A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost

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Aging infrastructure and growing interests in river restoration have led to a substantial rise in dam removals in the United States. However, the decision to remove a dam involves many complex trade-offs. The benefits of dam removal for hazard reduction and ecological restoration are potentially offset by the loss of hydroelectricity production, water supply, and other important services. We use a multiobjective approach to examine a wide array of trade-offs and synergies involved with strategic dam removal at three spatial scales in New England. We find that increasing the scale of decision-making improves the efficiency of trade-offs among ecosystem services, river safety, and economic costs resulting from dam removal, but this may lead to heterogeneous and less equitable local-scale outcomes. Our model may help facilitate multilateral funding, policy, and stakeholder agreements by analyzing the trade-offs of coordinated dam decisions, including net benefit alternatives to dam removal, at scales that satisfy these agreements.

rivers | dams | multiobjective genetic algorithm | trade-offs | multicriteria decision analysis

Decisions about building, removing, or altering dams loom large throughout the world, and are often accompanied by social and political conflicts stemming from divergent preferences related to their costs and benefits (1). For example, many regions of the developing world are dramatically expanding the number of multipurpose dams, often to meet increasing needs for electricity, water supply, and flood control. However, these projects often encounter strong stakeholder resistance based on concerns about the adverse effects of dams on fisheries, ecological connectivity, water quality, and human settlements (2–4). In contrast, there is a growing movement in the United States to restore rivers by the removal of dams that no longer fulfill their original purpose, are too costly to maintain, pose safety risks to surrounding communities, or have negative ecological or indigenous impacts (5, 6). But stakeholders who value the services and aesthetics provided by these dams may oppose their removal, underscoring technological, economic, sociocultural, and environmental trade-offs associated with alternative decisions (7–12). Regardless of the specific context, there is an urgent need for interdisciplinary, stakeholder-engaged methods that may inform deliberations about the trade-offs associated with dam decisions, akin to other sustainability challenges faced by humanity (13–16).

We use the 186,000 km^2 New England (NE) region of the United States (Fig. 1*A*) as a model system for quantifying these trade-offs, and demonstrate how this approach may inform dam decisions in multiple contexts. Several recent dam decisions in NE provide insight on how trade-off assessments may help reduce stakeholder conflict, efficiently allocate resources, and align with the constraints of dam ownership and regulation. For example, the Penobscot River experienced a dramatic increase in sea-run fish populations with a minimal impact on hydropower capacity through a restoration project combining the removal of two mainstem dams, hydropower improvements at tributary dams, and fish passage installations at an uncharacteristically broad scale (17, 18). The vast number of NE dams and rich diversity of ecosystem services make it a valuable location to quantify the range and scale-dependence of trade-offs. At least 14,000 dams have been constructed, modified, or rebuilt in this region in the last 3 centuries (6), ranging in height from <1 m to >80 m (*SI Appendix*, Fig. S3 and Table S1). More than 7,500 of these dams have a recorded upstream drainage area greater than 1 km^2 and are used in this analysis. More than 2,000 dams provide water storage in reservoirs, covering an area of 3,750 km^2; more than 230 are authorized to generate hydropower, with a cumulative capacity of more than 1.6 GW; more than 170 contribute to drinking water storage for major urban centers. However, more than 600 dams register as a high downstream hazard if they were to breach. Before widespread dam construction, NE waterways provided up to 11 sea-run fish species (19), with habitat extending more than 106,000 river km. At this time, about 90% of this total river length is completely obstructed by dams. An additional 7% is partially accessible through fish passage facilities at

Significance

We assess the trade-offs and synergies involved with coordinated dam removal at three spatial scales in New England. We find that increasing the scale of dam decisions improves trade-offs among ecosystem services, river safety, and cost, but the benefits of large-scale river restoration vary dramatically by location. Our model may help facilitate future dam decision negotiations by identifying appropriate scales, locations, and criteria that satisfy multilateral funding, policy, and stakeholder goals.

