*	r = 0.38*
Watershed characteristics: the maximum of erosion scores			
Connectivity restoration	r = 0.097, p = 0.35	r = -0.23*	r = -0.35*
Sedimentation reduction	r = 0.38*	r = 0.79*	r = 0.82*

* represents significant correlation ($p < 0.05$)

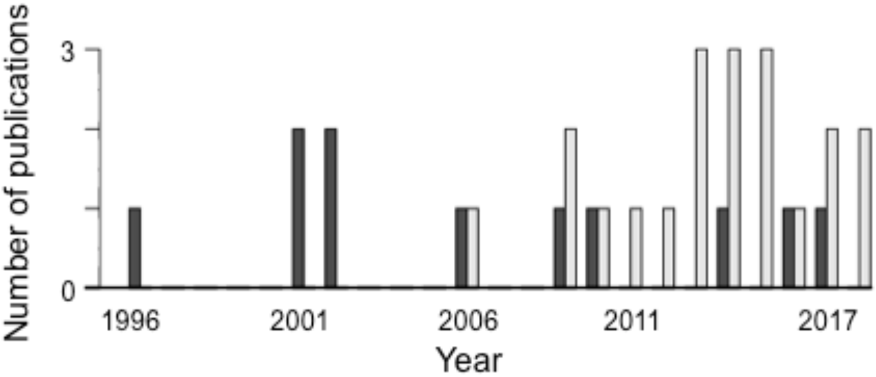

Fig. 1. Number of publications in peer-reviewed journals on Web of Science focusing on sedimentation (black bars) or connectivity (grey bars) for road-stream crossings prioritization during January 1996 – June 2018.

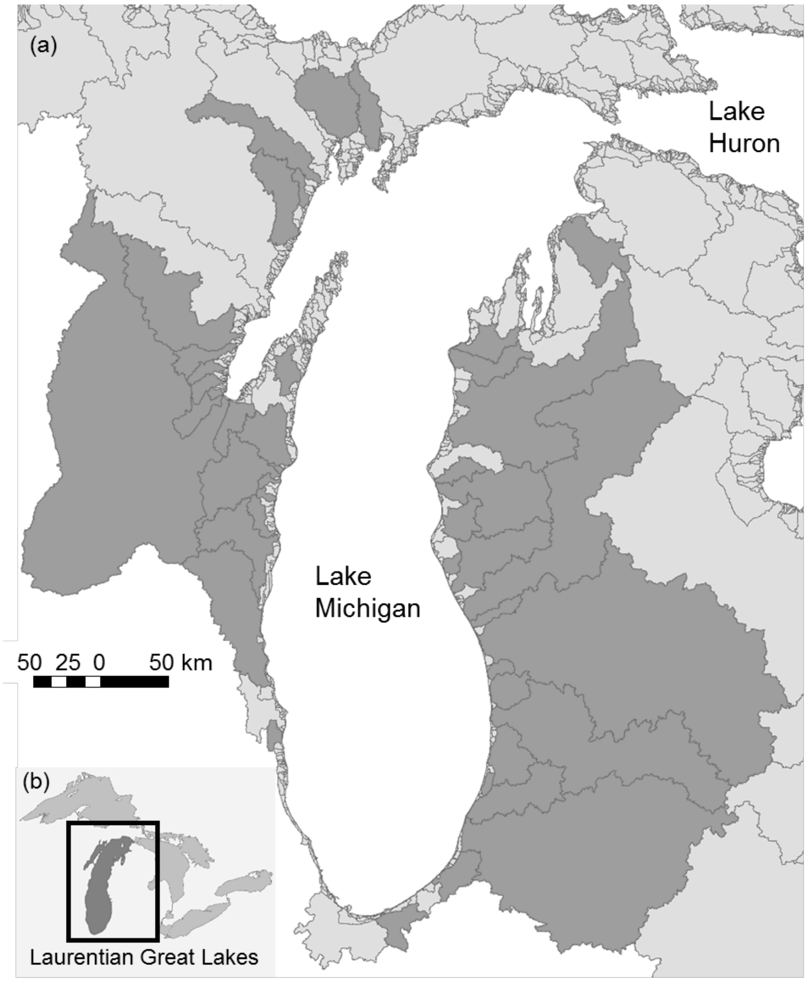

Fig. 2. Forty-four watersheds selected (dark grey) for individual analysis of the relationship between the cost-effectiveness of road-stream prioritizations and watershed characteristics.

