FEATURE

Linking Climate Change and Fish Conservation Efforts Using Spatially Explicit Decision Support Tools

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ABSTRACT: *Fisheries professionals are increasingly tasked with incorporating climate change projections into their decisions. Here we demonstrate how a structured decision framework, coupled with analytical tools and spatial data sets, can help integrate climate and biological information to evaluate management alternatives. We present examples that link downscaled climate change scenarios to fish populations for two common types of problems: (1) strategic spatial prioritization of limited conservation resources and (2) deciding whether removing migration barriers would benefit a native fish also threatened with invasion by a nonnative competitor. We used Bayesian networks (BNs) to translate each decision problem into a quantitative tool and implemented these models under historical and future climate projections. The spatial prioritization BN predicted a substantial loss of habitat for the target species by the 2080s and provided a means to map habitats and populations most likely to persist under future climate projections. The barrier BN applied to three streams predicted that barrier removal decisions—previously made assuming a stationary climate—were likely robust under the climate scenario considered. The examples demonstrate the benefit of structuring the decision-making process to clarify management objectives, formalize assumptions, synthesize current understanding about climate effects on fish populations, and identify key uncertainties requiring further investigation.*

Acoplamiento entre el Cambio Climático y la Conservación de Peces mediante Herramientas de Decisión Espacialmente Explícitas

RESUMEN: *los profesionales de las pesquerías están siendo presionados para incorporar proyecciones de cambio climático en sus decisiones. En este trabajo se demuestra cómo un marco de decisiones bien estructurado, acoplado con herramientas analíticas y bases de datos espaciales, puede ayudar a integrar información climática y biológica para evaluar alternativas de manejo. Se presentan ejemplos que relacionan escenarios de cambio climático con poblaciones de peces, con el fin de abordar dos tipos comunes de problemas: (1) priorización espacial estratégica de recursos limitados para la conservación y (2) decidir si la remoción de barreras migratorias beneficiaría a los peces nativos, los cuales también están amenazados por la introducción de competidores foráneos. Se utilizaron redes Bayesianas (RBs) para traducir cada problema de decisión en una herramienta cuantitativa y se implementaron estos modelos bajo proyecciones climáticas históricas y hacia el futuro. La priorización espacial por medio de RB predijo una pérdida sustancial de hábitat de las especies objetivo para el año 2080, y proveyó medios para mapear tanto los hábitats como las poblaciones que más posibilidades tienen de persistir considerando los distintos escenarios climáticos en el futuro. La simulación de barreras mediante RB aplicadas a tres ríos predijo que las decisiones que implicaban una remoción–previamente hechas asumiendo un clima constante–serían, muy posiblemente, robustas bajo el escenario climático considerado. Estos ejemplos demuestran los beneficios de estructurar el proceso de toma de decisiones con la finalidad de clarificar objetivos de manejo, formalizar las suposiciones de los modelos, sintetizar el entendimiento que hasta la fecha se tiene acerca del efecto del clima en las poblaciones de peces e identificar piezas clave de incertidumbre que requieren de investigación ulterior.*

INTRODUCTION

Climate is changing in ways that may profoundly affect aquatic systems (O'Reilly et al. 2003; Winder and Schindler 2004; Parmesan 2006). Trends in climate-influenced abiotic factors, such as water temperature and streamflow, are already apparent in North America (Stewart et al. 2005; Kaushal et al. 2010; Isaak et al. 2011), as well as worldwide (Moatar and Gailhard 2006; Webb and Nobilis 2007; Schneider and Hook 2010). These changes have already been associated with fish population declines in Europe (Hari et al. 2006; Winfield et al. 2010; Almodóvar et al. 2012) and extirpations in populations of other aquatic species (Pounds et al. 2006; Durance and Ormerod 2010) and are predicted to alter coldwater fish distributions across Western North America (Keleher and Rahel 1996; Rieman et al. 2007; Wenger et al. 2011b). As a consequence, biologists are beginning to consider climate trends in planning and assessment, and resource management agencies are adopting climate change policies (U.S. Forest Service 2008, 2011; U.S.

Fish and Wildlife Service 2010). Managers need tractable approaches to assess the vulnerability of populations and habitats and to guide the prioritization of limited management resources.

The amount of climate science information available to conservation professionals is rapidly expanding (Overpeck et al. 2011; Porter et al. 2012). However, the sheer volume of data can be overwhelming and compound an already complicated decision context that may include other non-climate stressors, such as consumptive water use, habitat fragmentation, and invasive species. Initiatives to integrate climate data are helping bring that science into application, but challenges remain. For example, climate assessments for freshwater salmonids have utilized qualitative indices based on expert opinion or rules (Williams et al. 2009) or statistical relationships expressed in bioclimatic models (Flebbe et al. 2006; Rieman et al. 2007; Wenger et al. 2011b) to predict effects or “risks.” These approaches are useful, but greater utility could be achieved by explicitly linking these models to the decision process and management objectives. One approach is to develop and apply integrative decision support tools that formalize known or potential linkages between climate and fish population biology. These tools help structure the decision and also identify mechanisms, refine critical management questions, and make it possible to explore model assumptions. In an increasing number of instances, data can be derived from spatially explicit stream habitat models representing climate scenarios, which permits evaluation of choices in real-world coordinates.

Our objectives are to present two examples of a decision process and explore the utility of decision support tools that link climate change to fish population responses. A number of general frameworks have been proposed to assess the effect of climate change on aquatic systems (e.g., Johnson and Weaver 2009) or fisheries (e.g., Chin et al. 2010; Johnson and Welch 2010); these examples draw extensively on risk assessment or structured decision making. Our approach is grounded in these methods. This article describes the three steps we followed to adapt a decision support tool for two fishery management problems: (1) clearly defining essential problem elements (e.g., Johnson and Weaver 2009; National Research Council [NRC] 2009); (2) building conceptual models linking climate drivers to focal species; and (3) converting the conceptual model to an analytical decision support tool parameterized with relevant ecological data and driven by future climate projections. Our objective was not to build the most comprehensive models possible but to illustrate the process through case studies of two decision problems from the Northern Rocky Mountains of the Western United States (Figure 1). We demonstrate how the models could provide a conduit between the growing amount of climate information for streams and the decision-making process (NRC 2009).

The first decision problem involves spatial prioritization. The goal is to rank a number of streams, watersheds, or populations for conservation, restoration, or some other purpose that requires a strategic allocation of limited management resources. Our example here focuses on habitat potential related to climate

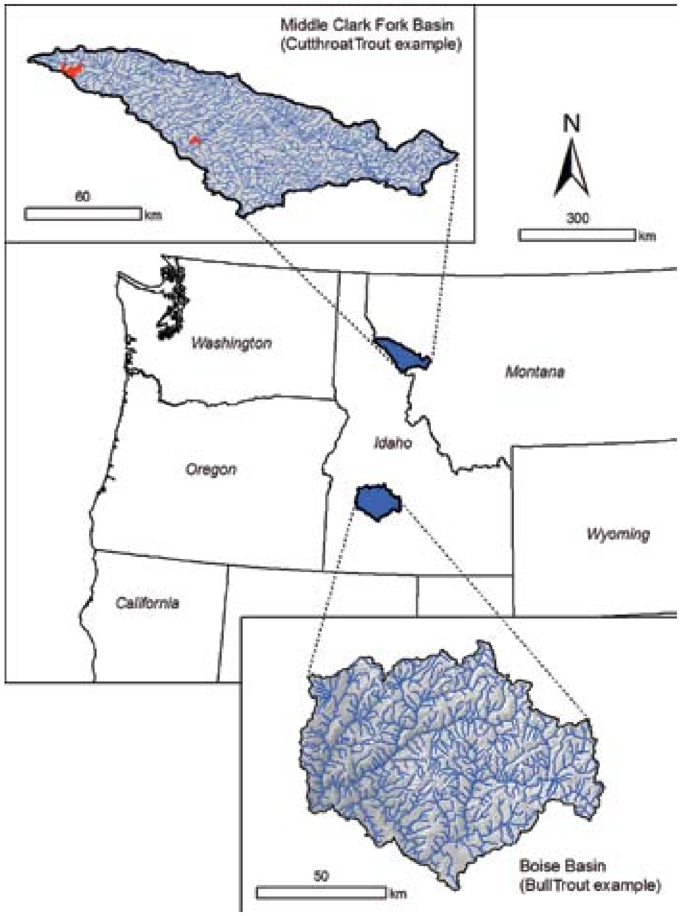

Figure 1. Location of two case studies used to illustrate application of spatially explicit decision support tools to evaluate management decisions for aquatic species under climate change.

change scenarios for Bull Trout (*Salvelinus confluentus*) populations across a river network. The second problem illustrates a yes-or-no decision about a specific management action among streams. This example focuses on removing or maintaining fish barriers in streams containing isolated populations of Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) threatened by invading Brook Trout (*Salvelinus fontinalis*) and whether this decision changes in the context of future climate conditions.

APPROACH AND METHODS

A Generalizable Approach to the Decision Process

To help organize our thinking, we structured our analytical process around a logical sequence of steps; here we describe the sequence in general terms. In subsequent paragraphs we build and apply decision support models for the two examples.

1. *Define the essential elements of the problem.* The first step in decision analysis is to identify the essential elements of the problem, including (a) values and objectives; (b) the decision to make; (c) uncertainty; and (d) consequences (Clemen 1996). This process may sound obvious but can be surprisingly difficult in decisions related to how climate affects species. Often management agencies are given vague mandates to incorporate climate projections into

their management activities or to conduct a climate vulnerability or climate sensitivity analysis. This needs to be translated into a clear decision problem or series of decision problems.

2. *Build a conceptual model linking climate drivers to focal species.* A conceptual model can be represented initially as a box-and-arrow diagram: boxes represent variables or conditions integral to the decision and arrows depict causal relationships. The conceptual model synthesizes the most plausible hypotheses, experimental data, observational data, statistical or empirical relationships, and expert opinion. Constructing this model helps formalize understanding and assumptions; this focuses discussion, refines logic, and identifies uncertainties. Overall, the conceptual model provides a template to structure thinking about the problem (Marcot et al. 2001, 2006; Uusitalo 2007). The models can be as detailed or simple as information and knowledge allow, but in general they should be no more complex than necessary to represent the problem at hand. Additional detail can always be added if it becomes clear that it is needed.

3. *Convert the conceptual model to a decision support model.* The next step is to quantify the relationships in the conceptual model so that it can be used to make predictions and evaluate management alternatives. There are different tools available for creating such a parameterized decision support model. We used Bayesian networks (BNs) in both examples. Bayesian networks are graphical models that represent probabilistic relationships among a set of variables or nodes and support consistent reasoning based on existing knowledge and uncertainty (Jensen 1996; Marcot et al. 2001; Newton et al. 2007). Causal relationships among nodes are represented by directed arrows called "links." Bayesian networks are graphical, so there is a natural connection between the conceptual model and the quantitative tool. Parameterization is accomplished by quantifying the conditional relationships represented by the nodes and their links. For each node, a discrete set of states representing possible conditions or values is defined based on that node's meaning. A node's conditional probability table quantifies the probability of any state given the conditions in the contributing nodes, including any interactions among them. Bayesian networks have some recognized limitations. For one, they are not able to directly represent cycles or feedback loops (Borsuk et al. 2006). Other decision support constructs, such as decision trees (Clemen and Reilly 2001), structural equation models (Pearl 2009), or fuzzy sets (Zadeh 1988), can be used in similar ways. We chose BNs because of their previous application to climate modeling (Amstrup et al. 2010; Jay et al. 2011) and our familiarity with development and application of these models in fisheries management (Rieman et al. 2001; Peterson et al. 2008) Bayesian networks are well suited for climate modeling because they are transparent, can integrate different classes of information, and are good for exploring uncertainty and competing hypotheses.

   The information used to parameterize and implement the model can come from many sources: field data, empirical relationships from external studies, expert opinion, output from other process-based physical models (e.g., climate models), or stochastic life history models (e.g., Lee and Rieman 1997). In Bayesian networks, nodes that do not have arrows pointing to them are called "root nodes," and they require some form of external input data to drive the model. We used climate variables to initiate the root nodes and drive the BNs in our examples, and a variety of climate data are available to model aquatic species (Appendix A, see http://fisheries.org/appendices). The probabilities for all other nodes, which have one or more arrows pointing to them, are calculated based on the relationships defined in the probability tables. The probability tables can be developed using the same suite of information described above.

Application of the Decision Process to the Examples

Here we show how we organized the decision analyses and built analytical tools for the two real-world examples. We then link climate projections to the tools to help with prioritization at the basin scale (Bull Trout) or evaluate management decisions with barriers (Cutthroat Trout).

Example 1. Prioritization of Bull Trout in the Boise River Basin

Study Area and Context

Bull Trout is listed as threatened under the U.S. Endangered Species Act (USFWS 1999) and is the focus of active management efforts by state and federal agencies. The species' temperature sensitivity (Selong et al. 2001) has prompted concerns that climate change could lead to substantial range contractions (Rieman et al. 1997, 2007). Our focal area in the Boise River basin (BRB) of central Idaho is near the southern limit of the species' range (Figure 1) and is characterized by high seasonal and spatial variability in temperature and precipitation. Bull Trout spawn and juveniles rear in the coldest headwater streams, so natal habitats are often patchy across river networks. The BRB contains 22 habitat patches occupied by Bull Trout (Dunham and Rieman 1999; Whiteley et al. 2006), where a "patch" is defined as a continuous network of thermally suitable habitat (Rieman and McIntyre 1995; Dunham and Rieman 1999). Habitat conditions appear to be changing in the BRB, and thermally suitable and high-quality habitats have been lost in recent decades (Isaak et al. 2010).

Problem Definition

We assume that a land management agency or another entity has been directed to consider climate change in its management plans. We assume also that the biologists involved focus on Bull Trout and their ultimate objective is to maintain a healthy, self-sustaining Bull Trout metapopulation by creating or maintaining suitable spawning habitats and connectivity over the next 70 years. A specific decision is where to focus conservation efforts, such as habitat protection or restoration. A key issue to consider will be the size and distribution of suitable spawning habitats, which are constrained, in part, by climatic conditions (Dunham and Rieman 1999; Rieman et al. 2007). Consequences of the decision include which populations are supported, as well as financial costs associated with implementing conservation efforts, whether additional Bull Trout management activities are needed, and what effects will occur for other species. A common conservation approach is to build from existing strengths. The idea here is to focus on populations with the best chance to persist or habitats most likely to support Bull Trout in the future and invest where the greatest benefits can be achieved for the least cost. A different objective might entail different decision logic. If the objective were to maximize among-population genetic diversity or distinct traits that reside within specific populations, then so-called peripheral populations may be of greater importance (Lesica and Allendorf 1995). For simplicity, we focus on building from existing strengths.

Conceptual Model

Our goal was to estimate the occurrence probability of Bull Trout for many individual stream segments, and the conceptual model represents the key processes that we think likely to influence those probabilities (Figure 2A). We constructed the conceptual model from first principles, and it resembles a simplified version of one described in Rieman and Isaak (2010).

Habitat potential for Bull Trout is determined by stream size, temperature, flow regime, and channel gradient. We assumed that nonnative Brook Trout would interact competitively with juvenile Bull Trout, and the strength of that interaction might vary with climate (Rieman et al. 2006; McMahon et al. 2007; Rodtka and Volpe 2007). We did not consider habitat degradation because the objective was simply to determine which stream segments would most likely support Bull Trout based on intrinsic factors and biotic interactions with Brook Trout. We assumed that extrinsic factors associated with degradation could later be mitigated through restoration actions where it made sense to do so. For convenience the decision is not formally represented in the diagram, because it involves comparisons across all stream segments or groups of segments after the predictions are made.

Bayesian Network

The BN model captured the key physical and ecological processes that we believe, given existing knowledge, will influence the occurrence of Bull Trout in response to climate change (Table 1, Figure 2B).We sought to keep the model relatively simple because it is easier to track the logic and implement conditional probability tables for nodes with three or fewer links (Marcot et al. 2006)—though that is not a constraint of the approach. The model can be revised as new information and questions emerge.

The parameterized BN predicts the occurrence of Bull Trout as a function of habitat suitability, occurrence of Brook Trout, and their interactions mediated by climate—in this case streamflows and temperature. Node states represent potential conditions or thresholds important for the characteristic or relationship of interest. For example, Bull Trout and Brook Trout have different thermal optima, with Brook Trout more tolerant of higher water temperatures (McMahon et al. 2007; Isaak et al. 2009). Rearing areas for Bull Trout are generally associated with colder stream reaches. We used five states for mean summer water temperature to depict these preferences. Thermal influences for Bull Trout were modeled as a logistic-type relationship across the five states, with the species preferring mean water temperatures <10°C (e.g., Dunham et al. 2003; Isaak et al. 2010) and preference declining rapidly as temperature increases (e.g., Wenger et al. 2011a). In contrast, thermal influences for Brook Trout were portrayed as a dome-shaped curve with preferred temperatures between 10°C to 15°C (e.g., Isaak et al. 2009; Wenger et al. 2011a). Synthesis of relevant information and a similar logic process was used to define states of the other nodes (Appendix B, see http://fisheries.org/appendices).