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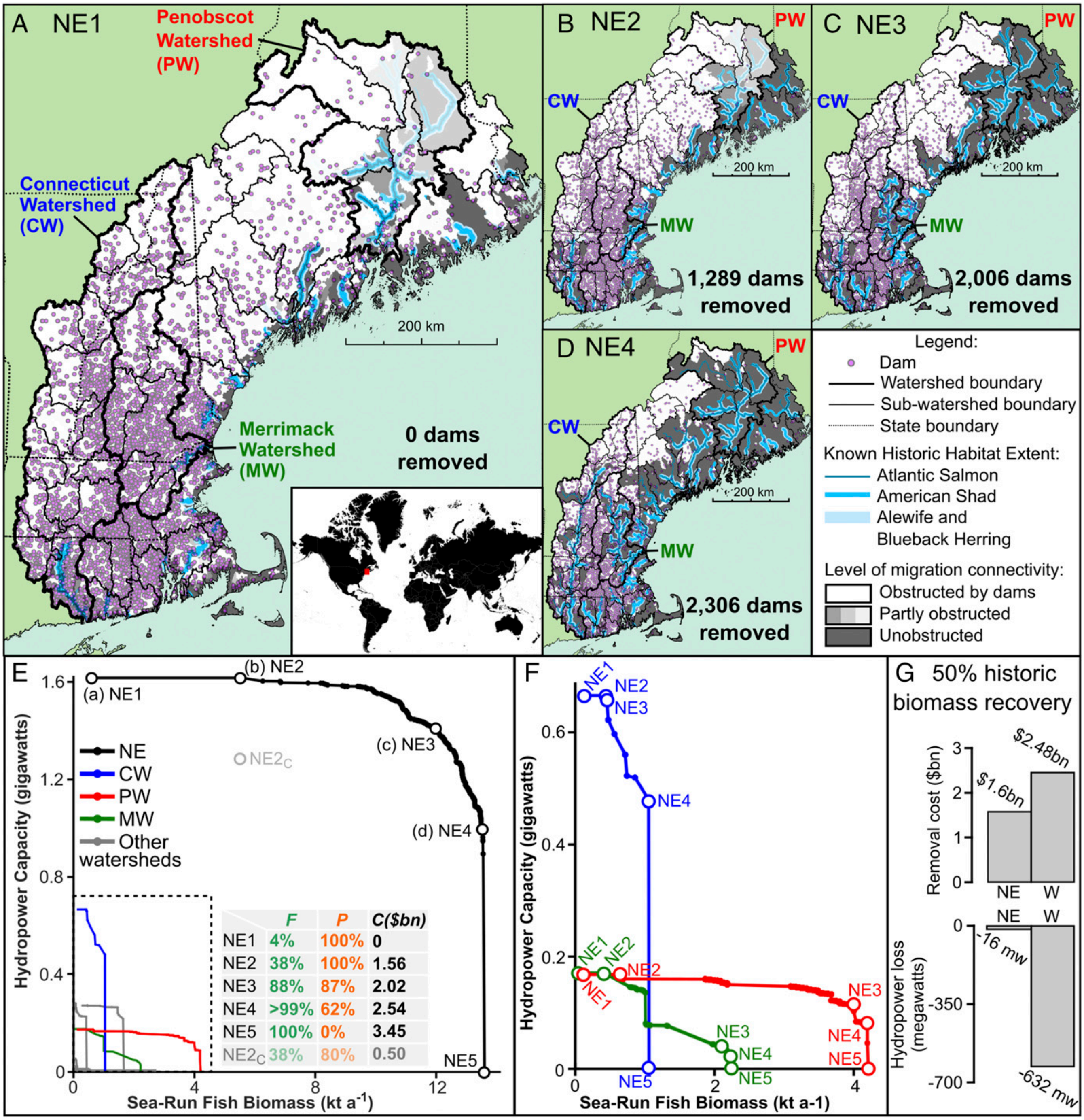