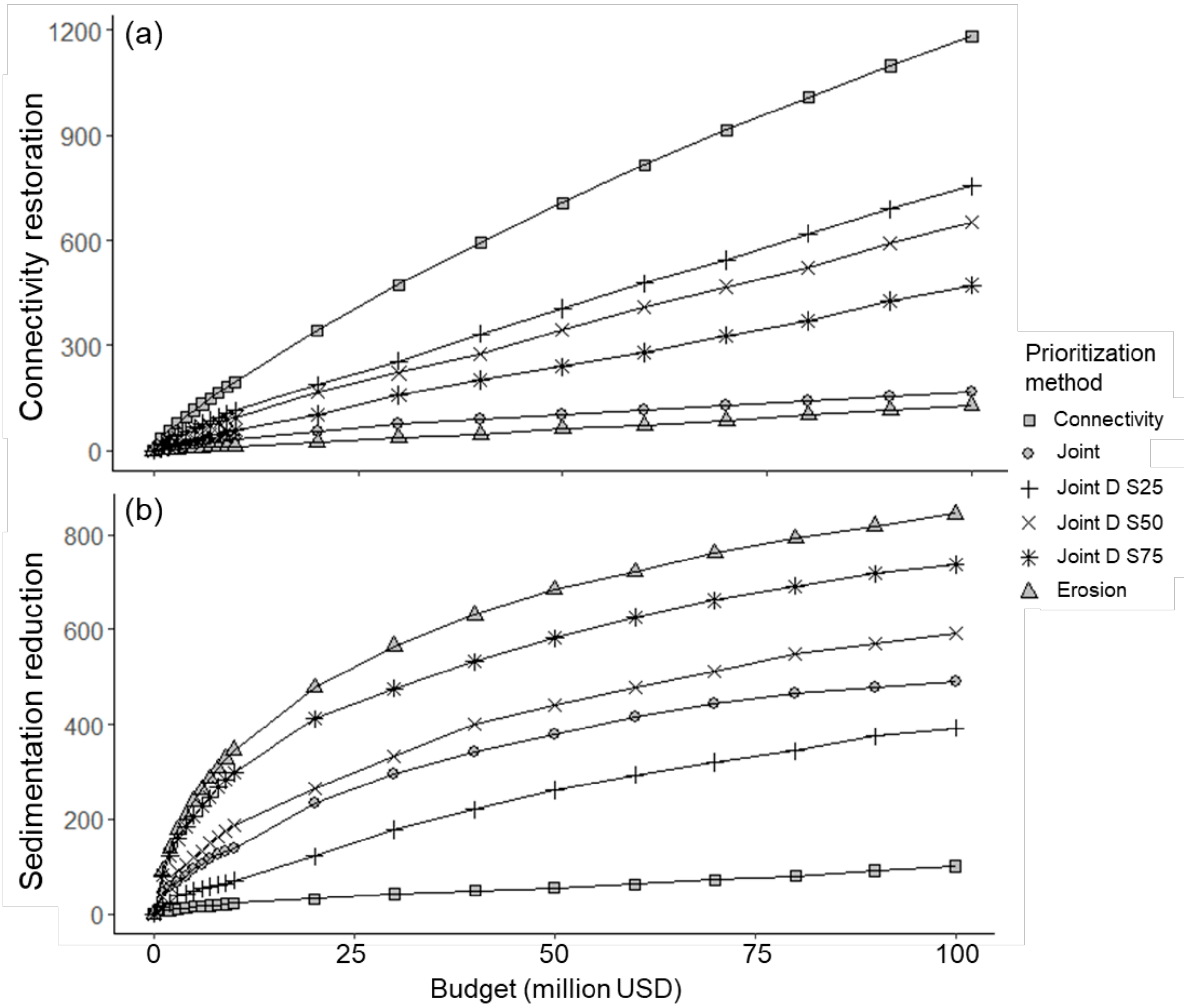

Fig. 3. The changes in connectivity restoration (i.e., the increase of accessibility-weighted habitat, a) and sedimentation reduction (i.e., the decrease of total erosion scores, b) with increasing budget among simulated prioritization methods.