Climate Data

We used a single climate scenario (A1B) with downscaled projections of temperature and hydrology consistent with the Parallel Climate Model, Version 1 (PCM1) general circulation model (GCM) to provide representative climate projections for the 2040s and 2080s. The A1B scenario is considered a "mid-range" scenario for greenhouse gas accumulation that assumes a world of rapid economic growth, a global population that peaks in mid-century, and rapid introduction of new technologies balanced between fossil-intensive and non-fossil-intensive energy resources (Intergovernmental Panel on Climate Change 2007). The PCM1 GCM projects less warming and more summer precipitation across the interior Western United States compared to other GCMs (Littell et al. 2010). Projections based on scenario A1B and the PCM1 model have been used to model changes in trout distributions in the Northern Rockies (e.g., Wenger et al. 2011b).

There are a variety of statistical methods and data sources available to generate temperature and hydrologic projections (Appendix A, see http://fisheries.org/appendices). For the Bull Trout example, historical and future summer air temperatures were translated to stream temperatures in the BRB using the temperature model developed in Isaak et al. (2010). Historic conditions were based on averages of recent air temperatures and flows observed at climate stations in the basin. The future stream temperature scenarios were based on rates of air temperature increases of 0.44°C per decade and flow declines of 5% per decade. These rates approximate that of the PCM1 GCM used to force a hydrologic model and derive stream flows for individual National Hydrography Dataset Plus (NHD+) segments (Wenger et al. 2010, 2011b).

Strategic Prioritization

The probability of occupancy of Bull Trout within a stream segment was calculated during historical and future

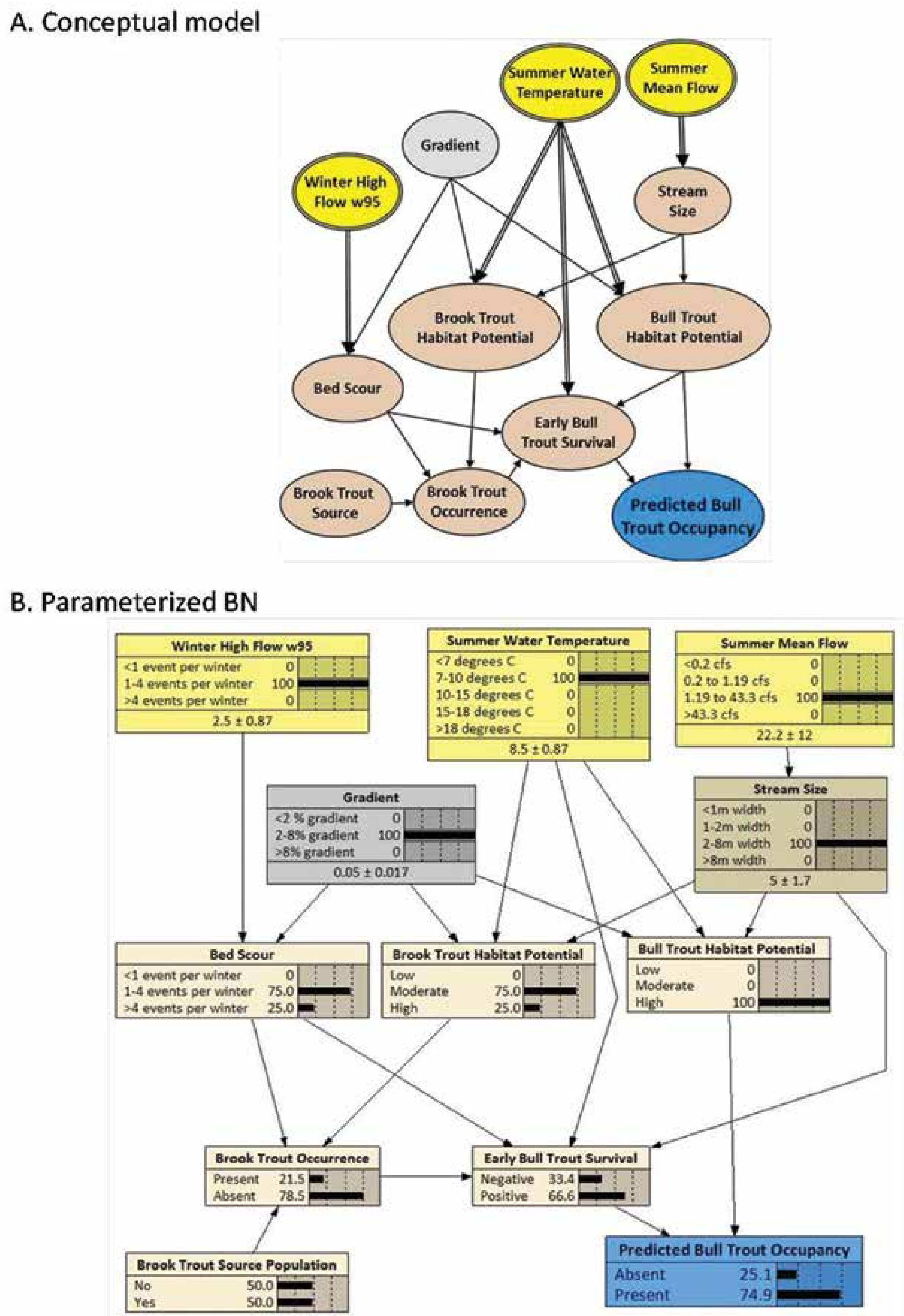

Figure 2. (A) Conceptual model and (B) resulting Bayesian network used for the spatial prioritization exercise with Bull Trout in the Boise River basin. Arrows indicate functional or cause-and-effect relationships between connected variables or nodes. The BN estimates the probability that Bull Trout will occur in a steam segment (blue box) as a function of climatically controlled variables (yellow boxes) that affect habitat or survival, channel gradient, and presence of a nonnative competitor. The probability that a node will be in a particular state is indicated by the value of the bar next to each state name. For example, panel B depicts a case where the mean summer water temperature is known (100% probability 7–10°C) but the presence of Brook Trout source population is unknown (50% yes, 50% no).

Table 1. Node (variable) and state definitions for Bull Trout Bayesian network (BN).

Node	Definition	States
Winter high flow w95[a]	The number of days in the winter (December 1–February 28) in which flows are among the highest 5% for the year	<1 event per winter, 1–4 events per winter, and >4 events per winter
Summer water temperature[a]	Mean water temperature from mid-July through mid-September	<7°C, 7–10°C, 10–15°C, 15–18°C, and >18°C
Summer mean flow[a]	Mean surface water flow in cubic feet per second (cfs) during the summer, defined as the first day after June 1 when flows fell below the mean annual value through September 30	<0.2 cfs, 0.2–1.19 cfs, 1.19–43.3 cfs, and >43.3 cfs
Gradient	Channel gradient in the stream segment	<2%, 2–8%, and 8%
Stream size	Mean wetted width during summer base flow	<1 m, 1–2 m, 2–8 m, and >8 m
Bed scour	Frequency of winter scour, which can cause direct mortality of developing embryos and newly emerged fry of fall-spawning Brook Trout and Bull Trout	<1 event per winter, 1–4 events per winter, and >4 events per winter
Brook Trout habitat potential	Intrinsic potential for stream segment to support Brook Trout (natal habitat) at a given density, assuming that the habitat is fully seeded and constrained only by channel gradient, water temperature, and stream size	Low: Brook Trout absent or rare; moderate: Brook Trout present at low-moderate density; and high: Brook Trout present at high density
Brook Trout source population	Presence of a Brook Trout population in a connected stream network that is capable of producing immigrants that invade a stream segment during a given time horizon	No, yes
Brook Trout occurrence	Potential occurrence of Brook Trout in a segment is constrained by the presence of a source population, bed scour, and habitat potential	Present, absent
Bull Trout habitat potential	Intrinsic potential for stream segment to support Bull Trout spawning and early rearing (natal habitat) constrained only by channel gradient, water temperature, and stream size	Low: Bull Trout absent or rare; moderate: Bull Trout present at low-moderate density; and high: Bull Trout present at high density
Early Bull Trout survival	Potential population growth rate as a function of survival from embryo deposition to age 2 as mediated by interactions between scour, stream size, and competitive interactions with nonnative Brook Trout. This stage-specific survival rate is assumed to be the only constraint on population growth	Positive: survival rate sufficient for positive population growth; negative: survival rate not sufficient for positive population growth
Predicted Bull Trout occupancy	Probability that Bull Trout occur in a segment depends on the natal habitat potential and whether survival has the potential to confer a stable or positive population growth rate. In effect, this represents the habitat's realized potential to support Bull Trout	Present, absent

[a] Climatically driven nodes that are equivalent to the same nodes in the Cutthroat Trout BN (see Figure 4) but have different state or threshold values

scenarios and with or without Brook Trout. The historical period represents contemporary conditions based on recent stream temperature and flow and provides a baseline for comparison of future climate projections. The "with Brook Trout" case assumes that Brook Trout could occur anywhere in the stream network where the habitat can support the species and with no condition on its current distribution. We used the modeling program Netica (Norsys 2010) to implement the BN and generated predictions for each of the 1,847 NHD+ stream segments in the BRB by inputting a data file containing temperature and flow projections for each time period. To provide a model output that was also amenable to population-level interpretation, we aggregated segment predictions into continuous networks or patches of habitat (sensu Dunham et al. 2002; Rieman et al. 2007). Each patch consisted of all stream segments above and including stream segments where mean summer temperatures were 10°C or lower (Isaak et al. 2010). Thus, patches here delineate stream networks judged to have high habitat potential based strictly on the current thermal regime. Patches of this sort have been used previously to approximate local populations of Bull Trout that may compose larger metapopulations (Rieman and McIntyre 1995; Dunham and Rieman 1999; Whiteley et al. 2006). Patch size is also believed to be an important constraint on the resilience of populations (U.S. Fish and Wildlife Service 2008) that may be influenced by climate change (Rieman et al. 1997, 2007; Dunham et al. 2003). For each segment, we multiplied the predicted probability of occurrence by segment length to provide an estimated length of occupancy. For example, a 10-km segment with occurrence probability 0.6 yielded an estimated occupancy length of 6 km. We summed the predicted occupancy length across segments within a patch to provide a patch-level estimate for occupancy. Patches were then mapped in one of five categories based on occupancy lengths, with categories selected to approximate those used previously for describing a range of Bull Trout occupancy probabilities from high to low (Rieman and McIntyre 1995; Isaak et al. 2010).

Example 2. Barrier Decision for Cutthroat Trout in the Middle Clark Fork Basin

Study Area and Context

Cutthroat Trout are native to much of the interior West and the West Coast of the United States. The number of healthy populations has declined and local abundances have decreased substantially due to habitat alteration and the introduction of nonnative species (Young et al. 1995 and references therein). In many regions, artificial barriers have been used to isolate local populations from invasive fishes, particularly Brook Trout and Rainbow Trout (*Oncorhynchus mykiss*). Although this practice is often effective in its main purpose, it limits migration and genetic exchange among Cutthroat Trout populations. Thus, the question of whether isolation is a benefit or threat has been the subject of research and debate and is generally believed to be context dependent (Fausch et al. 2009). It is possible that climate change could alter the decision regarding barrier removal at a given location because warming could have differential effects on Cutthroat Trout and nonnative competitors such as Brook Trout (Wenger et al. 2011b).

In the Cutthroat Trout example, we reassess the results of a previous study of this problem (Peterson et al. 2008) by incorporating climate change projections. The focus area covers three small watersheds in the Middle Clark Fork basin in western Montana: Deep, Dominion, and Silver creeks. Each stream contains a resident population of Westslope Cutthroat Trout fragmented by one (Silver), two (Dominion), or three culvert barriers (Deep). The streams would presumably support migratory individuals if some or all of these barriers were removed. The barriers isolate very small (<3 km) stream networks in Deep and Dominion creeks and a much larger one (>10 km) in Silver Creek. Habitat conditions have been degraded by land use in Deep Creek. For all streams, Brook Trout are present in and likely to invade from adjacent main-stem habitats and tributaries or may already be present in lower reaches (Dominion).

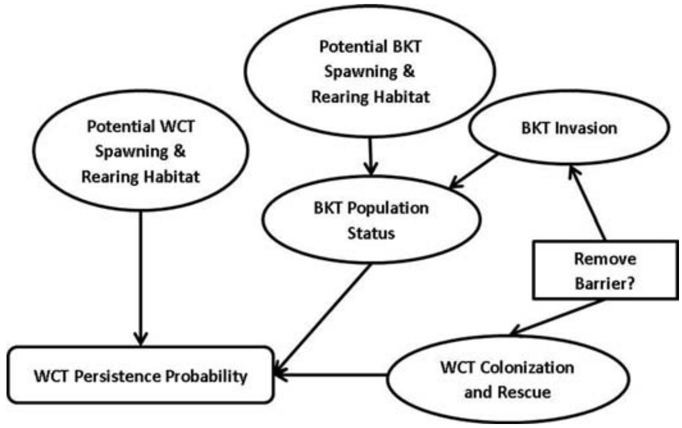

Figure 3. Simple conceptual model representing the decision context for the Cutthroat Trout barrier removal example.

Problem Definition

The decision is whether to keep or remove barriers isolating local populations of Cutthroat Trout. The ultimate objectives are to maximize the probability of persistence for individual populations and focus resources available for barrier management in the most effective way. Uncertainties involve whether Brook Trout will invade, whether this invasion will displace Cutthroat Trout, and whether the connectivity with other Cutthroat Trout populations or the expression of migratory life histories will offset the effects of invasion by Brook Trout or hybridization with Rainbow Trout. Each of these may be influenced by future climate. The consequences are the future probabilities of persistence for the Cutthroat Trout populations and the relative benefits that can be anticipated for the costs of barrier removal or alternative management actions, such as habitat restoration or removal of nonnative trout species.

Conceptual Model

The objective expressed in the simple conceptual model is to maximize the probability of persistence of Cutthroat Trout; the decision is whether to remove a barrier that prevents Brook Trout invasion but also prevents connections with other Cutthroat Trout populations (Figure 3). Persistence of Cutthroat Trout depends on the habitat constraints on population growth rate, population size, and demographic support from other populations (see Peterson et al. [2008] for supporting discussion). Cutthroat Trout population growth rate will be influenced by interaction with Brook Trout, which in turn depend on their own habitat potentials and strength of source populations.

This simple model is a good start but may not be sufficient because we know that habitat potential for both species varies from location to location. If the additional detail is important, this variability can be measured through field surveys or estimated from other information, such as geographic information system (GIS) layers, remote sensing data, or model outputs. We assume that habitat potential for both species varies along a continuum of stream size, temperature, flow regime, channel gradient, and perhaps other variables that are intrinsic to the watershed and streams of interest (Wenger et al. 2011a). We added some of these additional variables to express spatial variation in habitat potential. The notion of species-specific habitat potential used here represents the association between fish use and persistent stream attributes (equivalent to intrinsic potential; sensu Burnett et al. 2007). Realized habitat conditions depend on how that potential is modified by extrinsic factors, such as habitat degradation. Ultimately the presence and size of the population in any stream will be some function of the realized habitat conditions and the outcome of inter- and intraspecific biotic interactions. Competition between the two species is central to the decision problem, so this mechanism must be considered in the model. Of particular importance is the potential for reduced survival of juvenile Cutthroat Trout when Brook Trout are present (Peterson et al. 2004).These and other ideas are incorporated into an expanded version of the conceptual model based on a previous study of the invasion or isolation problem (Peterson et al. 2008). In the expanded model (Figure 4), yellow ovals represent the variables directly or indirectly influenced by climate that could change in the future.

Bayesian Network

To evaluate potential climate effects on barrier management decisions, we modified an existing BN by adding links to streamflow and temperature variables that are influenced by climate (Figure 4). Briefly, the existing BN considers the environmental factors influencing Westslope Cutthroat Trout and nonnative Brook Trout habitat, the species' interactions, and how placement or removal of invasion barriers may affect persistence of a local Cutthroat Trout population (Peterson et al. 2008). To revise the model to consider climate, we simply added three new nodes—summer air temperature, summer mean flow, and winter high flow w95—that were derived from downscaled climate projections (Wenger et al. 2011b). These new nodes were then linked to existing nodes for water temperature, stream width, and flow regime. Formally, these linkages were defined by the conditional probability tables that translate one variable into another. For example, the conditional probability table for stream width was based on a regression relationship between stream width and summer mean flow derived in the interior Columbia River basin (Appendix C, see http://fisheries.org/appendices).