	F	*P*	*C($bn)*
NE1	4%	100%	0
NE2	38%	100%	1.56
NE3	88%	87%	2.02
NE4	>99%	62%	2.54
NE5	100%	0%	3.45
$NE2_C$	38%	80%	0.50

Fig. 1. (*A*) Status quo of NE watersheds, dams, and historic habitat extent for major sea-run fish species (scenario NE1). Migration connectivity varies by dam location and survival through fish passage facilities. Dam removal scenarios (*B*) NE2, (*C*) NE3, (*D*) NE4. (*E*) NE-scale PPF comparing absolute potential hydropower (in gigawatts) and biomass capacities (in kilotons per year, kt·a^{-1}) for NE region and individual watersheds. Points along the PPFs denote efficient scenarios. *C*, cost of dam removal; *F*, sea-run biomass; *P*, hydropower capacity. Dashed box: watershed-scale PPFs, detailed in *F*, where symbols represent the scenarios described in *E*. (*G*) Costs of dam removal and hydropower loss for a hypothetical scenario: 50% of historic sea-run biomass is restored, coordinated strategically over NE region and separately over all NE subwatersheds (W).

more than 100 dams, leaving 3% of total river length that remains unobstructed (20) (Fig. 1*A*). Populations of sea-run fish that once shaped the ecology and economy of coastal NE have been dramatically reduced by dams, although additional factors such as climate change and overfishing have also contributed to this decline (19).

We quantify key economic, social, and ecological trade-offs and synergies of NE dam decisions, using the basic economic concept of the production possibility frontier (PPF) paired with a multiobjective genetic algorithm (MOGA). We first explore trade-offs between two criteria, hydropower capacity and sea-run fish biomass capacity (biomass), to illustrate the method, then explore more complex multilateral trade-offs among 10 criteria. PPFs indicate the various combinations of two or more criteria that can be efficiently produced with a given amount of resources (21) (*Methods*, *PPF*). A MOGA is a metaheuristic designed to provide a satisficing solution to optimization problems that cannot be solved by enumeration (22) (*Methods*, *MOGA*). We combine these methods to provide a systematic, coordinated decision-making approach to reveal how dam decisions influence trade-offs in productivity among multiple criteria. We expand on previous analyses of optimized watershed-scale barrier removal (23–25) and construction (2) by incorporating a greater diversity of spatially explicit data including fish passage facilities, analysis of trade-offs at multiple scales and locations, and a preliminary exploration of alternatives to dam removal. Although we recognize the significance of other barrier types that obstruct river flow, such as culverts (24), we focus on the effect of dams because of their dominant and persistent influence on large rivers in NE (6, 24).

Results

We first evaluate trade-offs between hydropower capacity and biomass for NE rivers, two criteria of significant global interest (2, 4, 17). The resulting PPF is based upon our model estimates of production for each decision criteria (*Methods*, *Decision Criteria*). The convex trend of the PPF (Fig. 1*E*) indicates that many dams obstruct a significant amount of sea-run habitat, but considerable hydropower capacity originates from dams that do not interfere with migration. For each PPF (Fig. 1 *E* and *F*), the upper left terminus represents production under the status quo (scenario NE1). Scenario NE2 represents the removal of nonhydropower dams that obstruct fish migration, and accounts for 38% restoration of historic biomass levels with no loss in hydropower (Fig. 1 *B* and *E*). Beyond this point there are relatively small losses in hydropower capacity with relatively large gains in biomass. Slope gradually steepens toward scenario NE3, in which 88% of historic biomass is restored, with 13% hydropower loss (Fig. 1 *C* and *E*). Increasing biomass after this point comes at a greater opportunity cost to hydropower. For example, scenario NE4 (Fig. 1 *D* and *E*) reduces hydropower by 38% to increase biomass to >99% of maximum capacity. To go beyond this scenario would be to lose another 62% of hydropower capacity to increase biomass by a fraction. The lower right terminus represents production if all dams are removed (scenario NE5).