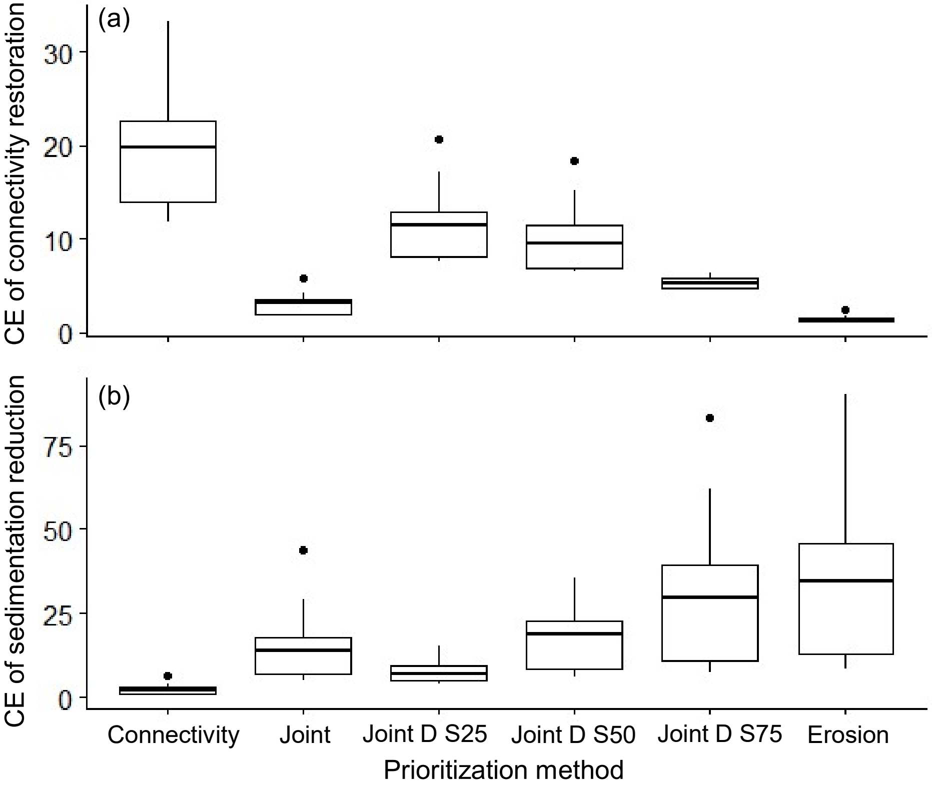

Fig. 1. Cost-effectiveness (CE) of connectivity restoration (a) and sedimentation reduction (b) among prioritization methods for the Lake Michigan basin. Significant differences were found among most groups except between joint D S25 and joint D S50 in panel (a) and between joint and joint D S50, between joint D S50 and joint D S75, and between joint D S75 and erosion in panel (b).

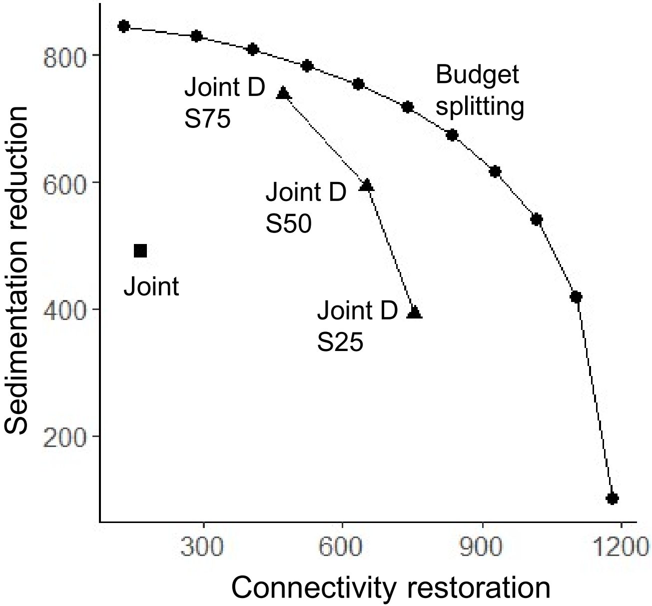

Fig. 2. The curve of sequential budget splitting for connectivity and erosion prioritization (circles) and the effectiveness of joint (square) and joint D prioritizations with different weightings (triangles) given a total 100 USD million budget.

