Economics of the Northern Pike Invasion in the Columbia River Basin

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Table of Contents

Cover Image

"Northern pike (*Esox lucius*)" U.S. Fish and Wildlife Service Image Library via Wikimedia Commons. Available at: https://en.wikipedia.org/wiki/File:Esox_lucius1.jpg (last accessed 6/8/19).

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Executive Summary

In a recent letter from the Northwest Power and Conservation Council (*hereinafter* the Council) to the Independent Science Advisory Board (ISAB), the Council posed two questions to be reviewed by economists.

The first question is:

1) **What information is needed to assess the economic impacts to natural resources in the Basin should Northern Pike spread throughout the anadromous and non-anadromous zones? If such information exists, can you estimate the economic impacts of the spread of Northern Pike?**

Estimating the economic costs of the spread of Northern Pike (*Esox Lucius*) (*hereinafter* NP) throughout the Columbia River Basin (CRB) would involve a large-scale, ecological-economic modeling exercise. Such a study is beyond the scope of this report. Instead, we describe the economic and ecological modeling that would be necessary to estimate the range of possible medium- and long-run consequences of an expanded NP invasion according to best practices for economic analysis. The main points from our review include:

- Evaluating the consequences of an expanded NP invasion would require understanding multiple potential outcomes of interactions among species once NP spread to the anadromous zones and currently uninvaded non-anadromous zones of the CRB.

- Parallel to (and integrated with) the ecological research required, a social science research effort would be needed to estimate the social and individual behavioral responses to, and the resulting costs arising from, an expanded NP invasion.

- Some useful information is available now or may be obtained/estimated in the near-term (e.g., potential costs associated with modifying hydro-operations, activity that may potentially be used to partially compensate for a net increase in predation on native species of concern).

- A fully-developed model integrating biological and socioeconomic processes will also focus on quantifying uncertainty, including uncertainty over how the population dynamics in the model will influence estimated costs over time.

The second question from the Council to be reviewed by economists is:

2) For the related ISAB question regarding level of Northern Pike suppression needed (question 5, above), can you calculate the costs associated with that?

Here “question 5” refers to the following question for ISAB:

5) In consideration of ISRP 2018-3 regarding Northern Pike, do we know what level of suppression (exploitation) through gill net removal, angler removal or other methods is needed to reduce the population in Lake Roosevelt to a level sufficient to reduce risk of emigration from the lake or risk to other focal management species?

In a recent report (ISAB 2019), the ISAB responded to question 5. ISAB was unable to determine either:

- The level of Lake Roosevelt northern pike suppression "sufficient to reduce risk of emigration from the lake"; or

- The level of Lake Roosevelt northern pike suppression "sufficient to reduce [...] risk to other focal management species"

Given that ISAB is unable to provide the quantitative targets requested by the Council, we approach the second economic question by describing the information needed to produce a cost estimate for a hypothetical management program that meets best practices for economic analysis. Our observations include:

- A multi-species spatial population model for Lake Roosevelt (LR) that includes NP and NP prey species is required to estimate long-term costs of suppression.

- Some costs may be drawn from recent LR suppression effort and planning. However, these are not adequate to provide a useful upper or lower bound on the range of expected costs of suppression in LR.

- Monitoring and research are likely to remain components of NP suppression in LR. Both activities should be included in an overall cost estimate.

Our hope is that this report will be read as an invitation for investment in interdisciplinary research on human-natural systems in the CRB, and in particular the economics and ecology of invasive species control. Substantial evidence suggests that NP may prove to be a costly invader in the CRB that is unlikely to be eradicated. Unfortunately, it is also unlikely to be the last harmful aquatic invader introduced to the region. Investment in quantitative decision support tools now, with input from economists and natural scientists, may facilitate rapid assessment and informed prioritization of management resources in the future.

Lastly, we do not attempt to draw conclusions regarding the economic merits of any particular method of suppression or level of funding for NP management in the CRB.

I. Introduction

Invasive Northern Pike (*Esox Lucius*) (hereinafter abbreviated NP) are spreading in the Columbia River Basin (CRB), with a recent capture placing them within 10 km of Grand Coulee Dam (ISAB 2019). Invasive NP are predatory fish that pose a severe threat to valued species, in particular salmonids (Dunker et al. 2018). Motivated by the impending threat of NP spreading to the anadromous zone of the CRB, the Northwest Power and Conservation Council (NWPCC) (hereinafter referred to as the Council) requested in a letter that economists be contracted to answer a set of questions about the economic effects of the NP invasion (NWPCC 2018).

This report addresses the Council's questions for economists. In what follows, we first provide some background on economic concepts and results. This review provides a foundation for our response. We conclude our report by recommending some potential directions for interdisciplinary research on biological invasions in the CRB which the Council may wish to support in the future.

Fig. 1. An illustration of a Northern Pike (Alexander Francis Lyndon). Available at: https://www.goodfreephotos.com/animals/fish/drawing-of-a-northern-pikr.jpg.php (last accessed 6/10/19).

II. Literature and Concept Review

Before moving on to our response to the Council's questions, it is worth briefly reviewing selected economic concepts and the interdisciplinary literature on decision problems involved in the control of invasive species.

II.A. Economic decision-making frameworks for policy analysis

In economics, there are three main decision-making frameworks used in policy analysis: benefit-cost analysis, cost-effectiveness, and economic impact analysis. The three frameworks require different levels of information and provide different metrics for a project or policy intervention. Cost-benefit analysis is the most comprehensive and requires estimates of benefits (e.g., reduction in damages), including those that are realized in markets (e.g., changes in home prices) and those that are realized outside of markets (e.g., changes in cultural values). These frameworks are often applied before a policy change as a means of understanding the potential economic effects. In what follows, we provide a short discussion of each. For additional discussion of these evaluation methods, see Greenberg et al. (2001), Freeman (2003) and Holland et al. (2010).

Cost-benefit analysis (CBA) is a methodology for measuring the expected net economic benefits from a policy action (or actions) that considers both consumptive use and non-consumptive use values. Here an example of a consumptive value is catching and keeping a fish, while an example of a non-consumptive value use value is satisfaction from observing a fish in the wild. In the case of the invasion of the northern pike into the Columbia River Basin, a cost-benefit analysis would include measuring the losses in consumptive use (e.g., lost recreational fishing values for Salmon) and the losses to society from reductions in endangered salmon populations (non-consumptive use). A well-done CBA is comprehensive in its coverage of the benefits and costs and is often costly and time-intensive.

Cost-effectiveness analysis (CEA) is a methodology to measure the expected costs of a set of policy actions in meeting a policy goal. Often in a CEA cost of a policy action includes just the accounting costs or outlays (e.g., labor costs, cost of control methods). In this case the CEA might do a good job of reflecting the project costs but will fail to capture the full costs of the different policy actions, which include the foregone consumptive and non-consumptive use values or opportunity costs. For example, the economic cost of eradicating NP in Lake Davis in California included (but was not limited to) the outlays and the lost foregone recreational benefits during the recovery of the Lake (Zelasko et al. 2018). CEA differs from CBA in that it does not try to determine the policy action that achieves the greatest return to society (largest net benefits) but rather takes the policy goal as given and tries to find least cost way in expectation to achieve a goal (e.g., a 10% reduction in the risk of Northern Pike getting downstream of Lake Roosevelt – see also Section IV below).

Economic Impact Analysis (EIA) is a methodology to track the transfer of money from one sector to another, including gross output, income, and employment resulting from a policy action or other events (Lipton et al. 1995; Hushak 1987). The linkages between measures in an EIA and net social benefits from a policy action are often not very clear and can be counterintuitive. For example, a local economy might experience a significant amount of economic activity in recovering from an extreme event (e.g., hurricane, flooding), such as increases in employment and expenditures for building materials. An EIA analysis would capture these positive changes to the local economy, but it would be hard to argue that society is better off because of the extreme event. EIA cannot determine the set of policies that are "best" for society—only the policy that will generate the greatest gross economic activity. Another shortcoming of EIA models is that their estimated response to an event or policy change in a region will only capture short-term adjustments and responses (i.e., for a year or two), and are not reliable to measure impacts over longer periods of time.