Comparisons of PPFs for different watersheds reveal some striking location-specific disparities (Fig. 1*F*). We focus on results from the Penobscot, Connecticut, and Merrimack watersheds because they illustrate significant local contrasts. For example, hydropower capacity in Connecticut is around fourfold greater than in Penobscot, but with around fourfold less potential biomass. As a result, efficient scenarios frequently preserve hydropower capacity in Connecticut and restore biomass in Penobscot, represented by the positions of scenarios NE3 and NE4 on the watershed PPFs (Fig. 1*F*). NE-scale hydropower capacity decreases by 8% between scenarios NE2 and NE3, but this represents an 81% decrease for hydropower capacity in Merrimack. This significant local drop in hydropower capacity, located near the midpoint of the Merrimack PPF, indicates that roughly half of all local biomass capacity is located upriver of several clustered, large-capacity hydropower dams. Note that removal of a subset of these dams will decrease hydropower capacity without significant biomass improvements until all are removed. In contrast, PPF slopes for Penobscot and Connecticut are steepest near their right terminus, indicating that most local hydropower capacity is located near or above the extent of most sea-run habitat. These examples imply that efficient scenarios located before major steepening in the PPF, such as NE3, involve the removal of downriver mainstem dams that do not provide effective fish passage to upstream habitat and/or do not provide a relatively significant contribution to hydropower capacity. The Connecticut PPF is the steepest, suggesting that significant hydropower capacity exists in this watershed, and it has a strong influence on the shape of the NE PPF from scenario NE4 to NE5 (Fig. 1*E*). Dam removal in Penobscot provides the lowest opportunity cost for improving biomass: 29% of regional biomass capacity may be achieved by reducing regional hydropower capacity by 3.5%. Spatial planning for efficient dam decisions is complicated by the heterogeneous and often overlapping distributions of valuable sites for hydropower capacity and sea-run fish habitat (26). However, it is at least possible at the regional scale to dramatically improve biomass and minimize hydropower loss by concentrating dam removal efforts in Penobscot and largely maintaining current dam infrastructure in Connecticut.

Decisions are far more efficient when strategically coordinated across more dams. To further demonstrate, we set a hypothetical goal of restoring biomass to half of its estimated maximum capacity (Fig. 1*G*). According to our results, it is possible to achieve this goal in NE with a loss of 16 megawatts and $1.6 billion in estimated dam removal costs by the focused removal of dams from specific watersheds. In contrast, if we apportion restoration evenly across all NE subwatersheds (Fig. 1*A*) with at least partial sea-run fish access, there would be a loss of 632 megawatts and $2.48 billion in estimated dam removal costs. Increasing the planning scale increases the potential number of high-efficiency decisions that can be distributed over a large geographic area. Subwatershed decisions are often limited by inefficient local opportunity costs compared with decisions distributed over a larger region. Similar results for scale-dependent monetary restoration costs have been shown for the Great Lakes region (24).

Costly infrastructure and restoration decisions rarely hinge on just two criteria (13, 15, 16), and dams are no exception (7–12, 27). For example, the monetary cost of dam removals is an important criteria for decision-makers with limited budgets (6, 7, 27). We estimate a cost of $1.56 billion to remove all nonpowered dams in NE that potentially limit watershed connectivity (NE2; Fig. 1 *B* and *E*). Estimated costs increase by almost $1 billion between scenarios NE2 and NE4 (Fig. 1 *C*–*E*). We do not optimize for cost in these examples, but we do so as a third criteria for scenario $NE2_C$ (Fig. 1*E*). This scenario provides the same magnitude of biomass restoration as NE2, while producing 20% less hydropower, but it is about 68% less expensive. Despite its location under this PPF, scenario $NE2_C$ may be more suitable for stakeholders who would forfeit some hydropower to reduce cost.

Stakeholders may have additional concerns about water supply, quality, safety, recreation, and other dam-related criteria (7–12, 27). We explore the multilateral trade-offs associated with 10 common dam removal criteria based on their requirements for river connectivity or dam infrastructure (6, 7, 27) (*Methods*, *Decision Criteria*). Because of the difficulties of visualizing trade-off patterns across 10 criteria, we focus on three general scenarios: the status quo (Fig. 2*A*), ecological restoration (Fig. 2*B*), and equal weight for all criteria (Fig. 2*C*). Hypothetical stakeholder preferences are used in a weighted product model to rank and select these scenarios, and could be replaced by real preference data when available (28, 29) (*Methods*, *Weighted Product Model* and *SI Appendix*, Table S3). The status quo scenario (Fig. 2*A*) simulates conditions in their current state, representing maximum capacities for dam-related criteria, minimum safety from potential dam breach, minimal capacities for biomass and river recreation, and no dam removal cost. Conversely, the restoration scenario (Fig. 2*B*) improves biomass and dam breach safety. Remaining dams tend to be upstream of sea-run fish habitat (Fig. 2*B*) and fulfill further preferences for flow releases for river boating recreation (30) and dam reservoir nitrogen removal to reduce coastal eutrophication (31).