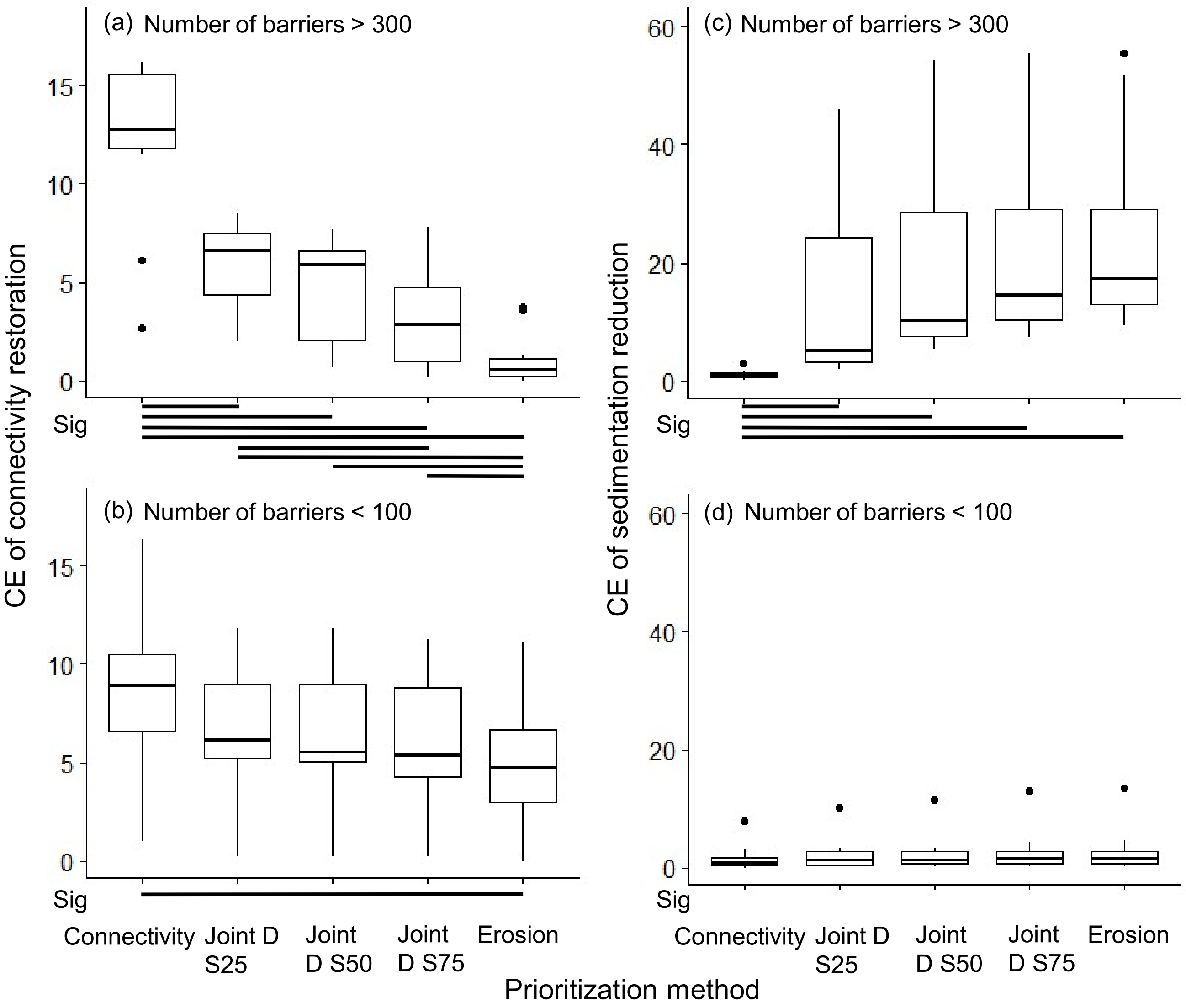

Fig. 3. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with a high (> 300; *n* = 11) or low (< 100; *n* = 18) number of barriers. Horizontal lines on the bottom of each plot represent significant ($p < 0.05$, solid) differences between objectives.