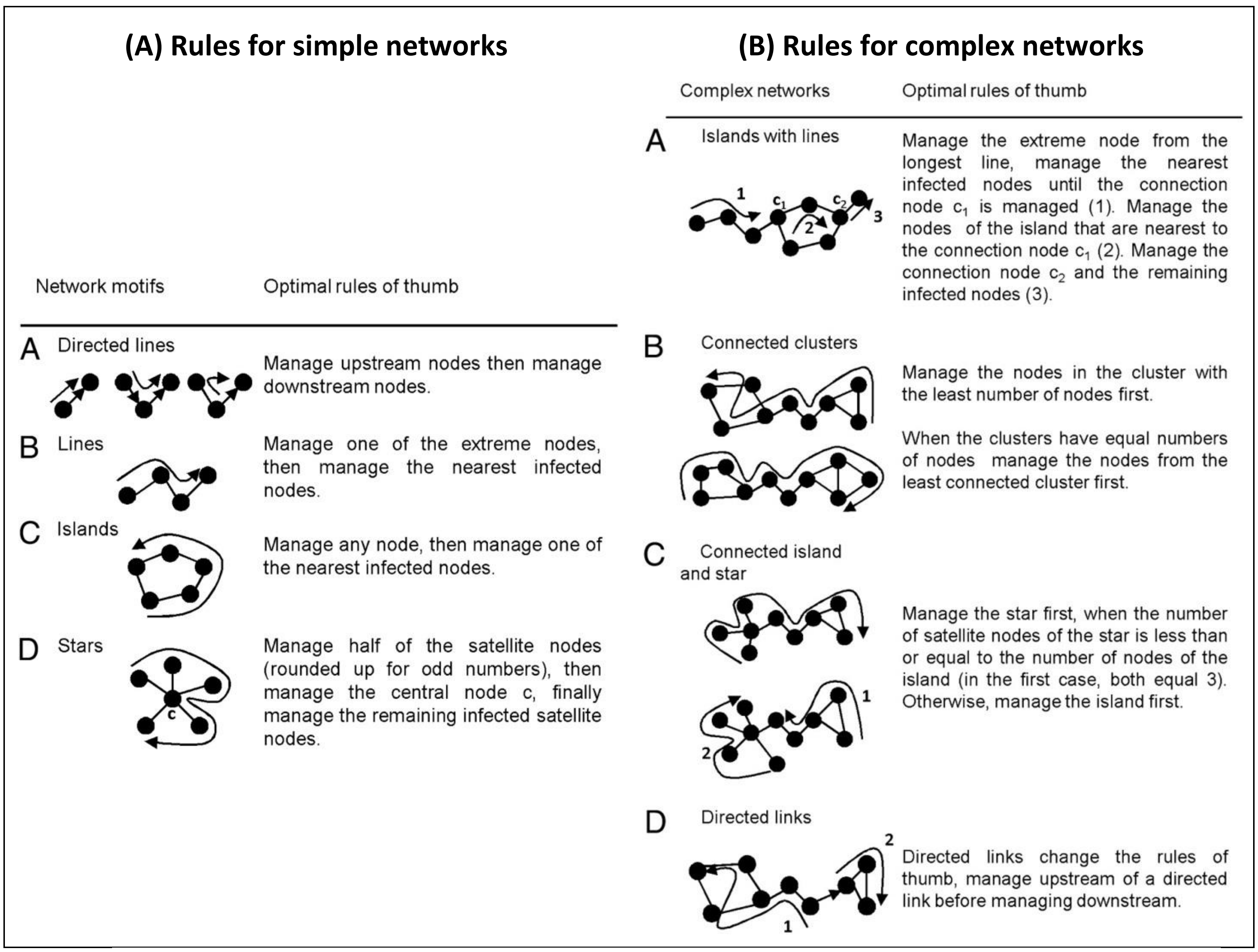

Fig. 2. Rules of thumb for eradicating a pest in a network adapted from Chadès et al. (2011, p. 8324). In the source paper, the objective function of the manager of the entire network is to minimize the number of infected nodes by taking actions to increase the probability of extinction of an infected node

II.B. Economics of invasive species control

In an invasive species control problem, the evaluation of a project controlling an established invasion at any one point in time requires understanding the following: (1) invasion dynamics of the invader; (2) the effectiveness of the project in reducing the population of the invader and likelihood of reducing its spread; (3) money-metric damage caused by the invader both in its current location and potential future locations; (4) collateral damages caused by the control efforts on native species and ecosystems; and (5) costs of controlling the invader in its current and future locations.

A review of the literature finds that general conclusions on where, when, and how to control established invasive species are rare as the answers to these questions depend on the biological, economic, and institutional context (Epanchin-Niell and Hastings 2010). For example, a common consideration in the control is whether to target core versus satellite populations. Epanchin-Niell and Hastings state that the "relative merits of the two prioritization approaches appears to depend on dispersal and growth rates in core vs. satellite populations and relative control and search costs" (2010, p. 537).

Chadès et al (2011) investigate eradication of an invasive species within a network context and highlight that simply rules such as controlling the outer nodes and moving inside the network can be inefficient. Figure 2 is reproduced from Figs. 1 and 2 in their paper and shows the optimal rules developed in their analysis for basic and complex networks. Clearly the CRB is more complex than these simple networks but the intuition that control efforts focus solely on the front of an invasion is not universal. One important aspect that is not addressed by Chadès and coauthors is the institutional scale of the control efforts. In their paper, they assume that a manager has complete control over the entire network but often authority over management is shared among a number of agencies at the federal and state levels.

As discussed in Epanchin-Niell and Hastings, some intuitive conclusions from the literature are available. For example, species with higher damages justify higher control efforts, species with higher costs of control will have lower control efforts, and the less weight placed on damages and costs of control in the future, the lower the control efforts today. One mechanism for higher damages could be higher rates of spread and/or the pattern of spread (linearly vs radially). Olson and Roy (2008) show higher damages could result in eradication being the policy that maximizes net benefits to society. On the other hand, other researchers have shown that as the size of the invasion grows, the policy maximizing net benefits can switch from eradication to slowing the spread to eventually stopping all control efforts (Sharov and Libehold 1998). The potential for reinvasion into a location, which is likely in the northern pike scenario, would reduce the benefits of programs to eradicate the species in that location (Simberloff 2003).

In some cases, control of an invasive species might have collateral damage on other components of the ecosystem. Lampert et al (2014) model a case where eradication of an invasive plant, hybrid Spartina, threatens the recovery of an endangered bird that uses Spartina for nesting. Achieving both goals requires restoration of native Spartina. To determine whether restoring native Spartina is cost-effective–and if so, how to best allocate efforts and a budget over time to combine native Spartina restoration with invasive Spartina eradication–they developed an ecological-economic model of Spartina management. The model based on ecological and economic field data that was collected over several years. They show that the optimal management entails less intensive treatment over longer time scales to fit with the time scale of natural processes, specifically recovery of the native Spartina after plantings. In contrast, both eradication and restoration, when considered separately, would optimally proceed as fast as possible. Thus, managers should simultaneously consider multiple, potentially conflicting goals, which may require flexibility in the timing of expenditures.

Box 1: Basic Concepts of Risk and Uncertainty (adapted from Holland et al. (2010), Ch. 5)

While the terms "risk" and "uncertainty" are often used interchangeably, there have been historical distinctions between the two concepts in decision theory. The distinction is attributed to Knight (1921) who characterized uncertainty as the case in which there is no reliable probabilistic depiction of possible outcomes, and risk as the case in which there is a probability distribution of possible outcomes. This distinction has been blurred more recently (Freeman 2003) and in a Bayesian view of the world, the difference between these two concepts is a matter of degree (Berger 1985). For expositional reasons, we follow the NRC report on ecosystem services (NRC 2004) and classifies the case in which there is no reliable information or data on which to estimate probabilities as ambiguity. In contrast, risk is classified as the case in which probabilities are known or may be estimated, and uncertainty is classified as the more general case that encompasses either risk or ambiguity.[1] For example, analysts might know that water quality and the mortality of fish populations are related, but lack any basis for making claims regarding the likelihood of different ecosystem function-to-process relationships. This inability—a case of ambiguity—prohibits the assignment of estimated probabilities to different outcomes; therefore, the ability to map water policy impacts on fish populations is more difficult. Incorporating the potential value of learning is one way that such ambiguities can be acknowledged and addressed within policy analysis. Unlike ambiguities, risks can be assigned reliable probabilistic information on outcomes and relationships. This information is usually based on past empirical studies or observed patterns. Risks are not synonymous with bad or negative

One of the key components to understanding management trade-offs with invasive species control is measuring the cost of such efforts. In many cases we can observe the expenditures of control (e.g., cost of aerial spraying) but the effectiveness of the effort is unobservable (e.g., reduction in the invasive species population). Because we do not observe directly changes in the invader population, measuring the costs of invasive species control and how these costs change as the population of the invader changes is difficult. Jardine and Sanchirico (2018) develop a structural way to estimate the costs of monitoring and control for the invasive cordgrass Spartina in San Francisco Bay. Figure 3 below illustrates the patterns in coverage of the invasive, treatment, monitoring, and overall costs in the San Francisco Bay eradication program for Spartina. They find that overall the costs increase linearly and negatively with the invader population. Interestingly, the monitoring costs increase at an increasing rate as the population of the invader decreases while the treatment costs follow the opposite pattern.