The equal preference scenario (Fig. 2*C*) represents a modest increase in biomass, river recreation, and dam breach safety with a relatively small negative effect on capacity for dam-related services. Much like our two-criteria assessment (Fig. 1*F*), however, the 10-criteria equal preference scenario (Fig. 2*C*) shows significant location-specific disparities at the watershed scale. For example, the equal preference scenario in Connecticut does

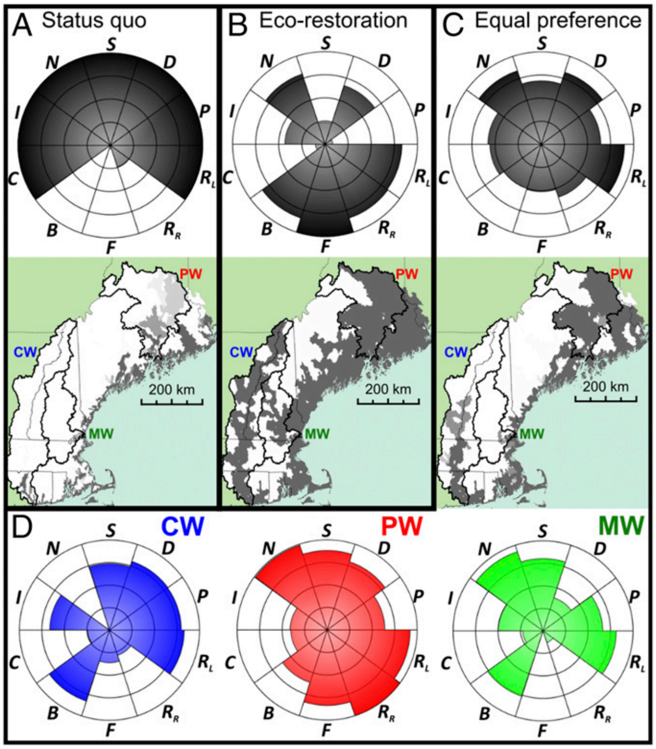

Fig. 2. Ten-criteria analysis, quantities reported as values normalized to maxima (counter clockwise from right) *B*, dam breach safety score; *C*, dam removal cost; *D*, drinking water; *F*, sea-run fish biomass; *I*, number of properties affected by dam removal; *N*, nitrogen removal; *P*, hydropower; R_R, river boating recreation; R_L, lake boating recreation; *S*, water storage. Scenarios: (*A*) status quo, (*B*) eco-restoration, (*C*) equal preference scenario. (*D*) The regional scale equal preference scenario produces uneven changes in criteria for individual watersheds.

not show significant changes in restoration- and dam-based criteria compared with the status quo with the exception of a strong improvement in dam breach safety. Penobscot has relatively dominant increases in biomass and river recreation, with less improvement in dam breach safety, while providing large quantities for most dam-related criteria. These results again suggest that river restoration is strategically more significant in watersheds such as the Penobscot, where there are relatively few dams and relatively large habitat gains, if these removal decisions coordinate with other major watersheds in NE that benefit more from dam-related criteria, such as the Connecticut.

Dam removal is only one of several alternatives available to decision-makers. Including others may improve efficiency and increase production, particularly in cases in which there are restrictions on dam removal. We consider combinations of the following decision alternatives for Penobscot: keep dams, remove dams, improve fish passage (32), improve existing hydropower capacity (33), and build new hydropower dams at candidate sites (34). These alternatives could provide many opportunities to improve both biomass and hydropower capacities, or fully compensate for biomass restoration with no loss in hydropower (Fig. 3). Decisions to increase hydropower stretch the PPF vertically, whereas decisions to improve fish passage shift the PPF horizontally toward maximum biomass capacity. Constructing new hydropower dams could allow decision makers to compensate for dam removals by strategically focusing hydropower capacity in tributaries with low biomass potential (26). Cost may again be important to consider. Dam removal is often found to be the least expensive alternative compared with repairs or improvements (6, 7, 33). Available data suggest that removal costs are on average 50% less than fish passage installation and 82% less than new turbine installation (33, 35–37). Combining dam removals with investments in alternative water supply and renewable energy sources could dramatically improve efficiency (38).