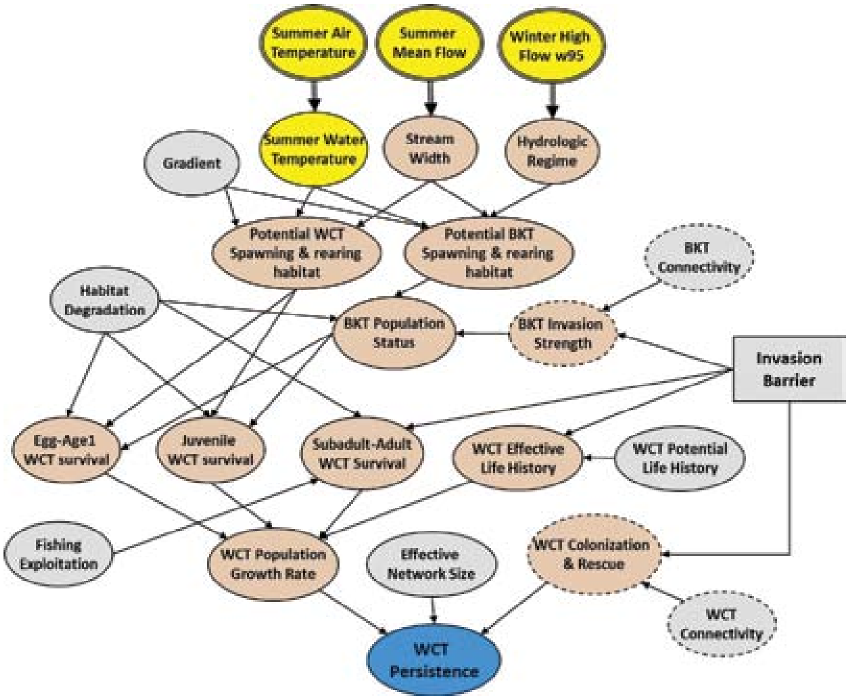

Figure 4. Detailed conceptual model depicting how climatically driven changes in stream temperature and hydrology influence persistence of Westslope Cutthroat Trout when managers are balancing trade-offs between intentional isolation by barrier versus potential invasion by nonnative Brook Trout. The conceptual model was based on Peterson et al. (2008), with the addition of three variables (double outline) that link thermal and hydrologic changes to habitat suitability for both species. Climatically controlled variables are shown in yellow.

This highlights the relative ease with which BNs can be modified to integrate new knowledge (Marcot et al. 2006). This flexibility is advantageous when biologists and managers have neither the time nor resources to develop a new model or tool. Moreover, we were interested in the implications of climate change for a decision framework that already had considerable investment and support in the ongoing discussion regarding barrier management (Fausch et al. 2006, 2009; Peterson et al. 2008). The modified BN retains the parameterization of the original model, and the new nodes allow the user to evaluate how climate might alter interactions between barriers, Brook Trout, and Cutthroat Trout in the future.

Climate Data

Hydrologic variables for the middle Clark Fork were based on Variable Infiltration Capacity hydrologic model (VIC) output forced by climate data from the PCM1 GCM under an A1B emissions scenario. Mean summer air temperatures were based on the same gridded air temperature values used to force the VIC hydrologic model (Wenger et al. 2011a). To translate from air to water temperature, we assumed that mean summer water temperature was ~0.8 times the mean summer air temperature (Wenger et al. 2011a). To generate water temperature values for the 2040s, we assumed air warming rates of 0.6°C per decade and that stream temperatures warmed at 60% of this rate.

Barrier Decisions

We used the BN to evaluate a range of possible decisions in these streams under historical and future conditions (2040s), given the number and location of barriers and any additional threats (Peterson et al. 2008). In Silver Creek, the only decision was whether or not to remove the barrier at the creek mouth. In Dominion Creek, potential actions were to (1) remove the upper barrier, (2) remove the lower barrier, (3) remove both barriers, (4) eradicate Brook Trout between the barriers, and (5) combine actions 1 and 4. In Deep Creek, the two upper barriers were very close together and were considered jointly. Options in Deep Creek were to (1) remove the lower barrier, (2) remove the upper barriers, (3) remove all barriers, and (4) restore degraded habitat alone or in conjunction with barrier removal scenarios 1–3. In each stream we applied the Cutthroat Trout BN under these different combinations of barrier removal and habitat rehabilitation.

RESULTS

Prioritization of Bull Trout in the BRB

Under historical conditions, the BN predicted moderate to high probability (>0.4) of Bull Trout occupancy in 28.6% of the total segment length (TSL) in the BRB and that there were 12 of 22 patches with at least 10 km of stream likely to be occupied by Bull Trout (Table 2). The extent and size of stream segments and patches capable of supporting Bull Trout in the future were predicted to shrink dramatically (Table 2; Figure 5). By the 2040s, the aggregate length of moderate-to-high probability segments and number of patches were predicted to decline to 10.8% of TSL and to 7 patches where at least 10 km of stream could be occupied by Bull Trout; by the 2080s, these lengths shrank to 1.4% of TSL and there were only 4 patches where at least 10 km of stream could be occupied. Reductions in the probability of occupancy of Bull Trout were most evident at lower elevations and were attributed to temperature increases, but summer flow reductions at the upper extent of the stream network also reduced the probability of occurrence.

The presence of Brook Trout within a stream segment was predicted to have small effects on the probability of occupancy of Bull Trout compared to changes in climatic factors, especially by the 2080s (Table 2). Brook Trout had little effect in segments where the probability of Bull Trout occurrence was relatively high (>0.6) but larger effects in segments initially having a moderate probability of occupancy (0.4–0.6). Within patches, occupied stream length tended to decrease when Brook Trout were present but, again, these changes were small compared to climate effects. In the future scenarios, Brook Trout did not dramatically alter the distribution and relative position of habitats likely to be occupied by Bull Trout, which were increasingly constrained to headwater reaches.

There are different ways in which a manager could use these results to prioritize populations for conservation and restoration. The future warming trajectory of the Earth is uncertain, so a conservative approach might focus conservation efforts on the patches most likely to support Bull Trout in the future and that also meet a minimum size criterion (i.e., build from existing strengths). Three patches contain greater than 40 km of habitat predicted to be occupied under recent historical conditions (shown in dark green in Figure 5A) and are projected to still have greater than 20 km of habitat occupied by the 2080s if Brook Trout are not present (Appendix B, see http://fisheries.org/appendices). These three might be viewed as "key patches" (Verboom et al. 2001) or "strongholds" (Haak and Williams 2012) that form the core of a conservation strategy, and management efforts might focus on maximizing the quality of these habitats and removal of any internal migration barriers. If resources permit, a lower patch size criterion could be used and conservation efforts extended to additional patches that would be ranked based on spatial representation and connectivity to larger patches or climate-resistant patches (e.g., Vos et al. 2008). A manager might also choose to conduct targeted monitoring to confirm the effects of predicted habitat declines. For example, Bull Trout populations should be lost first from small, isolated patches or the warmest stream segments at the downstream extents of patches, and monitoring designs could target these areas specifically (Rieman et al. 2006; Isaak et al. 2009).

Table 2. Summary of probability of occurrence and predicted occupancy of Bull Trout by NHD+ segment and patch, respectively, in the Boise River basin (BRB). The analysis encompassed 1,846 NDH+ segments totaling 3,256.2 km habitat and 22 patches.

	Total segment length (km)				
	Predicted probability of occupancy				
Situation	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
Historical—no Brook Trout	1,776.2	547.7	485.2	228.0	219.2
Historical—with Brook Trout	1,809.8	973.1	26.0	228.0	219.2
2040s—no Brook Trout	2,168.7	736.8	213.1	127.3	10.2
2040s—with Brook Trout	2,168.7	883.9	66.0	127.3	10.2
2080s—no Brook Trout	2,465.9	743.0	18.7	28.4	0
2080s—with Brook Trout	2,465.9	749.8	12.0	28.4	0
	Number of patches				
	Occupied stream length within patch				
	<5 km	5–10 km	10–20 km	20–40 km	>40 km
Historical—no Brook Trout	8	2	6	3	3
Historical—with Brook Trout	9	3	5	2	3
2040s—no Brook Trout	10	5	4	1	2
2040s—with Brook Trout	11	5	3	1	2
2080s—no Brook Trout	14	4	1	3	0
2080s—with Brook Trout	15	4	1	2	0

Barrier Decisions for Cutthroat Trout in the Middle Clark Fork Basin

Mean summer air temperature near the three streams was projected to increase ~2°C by the 2040s, which shifted water temperatures from optimal (10–15°C) to high (15–18°C; Table 3). In Dominion and Deep creeks, winter flood frequencies were predicted to increase from 0.65–0.80 to 2.65–3.85 times per winter as the hydrologic regimes shifted from snowmelt to mixed rain and snowmelt (Table 3). Silver Creek was predicted to experience more than a twofold increase in winter flood frequency. This had no biological effect in the model relative to the historical conditions, because the hydrologic regime did not change and was already in the mixed rain and snowmelt category. Declines in summer mean flow were projected for all streams, but a shift in stream width categories was predicted only for Dominion Creek (Table 3).

In all three streams, the decision with the highest probability of Cutthroat Trout persistence was similar whether the climate was assumed stationary (Peterson et al. 2008) or changing (this study). This suggests that the decision was largely robust to the climate scenario considered. We focus here on Deep Creek (see Figure 6) and Dominion Creek as representative examples (see Appendix C for Silver Creek results).

In Deep Creek, removing all barriers and letting Brook Trout invade, instead of removing just the upper two and preventing invasion, would result in a larger increase in persistence under climate change (0.11 to 0.53, a 3.7-fold relative increase) relative to historical environmental conditions (0.15 to 0.59, 3.0-fold relative increase; Figure 6). Restoring degraded habitat provides an even greater relative benefit under climate change (persistence = 0.73, a 5.5-fold increase) than under historical conditions (0.77, a 4.2-fold increase), and habitat restoration appears even more important if Brook Trout are likely to invade.

In Dominion Creek there was no difference between the 2040s time periods for any barrier removal scenario. Changes in temperature and stream flow (Table 3) had a counteracting effect on Cutthroat Trout, with the net result that the probability of persistence did not change (Appendix C, see http://fisheries.org/appendices).

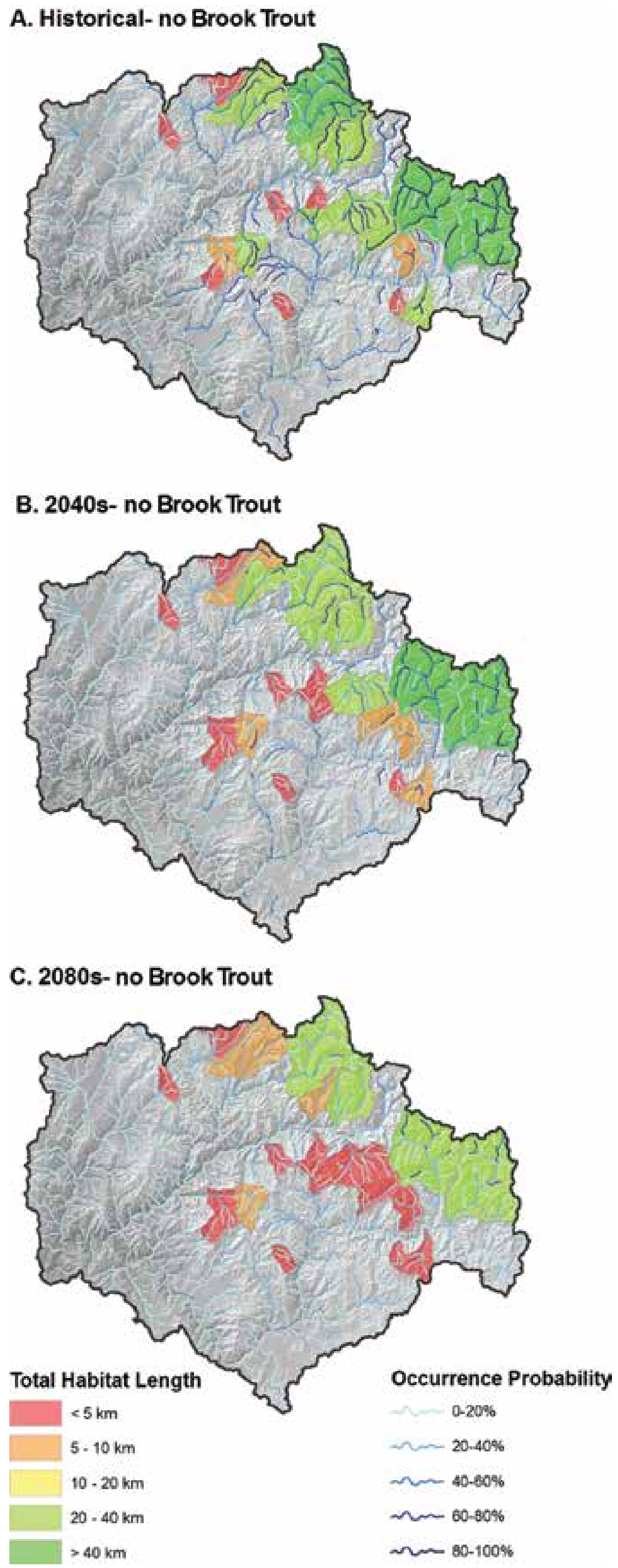

Figure 5. Probability for occurrence and predicted occupancy of Bull Trout in the Boise River basin in the absence of Brook Trout. The individual panels show the probability of occurrence for each segment estimated by the BN under (A) historical or (B) and (C) future environmental conditions. Shaded areas within each panel indicate the estimated length of occupancy within each patch (see text for additional details).

DISCUSSION

We have argued that formal decision models help structure our understanding of climate effects on fish populations. We demonstrated this approach with two real-world examples and found that climate change did not always lead to a radically different outcome. For Bull Trout in the BRB, those habitat patches that are currently the largest and have the highest probability of occurrence are predicted to remain so in the future. Managers and scientists came to similar conclusions in a 2011 workshop (Text Box 1). Application of the Cutthroat Trout BN for three streams indicated that the optimal decision—in terms of maximizing persistence in the presence of Brook Trout—was generally robust to climate change; climate simply reinforced the importance of barrier removal and reestablishing connectivity (e.g., Figure 6). From a manager's perspective, the models may make them more confident that they are proceeding correctly. In the Bull Trout example, the BN model output created a stronger consensus regarding which habitat patches to prioritize (Text Box 1), which could counter the practice of trying to save everything everywhere (Rieman and Isaak 2010). Conservation resources are limited, so choices must be made about where to prioritize; climate change simply adds urgency to these decisions.

The Bull Trout model projected that future occupancy would be strongly influenced by water temperature and that patches with higher probability of occupancy would be distributed further upstream in the BRB in the 2040s and especially in the 2080s. Declines in the probability of occupancy within patches might proceed in two directions simultaneously (range collapse; sensu Moritz et al. 2008): upstream, presumably driven by anticipated increases in water temperature (Rieman et al. 2007; Isaak et al. 2010), and downstream, caused by seasonal dewatering of very small headwater streams. These results notwithstanding, we caution against making irreversible commitment of conservation resources or reprioritizing before decision models and predicted climate effects are adequately validated. The ability to accurately project hydrologic conditions at the fine scale using macroscale models is limited (Wenger et al. 2010). Therefore, short-term management priorities might include (1) biological monitoring to determine whether and how fast distributions are actually shifting, (2) development of better hydrologic estimates through additional empirical monitoring and finer-scale modeling, and (3) establishment of stream temperature monitoring sites (Isaak et al. 2012).

The models can sometimes generate counterintuitive results that suggest the need to revisit current understanding or open new lines of inquiry. In Dominion Creek, the Cutthroat Trout BN predicted no difference in the probability of persistence under the A1B climate scenario compared to recent historical conditions. This cancellation of effect was unexpected. Given projected increases in stream temperatures and decreases in summer base flow, we would have hypothesized that the probability of persistence would decrease. We cannot discount that this could be a modeling artifact influenced by the choice of state values within the BN. However, it will be

Table 3. State and point estimates of climate and surrogate variables (nodes) for three streams used in the invasion barrier Bayesian network (BN) analysis for Westslope Cutthroat Trout under recent historical and future conditions (2040s). Future conditions were based on the A1B emissions scenario and the PCM1 global circulation model, and were used to generate the downscaled estimates for the BN analysis.