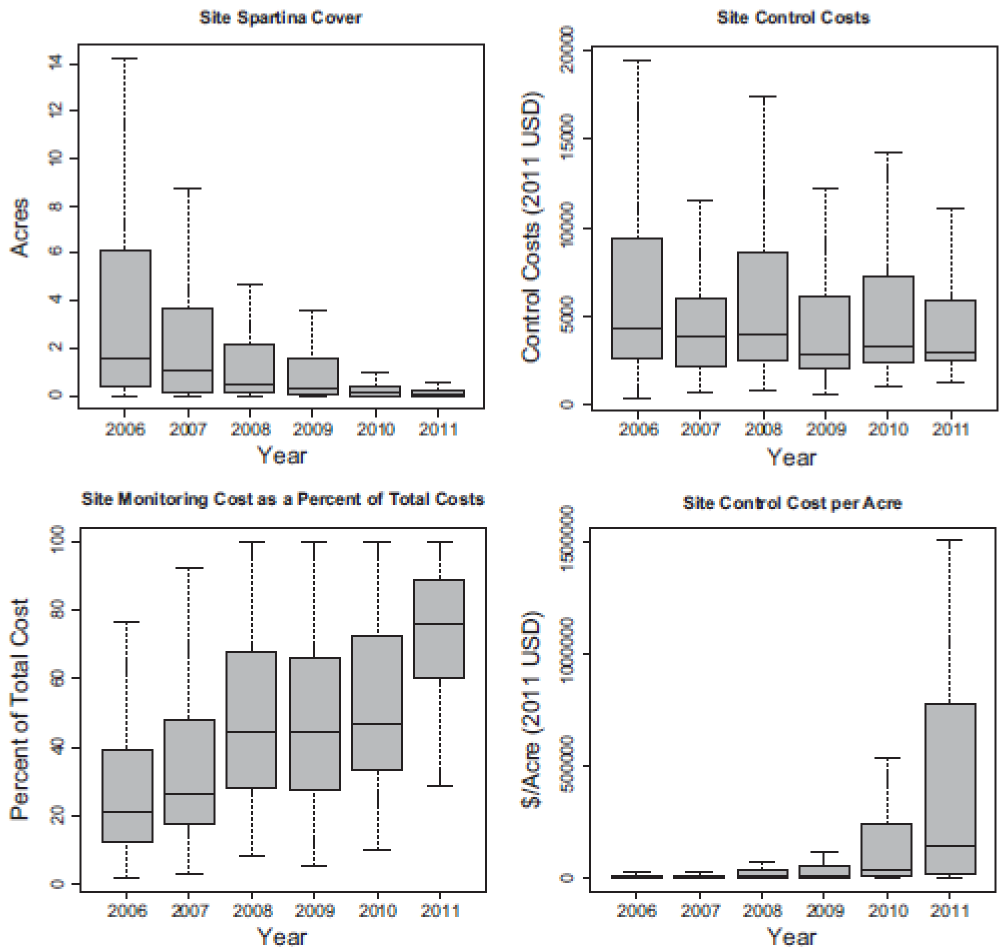

Fig. 3. Invasive Spartina cover (top-left), site treatment costs (top-right), site monitoring costs (bottom-left) and total site control costs (bottom-right). Source Jardine and Sanchirico (2018).

Another key component is considering the interactions between management actions and human behavior, especially when human behavior is the source of dispersal of the invader. Zipp et al (2019) develop an empirical coupled natural-human model of the spread of aquatic invaders across a complex lake system in northern Wisconsin that combines: (1) a behavioral model of recreational boater decisions; (2) an ecological model of the invasive watermilfoil including the probability of establishment in lakes; and (4) estimates of the direct welfare losses from watermilfoil for individual lakes that captures the reduction in shoreline housing prices and reductions in the boating experience due to the presence of watermilfoil. Watermilfoil is largely spread inadvertently through the movement of recreational boaters from lake to lake and as such, a model investigating the implications of different control options needs to consider the decisions of boaters to visit different lakes over the course of a season. They find that "…coordinated management across lakes provides its highest economic value in the early years of an invasion, before high-value, high-traffic lakes are invaded, and drops quickly once the invasion claims these lakes" (2019, p. 1).

Policy decisions regarding the monitoring and control of an invasive species are often complicated by significant economic or ecological uncertainty (Box 1). For example, an analyst's ability to predict policy outcomes may be affected by uncertainty regarding such factors as future introductions, climatic conditions, effectiveness of the control efforts and how the policy and other factors will affect the actions of resource users. Similarly, estimates of the benefits associated with various policy outcomes may be subject to uncertainty about future human preferences (e.g., whether and how demand for various ecosystem services will change). The literature investigating invasive species management under uncertainty demonstrates the value of incorporating such factors in decision making, and current research attempts to measure the value of learning about these factors within their context. Highlighting the trade-offs between monitoring and control efforts, Kling et al (2017), for example, showed the value of investing in monitoring early in the invasion as a means to learn about the invasion dynamics reduces the overall costs of controlling an invasion over time. Active adaptive management is one management strategy that actively invests in learning about the system (if the net benefits of these investments are positive) where this learning can come from non-control activities (e.g., surveillance and monitoring) as well as control activities (e.g., harvesting of the invader).

II.C. Economic concepts and practices

In approaching the Council's questions, we strive to apply economic concepts and research norms. This section provides a short overview of some of these ideas, which we will refer to below in our analysis. For convenience, we organize this information in glossary form.

"All else being equal" In economic reasoning, it is common to assume as a thought experiment that one factor changes in isolation while other factors are held constant. All else being equal (*ceteris parabus*) is a sometimes useful perspective, however it must be used with care since in the real world, rarely can one factor change by itself, or do so without immediately influencing other features of a system.

Best practices This phrase refers to our understanding of current norms for applied economic research. We will often use "state-of-practice" to describe an approach to quantitative economic analysis that follows best practices. Note that this is not the same as "state-of-the-art"; a study may follow best practices without applying techniques that are at the frontier of economic methodology. In fact, typically a state-of-practice study will apply methods that are well-understood by the economics community, unless the problem at hand requires methodological innovation to address adequately.

Control variable In a decision problem, a control variable is a "lever", or intervention that influences an economic system, usually at some cost. A control variable is typically a "flow", or quantity that must be understood with reference to a timeframe (e.g., gillnet sets per week).

Discounting All else being equal, economic agents (individual people and organizations) tend to prefer receiving rewards (for example, money) sooner rather than later (or, equivalently, delaying costs until the future). This observation leads economists to assume that people weight rewards received in the future less than they would be if received today. In policy analysis, this is often operationalized as a constant discount rate r. For example an annual discount rate $r = 3\%$ might be chosen for assessing future costs of an invasive species control program.

Expectation When future costs or benefits are uncertain, for policy analysis it is necessary to evaluate the expected outcome. This involves weighting potential future outcomes by their likelihood and essentially computing the weighted average. See also the discussion of uncertainty (Box 1).

Learning-by-doing The phenomenon of economic agents gaining experience from an activity that facilitates increased efficiency, or lower costs.

Net present value (NPV) Net present value (or just present value (PV) when not dealing with gross as opposed to net quantities) is a calculation that brings totals realized over time into the same units by discounting so that the totals are measured in terms of their (discounted) value from the standpoint of today (or any particular reference period). When totals are uncertain, the proper computation is *expected* NPV (or PV); consideration of uncertain NPVs may lead to complex differences relative to the counterfactual case where there is no uncertainty.

State variable State variables are durable dynamic quantities (or stocks). For example, the total population of Northern Pike in Lake Roosevelt may be interpreted as a state variable.

Uncertainty Uncertainty arises from the standpoint of a decision problem whenever a system is not predictable in some economically-significant form (i.e., not all unpredictability is important for decision making). Uncertainty is a very common challenge in invasive species control. See also Box 1 above.

III. Council Question #1

This section focuses on the Council's first question. We first restate the question and deliver our response. Next, building on the concepts and literature introduced above, we attempt to bound the scope of economic (as well as interdisciplinary) research that would be needed to answer Question 1 according to best practices. This section closes with an important note regarding how to interpret our conclusions in relation to current Northern Pike management policy in the Columbia River Basin.

III.A. Question 1 and our response

The first question posed for economic analysis by the council consists of two parts. We respond to each part in turn. The first is:

> "What information is needed to assess the economic impacts to natural resources in the Basin should Northern Pike spread throughout the anadromous and non-anadromous zones? (NWPCC 2018, p. 3)

Our response is that a large array of economic and ecological information is needed to assess the economic cost of an expanded NP invasion. We address information needs below.

The second component of Question 1 is:

> If such information exists, can you estimate the economic impacts of the spread of Northern Pike?" (NWPCC 2018, p. 3)

At this time, there are several information gaps that need to be addressed before an analysis can be completed. Additionally, even if most of the data and models were readily available, synthesizing the inputs needed for an economic assessment would involve a large-scale research enterprise devoted to constructing a collection of original ecological-economic models.

In summary, our assessment of future Northern Pike impacts in uninvaded areas of the CRB must be limited to describing the components (or sub-analyses) involved in the ambitious scope of work defined by Question 1.

III.B. Scoping costs of Northern Pike: the causal chain to economic endpoints

To better understand the portfolio of controls and sources of costs associated with the Northern Pike, we represent a causal chain that begins with a scenario where NP invade a new area of the Columbia River Basin and includes the resulting cascade of impacts and interventions to be considered. The causal chain is represented in Figure 5. Blue boxes represent the ecological impacts including potential damage to the ecosystem, as discussed in the ISAB report. The red boxes highlight examples of the economic endpoints that represent the damages due to the invasion (e.g., change in recreational experiences) and associated economic costs (change in utility rates). The yellow boxes represent selections from the suite of controls available, where some directly target reducing the Northern Pike population and other focus on trying to mitigate the impacts by reducing other threats to the species of concern and the ecosystem.