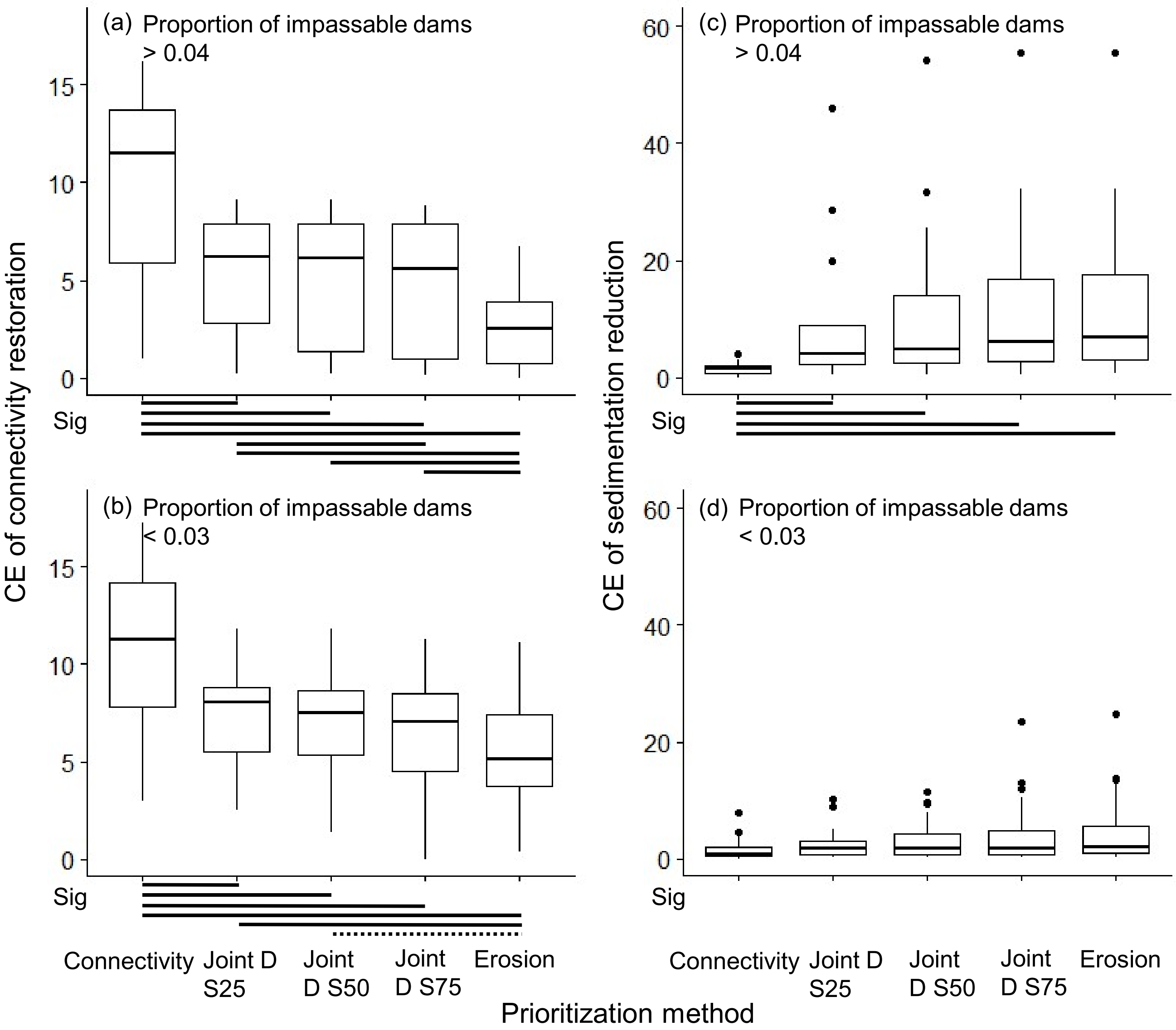

Fig. 4. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with a high (> 0.04; *n* = 12) or low (< 0.03; *n* = 24) proportion of impassable dams among all barriers. Horizontal lines on the bottom of each plot represent significant ($p < 0.05$, solid) or near significant ($0.05 < p < 0.1$, dotted) differences between objectives.