	Most probable state (point estimate)					
	Silver Creek		Dominion Creek		Deep Creek	
Node	Historical	2040s	Historical	2040s	Historical	2040s
Water temperature (°C)[a,b]	10–15 (air = 17.2)	15–18 (air = 19.3)	10–15 (air = 17.7)	15–18 (air = 19.7)	10–15 (air = 17.8)	15–18 (air = 19.8)
Winter high flow w95[a,c]	>2 events per winter (3.45)	>2 events per winter (7.35)	<2 events per winter (0.65)	>2 events per winter (3.85)	<2 events per winter (0.8)	>2 events per winter (2.65)
Hydrologic regime[d]	Mixed	Mixed	Snowmelt	Mixed	Snowmelt	Mixed
Summer mean flow (cfs)[a]	1.19–43.3 (7.63)	1.19–43.3 (5.42)	1.19–43.3 (4.29)	1.19–43.3 (2.99)	1.19–43.3 (5.31)	1.19–43.3 (4.22)
Stream width (m)[e]	3–10 (4.09)	3–10 (3.59)	3–10 (3.28)	<3 (2.85)	3–10 (3.56)	3–10 (3.26)

[a]Node definition and/or states are listed in Table 1.
[b]Values in parentheses are mean summer air temperatures (mean air temperature) estimated for the watershed (wtemp; Wenger et al. 2011b). We generated air temperature categories corresponding to those water temperature states by examining the relationship between Brook Trout occurrence and the mean summer air temperature at a point (ptemp; Wenger et al. 2011b). Additional details are found in Appendix C (see http://fisheries.org/appendices) .
[c]A threshold value of two events per winter delineated hydrologic regimes as either predominantly snowmelt (less than two) or mixed rain-on-snow and snowmelt (more than two). The threshold value was based on ad hoc interpretation of the geographic distribution of modeled winter high flow frequencies across the Pacific Northwest and Intermountain West United States. Similar approaches have been used to approximate transition points between so-called hydrologic regimes (e.g., Mantua et al. 2010).
[d]"Hydrologic regime" is defined as the seasonal pattern of runoff and flooding that might influence bed scour and subsequent incubation or emergence success of fall spawning salmonids like Brook Trout. Hydrologic regime has two states: Snowmelt and mixed rain-on-snow and snowmelt. See Peterson et al. (2008) for additional details.
[e]"Stream width" is defined as mean wetted width over the stream network during base flow. Stream width has three states: <3 m (small), 3–10 m (medium), and >10 m (large). See Peterson et al. (2008) for additional details.

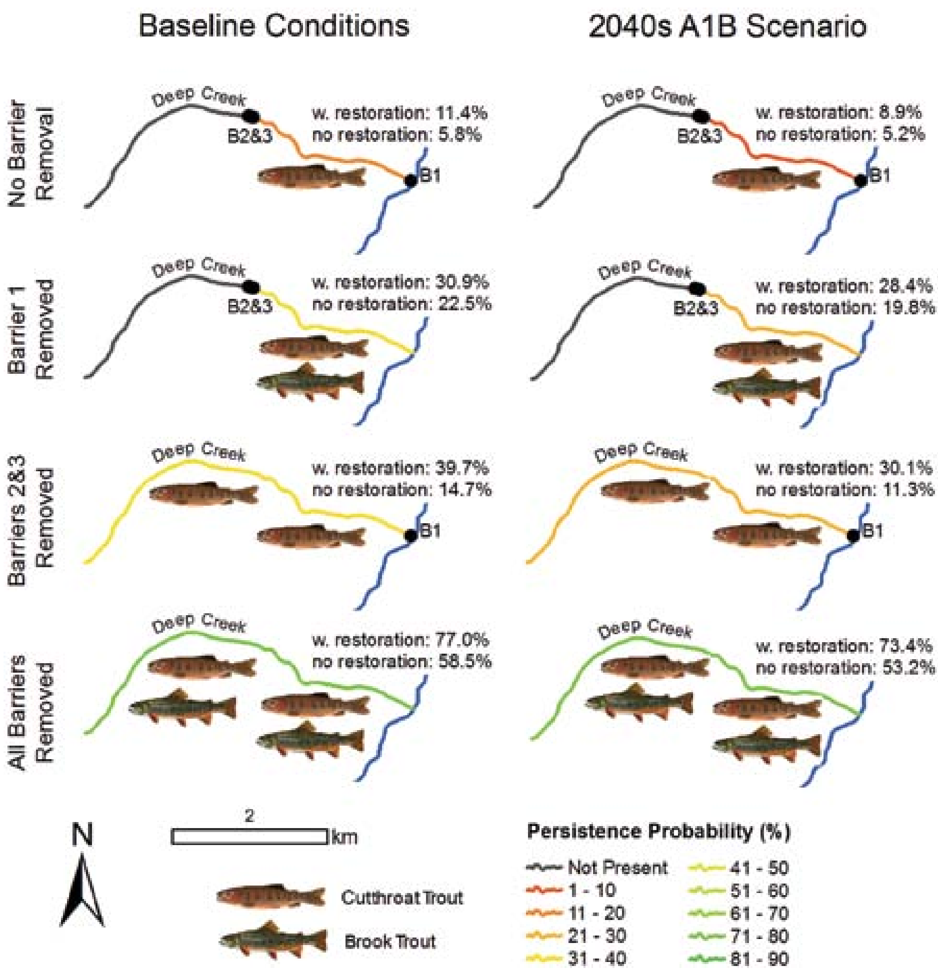

Figure 6. Decision analysis for barrier removal in Deep Creek, Montana, under current and future climate conditions. Colored lines represent the probability of persistence for Westslope Cutthroat Trout in that stream fragment under different combinations of barrier removals (rows) and climatic conditions (columns) assuming that habitat has been restored from its current condition. Actual probability values assuming habitat has been restored (w. restoration), or not restored (no restoration), are above each fragment. Black circles (•) denote existing migration barriers, and fish icons represent species with access to that stream fragment.

TEXT BOX 1. A WORKSHOP APPLICATION OF THE BULL TROUT DECISION SUPPORT TOOL

Application of the Bull Trout decision support tool was explored with a diverse group of 60 scientists and managers from 16 different state, federal, and private resource organizations during a 2-day workshop held in Boise, Idaho, in 2011. The objective was to see whether detailed climate projections and a formal decision tool could support a more refined or objective spatial prioritization process within a specific river network. Essentially, we asked whether the additional information provided by downscaled climate projections—filtered through a spatially explicit model of Bull Trout climate vulnerability—would affect the decisions people made.

On day 1, workshop participants were given a short primer on climate change and the anticipated effects on stream environments and fish populations (presentations archived online at the U.S. Forest Service Climate Change Resource Center: http://www.fs.fed.us/ccrc/video/boise-aquatics.shtml). Participants were then split into groups of four to six individuals and provided GIS layers summarizing topography, hydrography, and land ownership within a river network in central Idaho. Spatially explicit information on Bull Trout populations and potential threats to these populations—for example, road networks, movement barriers, wildfire, invasive Brook Trout—was provided, as well as GIS layers of stream temperatures (Isaak et al. 2010) and hydrologic regimes (Wenger et al. 2010, 2011a) representing recent historic conditions.

Each group was asked to prioritize 5 populations (of 22 total) where limited conservation resources should be directed to conserve Bull Trout and maximize their chances of persistence pending future climate change. There was general agreement that the largest habitat networks for existing populations should be less vulnerable to climate change and should be priorities for conservation while the smallest, most isolated populations or habitats should not be. There was less agreement on populations of intermediate size and connectivity, with diverse actions and rationales offered to support choices based on existing tenets of conservation biology (e.g., increase spatial diversity, spreading risk from catastrophic events).

On day 2, participants were given future climate scenarios showing predicted stream temperature and hydrologic conditions for 2046 and 2086. The decision support tool was introduced with a brief demonstration and participants were asked to reconsider their prioritization using the tool. Concordance among the groups was more consistent on day 2 and the number of populations receiving votes declined from 15 to 12. Priority populations were again those that were largest, and several small populations that had received votes on day 1 were not voted for on day 2. The number of populations in an intermediate "maybe" category dropped by half.

We made several observations from this exercise. First, consistent, spatially explicit information served as a useful means of focusing people from diverse backgrounds on a common problem. Despite the length and intensity of the workshop, participants remained fully engaged in examining the data and discussing alternatives. Second, basic principles of conservation biology strongly influenced initial priorities. Third, the decision support tool and climate projections did not result in wholesale changes, but they did bring clarity to the discussions and confidence to participants that many of their initial choices were supported by the available science. The example also served as a sobering reminder of how much habitat might be lost this century for Bull Trout. One participant remarked that their most powerful insight was how difficult it would be to save every population, which is a departure from what many biologists and managers have attempted to do in the past. Interested readers can access the decision support tool and spatial data layers used in this example at the workshop website: http://www.fs.fed.us/rm/boise/AWAE/workshops/climate_aquatics_decision_support.shtml.

important to understand whether such interactions are real. Managers could consider monitoring invaded Cutthroat Trout streams to identify whether there are threshold values for temperature or flows that mediate co-occurrence with Brook Trout.

The two examples presented here do not encompass the full range of environmental conditions or decision contexts that a biologist or manager may encounter. A more pessimistic emissions scenario may have dramatically altered the invasion dynamics of Brook Trout and reduced the potential benefits of barrier removal for Cutthroat Trout. Use of the Bull Trout BN to conduct a similar prioritization exercise elsewhere in the species range may reveal more dramatic or unexpected patterns. Managers still need to make decisions despite the uncertainties inherent in climate change analysis (Johnson and Weaver 2009). The process we described—a stepwise approach and use of decision support tools, like BNs, that link climate to biology—facilitates decisions, makes the scientific learning process explicit (Uusitalo 2007), and promotes "maturity in reasoning" on a management problem (Hamilton et al. 2005; Johnson et al. 2012).

Decision support systems have been developed to assist natural resource managers, but BNs generally have been underutilized in ecological and environmental disciplines (Aguilera et al. 2011). That is changing quickly with the recognition that they can be useful in climate vulnerability assessment and adaptation planning (e.g., Catenacci and Giupponi 2010). Bayesian networks recently have been used to predict effects of sea level rise (Gutierrez et al. 2011), determine whether extreme hydrologic events can be attributed to climate change (Hall et al. 2005), evaluate how greenhouse gas mitigation can influence loss of sea ice (Amstrup et al. 2010), and model vegetation response to climate warming (Dlamini 2011). The Bull Trout BN in our example is admittedly simple and the Cutthroat Trout BN directly addresses only a single type of management decision, but they can be thought of as individual modules or plug-ins to address pieces of a larger, more complex ecological problem (Johnson and Mengersen 2012). Indeed, individual BNs provide a natural way to decompose seemingly intractable problems into lower-dimensional subproblems (Uusitalo 2007; Johnson and Mengersen 2012) and create building blocks to handle multi-objective or multicriteria decision analysis.

We have demonstrated how these models can be used for spatially explicit prioritization and passage barrier decisions. Other modeling platforms could, in theory, accomplish similar tasks. For example, Marxan is a software package designed for conservation reserve planning (Ball et al. 2009) and is being used to identify so-called salmon strongholds in California (Wild Salmon Center 2010). The interactive tool NetMap (Benda et al. 2007) contains an expanding suite of data layers relevant to watershed analysis and planning—geomorphic attributes, hydrology, road networks, and land use—that could facilitate habitat prioritization and evaluation of management actions under climate change. The EAGLES modeling platform can be used for landscape- and regional-level geospatial analysis and decision support (Crabtree and Sheldon 2012); it incorporates species distribution and habitat selection models and therefore can be used to identify critical habitats or migration corridors under climate change (Crabtree et al. 2011). Additional decision support models are available for biologists conducting climate change analyses, and off-the-shelf options are appealing as resource management agencies face shrinking budgets and decreased staffing levels. A potential drawback here is that readily available models might constrain articulation of the management problem and objectives. We argue that the more robust process proceeds in the opposite direction, where the tools are developed after the management problem and objectives are specified. A biologist with sufficient time and resources can coordinate this process and help develop a conceptual model and decision analysis tool for their particular management issue. This should not be a solo effort; the process typically involves a small working group that collaborates closely with additional stakeholders and domain experts—biologists, scientists, decision makers—who contribute knowledge and peer reviews (Marcot et al. 2001, 2006). Model building can be done through a well-organized series of workshops or panel sessions designed to ensure scientific rigor and elicit expert judgment (Johnson and Weaver 2009; Marcot et al. 2012). Biologists without previous experience can consult with decision analysis experts for guidance on how to structure these workshops or find suitable decision analysis methods.

Process can be important. A quantitative decision support tool can be helpful, but following a sequence of steps to define and analyze a problem, which we refer to as the "decision process," can also make a tangible contribution to conservation planning (NRC 2009; Pollinio and Henderson 2010). Our examples included three steps—problem definition, conceptual model development, and process-based model construction. There are at least two advantages to following these steps. First, it facilitates acceptance of the conceptual model and decision support tools by biologists and their administrators, because the biological mechanisms are largely transparent and the biologists or administrators may have participated in the model-building process. Second, the process can identify information gaps and motivate important research that might be overlooked or is suggested by counterintuitive results. In fact, completion of just the first two steps, or even just the first step, offers potential benefits. Consider that agency biologists are sometimes forced to proceed under a strongly worded, yet ambiguous, directive to "consider climate change" in their planning and management activities. This is virtually meaningless if the conservation objectives are not clearly defined and important uncertainties in domain knowledge are not acknowledged. The process of defining the problem and building a conceptual model is not always easy when many stakeholders are involved and can be humbling when it forces a critical evaluation of purpose and knowledge. However, it is beneficial if it leads to a clearly articulated decision problem that sets the stage for consistent and transparent decision making.

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APPENDIX A. Availability of Stream Temperature and Discharge Data for Climate Assessments

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The quality of a climate change assessment depends heavily on the quality of information about the climatic conditions that constrain populations within the area of interest. For stream organisms, "climate" manifests most directly through the local thermal and hydrologic regimes. Early climate assessments often represented these factors using variables like air temperature, elevation, and latitude but the growing availability of inexpensive and reliable sensors, stream databases, and analytical techniques is rapidly improving the amount and accuracy of climate data available for streams. In our Bull Trout BN, for example, we used temperatures predicted from a new type of spatial statistical stream network model (Peterson et al. 2007; Ver Hoef and Peterson 2010; Ver Hoef et al. 2012) that was fit to a temperature database compiled from several resource agencies (Isaak et al. 2010; Figure A1). Spatial network models may be especially promising for such applications because they account for autocorrelation among non-random, clustered samples that often characterize such databases but provide unbiased parameter estimates and more accurate predictions than many non-spatial techniques. However, a wide variety of statistical and mechanistic models are available for modeling stream temperatures (Caissie 2006; Webb et al. 2008; Wehrly et al. 2009) and are now being used in many areas (e.g., Flint and Flint 2008; Lyons et al. 2009; McKenna et al. 2010; van Vliet et al. 2011; Ficklin et al. 2012).