For example, reducing the commercial catch of salmon is not going to impact the Northern Pike population directly, but it will reduce a component of the salmon mortality that in turn could partially offset additional mortality due to increased predation by NP. Of course, the effectiveness of these indirect methods, while intuitive from a theoretical perspective, is overall very difficult to demonstrate empirically as there are many confounding factors. Some interventions can act through multiple pathways such as modifying hydro-operations. For example, ISAB (2019) discusses how changing lake levels might reduce the spawning habitat of NP at the same time if these lower lake levels correspond to greater flows, the faster currents through the lake might reduce the overall level of predation on the salmon. There is however considerable uncertainty of the effectiveness of these hypothesized effects of modified hydro-operations.

A full accounting of the economic costs due to the expansion of the NP requires being able to capture the causal chain and measuring the changes in the endpoints. Different phases of the invasion may produce different area-specific chains, involving different links, additional endpoints, or different weighting of the endpoints included in Fig. 5. For this report it is not practical to compile a master list of data and modeling needs for each node and link in the chain, and there is substantial regional variation within the CRB in terms of ecological and economic processes that would make a generic list of questionable value. Such an enumeration task would itself be a research scoping exercise that would involve substantially more time and resources than were allocated for our report.

However, it is possible to recognize broad patterns in terms of data gaps. For example, while there is a significant amount of information on the costs of modified hydro-operations (and this management response is itself highly uncertain and of varying relevance depending on the region of the CRB that the NP invasion may reach), there is currently limited research available to draw on for the other economic endpoints, in particular conservation values for multiple native species at risk. Without such information, researchers sometimes revert to what is known in economics as benefit transfer methods. These methods, which have a number of challenges, use studies from other locations to generate estimates of the damages in another location (see, e.g., Boyle et al. 2010).

We note also that a critical barrier to benefit transfer is the limited available modeling capacity for many of the causal links in Fig. 5. For example, the “net effect on food web” box is, to the best of our knowledge, not the focus of an empirical study tailored for the CRB. There is currently no model for the future food web in the anadromous zone of the CRB that includes NP, and therefore no empirical link that can be made to many of the economic endpoints, whether effects on those endpoints are measured using benefit transfer or original economic analysis.

Fig. 4. Drawing of northern pike (Virgil Beck via Wisconsin Department of Natural Resources). Available at: https://www.flickr.com/photos/widnr/6506502765 (last accessed 6/8/19).

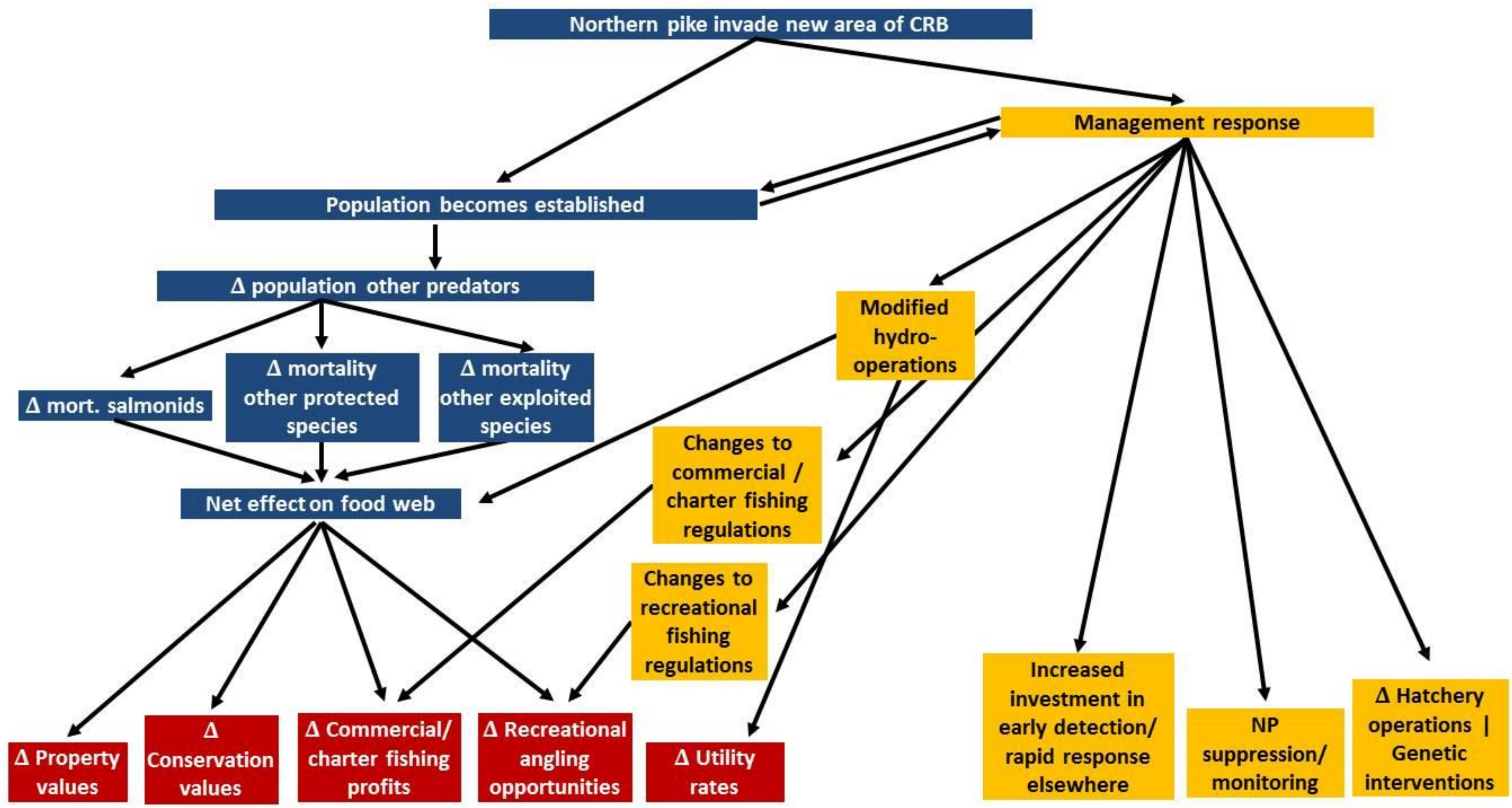

Fig. 5. Sketch of causal chain linking an expansion of Northern Pike to a new area of the Columbia River Basin to potential economic endpoints

Notes: Here "Δ" is short-hand for a change in the associated quantity. We use "mort." as an abbreviation for mortality.

III.C. Limitations of Economic Impact Analysis for Question 1

It is worth considering why an Economic Impact Analysis (EIA) may produce misleading results if conducted in response to Question 1. The Council's question addresses the potential for large-scale and long-term ecosystem change brought about by an expanded Northern Pike invasion in the Columbia River Basin. EIA is best suited for tracking short-run monetary flows in an economy under a number of assumptions, among them: a) an assumed "forcer", or particular form of ecosystem change coupled with a policy response; and b) little or no adaptation by economic agents. Moreover, as discussed in the Introduction, monetary flows may conflate economic benefits with economic harms. Perhaps the most severe limitation of an EIA for the Council's question is that neither the ecological outcomes from an expanded NP invasion or the form of management response are at this point known. While a scenario may be provided for an EIA, given the current state of knowledge there would be no scientifically-grounded basis for measuring the likelihood of that scenario, and therefore also the likelihood of the predicted monetary flows.

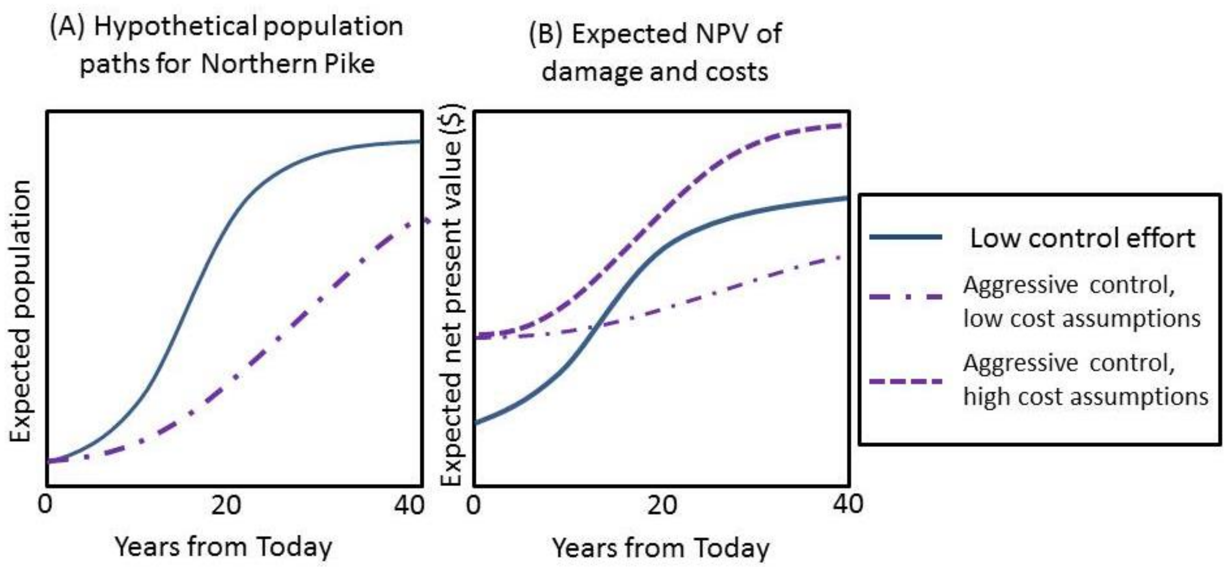

Fig. 6. Hypothetical value of delay and role of uncertainty in the net benefit of Northern Pike suppression