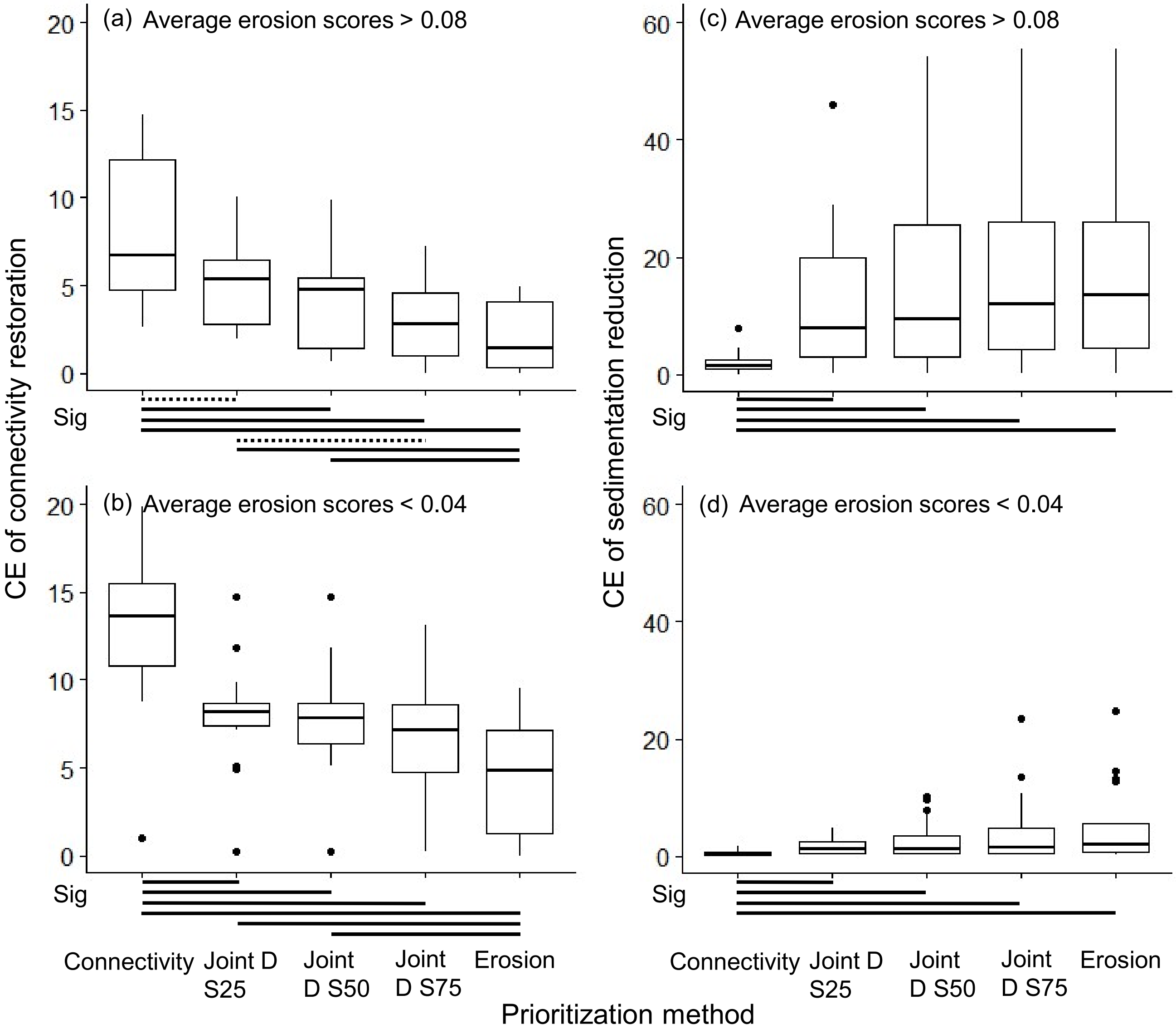

Fig. 5. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with high (> 0.08; *n* = 13) or low (< 0.04; *n* = 17) average erosion scores. Horizontal lines on the bottom of each plot represent significant (*p* < 0.05, solid) or near significant (0.05 < *p* < 0.1, dotted) differences between objectives.