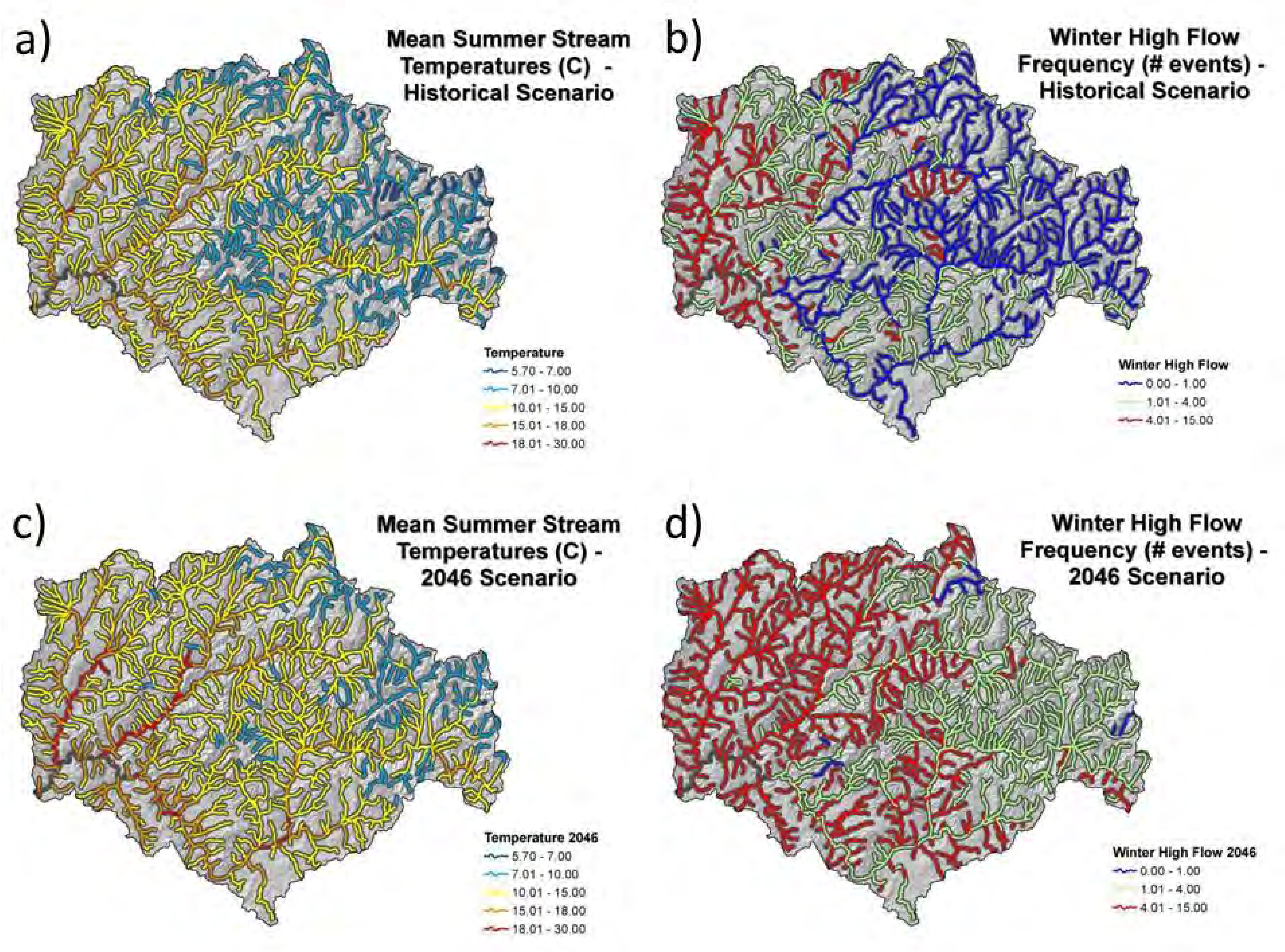

Figure A1. Maps of mean summer stream temperature and winter high flow (w95) in the Boise River Basin during historical and 2040s climate scenarios. These were among the individual variables integrated into the Bull Trout BN which was used to map the probability of occupancy across the basin.

For information about stream discharge in our BNs, we used flow metrics derived from the mechanistic Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994; Hamlet and Lettenmaier 2007) after it had been validated for making predictions in small, headwater streams (Wenger et al. 2010; Wenger et al. 2011; Figure A1). Similar flow metric predictions have been made for both historical and future climate conditions for most stream segments within the NHD+ national hydrography layer (Cooter et al. 2010) across the western U.S. and are archived online for easy access (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml). As with stream temperature models, a variety of hydrologic models are available in different areas and outputs from these models could be linked to biological parameters in climate vulnerability assessments (Storck et al. 1998; Ajami et al. 2004; Gassman et al. 2007).

Regardless of which models are selected to provide information about stream temperature and discharge, all require empirical measurements for calibration. For discharge data, the best source is the U.S. Geological Survey National Water Information System (NWIS; http://waterdata.usgs.gov/nwis/) that provides real-time and historical information from a national network of flow gages (Falcone et al. 2010). Comparable stream temperature databases that consist of long-term monitoring records are rare (Kaushal et al. 2010; Isaak et al. 2011) but large amounts of short-term temperature data (i.e., 1 – 3 years' duration) often exist and efforts are underway in many places to develop regional databases and establish better monitoring networks. For both stream temperature and discharge, modern digital sensors make data collection routine and inexpensive (Stone and Hotchkiss 2007; Isaak and Horan 2011) and expansion of these data types is occurring rapidly (Porter et al. 2012).

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APPENDIX B. Bayesian network (BN) model development and additional results for Boise River Bull Trout spatially-explicit prioritization case study.

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Summary

The Bayesian Network (BN) models habitat potential in a stream segment for both Bull Trout (*Salvelinus confluentus*) and nonnative Brook Trout (*S. fontinalis*) as a function of channel gradient, summer stream temperature, and summer wetted stream width. The species-specific *habitat potential* nodes represent the possibility that a habitat can support spawning and rearing based on persistent attributes (e.g., gradient, temperature, stream size) of the constituent stream segment. This definition is equivalent to intrinsic potential (sensu Burnett et al. 2007). The probability that Brook Trout occur in a segment depends on the existence of a source population, the segment's potential as natal habitat, and whether winter floods that could cause bed scour and mortality of embryos and newly emerged fry were common. The probability that Bull Trout occur in the segment is also a function of habitat potential and bed scour and the interaction with Brook Trout which is mediated by stream size. We also anticipate that competition with Brook Trout will be strongest in smaller habitats (≤ 2 m width, Rich et al. 2003). A node for juvenile survival in the Bull Trout portion of the model was included because we believe the key interactions and major changes in survival that constrain population growth and thus occupancy occur primarily at this stage. Bull Trout and Brook Trout have different habitat preferences, suggesting they are likely to respond to climate change in different ways. For example, winter high flows can affect both species, but we reason that it will have a stronger effect on Brook Trout because their smaller body size (relative to female migratory Bull Trout) results in shallower egg burial depth (Steen and Quinn 1999). Brook Trout also occur at lower elevations than Bull Trout (Rieman et al. 2006) where winter high flows generated by winter rains may be more likely. These effects may also mediate the outcome of interspecific competition.

Node definitions and rationale

Gradient

Gradient characterized the channel slope as percent rise in elevation over length in the stream segment; the states are defined jointly for Bull Trout and Brook Trout. In general, the distribution of both species appears to be constrained by higher channel gradients. Rich et al. (2003) and Wenger et al (2011a) both found negative associations between channel gradient and Bull Trout occurrence in Montana and across the Columbia River basin, respectively. Data for juvenile Bull Trout distribution from the Secesh River and 12 streams in central Idaho indicate a strong decline in density and probability of occurrence when gradients exceed about 5% (Isaak et al. 2009). A negative relationship between gradient and Brook Trout occurrence has been widely reported (e.g., Fausch 1989; Adams 1999; Rieman et al. 1999; Wenger et al. 2011a) as well, and was used within a BN used to assess invasion threats posed by Brook Trout (Peterson et al. 2008 and references therein). The definition used here refers to a stream segment as delineated by the National Hydrography Dataset Plus (Cooter et al. 2010).

States defining *Gradient*: <2%; 2-8%; >8%:

Summer Water Temperature

Summer Water Temperature was defined as the mean water temperature in a stream segment from mid-July through mid-September. This is the period of maximum water temperature observed in mountain streams in the western U.S. (Dunham et al. 2003). Temperature has been consistently associated with the occurrence and abundance of Bull Trout, Brook Trout, and related species (Paul and Post 2001; Rieman et al. 2006; Wenger et al. 2011a) and is expected to influence physiological processes linked to both growth and survival. Bull Trout and Brook Trout appear to have different thermal optima, with Brook Trout more tolerant of higher water temperatures (McMahon et al. 2007; Isaak et al. 2009) than Bull Trout which are commonly associated with the coldest waters available (Rieman and Chandler 1999; Dunham et al. 2003; Isaak et al. 2009; Isaak et al. 2010; Wenger et al. 2011a). Summer water temperatures associated with highest abundance or probability of occurrence of Bull Trout appear to be less than or equal to about 10^{o}C (Dunham et al. 2003; Isaak et al. 2010), whereas temperatures between 10-15^{o}C appear to be most suitable for Brook Trout. Because we have relatively detailed knowledge of temperature influences for these species we used five temperature states similar to Peterson et al. (2008).

States defining *Summer Water Temperature*: *<7°C; 7-10°C; 10-15°C; 15-18°C; >18°C*

Winter High Flow w95

Winter High Flow w95 was defined as the expected number of days in the "winter" (considered here as December 1-February 28) in which flows are among the highest 5% of all flow days for the year (following Wenger et al. 2010; Wenger et al. 2011a; Wenger et al. 2011b). High flows in the post-spawning period of embryo incubation and pre-emergence are believed to influence the occurrence and productivity of fall-spawning trout species (Nehring and Anderson 1993; Latterell et al. 1998; Wenger et al. 2011b), and w95 was negatively related to occurrence of Brook Trout and Bull Trout in the interior Columbia River basin (Wenger et al. 2011a). The *Winter High Flow w95* metric is assumed to represent flows with power capable of mobilizing much of the stream bed, displacing and killing embryos and pre-emergent or newly emerged fry under some channel and bed conditions, but not necessarily destroying all embryos and individuals within any stream segment (e.g., Wenger et al. 2011a). We defined three states for *Winter High Flow w95* based on the range of observed values from Wenger et al. (2011a).

States defining *Winter High Flow w95*: *<1 event per winter; 1-4 events per winter; >4 events per winter*

Bed Scour

Bed Scour was defined as the frequency of winter scour which can cause direct mortality of developing embryos, pre-emergent or newly emerged fry of fall-spawning Brook Trout and Bull Trout. This node was influenced by *Winter High Flow w95*, mediated by *Channel Gradient* which is likely to constrain scour depth (e.g., Montgomery et al. 1999). For example, Shellberg et al. (2010) demonstrated that scour was less likely in complex low-gradient channels (poolriffle reaches) that are transport limited, have increased bed armoring, woody debris and off channel habitats that provide scour 'refugia'. They also noted a strong relationship in flood magnitude and scour depth, with scour reaching egg burial depths of Bull Trout more likely with floods greater than 2-year recurrence interval. Tonina et al. (2008) modeled the increased depth and frequency of winter scour linked to rain-on-snow precipitation events, and concluded such hydrologic events could increase embryo mortality in Bull Trout, especially for shallow egg pockets. In general, egg burial depth is directly related to female body size in salmonids (Steen and Quinn 1999). We defined three states, equivalent to those for *Winter High Flow w95*, with threshold values for low, moderate and high frequency of bed scour events.

> States defining *Bed Scour*: *<1 events per winter; 1-4 events per winter; >4 events per winter*

Table B 1. Conditional probability table for *Bed Scour*. Values represent the probability that *Bed Scour* is in particular state, conditioned on the values of the parent nodes.

Parent nodes		*Bed scour*	
Winter High Flow w95	*Gradient*	1 to 4 per winter [a]	>4 per winter [a]
<1 per winter	<2%	0	0
<1 per winter	2-8%	0	0
<1 per winter	>8%	0	0
1 to 4 per winter	<2%	0.5	0
1 to 4 per winter	2-8%	0.75	0.25
1 to 4 per winter	>8%	0.5	0.5
>4 per winter	<2%	0.5	0.5
>4 per winter	2-8%	0	1
>4 per winter	>8%	0	1

[a] The probability that *Bed Scour* is "<1 per winter" for a given combination of parent nodes is 1 minus the sum of the probabilities of "1 to 4 per winter" and ">4 per winter".

Summer Mean Flow

Summer Mean Flow was defined as the mean surface water flow in cubic feet per second (cfs) during the summer (considered here as the first day after June 1 when flows fall below the mean annual value, through September 30; from Wenger et al. 2010, 2011a). *Summer Mean Flow* is used to estimate *Stream Size* (see below), and provides a link between climate-influenced changes in hydrologic conditions and the geomorphic variable (summer wetted width or *Stream Size*) that is most commonly measured in fish distribution studies (Dunham and Rieman 1999). The states for this variable are based on a regression between measured wetted width data and climate model predictions of summer stream flow from sites in the interior Columbia River basin, U.S. (see *Stream Size* below).

States defining *Summer Mean Flow*: *<0.2 cfs; 0.2 to 1.19 cfs; 1.19 to 43.3 cfs; >43.3 cfs*

Stream Size

Stream Size was defined as mean wetted width of the stream segment during the summer low flow period (see *Summer Mean Flow* above). Geomorphic features such as stream size directly influence the capacity of fish habitat, and stream size has commonly been associated with the distribution and abundance of salmonids in the western US and elsewhere (Peterson et al. 2008 and references therein; Wenger et al., 2011a). Longitudinal patterns in the distribution and abundance of Bull Trout and Brook Trout in the western US indicate that both species have similar associations with stream sizes for spawning and early rearing, but Bull Trout appear much less likely to occur in the smallest streams (< 2m; Dunham and Rieman 1999; Rich et al. 2003; Isaak et al. 2009). In the upper Secesh River basin, Idaho, Isaak et al. (2009) did not observe juvenile Bull Trout at any site with stream width >6 m. In contrast, Rich et al. (2003) found that Bull Trout were almost always present in streams with widths 6-7 m if Brook Trout were absent (they did not have any sites >7 m). Juvenile Brook Trout can be abundant in streams as small as 1 m wide (Rieman et al. 1999), but are commonly found in higher densities when stream widths are >2 m (Peterson et al. 2008). Rahel and Nibbelink (1999) found that Brook Trout were generally restricted to streams <4 m width in southeastern Wyoming. *Stream Size* was estimated directly from *Summer Mean Flow*. The regression equation was: $\ln(Stream\ Size) = 0.625 + (0.386 * \ln(Summer\ Mean\ Flow))$ where stream size is wetted width (m) and *Summer Mean Flow* is in cubic feet per second (cfs) (based on data from Wenger et al. 2011a for N=2197 sites where stream width data were available; R^2= 0.481, Intercept 0.625, SE 0.169; slope 0.386, SE=0.00855). To generate state values for *Summer Mean Flow*, one solves the equation for *Summer Mean Flow* and inserts the appropriate state value for *Stream Size*. Consequently, the flow estimate for 1m stream width $= \exp\left(\frac{\ln(1)}{0.386} - \frac{0.625}{0.386}\right) = 0.198 \approx 0.2\ cfs$ and the estimate for 2 m stream width $= \exp\left(\frac{\ln(2)}{0.386} - \frac{0.625}{0.386}\right) = 1.193 \approx 1.19\ cfs.$

States defining *Stream Size*: *<1 m; 1-2 m*; *2-8 m*; *>8 m*

Table B 2. Conditional probability table for *Stream Size.* Values represent the probability that *Stream Size* is in particular state, conditioned on the values of the parent node.

Parent node	*Stream Size*			
Summer Flow	< 1m	1-2 m	2-8 m	>8 m
<0.2 cfs	1	0	0	0
0.2 to 1.19 cfs	0	1	0	0
1.19 to 43.3 cfs	0	0	1	0
>43.3 cfs	0	0	0	1

Brook Trout Habitat Potential

Brook Trout Habitat Potential was defined as the potential (sensu Burnett et al. 2007) of a stream segment to support Brook Trout with channel gradient, water temperature and stream size the primary constraints. The potential is independent of disturbance, biotic interactions or other conditions that may modify the quality of habitat (e.g, sediment, large wood; species interactions). We define three states based on the anticipated occurrence and abundance of Brook Trout given that they have access to the habitat. Conditional probabilities for the very low (<7^{o}C) and high temperature (>18^{o}C) states were estimated directly. Conditional probabilities for the three intermediate temperature states were estimated directly for low (<2%) and high-gradient (>8%) situations, and interpolated for intermediate gradient.

States defining *Brook Trout Habitat Potential*:

Low: Brook Trout absent or rare

Moderate: Brook Trout present at low-to-moderate density

High: Brook Trout present at moderate-to-high density

Table B 3. Conditional probability table for *Brook Trout Habitat Potential.* Values represent the probability that *Brook Trout Habitat Potential* is in particular state, conditioned on the values of the parent node.