III.D. Interpreting our response to Question 1

We emphasize that while we are unable to produce a quantitative response to Question 1 for this report, this outcome should not be interpreted as weighing for or against any particular level of funding for suppressing NP Columbia River Basin. Figure 6 above presents a qualitative perspective on potential outcomes for NP suppression. Here we abstract from uncertainty within dynamic paths (for example, a confidence range represented by "error bounds" on population projections for NP in Panel A) and potential legal or other constraints on decision making, focusing instead on (in principle) quantifiable damage caused by NP and costs of suppression. All else being equal, a conventional economic assumption is that, from the perspective of today, damage from the invasion realized today is more costly than the same amount of damage where it to occur decades from now (due to discounting). From this perspective, an outcome where the expansion of NP is slowed through aggressive control may be valuable due to the slowed rate of NP population expansion in addition to the lower long-term population relative to less aggressive control (Panel A).[1]

The relative economic performance of aggressive NP suppression at this time is uncertain. Again abstracting from within-scenario uncertainty, it is possible in a hypothetical scenario that aggressive NP suppression will involve higher up-front costs but ultimately low net economic loss relative to lower control effort (Figure 6, Panel B). This may be because damage is lower due to lower densities and slower spread, combined with low realized costs and potentially also innovations in suppression methods (e.g., YY male NP – see ISAB (2019)) or learning-by-doing. Given currently available information, it is unfortunately not possible to rule out (or even assign a likelihood) to another outcome: a scenario where heavy investment in suppressing NP becomes very costly due to some combination of adverse factors (favorable conditions for NP population growth, more rapid than expected spread and establishment). For these scenarios, although aggressive suppression may result in the same population trajectory for NP (Panel A), damage and costs over time are actually *higher* than lower suppression effort and accompanying faster NP spread.

Since at this time we are unable to quantify or assign probability to outcomes for the CRB of the variety sketched above, we have no basis for judging or ranking the economics of the current or alternative strategies or funding levels for NP suppression. In particular, we are not arguing for or against any particular level of funding or management strategy for NP in the CRB now or in the future.

[1] This same reasoning may be applied on smaller scale to the population within Lake Roosevelt, which we consider in the next section.

IV. Council Question #2

This section addresses the second question for economic analysis posed by the Council. Question 2 focuses on the cost of Northern Pike suppression in Lake Roosevelt (hereinafter LR), a 150-mile long impoundment of the Columbia River created by Grand Coulee Dam located in Eastern Washington (WDFW 2019). We begin by reviewing Question 2 and the expected input for this question from the ISAB. This is followed by an overview of the data and models necessary to estimate the long-run expected cost of an NP control program for LR.

IV.A. The Council's question, ISAB input, and our response

The second question posed for economic analysis by the council is:

> "For the related ISAB question regarding level of Northern Pike suppression needed (question 5, above), can you calculate the costs associated with that?" (NWPCC 2018, p. 3)

Here "question 5" (hereinafter referred to as ISAB Question 5) refers to the following question for the ISAB:

> "In consideration of ISRP 2018-3 regarding Northern Pike, do we know what level of suppression (exploitation) through gill net removal, angler removal or other methods is needed to reduce the population in Lake Roosevelt to a level sufficient to reduce risk of emigration from the lake or risk to other focal management species?" (NWPCC 2018, p. 3)

On May 3, 2019, the ISAB produced a report (ISAB 2019) that responds to ISAB Question 5. Table 1 reproduces ISAB's conclusions.

An important aspect of the findings reached by the ISAB is that they are primarily qualitative. In other words, potential future management of NP in LR is described in terms of broad characteristics rather than particular metrics. As a result, the ISAB report does not provide specific estimates for either:

- The level of Lake Roosevelt northern pike suppression "sufficient to reduce risk of emigration from the lake"; or

- The level of Lake Roosevelt northern pike suppression "sufficient to reduce [...] risk to other focal management species"

Table 1. Conclusions for ISAB Question 5

Conclusion	Text
1	It is not possible to estimate the level of suppression necessary to eliminate the risk of emigration of pike downstream from Lake Roosevelt because there is no simple or quantifiable relationship between abundance and the probability of emigration or establishing a population downstream.
2	Each individual female pike produces tens of thousands of eggs, so given the right conditions emigration by even one male and one female pike could produce thousands of juveniles. Nevertheless, evidence from other organisms indicates that reducing the numbers of fish emigrating from Lake Roosevelt will delay the establishment of new populations downstream. Reducing establishment also reduces new source populations that enhance further spread, either naturally or by humans.
3	Evidence from invasions of other organisms indicates that eradication is often possible only at the earliest stages, so once detected, rapid eradication of newly established populations is paramount.
4	Pike can be suppressed with great effort and expense, especially in reaches without much suitable habitat, but likely will not be eradicated from a large river like the Columbia or its major tributaries, especially if there are source populations within about 12 miles (20 km) by river that supply immigrants. Eradication has been successful only in individual lakes, reservoirs, or small watersheds, and so might be successful in isolated ponds and lakes that become invaded.
5	Evidence from past introductions indicates that about as many invasions of new waters were caused by illegal stocking as by dispersal of pike themselves, similar to the pathways of illegal introductions of nonnative fishes in another western state. This indicates development of additional efforts to discourage illegal stocking of pike by humans and analysis of their cost effectiveness are warranted.
6	It is essential to develop a monitoring program capable of accurately detecting newly established pike populations throughout the anadromous zone, not just near the current invasions. Evidence from the Colorado River Basin indicates that illegal introductions of pike into lakes and ponds, including those in the floodplain, are especially likely.
7	Shallow, vegetated floodplain sloughs, like those in the lower Columbia River, will likely provide ideal habitat for pike spawning, rearing, and growth. A species distribution model could be developed to estimate the habitat in the Basin most likely to be invaded and how it could change with a changing climate. Such information will be valuable in designing more cost-effective targeted monitoring activities.
8	To be successful in reducing mortality of focal salmonids, control efforts will need to be extensive, occurring river-wide where habitat is suitable for pike, and ongoing to be most effective for protecting salmon populations.

Source: ISAB (2019, p. 22-23)

The implication is that, for this report we do not have the specific recommendation from the ISAB that the Council originally envisioned being the focus of an economic cost assessment. For example, the ISAB addresses the suppression necessary to reduce the risk to focal species in Lake Roosevelt most closely in their conclusion #8 (Table 1). However, many different hypothetical long-term control programs could be interpreted as fitting the qualitative description of the "control effort" described ("extensive", "river-wise where habitat is suitable for pike", and "ongoing"). Different programs that fit the qualitative criteria provided by ISAB may have very different expected costs.

Given the current state of knowledge regarding the economics and ecology of NP control in LR, we conclude that supplying our own hypothetical control program with specific quantitative parameters, and then proceeding with an ex-ante cost assessment,[2] would be beyond the scope of this report. There are at least two reasons for our conclusion:

- Due to knowledge gaps (described below), we are unable to assess whether a plausible control program would represent an upper bound on cost necessary to satisfy one or both Council criteria (reduce risk of emigration or reduce risk to focal management species in LR).

- An assumed long-run spatial and temporal pattern of investment in mechanical removal effort and other methods would have an unknown likelihood of satisfying the Council's criteria. In other words, we have no way of knowing whether a given hypothetical program or level of funding would be either too little or a wasteful over-commitment of resources.

Therefore, our response to Question 2 may be put succinctly as: ***at this time we cannot produce a cost estimate due to lack of information***. Without a specific ISAB-specified control program to assess, we use the remainder of this section to describe model and data needs for a cost assessment of a long-term NP control program for LR should one be proposed.

IV.B. Limitations of projecting current budgets forward

Before discussing data and model needs for a cost assessment, we first address some reasons why low-information approaches to calculating costs may produce misleading results. The Lake Roosevelt Northern Pike Suppression and Monitoring Plan (2018, p. 61) (hereinafter the LR NP Management Plan) requests roughly $900,000 per year to fund suppression of Northern Pike, monitoring (including research on dam operations), and public outreach. A simple estimate of the expected present value of NP management costs in LR would be to assume that this amount will be needed every year indefinitely, and calculate an expected present cost of management after FY 2022.[3]

[2] That is, a quantitative prediction of expected future costs before they occur and can be measured ex-post.
[3] From the standpoint of the end of FY 2019, assuming a $900,000 annual budget need in current dollars and applying a 5% discount rate, the *present value* of suppression and monitoring costs from the end of FY 2022 over

For several reasons, this back-of-the-envelope calculation is unlikely to be reliable as an estimate of expected future costs of NP management, although of course it is possible that it will ultimately turn out to be "in the ballpark".[4] In what follows, we briefly describe potential sources of error that may be associated with assuming a status quo budget for NP management each year into the future (or applying a fixed rate of increase to current budget requests, e.g. a 3% annual increase). This discussion is not intended to be exhaustive.