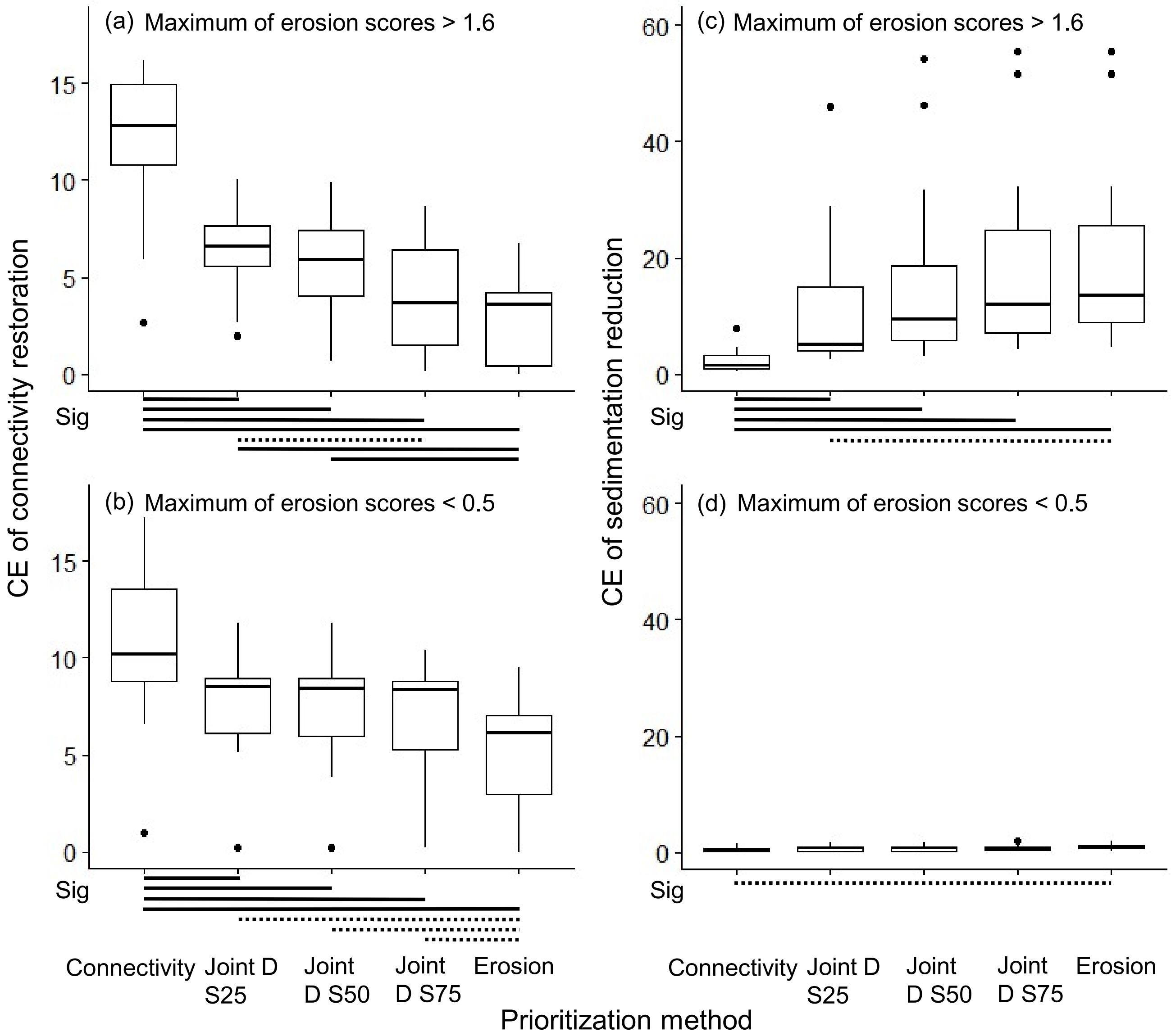

Fig. 6. The cost-effectiveness (CE) of connectivity restoration (a, b) and sedimentation reduction (c, d) among prioritization methods for watersheds with high (> 1.6; *n* = 15) or low (< 0.5; *n* = 14) maximum erosion scores. Horizontal lines on the bottom of each plot represent significant ($p < 0.05$, solid) or near significant ($0.05 < p < 0.1$, dotted) differences between objectives.