Parent nodes			*Brook Trout Habitat Potential*	
Summer Water Temperature	*Stream size*	*Gradient*	Moderate [a]	High [a]
<7 °C	<1 m	<2%	0	0
<7 °C	<1 m	2-8%	0	0
<7 °C	<1 m	>8%	0	0
<7 °C	1-2 m	<2%	0	0
<7 °C	1-2 m	2-8%	0	0
<7 °C	1-2 m	>8%	0	0
<7 °C	2-8 m	<2%	0	0
<7 °C	2-8 m	2-8%	0	0
<7 °C	2-8 m	>8%	0	0
<7 °C	>8 m	<2%	0	0
<7 °C	>8 m	2-8%	0	0
<7 °C	>8 m	>8%	0	0
7-10 °C	<1 m	<2%	0.25	0
7-10 °C	<1 m	2-8%	0.125	0
7-10 °C	<1 m	>8%	0	0
7-10 °C	1-2 m	<2%	0.5	0.5
7-10 °C	1-2 m	2-8%	0.625	0.25
7-10 °C	1-2 m	>8%	0.75	0
7-10 °C	2-8 m	<2%	0.5	0.5
7-10 °C	2-8 m	2-8%	0.75	0.25
7-10 °C	2-8 m	>8%	1	0
7-10 °C	>8 m	<2%	0.25	0
7-10 °C	>8 m	2-8%	0.125	0
7-10 °C	>8 m	>8%	0	0
10-15 °C	<1 m	<2%	0.5	0
10-15 °C	<1 m	2-8%	0.375	0
10-15 °C	<1 m	>8%	0.25	0
10-15 °C	1-2 m	<2%	0.25	0.75
10-15 °C	1-2 m	2-8%	0.375	0.625
10-15 °C	1-2 m	>8%	0.5	0.5
10-15 °C	2-8 m	<2%	0	1
10-15 °C	2-8 m	2-8%	0.125	0.875
10-15 °C	2-8 m	>8%	0.25	0.75
10-15 °C	>8 m	<2%	0.5	0

Parent nodes			*Brook Trout Habitat Potential*	
Summer Water Temperature	*Stream size*	*Gradient*	Moderate [a]	High [a]
10-15 °C	>8 m	2-8%	0.375	0
10-15 °C	>8 m	>8%	0.25	0
15-18 °C	<1 m	<2%	0.5	0
15-18 °C	<1 m	2-8%	0.375	0
15-18 °C	<1 m	>8%	0.25	0
15-18 °C	1-2 m	<2%	0.25	0.75
15-18 °C	1-2 m	2-8%	0.625	0.375
15-18 °C	1-2 m	>8%	1	0
15-18 °C	2-8 m	<2%	0.25	0.75
15-18 °C	2-8 m	2-8%	0.5	0.5
15-18 °C	2-8 m	>8%	0.75	0.25
15-18 °C	>8 m	<2%	0.5	0
15-18 °C	>8 m	2-8%	0.25	0
15-18 °C	>8 m	>8%	0	0
>18 °C	<1 m	<2%	0	0
>18 °C	<1 m	2-8%	0	0
>18 °C	<1 m	>8%	0	0
>18 °C	1-2 m	<2%	0.25	0
>18 °C	1-2 m	2-8%	0	0
>18 °C	1-2 m	>8%	0	0
>18 °C	2-8 m	<2%	0.5	0
>18 °C	2-8 m	2-8%	0.25	0
>18 °C	2-8 m	>8%	0	0
>18 °C	>8 m	<2%	0	0
>18 °C	>8 m	2-8%	0	0
>18 °C	>8 m	>8%	0	0

[a] The probability that *Brook Trout Habitat Potential* is “Low” for a given combination of parent nodes is 1 minus the sum of the probabilities of “Moderate” and “High”.

Brook Trout Source Population

Brook Trout Source Population was defined as the presence of a Brook Trout population that can act as a source of invasion to the stream segment of interest within the foreseeable future. We did not define any variables that influence invasion probability, such as distance from the source, dispersal corridor characteristics, or demographic and life history traits of the source population. This node functions as a switch to permit if-then comparison of Bull Trout occurrence under predicted climate change with, or without, Brook Trout, assuming the stream segment is capable of supporting a Brook Trout population

States defining *Brook Trout Source Population*:

No: Brook Trout source population absent or blocked

Yes: Brook Trout source population present and invasion is likely

Brook Trout Occurrence

Brook Trout Occurrence was defined as the probability for occurrence of Brook Trout in a segment as constrained by presence of a source population, bed scour, and habitat potential. We assume that bed scour will constrain the success of a population in otherwise suitable habitat via increased mortality of developing embryos or fry. Frequent bed scour should reduce the probability that brook are present in the stream reach, even when the habitat has high potential to support a robust Brook Trout population (Peterson et al. 2008).

States defining *Brook Trout Occurrence*: *Present*; *Absent*

Table B 4. Conditional probability table for *Brook Trout Occurrence.* Values represent the probability that *Brook Trout Occurrence* is in particular state, conditioned on the values of the parent nodes.

Parent nodes			*Brook Trout occurrence* [a]
Brook Trout Source Population	*Habitat potential*	*Bed Scour*	Yes
No	Low	<1 per winter	0
No	Low	1 to 4 per winter	0
No	Low	>4 per winter	0
No	Moderate	<1 per winter	0
No	Moderate	1 to 4 per winter	0
No	Moderate	>4 per winter	0
No	High	<1 per winter	0
No	High	1 to 4 per winter	0
No	High	>4 per winter	0
Yes	Low	<1 per winter	0
Yes	Low	1 to 4 per winter	0
Yes	Low	>4 per winter	0
Yes	Moderate	<1 per winter	0.5
Yes	Moderate	1 to 4 per winter	0.375
Yes	Moderate	>4 per winter	0.25
Yes	High	<1 per winter	1
Yes	High	1 to 4 per winter	0.75
Yes	High	>4 per winter	0.5

[a] The probability that *Brook Trout Occurrence* is “No” for a given combination of parent nodes is 1 minus the probabilities of “Yes”.

Bull Trout Habitat Potential

Bull Trout Habitat Potential was defined as the potential for a stream segment to support Bull Trout spawning and initial rearing (natal habitat) constrained by channel gradient, water temperature and stream size (Burnett et al. 2007) independent of disturbance, other influences on habitat quality or biotic interactions. Habitat potential as defined here (and for Brook Trout) represent persistent characteristics of stream segments that influence whether they are likely to support spawning and rearing. The definition is analogous to habitat potential for Brook Trout and also has three states, but the conditional probabilities reflect the different requirements or preferences of Bull Trout with the primary controlling habitat variables (e.g., greater sensitivity to temperature than Brook Trout).

States defining *Bull Trout Habitat Potential*:

Low: Bull Trout absent or rare

Moderate: Bull Trout present at low-to-moderate density

High: Bull Trout present at moderate-to-high density

Table B 5. Conditional probability table for *Bull Trout Habitat Potential.* Values represent the probability that *Bull Trout Habitat Potential* is in particular state, conditioned on the values of the parent nodes.

Parent nodes			*Bull Trout Habitat Potential*	
Summer Water Temperature	*Stream Size*	*Gradient*	Moderate [a]	High [a]
<7 °C	<1 m	<2%	0	0
<7 °C	<1 m	2-8%	0	0
<7 °C	<1 m	>8%	0	0
<7 °C	1-2 m	<2%	0.5	0
<7 °C	1-2 m	2-8%	0.5	0
<7 °C	1-2 m	>8%	0.25	0
<7 °C	2-8 m	<2%	0	1
<7 °C	2-8 m	2-8%	0	1
<7 °C	2-8 m	>8%	0.5	0.5
<7 °C	>8 m	<2%	0.75	0
<7 °C	>8 m	2-8%	0.75	0
<7 °C	>8 m	>8%	0.5	0
7-10 °C	<1 m	<2%	0	0
7-10 °C	<1 m	2-8%	0	0
7-10 °C	<1 m	>8%	0	0
7-10 °C	1-2 m	<2%	0.5	0
7-10 °C	1-2 m	2-8%	0.5	0
7-10 °C	1-2 m	>8%	0.25	0
7-10 °C	2-8 m	<2%	0	1
7-10 °C	2-8 m	2-8%	0	1
7-10 °C	2-8 m	>8%	0.5	0.5

Parent nodes			Bull Trout Habitat Potential	
Summer Water Temperature	*Stream Size*	*Gradient*	Moderate [a]	High [a]
7-10 ^{o}C	>8 m	<2%	0.75	0
7-10 ^{o}C	>8 m	2-8%	0.75	0
7-10 ^{o}C	>8 m	>8%	0.5	0
10-15 ^{o}C	<1 m	<2%	0	0
10-15 ^{o}C	<1 m	2-8%	0	0
10-15 ^{o}C	<1 m	>8%	0	0
10-15 ^{o}C	1-2 m	<2%	0.25	0
10-15 ^{o}C	1-2 m	2-8%	0.25	0
10-15 ^{o}C	1-2 m	>8%	0	0
10-15 ^{o}C	2-8 m	<2%	1	0
10-15 ^{o}C	2-8 m	2-8%	1	0
10-15 ^{o}C	2-8 m	>8%	0.75	0
10-15 ^{o}C	>8 m	<2%	0.5	0
10-15 ^{o}C	>8 m	2-8%	0.5	0
10-15 ^{o}C	>8 m	>8%	0.25	0
15-18 ^{o}C	<1 m	<2%	0	0
15-18 ^{o}C	<1 m	2-8%	0	0
15-18 ^{o}C	<1 m	>8%	0	0
15-18 ^{o}C	1-2 m	<2%	0	0
15-18 ^{o}C	1-2 m	2-8%	0	0
15-18 ^{o}C	1-2 m	>8%	0	0
15-18 ^{o}C	2-8 m	<2%	0.25	0
15-18 ^{o}C	2-8 m	2-8%	0.25	0
15-18 ^{o}C	2-8 m	>8%	0	0
15-18 ^{o}C	>8 m	<2%	0	0
15-18 ^{o}C	>8 m	2-8%	0	0
15-18 ^{o}C	>8 m	>8%	0	0
>18 ^{o}C	<1 m	<2%	0	0
>18 ^{o}C	<1 m	2-8%	0	0
>18 ^{o}C	<1 m	>8%	0	0
>18 ^{o}C	1-2 m	<2%	0	0
>18 ^{o}C	1-2 m	2-8%	0	0
>18 ^{o}C	1-2 m	>8%	0	0
>18 ^{o}C	2-8 m	<2%	0	0
>18 ^{o}C	2-8 m	2-8%	0	0
>18 ^{o}C	2-8 m	>8%	0	0
>18 ^{o}C	>8 m	<2%	0	0
>18 ^{o}C	>8 m	2-8%	0	0

Parent nodes			*Bull Trout Habitat Potential*	
Summer Water Temperature	*Stream Size*	*Gradient*	Moderate [a]	High [a]
>18 ^{o}C	>8 m	>8%	0	0

[a] The probability that *Bull Trout Habitat Potential* is "Low" for a given combination of parent nodes is 1 minus the sum of the probabilities of "Moderate" and "High".

Early Bull Trout Survival

The node for *Early Bull Trout Survival* was used to integrate the effects of habitat potential, bed scour, and competition with Brook Trout mediated by stream size and temperature. There is little empirical information on early Bull Trout survival so we only considered conditions where we believed the effects are likely to lead to a positive population growth rate (and a population with some resilience) or not. We assumed the population growth rate of Bull Trout is constrained primarily by early survival from embryo to age 2 when they are most vulnerable to the effects of bed scour and competition. The conditional probabilities consider the interactions between temperature and competition with Brook Trout based on observations by Rieman et al. (2006) and McMahon et al. (2007), and between stream size and competition based on Rich et al. (2003). We assumed the strength of competition generally increases with water temperature and is greater in smaller habitats. We assumed that scour decreases survival, but to a lesser extent when stream size is 2-8 m because increased habitat complexity in larger streams should create more refugia from those effects (e.g., Shellberg et al. 2010).

States for *Early Bull Trout Survival*:

Positive – survival rate sufficient for positive population growth

Negative – survival rate not sufficient for positive population growth

Table B 6. Conditional probability table for *Early Bull Trout Survival.* Values represent the probability that *Early Bull Trout Survival* is in particular state, conditioned on the values of the parent nodes.

Parent nodes				*Early Bull Trout Survival*
Bed Scour Frequency	*Brook Trout Occurrence*	*Stream Size*	*Summer Water Temperature*	Positive
<1 per winter	Present	<1 m	<7 °C	1
<1 per winter	Present	<1 m	7-10 °C	0.5
<1 per winter	Present	<1 m	10-15 °C	0.25
<1 per winter	Present	<1 m	15-18 °C	0
<1 per winter	Present	<1 m	>18 °C	0
<1 per winter	Present	1-2 m	<7 °C	1
<1 per winter	Present	1-2 m	7-10 °C	0.5
<1 per winter	Present	1-2 m	10-15 °C	0.25
<1 per winter	Present	1-2 m	15-18 °C	0
<1 per winter	Present	1-2 m	>18 °C	0
<1 per winter	Present	2-8 m	<7 °C	1
<1 per winter	Present	2-8 m	7-10 °C	0.75
<1 per winter	Present	2-8 m	10-15 °C	0.5
<1 per winter	Present	2-8 m	15-18 °C	0.25
<1 per winter	Present	2-8 m	>18 °C	0.25
<1 per winter	Present	>8 m	<7 °C	1
<1 per winter	Present	>8 m	7-10 °C	1
<1 per winter	Present	>8 m	10-15 °C	1
<1 per winter	Present	>8 m	15-18 °C	1
<1 per winter	Present	>8 m	>18 °C	1
1 to 4 per winter	Present	<1 m	<7 °C	0.75
1 to 4 per winter	Present	<1 m	7-10 °C	0.375
1 to 4 per winter	Present	<1 m	10-15 °C	0.125
1 to 4 per winter	Present	<1 m	15-18 °C	0
1 to 4 per winter	Present	<1 m	>18 °C	0
1 to 4 per winter	Present	1-2 m	<7 °C	0.75
1 to 4 per winter	Present	1-2 m	7-10 °C	0.375
1 to 4 per winter	Present	1-2 m	10-15 °C	0.125
1 to 4 per winter	Present	1-2 m	15-18 °C	0
1 to 4 per winter	Present	1-2 m	>18 °C	0
1 to 4 per winter	Present	2-8 m	<7 °C	0.75
1 to 4 per winter	Present	2-8 m	7-10 °C	0.625
1 to 4 per winter	Present	2-8 m	10-15 °C	0.375

Parent nodes				Early Bull Trout Survival
Bed Scour Frequency	*Brook Trout Occurrence*	*Stream Size*	*Summer Water Temperature*	Positive
1 to 4 per winter	Present	2-8 m	15-18 ^{o}C	0.125
1 to 4 per winter	Present	2-8 m	>18 ^{o}C	0.125
1 to 4 per winter	Present	>8 m	<7 ^{o}C	0.75
1 to 4 per winter	Present	>8 m	7-10 ^{o}C	0.75
1 to 4 per winter	Present	>8 m	10-15 ^{o}C	0.75
1 to 4 per winter	Present	>8 m	15-18 ^{o}C	0.75
1 to 4 per winter	Present	>8 m	>18 ^{o}C	0.75
> 4 per winter	Present	<1 m	<7 ^{o}C	0.5
> 4 per winter	Present	<1 m	7-10 ^{o}C	0.25
> 4 per winter	Present	<1 m	10-15 ^{o}C	0
> 4 per winter	Present	<1 m	15-18 ^{o}C	0
> 4 per winter	Present	<1 m	>18 ^{o}C	0
> 4 per winter	Present	1-2 m	<7 ^{o}C	0.5
> 4 per winter	Present	1-2 m	7-10 ^{o}C	0.25
> 4 per winter	Present	1-2 m	10-15 ^{o}C	0
> 4 per winter	Present	1-2 m	15-18 ^{o}C	0
> 4 per winter	Present	1-2 m	>18 ^{o}C	0
> 4 per winter	Present	2-8 m	<7 ^{o}C	0.5
> 4 per winter	Present	2-8 m	7-10 ^{o}C	0.5
> 4 per winter	Present	2-8 m	10-15 ^{o}C	0.25
> 4 per winter	Present	2-8 m	15-18 ^{o}C	0
> 4 per winter	Present	2-8 m	>18 ^{o}C	0
> 4 per winter	Present	>8 m	<7 ^{o}C	0.5
> 4 per winter	Present	>8 m	7-10 ^{o}C	0.5
> 4 per winter	Present	>8 m	10-15 ^{o}C	0.5
> 4 per winter	Present	>8 m	15-18 ^{o}C	0.5
> 4 per winter	Present	>8 m	>18 ^{o}C	0.5
<1 per winter	Absent	<1 m	<7 ^{o}C	1
<1 per winter	Absent	<1 m	7-10 ^{o}C	1
<1 per winter	Absent	<1 m	10-15 ^{o}C	1
<1 per winter	Absent	<1 m	15-18 ^{o}C	1
<1 per winter	Absent	<1 m	>18 ^{o}C	1
<1 per winter	Absent	1-2 m	<7 ^{o}C	1
<1 per winter	Absent	1-2 m	7-10 ^{o}C	1
<1 per winter	Absent	1-2 m	10-15 ^{o}C	1
<1 per winter	Absent	1-2 m	15-18 ^{o}C	1