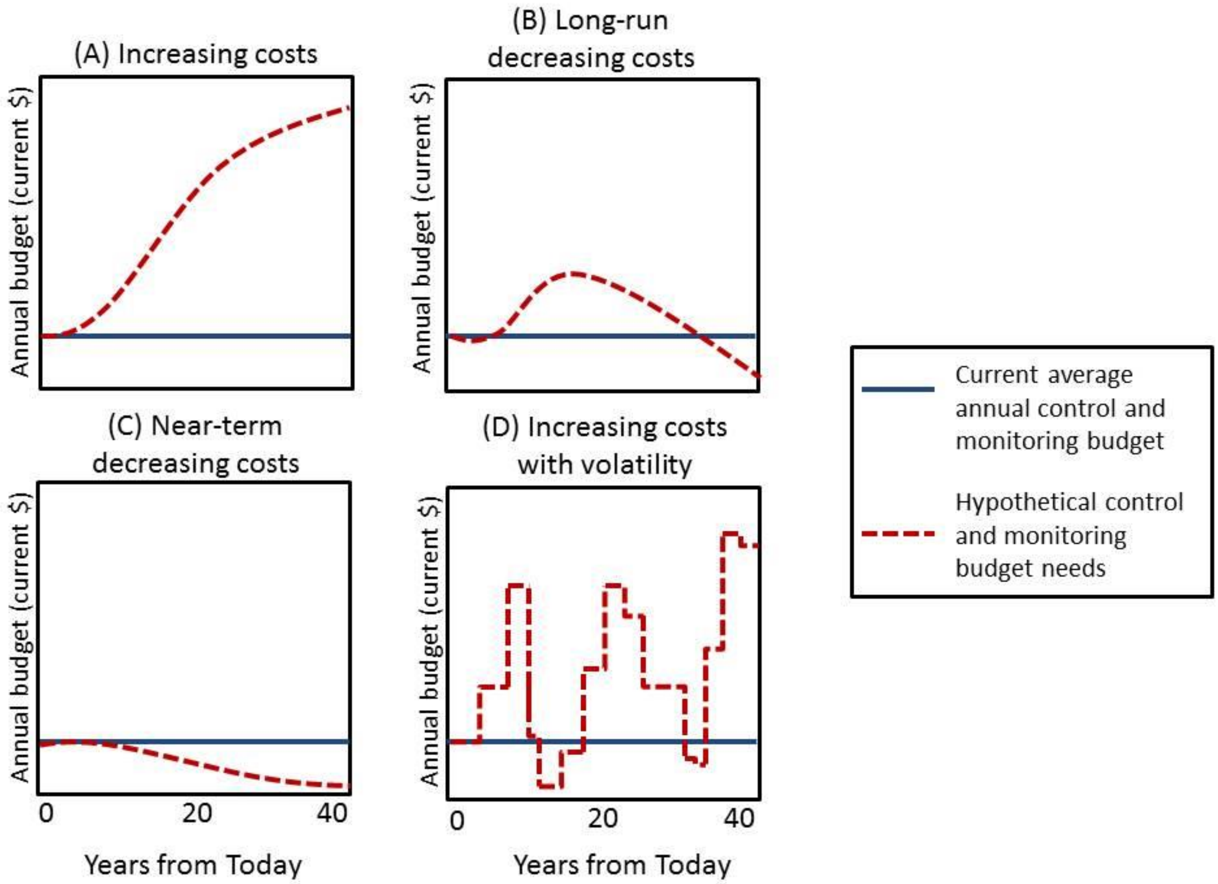

Fig. 7. Stylized and hypothetical annual control and monitoring funding needs for Northern Pike management in Lake Roosevelt relative to annual average requested for FY 2018-2022.

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the following 100 years would be approximately $16,208,300 in current dollars. Applying a 2% annual discount rate the same calculation produces $37,041,120 in current dollars.

[4] We do not endorse the adoption of this calculation for policy analysis or decision making.

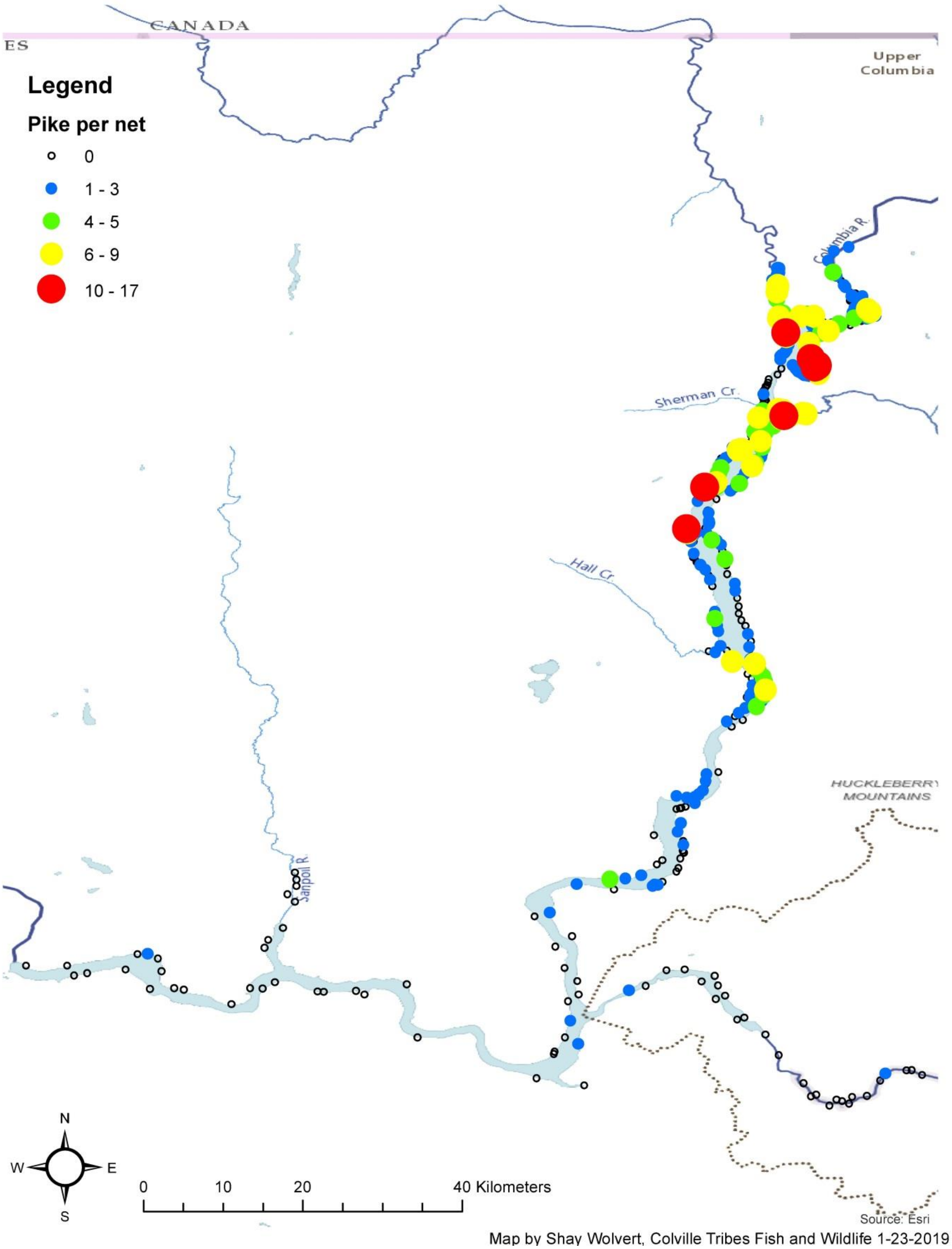

Fig. 8. Map of Northern Pike captures in Lake Roosevelt by State and Tribal agencies in 2018
Source: Holly McLellan (Colville Confederated Tribes)

To frame our arguments, we make use of Figure 7, which displays a selection of stylized and hypothetical trends in funding needs for NP monitoring and control. By "needs", we mean the amount of funding managers will end up requiring in order to meet objectives similar in spirit to those outlined in the LR NP Management Plan.[5] In other words, we are interested in envisioning the level of funding *necessary* from the perspective of managers, rather than a path of funding *allocated* for management (which may be more or less than realized funding requirements in any given year).

By design, the panels in Fig. 7 are intended to illustrate in an exaggerated manner a particular dynamic in isolation; in reality, multiple drivers that we describe are likely to be at work simultaneously in the future. These hypothetical trend lines are not intended to represent forecasts of expected funding needs for LR NP control.