Discussion

Our work in NE highlights the need for a balanced, informed approach to dam decisions that can scale to global concerns for dam construction and removal (1–6). Similar to other challenges in decision theory (13, 15), the trade-offs of dam decisions are nonlinear and unique to the scale, location, criteria, and alternatives. Our model is adaptable enough to identify how trade-offs shift with these different factors, and it may be helpful for facilitating exploratory discussions centered around efficient, multilateral trade-offs, from individual dam sites to multiple watersheds. These exploratory analyses could also help build an informed dialogue to anticipate potential losses for certain criteria that could be supplemented through other means. Incorporating culverts as a barrier would help improve overall accuracy (24), but require inclusion of transportation-related criteria to maintain a consistent trade-off analysis.

We further demonstrate that decisions involving more dams are more efficient, but the benefits and equity of these decisions are scale-dependent and may differ significantly by location. Stakeholders may not necessarily support a large-scale plan if the differences in outcome do not directly benefit them or their local community (8–10), such as the contrasting model outcomes for the Penobscot and Connecticut (Fig. 1*F*). These equity challenges require decision makers to understand how dams and rivers are valued at different scales and locations, and in social contexts (14). Some criteria may also be more sensitive to these location-dependent disparities than other criteria (15). For example, sea-run fish are sensitive to location-specific migration barriers (17, 19), whereas hydropower dams typically contribute energy to a regionally connected grid (38), regardless of location. Our model is well suited

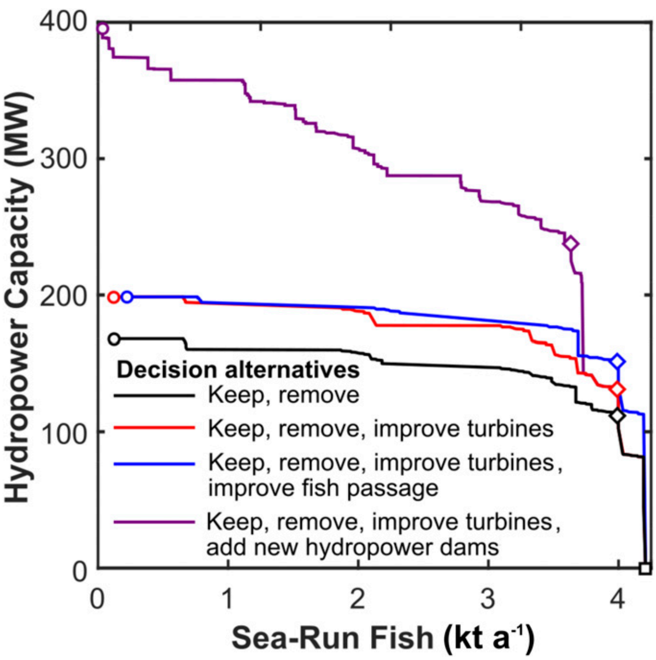

Fig. 3. PPFs for Penobscot depicting improvements in trade-off patterns associated with multiple decision alternatives. Hydropower capacity expansion based on turbine improvement estimates (33), fish passage expansion assumes survival rates improve by 50%. We include 54 candidate sites for the "add new hydropower dams" decision alternative (34).

to identify spatial scales for high management impact and greater planning efficiency that may attract broad stakeholder support (12, 21). Combining stakeholder engagement methods with our trade-off assessments will be critical to this end. Our model may aid decision makers by generating scenario analyses tailored to certain criteria. Studies in stakeholder participation, participatory multicriteria decision analysis, and content analysis can be effective at revealing stakeholder preferences (13, 14) and spatiotemporal scales of interest (12) that can be augmented with PPFs to tailor subsequent scenario analyses. Stakeholder preferences may also be quantified through nonmarket valuation based on interview and survey data, where ratios of estimated marginal utility and the slope of the tangent along the PPF would identify preferred scenarios (39).