Parent nodes				*Early Bull Trout Survival*
Bed Scour Frequency	*Brook Trout Occurrence*	*Stream Size*	*Summer Water Temperature*	Positive
<1 per winter	Absent	1-2 m	>18 ^{o}C	1
<1 per winter	Absent	2-8 m	<7 ^{o}C	1
<1 per winter	Absent	2-8 m	7-10 ^{o}C	1
<1 per winter	Absent	2-8 m	10-15 ^{o}C	1
<1 per winter	Absent	2-8 m	15-18 ^{o}C	1
<1 per winter	Absent	2-8 m	>18 ^{o}C	1
<1 per winter	Absent	>8 m	<7 ^{o}C	1
<1 per winter	Absent	>8 m	7-10 ^{o}C	1
<1 per winter	Absent	>8 m	10-15 ^{o}C	1
<1 per winter	Absent	>8 m	15-18 ^{o}C	1
<1 per winter	Absent	>8 m	>18 ^{o}C	1
1 to 4 per winter	Absent	<1 m	<7 ^{o}C	0.75
1 to 4 per winter	Absent	<1 m	7-10 ^{o}C	0.75
1 to 4 per winter	Absent	<1 m	10-15 ^{o}C	0.75
1 to 4 per winter	Absent	<1 m	15-18 ^{o}C	0.75
1 to 4 per winter	Absent	<1 m	>18 ^{o}C	0.75
1 to 4 per winter	Absent	1-2 m	<7 ^{o}C	0.75
1 to 4 per winter	Absent	1-2 m	7-10 ^{o}C	0.75
1 to 4 per winter	Absent	1-2 m	10-15 ^{o}C	0.75
1 to 4 per winter	Absent	1-2 m	15-18 ^{o}C	0.75
1 to 4 per winter	Absent	1-2 m	>18 ^{o}C	0.75
1 to 4 per winter	Absent	2-8 m	<7 ^{o}C	0.75
1 to 4 per winter	Absent	2-8 m	7-10 ^{o}C	0.75
1 to 4 per winter	Absent	2-8 m	10-15 ^{o}C	0.75
1 to 4 per winter	Absent	2-8 m	15-18 ^{o}C	0.75
1 to 4 per winter	Absent	2-8 m	>18 ^{o}C	0.75
1 to 4 per winter	Absent	>8 m	<7 ^{o}C	0.75
1 to 4 per winter	Absent	>8 m	7-10 ^{o}C	0.75
1 to 4 per winter	Absent	>8 m	10-15 ^{o}C	0.75
1 to 4 per winter	Absent	>8 m	15-18 ^{o}C	0.75
1 to 4 per winter	Absent	>8 m	>18 ^{o}C	0.75
> 4 per winter	Absent	<1 m	<7 ^{o}C	0.5
> 4 per winter	Absent	<1 m	7-10 ^{o}C	0.5
> 4 per winter	Absent	<1 m	10-15 ^{o}C	0.5
> 4 per winter	Absent	<1 m	15-18 ^{o}C	0.5
> 4 per winter	Absent	<1 m	>18 ^{o}C	0.5

Parent nodes				Early Bull Trout Survival
Bed Scour Frequency	*Brook Trout Occurrence*	*Stream Size*	*Summer Water Temperature*	Positive
> 4 per winter	Absent	1-2 m	<7 ^{o}C	0.5
> 4 per winter	Absent	1-2 m	7-10 ^{o}C	0.5
> 4 per winter	Absent	1-2 m	10-15 ^{o}C	0.5
> 4 per winter	Absent	1-2 m	15-18 ^{o}C	0.5
> 4 per winter	Absent	1-2 m	>18 ^{o}C	0.5
> 4 per winter	Absent	2-8 m	<7 ^{o}C	0.5
> 4 per winter	Absent	2-8 m	7-10 ^{o}C	0.5
> 4 per winter	Absent	2-8 m	10-15 ^{o}C	0.5
> 4 per winter	Absent	2-8 m	15-18 ^{o}C	0.5
> 4 per winter	Absent	2-8 m	>18 ^{o}C	0.5
> 4 per winter	Absent	>8 m	<7 ^{o}C	0.5
> 4 per winter	Absent	>8 m	7-10 ^{o}C	0.5
> 4 per winter	Absent	>8 m	10-15 ^{o}C	0.5
> 4 per winter	Absent	>8 m	15-18 ^{o}C	0.5
> 4 per winter	Absent	>8 m	>18 ^{o}C	0.5

[a] The probability that *Early Bull Trout Survival* is "Negative" for a given combination of parent nodes is 1 minus the probability of being "Positive".

Predicted Bull Trout Occupancy

Predicted Bull Trout Occupancy was defined as the probability that Bull Trout occur in the stream segment of interest, influenced by *Bull Trout Habitat Potential* and *Early Bull Trout Survival*. We assumed that Bull Trout occurrence is not constrained by any factors outside the stream segment (e.g., connectivity to other populations or downstream rearing habitats). In essence, *Predicted Bull Trout Occupancy* represents the likelihood that a stream segment can support Bull Trout given the local abiotic and biotic conditions, and the possibility that larger scale effects could be important but are uninformed. In other words Bull Trout may occur in habitats even where they have low early survival because of demographic support from Bull Trout in surrounding habitats. Because we do not have information about those larger effects, the probabilities reflect the uncertainty of local context.

States for *Predicted Bull Trout Occupancy*: *Present*; *Absent*

Table B 7. Conditional probability table for *Predicted Bull Trout Occupancy*. Values represent the probability that *Bull Trout Occurrence* is in particular state, conditioned on the values of the parent nodes.

Parent nodes		*Predicted Bull Trout Occupancy*
Bull Trout Early Survival	*Bull Trout Habitat Potential*	Present [a]
Negative	Low	0
	Moderate	0.125
	High	0.25
Positive	Low	0
	Moderate	0.5
	High	1

[a] The probability that *Predicted Bull Trout Occupancy* is "Absent" for a given combination of parent nodes is 1 minus the probability of "Present".

II. Additional results

Our objective for the Bull Trout example was to develop a representative BN to explore the utility of such models to integrate climate projections and conduct spatially-explicity prioritization. The preceding CPT tables attempt to characterize factors that are important and represent our interpretation of their relative importance. The CPT tables and the predictions from the BN should not be considered accurate in the absolute sense; rather, they are first approximations. Consequently, we present only summary results (e.g., Table B8; Figures B1-B6) relevant to the central questions relating to how climate change and Brook Trout will affect occupancy by Bull Trout. For brevity, we do not present the raw segment-by-segment BN predictions here, but can make them available upon request.

Table B 8. Total stream length predicted to be occupied by Bull Trout for different patch size categories in the Boise River Basin (BRB).

	Total occupied stream length (km) within each patch size category [a]				
Scenario	<5 km	5-10 km	10-20 km	20-40 km	>40 km
Historical – no Brook Trout	19.64	14.51	87.84	89.05	204.74
Historical – with Brook Trout	20.87	25.65	73.30	57.40	179.37
2040s – no Brook Trout	18.06	36.16	56.18	35.03	98.18
2040s – with Brook Trout	19.19	36.34	39.94	27.80	87.50
2080s – no Brook Trout	31.04	26.22	10.65	78.92	0.00
2080s – with Brook Trout	30.94	26.68	16.15	52.81	0.00

[a] The analysis encompassed 1,846 NDH+ segments totaling 3,256.2 km habitat, and 22 patches.

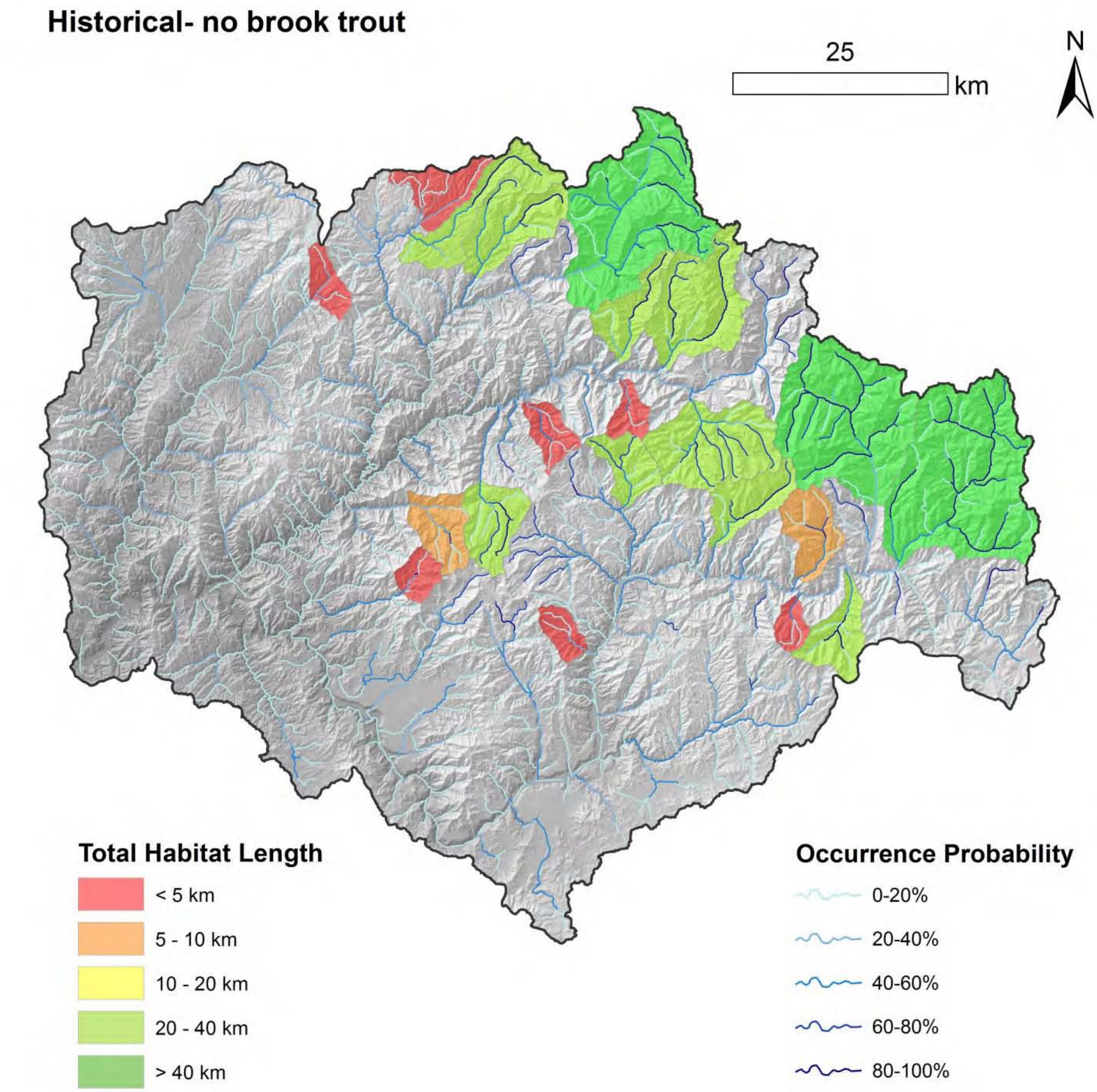

Figure B 1. Probability of occurrence and predicted occupancy of Bull Trout in the Boise River Basin (BRB) historical conditions and without Brook Trout.

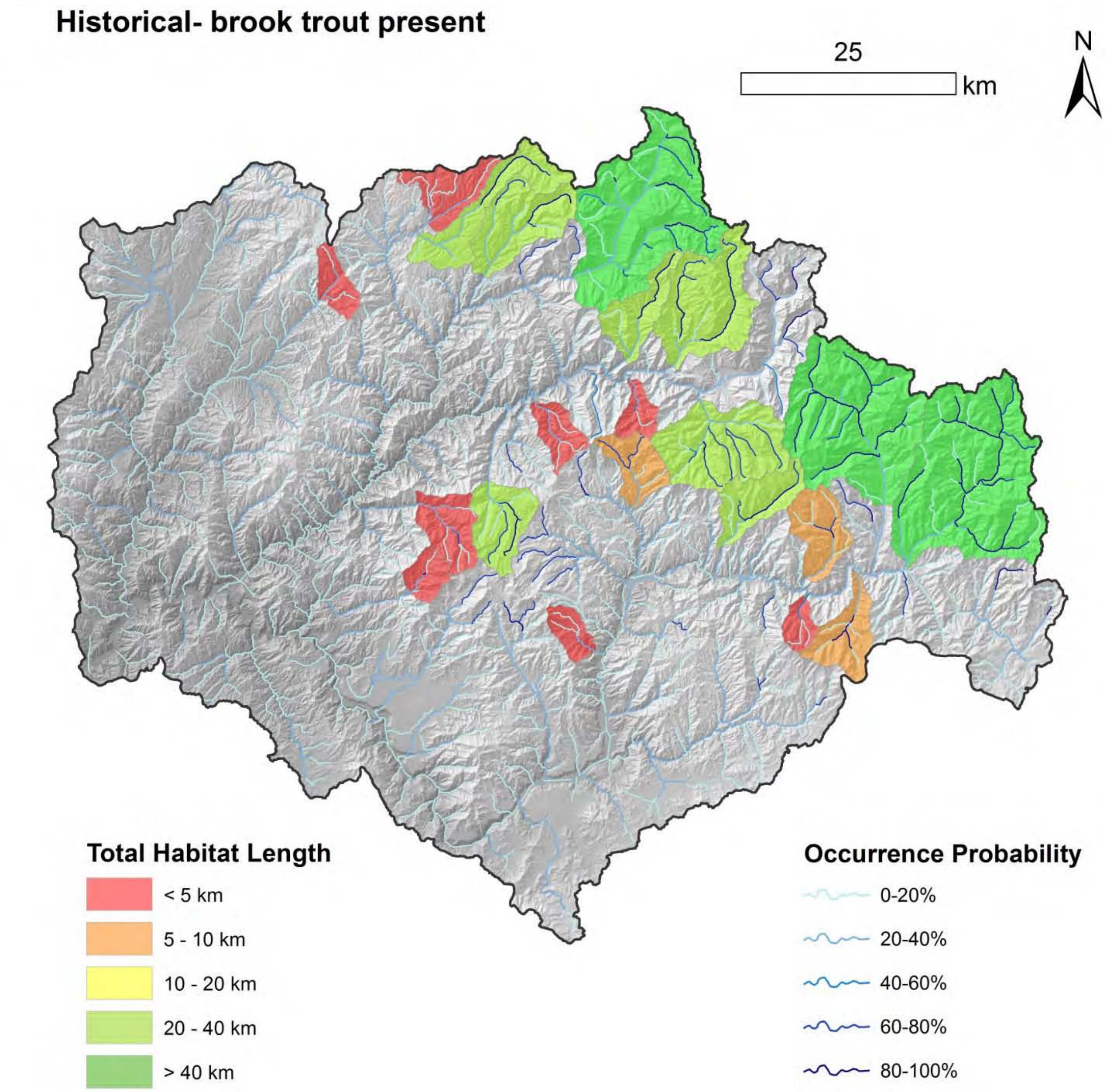

Figure B 2. Probability of occurrence and predicted occupancy of Bull Trout in the BRB under historical conditions and with Brook Trout present.