IV.B.1. *Nonlinear funding needs*

An obvious reason that assuming budget needs will remain constant into the future may be inappropriate is that budget needs will change nonlinearly over time (Fig. 7). This may occur if NP are more successful than anticipated in LR despite control efforts and the population continues to increase. A pessimistic but feasible scenario is one in which more resources are needed each year to suppress NP and protect species of concern in the lake, with year-on-year increases eventually tapering off but annual budget needs remaining some multiple of recent requests (Panel A). A qualitatively similar scenario involves funding needs first rising and then falling decades from now below the current annual average. This might occur, for example, if suppression efforts were successful in driving down NP densities to a level substantially below current fall survey CPUE[6] and the amount of mechanical removal conducted each year could eventually be reduced. In either case, the realized present value of management costs may be very different from the result obtained from assuming funding needs will remain constant.

IV.B.2. *Northern Pike spatial distribution*

Within LR, damage caused NP abundance is likely to vary spatially; a pike in one area may be substantially more harmful than it would be in another area all else being equal. Figure 8 above shows the spatial distribution of gillnet locations in LR and ranges of NP captured. It is likely that this distribution will change over time, possibly in a pattern that increases the need for suppression effort. For example, the Sanpoil Arm of the reservoir hosts a significant population of Redband Trout (*Oncorhynchus mykiss gairdneri* and hybrids) and is valuable habitat for Kokanee salmon (*Oncorhynchus nerka*) (McLellan et al. 2019).[7] In early 2019, at least two NP

[5] One simplification we make is that, although the Plan targets near-eradication of NP by 2026, the reality is more likely to follow predictions made by the ISAB (2019, p. 22) that eradication is unlikely and that substantial effort will be required to suppress NP in the Lake indefinitely.
[6] E.g., the 2024 interim target in the Lake Roosevelt Plan (McLellan et al. 2018).
[7] Northern Pike Suppression in Lake Roosevelt and Walleye and Smallmouth Bass Suppression in the Sanpoil River

were caught in the Sanpoil Arm, including a 28 pound female (Francovich 2019). If NP were to become fully established in the Sanpoil Arm, additional resources may be required to suppress the species in this area of the reservoir relative to the same NP abundance increase elsewhere.

IV.B.3. *Innovations in Northern Pike control and learning-by-doing*

Not all trends lean in the direction of increasing costs. As LR co-managers (State and Tribal agencies involved in NP management) gain experience, it is possible that costs may decline (learning-by-doing). Another potential reason management costs may decline is innovation, or introduction of control methods that are not currently in use. McLellan et al. (2018) propose to manipulate the reservoir level to deprive NP of spawning habitat. If successful, it is possible that this method could combine with mechanical removal to achieve high NP mortality at lower cost. Given currently available information we are unable to assess the potential cost savings from this particular strategy.

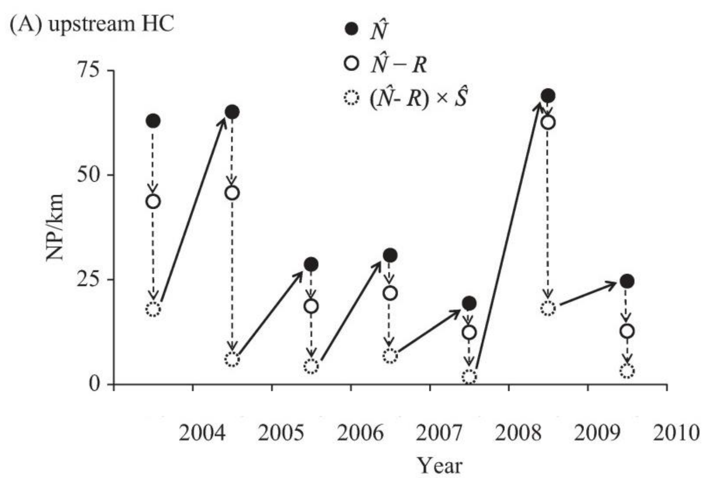

Fig. 9. Estimated Northern Pike densities (NP/km) ($\widehat{N}$), removal (R), and predicted survival rates ($\hat{S}$) in the Hayden to Craig (HC) stretch of the Yampa River, Colorado.
Source: Adapted from Zelasko et al. (2016, p. 1165)

IV.B.4. *Northern pike population stochasticity*

A fourth likely influence on future funding needs is NP population stochasticity. In a study of pike suppression in the Yampa River, Zelasko et al. (2016) find that stochastic recruitment and immigration to a given reach may result in local population changes that temporarily erase gains from earlier control (Fig. 9). While a spatial population model for LR does not exist for us to empirically assess NP population stochasticity in LR, stochasticity is a factor in measuring the expected present value of the cost of a management program. The stylized illustration in Fig. 7

Panel D depicts volatility in management funding needs that could be driven by NP population stochasticity (more boat trips during mechanical removal, higher demand for reward program payouts, pike population booms in high-priority habitat). Again, we emphasize that the timing and magnitude of variation depicted is for illustration only. However, results from natural resource economics demonstrate that a scenario where such variation is expected to occur around an upward trend (even if the peaks and troughs are smaller in magnitude) would lead to a sharply different expected present value calculation relative to a more predictable path (e.g., Fig. 7 Panel A). One implication is that a population model for Northern Pike in Lake Roosevelt that may be used to quantify population variability (particularly over space) will be useful for developing a more accurate estimate of the range of potential future suppression costs. Another point we stress is that stochasticity in NP abundance of the type shown in Fig. 9 is not necessarily an indication that a suppression program is failing to meet its objective over the medium-term.

IV.C. Towards assessing the cost of Lake Roosevelt Northern Pike management

The previous section argues that a variety of factors may result in an extrapolation of recent LR suppression budgets forward being inaccurate, even if the objectives of management remain similar to the status quo. In this section, we describe information that would be needed to carry out a high-quality assessment of the expected cost of a pre-specified Northern Pike control program for Lake Roosevelt, either one that mirrors the objectives of the current LR NP Management Plan or has different priorities. Here the pre-specified nature of the program suggests a cost effectiveness analysis (CEA) perspective must be applied. The objectives and methods for a pre-specified control program are not necessarily generated by an ecological-economic modeling exercise that evaluates whether program objectives perform well according to a cost-benefit analysis (CBA) test. Using a CEA lens, costs are determined by the expected funding requirements necessary to achieve the specified program objectives, assuming these objectives are feasible. This perspective is distinct from starting the assessment with a budget constraint already imposed, in which case costs are necessarily capped and the focus of analysis shifts to whether program objectives are feasible given the budget limits.

Similar to the LR NP Management Plan, we interpret a control program broadly to include removal effort (e.g., gillnetting), monitoring, research, and “fixed costs” of maintaining an ongoing management program each year. We first provide an overview of elements considered in a cost assessment. We then move on to a brief review of selected types of currently-available data as well as models and data that are not available but would be useful for estimating program costs.