Further decision-making criteria such as private ownership may also be incorporated in our model to explore how the challenges of multiple parallel owner negotiations may affect the efficiency and feasibility of decisions under current institutional arrangements (18). Our adaptive, multilateral approach to trade-off assessments is a critical feature for watershed-scale ecosystem restoration planning initiatives that are often seen as necessary to unlock funding mechanisms such as compensatory mitigation, as detailed by the US Army Corps of Engineers (18, 40), or federal and private grants (17, 18). For example, institutional frameworks such as the National Oceanic and Atmospheric Administration Habitat Blueprint (https://www.habitatblueprint.noaa.gov/) provide access to planning and funding resources for coordinated river restoration. Funding mechanisms are crucial for negotiating multilateral decisions under terms that are acceptable to owners, local officials, and other concerned stakeholders (7–10, 17, 18). Our study criteria can be modified to appropriately represent these concerns (27).

Our model can also provide insight on the drawbacks of current dam regulations that guide Federal Energy Regulatory Commission (FERC) relicensing procedures. Although the Federal Power Act and other governing statutes authorize FERC to integrate individual licenses into larger watershed management plans, license terms are almost always site-specific and do little to factor in cumulative watershed impacts. Operation of all FERC-licensed hydropower dams must comply with individual license terms or surrender their licensed/exempted status in preparation for removal or modification (41, 42). Licensing schedules may also make coordinated decisions difficult. FERC hydroelectric licenses last 30–50 y, and there is no incentive to coordinate those schedules in ways that support multidam decisions. Our results suggest that this fragmented relicensing strategy leads to inefficient outcomes (Fig. 1*G*). For example, hypothetical removal or modification of the next five Penobscot dams up for FERC relicensing (*SI Appendix*, Table S5) would provide a negligible increase in biomass because of inadequate downstream fish passage, and would strip most of the river's hydropower capacity. Fortunately, recent Integrated Basin-Scale Opportunity Assessment Initiative reports by the US Department of Energy (43) and legislative changes during the last 2 decades have lent support to basin-scale decisions; equal consideration for environmental, recreational, and hydropower criteria; and broader agency and stakeholder participation (41, 42).

Methods

Decision Criteria. We model quantities for 10 criteria that respond to dam removal and are seen as important providers of public benefit (7–10, 12) (Table 1). We do not account for potential feedback between criteria, but instead model changes in service production based on whether each dam is kept or removed. Most criteria are measured based on the sum of contributions of each dam. We calculate sums for hydropower capacity, water storage, drinking water, nitrogen removal, lake boating recreation, dam breach safety, and properties affected (*SI Appendix*, section 1 and Table S1). For removed dams, we relate removal cost to the height and length of each dam using a linear regression model (35), and assume that there are no additional costs associated with remediation (e.g., contaminated sediment, invasive species, riparian restoration) (27). However, criteria such as biomass depend on the order in which dams are located in river networks, and their spatial position relative to upstream habitat. We calculate biomass capacity for four primary species: alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), American shad (*Alosa sapidissima*), and Atlantic salmon (*Salmo salar*). These species were selected based on historic NE fisheries records (17, 19). We combine these species as a single measure of biomass for simplicity with the equation

$$F = \sum_{k \in n_s} \left\{ c_k \sum_{i \in n_d} \left[h_{ik} \prod_{j \in n_{di}} \left(p_{jk} \right) \right] \right\}, \qquad [1]$$

where F is annual sea-run fish biomass capacity ($\mathrm{kt \cdot a^{-1}}$); n_s is the set of all fish species, indexed by k; n_d is the set of all dams, indexed by i; n_{di} is the set of all dams downstream from and including i, indexed by j; h_{ik} is the accessible functional habitat above dam i for species k; p_{jk} is the product of upstream and downstream survival through downriver dam j for species k; and c_k is annual biomass carrying capacity ($\mathrm{kt \cdot m^{-2} \cdot a^{-1}}$) for species k. We calculate survival for different species and types of passage facilities based on empirical data (32). Functional habitat h_{ik} represents the known spatial distribution, based on physical surveys and historic accounts, and estimated quality of habitat, based on temperature and flow velocity model data and habitat suitability indices (*SI Appendix*, section 1 and Table S2).