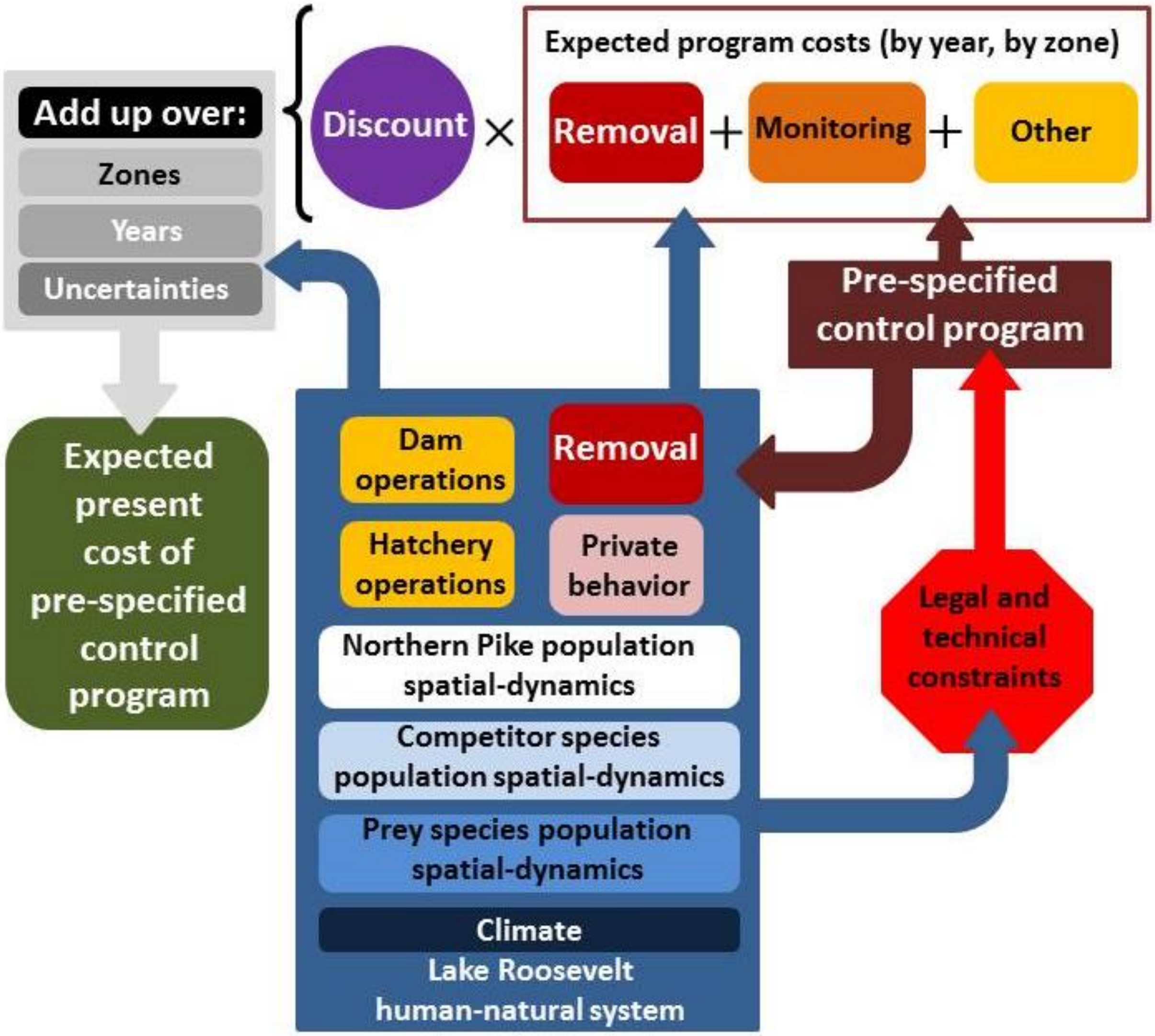

Fig. 10. Schematic of model and data inputs required to estimate the expected long-run cost of a pre-specified Northern Pike control program for Lake Roosevelt

IV.C.1. *Components of a cost assessment*

Figure 10 above displays a diagram of elements of a high-quality cost assessment. Moving counter-clockwise from the right-hand side, the first input is a pre-specified control program. The more specific and quantitative the specified program is in terms of its objectives, the more likely an informative cost assessment may be carried out. For example, depending on the detail and predictive power of other model components (see below), program objectives could be described in terms of inputs (e.g., maximum level of effort), outputs (NP removal yield), or threshold average abundances of either Northern Pike or species of concern. Objectives may be further specified spatially (e.g., target estimated NP abundances within 12 km of Grand Coulee dam) and temporally (achieve no more than a given target estimate mortality on Rainbow Trout (*Oncorhynchus mykiss*) lake-wide attributable to NP by 2030).

The program may be further specified to account for legal or institutional constrains (red octagon with arrow). Constraints may be explicitly laid out as part of a program description (e.g., a stated minimum application of some specific method of NP removal within a given zone of LR), or may necessarily follow due to some known array of laws or standards. Essentially, constraints are important for analysis when they remove from consideration one or more cost-effective paths for implementing a policy. Constraints are also a transparent way of incorporating values that cannot be monetized; for example, limiting NP abundance in culturally-significant zones of the CRB that would otherwise be weighted less by a cost-effective implementation of a control policy focused on NP impacts over larger spatial scales.

Moving counterclockwise to the top of Fig. 10, the pre-specified program (subject to constraints) takes the form of "controls," or activities that generate measurable expected costs each year. For example, "variable costs" of removal effort through different methods (e.g., electrofishing) are fairly well-understood and have been documented for LR (see below). Here variable cost is common economic label for costs that tend to change from year-to-year and can be readily adjusted by managers; typically increasing activities considered within this category generates additional costs (more electrofishing trips costs more money, all else being equal). "Non-sunk" fixed costs like employee benefits must also be tracked. While many costs are relatively straightforward to quantify most will be expected to change over time (e.g., healthcare costs) and may exhibit substantial year-to-year variation (fuel prices), which creates uncertainty not directly stemming from the ecology of the lake. This variation should be accounted for to the extent possible in the assessment.

Once potential channels of costs are identified, substantial ecological-economic modeling may need to be undertaken to predict how even a pre-specified control program will unfold over time. This feedback is captured by the blue arrow emanating from the "Lake Roosevelt human natural system" box in the middle of Fig. 10. Feedback is necessary to consider since even spatially- and temporally-delineated program objectives may leave important details unaddressed. For example, if the spatial distribution of NP 10 years were predicted to be much different than it is presently (see below), how might that effect fuel usage or labor hours? In order to operationalize a program in terms of predicted input needs and outcomes for relevant populations, the state-of-practice methodology is quantitative human-natural systems modeling. Ideally, a multi-species model of the Lake Roosevelt food web would be available to predict how controls on the system affect NP and prey species of concern over time and space.

Potentially significant adjustments and feedback induced by a program are not limited to changes to fish populations. One potential form of feedback is learning-by-doing; over time results from control may allow LR co-managers to apply removal effort more cost effectively. Another category is private activity. The unfortunate history of the Northern Pike invasion is that people have been instrumental to its spread, and in some areas invasive NP are viewed as desirable sport fish (ISAB 2019; Zelasko et al. 2019). Moreover, the current Lake Roosevelt Management Plan counts on influencing private behavior through a combination of public outreach and a modest incentive program for NP capture.[8]

The most important use of a LR human-natural system model is to predict how the pre-specified NP control program will influence key state variables over time and space. In addition to the NP population, populations of key prey species and competitors will also be important to consider. Environmental influences on NP dynamics, for example intra-annual trends in water temperature and dam operations (which may constitute a control variable that is part of the program) would ideally be included. Given that the invasive NP population is not closed (that is reinvasion from other parts of the CRB are likely), and eradication is unlikely, long-term environmental trends including those associated with climate change will be important to consider as well if the focus is on measuring costs of an NP control program decades into the future.

With these components in place, the assessment boils down to the relatively straightforward operation (conceptually, if not in implementation) of discounting expected costs and then adding them up to compute the expected present value (top of Fig. 10). Here ecological and economic uncertainty is collapsed into a common metric (the effect on money-measured costs) and averaged over time and space. It is important to note that costs that are either difficult or not appropriate to monetize (e.g., cultural value of threatened fish populations) may be incorporated as constraints on the pre-specified policy rather than included directly in the expected present value calculation.

Table 2. Examples of potentially relevant data and models available now

Description	Source(s)
Management personnel compensation	Available from current budgets for the LR NP Management Plan (via Holly McLellan, Colville Confederated Tribes)
Boat use fees per trip	Available from current budgets for the LR NP Management Plan
Current fuel prices and fuel price forecasting tools	Energy Information Administration
NP bioenergetics results from other systems	Bean (2010) for Box Canyon
Climate model projections	RMJOC (2018)

[8] In 2019 the Colville Tribes continue to offer a $10 bounty per NP head. *See* “2019 Northern Pike Reward Program Rules” (*available at* https://www.cct-fnw.com/s/2019-Northern-Pike-Reward-Program-Rules-updated-010219.pdf) [last accessed 6/10/19].

IV.C.2. *Examples of models and data for a cost assessment*

In this section we present some examples of information that would be useful for a state-of-practice assessment of long-term management costs similar to the approach described above. This review is not intended to be a complete catalogue of inputs for an application to the Lake Roosevelt Northern Pike invasion. Also, without the benefit of experience resulting from developing an analysis, we acknowledge that the components or sources listed may not be the best available inputs. For example, in Table 2 above, recent work on NP bioenergetics in Box Canyon may be useful for developing a bioeconomic model. However, as discussed above, for the purpose of a cost assessment such work is not a substitute for a spatial population model for LR that is capable of mapping current abundance estimates, removal effort, exogenous factors (e.g., environmental conditions in the reservoir) to predictions of the future spatial distribution and age/size structure of NP and prey species of concern.

Table 3. Potentially useful models and data not currently available

Description	Note
Effectiveness of modified hydro-operations to reduce NP abundance	
Multi-species spatial population model of NP and prey species abundance	
Model of emigration risk from LR as a function of NP population abundance	

While there is large array of data and models that would be need to perform a cost assessment, in Table 3 we focus on three examples that may be worthwhile targets for future research investment. Above we mention need of population modeling, a priority that we also include in this list. An understanding about the potential effectiveness of modified hydro-operations would be particularly important if such operations were included in a portfolio of alternatives for a pre-specified management plan (McLellan et al. 2018, p. 33). We do not take a positon on the economic merits of this strategy or its likely effectiveness. A model of emigration risk from LR would address the knowledge gap identified by the ISAB. It is particularly important for a cost assessment if an objective of a management plan is to limit “propagule pressure” of NP areas downstream of LR.

V. Conclusion

This report responds to a recent request by the Northwest Power and Conservation Council for input from economists on: 1) the potential costs of Northern Pike suppression in Lake Roosevelt, WA; and 2) potential future economic damage and management costs expected to be caused by further NP spread through the Columbia River Basin, including the anadromous zone. For both questions, currently available models and data fall well short of what is needed to produce a state-of-practice quantitative economic analysis. In particular, the problem of estimating the cost of NP suppression in Lake Roosevelt over time–a task that is far less ambitious than estimating future economic consequences of NP for the CRB as a whole–highlights the complex *interdisciplinary* research challenge. **We stress that our conclusions should not be interpreted as an argument for or against current NP control efforts in Lake Roosevelt or elsewhere.** For essentially any potential NP control project in the CRB, there is simply not enough information to produce informative quantitative analysis of future expected costs or benefits within the scope of work for this report.

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