PPF. We use PPF curves to visually represent the productivity of efficient dam decision scenarios. Each axis in a PPF plot represents quantities for a unique decision criterion (Fig. 1 *E* and *F* and *SI Appendix*, Fig. S1). PPFs represent trade-offs between two or more criteria, and attempting to improve production of one can decrease the production of others when transitioning between efficient scenarios. Inefficient scenarios fall under the PPF curve and do not reflect maximum production (21). Decision makers can use PPFs to identify a diverse set of decisions that are most efficient under certain constraints, and the various trade-offs in criteria that are possible under different scenarios based on the PPF's shape (39). The PPF represents the

Table 1. Model decision criteria

Decision criteria	Description*	Units
Hydropower capacity	Power capacity for all FERC licensed/exempted dams obstructing river flow (D)	megawatt
Sea-run fish biomass	Sea-run fish biomass carrying capacity calculated from functional habitat (R)	$\mathrm{kt\ a^{-1}}$
Water storage	Storage volume of dam reservoirs constrained from bathymetry and dam height (D)	$\mathrm{km^3}$
Drinking water	Population served by dammed drinking water reservoirs (D)	No. people
Nitrogen removal	Mass of nitrogen removal by lakes/reservoirs to prevent marine hypoxia (D)	$\mathrm{kg\ a^{-1}}$
Lake recreation	Lake/reservoir area available for flatwater boating recreation (D)	$\mathrm{km^2}$
River recreation	Functional river recreation area based on optimal flow conditions for canoe, kayak, raft (R)	$\mathrm{km^2}$
Dam breach safety	Score based on number and degree of hazardous dams (R)	Unitless
Properties impacted	Number of abutting properties with changes in viewshed, property value, or community identity caused by dam removal (D)	No. properties
Removal cost	Monetary cost of dam removal excluding environmental risks (C)	$USD2016

*Criteria are labeled based on if they benefit from dams (D), dam removal (R), or are a decision cost (C).

limits of production under current constraints, but it can be expanded to represent future increases that could be related to infrastructural, technological, or managerial improvements (21). Empirically, we generate PPFs regionally for NE, and then locally for watersheds using a MOGA.

MOGA. A MOGA is used to identify efficient scenarios that delineate our PPFs (22) (*SI Appendix*, Fig. S2). We use the MOGA at three scales delineated from the National Hydrography Dataset (44): regional, watershed, and subwatershed. Scenarios are represented as a binary numeric array with length equal to the number of dams in the study area. For each array position, a value of 1 means a dam is kept, 0 if removed. Integer values are used for optimization runs with more than two decision alternatives. The algorithm initiates by generating a set of scenarios, each composed of a random binary sequence. Quantities for each criteria are calculated and used to determine rank. Scenarios that have higher rank and/or are unique, measured as a "distance" from other scenarios, are used to generate, rank, and select a new set of scenarios through multiple iterations. Scenarios with poor rank and/or distance are replaced iteratively by new scenarios with higher rank and distance. New scenarios are iteratively generated from old ones, using crossover and mutation algorithms (22). In this way, efficient scenarios are preserved across multiple generations while still diversifying the selection process. The MOGA terminates under the condition that there is no longer any change in the position of the PPF.

Weighted Product Model. The weighted product model is an evaluation technique in which practitioners rank scenarios on the basis of the quantities of several criteria. Developed in the field of operations research, this model is commonly used to assess a variety of complex decision problems in which stakeholders respond to changes in criteria with nonlinear preferences (28, 29). We use weights to represent hypothetical decision maker preferences for certain criteria over others (*SI Appendix*, Table S3). These weights are meant to show a range of plausible outcomes and are not based on actual stakeholder input. We rank scenarios based on the maximum weighted product with the equation

$$s_i = \prod_{j=1}^{n} {f_{ij}}^{w_j}, \qquad [2]$$

where s_i is the weighted product for scenario i, f_{ij} is the quantity of criteria j for scenario i, w_j is the fractional weight for criteria j, and n is the number of criteria used for ranking scenarios. The scenario with maximum weighted product is preferred. Reciprocals are used for criteria where minimal amounts are preferred, such as removal cost. We then select the scenario with maximum weighted product and normalize each criteria relative to its preferred quantity for representation in rose plots.

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