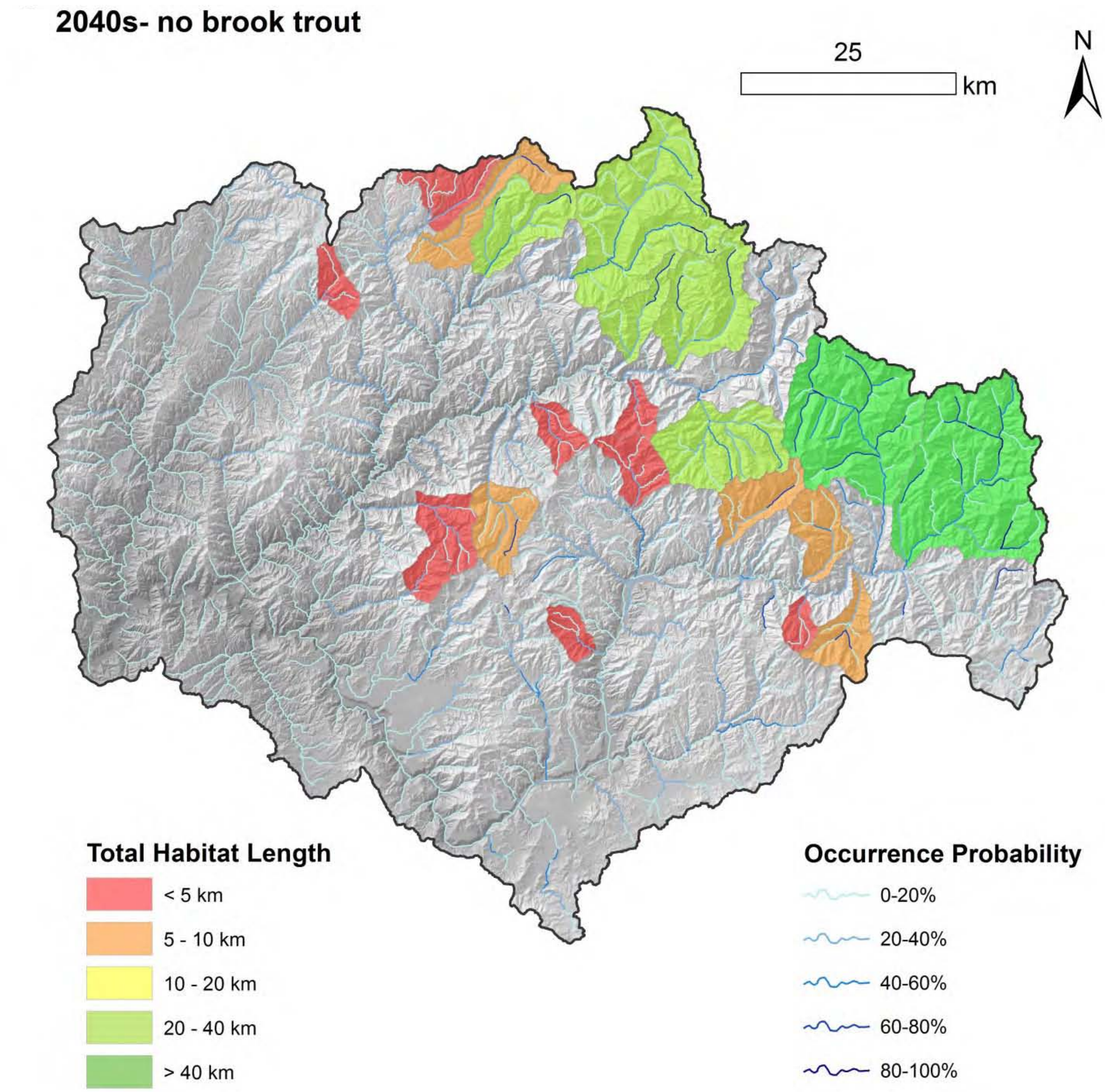

Figure B 3. Probability of occurrence and predicted occupancy of Bull Trout in the BRB in the 2040s and without Brook Trout. Climate projections are based on the A1B emissions scenario using the PCM1 global circulation model.

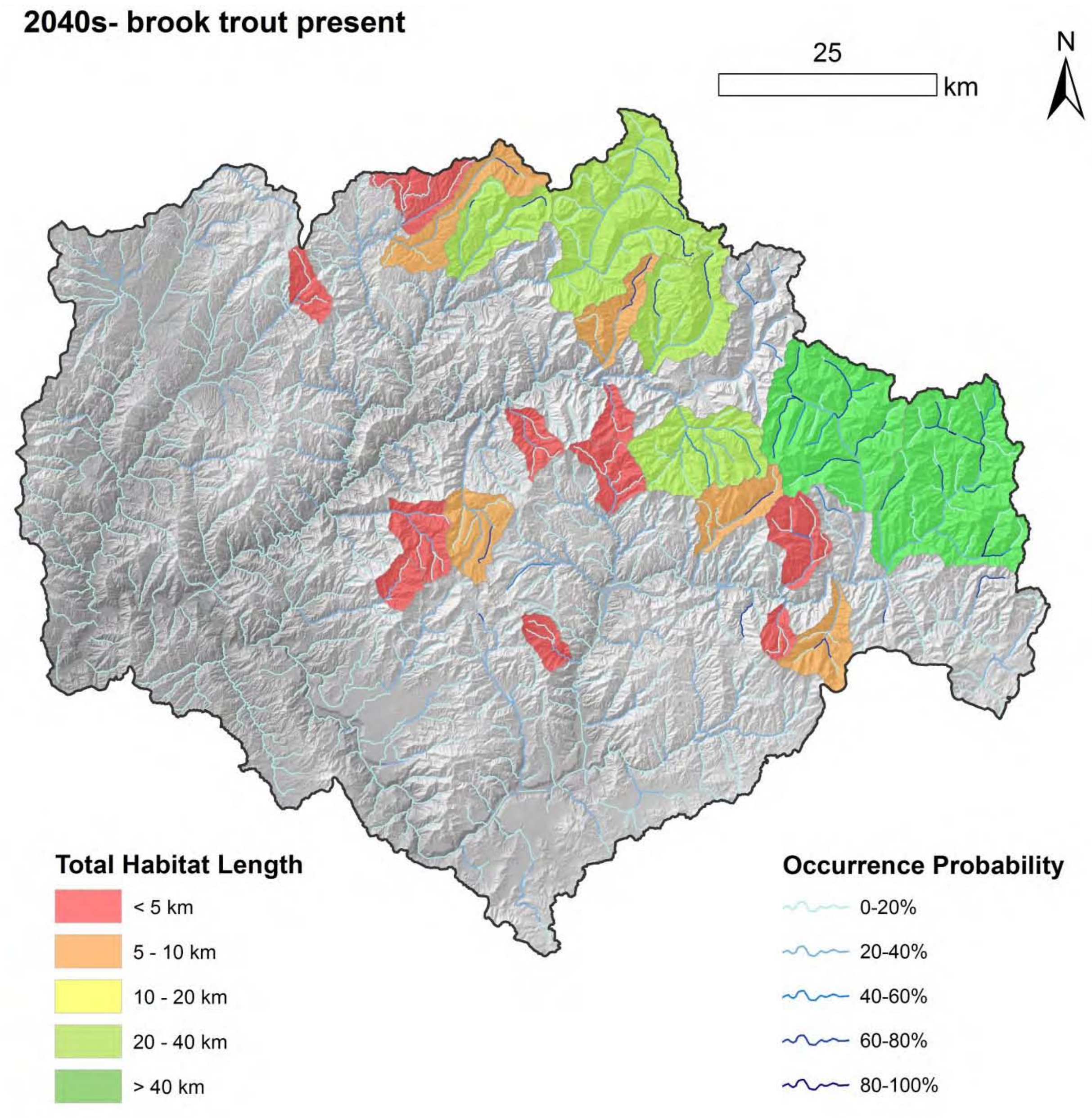

Figure B 4. Probability of occurrence and predicted occupancy of Bull Trout in the BRB in the 2040s and with Brook Trout present. Climate projections are based on the A1B emissions scenario using the PCM1 global circulation model.

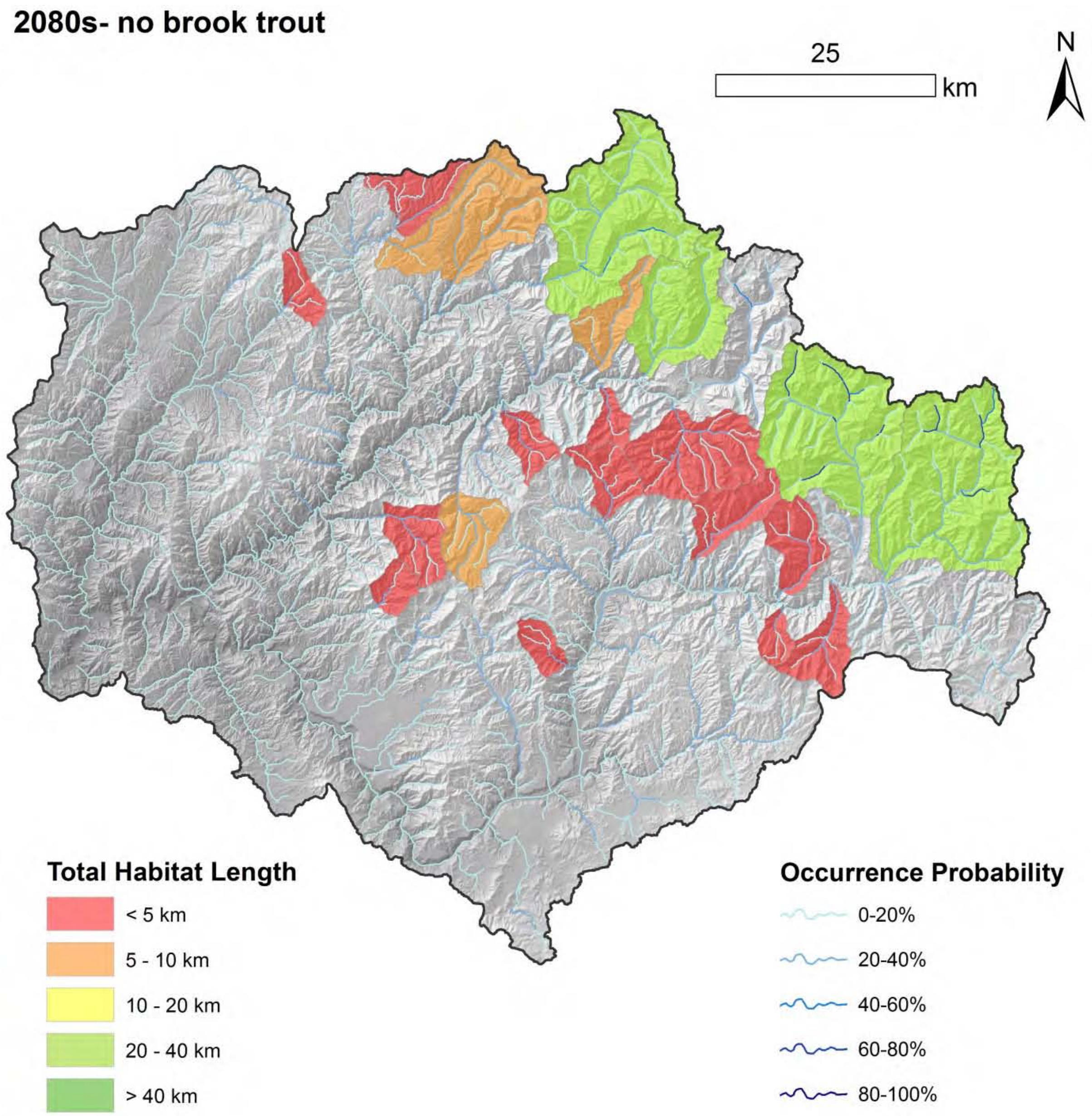

Figure B 5. Probability of occurrence and predicted occupancy of Bull Trout in the BRB in the 2080s and without Brook Trout. Climate projections are based on the A1B emissions scenario using the PCM1 global circulation model.

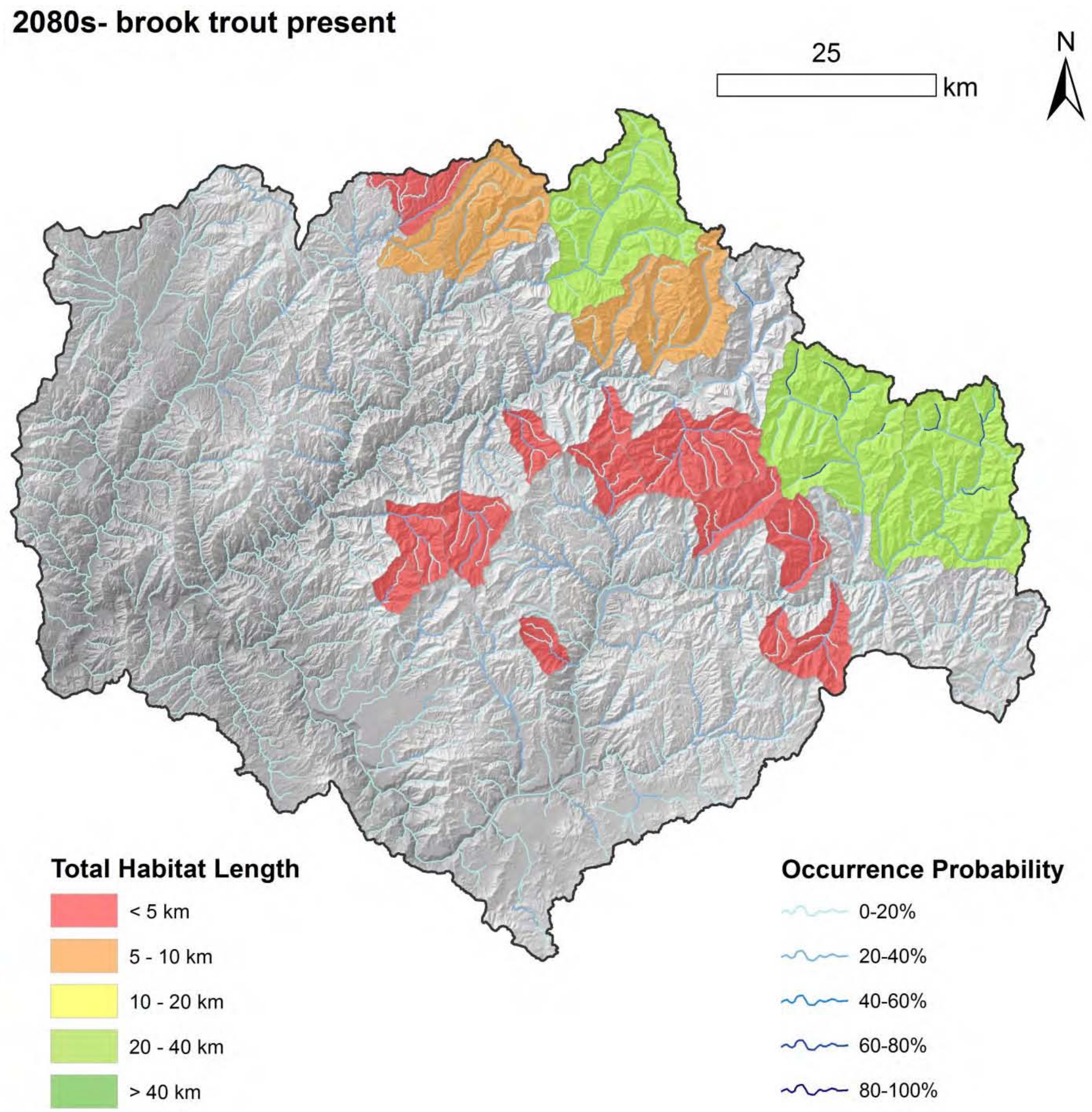

Figure B 6. Probability of occurrence and predicted occupancy of Bull Trout in the BRB in the 2080s and with Brook Trout present. Climate projections are based on the A1B emissions scenario using the PCM1 global circulation model.

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APPENDIX C. Bayesian network (BN) model development and additional results for Westslope Cutthroat Trout invasion barrier case study.

Citation: Peterson, D.P., S.J. Wenger, B.E. Rieman, and D.J. Isaak. 2013. Linking Climate Change and Fish Conservation Efforts Using Spatially Explicit Decision Support Tools. Fisheries 38(XX):xx-xx.

List of Tables

List of Figures

I. Model summary and node definitions for Bayesian Network (BN) to analyze barrier decisions for Westslope Cutthroat Trout in the middle Clark Fork River, USA.

List of additional or modified nodes

Model summary

We modified an existing BN used to evaluate individual barrier decisions assuming a static climate (Peterson et al. 2008) to facilitate the same analysis under climate change. The following paragraphs describe the nodes added to the published model and present a diagram of the final model used to conduct the analysis (Figure B1).

Briefly, the BN considers the environmental factors influencing habitat for Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) and nonnative Brook Trout (*Salvelinus fontinalis*), the species' interactions, and how construction or removal of invasion barriers (i.e., the management decision) may affect persistence of local a Cutthroat Trout population. Details on the development and application of this model are found in Peterson et al. (2008); the context and decision framework are considered in Fausch et al. (2006, 2009). *Summer Water Temperature*, *Hydrologic Regime* and *Stream Size* nodes were already used in the model to describe habitat potential across streams. We simply used those to consider how climate might alter those conditions and the interactions of barriers, Brook Trout and Cutthroat Trout in the future. To account for climate-related changes to stream width, we added a *Summer Mean*

Flow as a root node. We estimated *Stream Width* from macroscale hydrologic model (variable infiltration capacity, or VIC) outputs using a linear regression. Winter flooding and bed scour can cause mortality of embryos and fry of fall spawning stream salmonids like Brook Trout (Nehring and Anderson 1993; Latterell et al. 1998), and flood frequency and magnitude is anticipated to influence their distribution under climate change (Wenger et al. 2011b). To account for this we added a *Winter High Flow w95* root node (Wenger et al. 2010) with a link to hydrologic regime to formalize the concept that increasing flood frequency is associated with rain-on-snow precipitation events and a transitional hydrologic regime.   This link and the resulting conditional probability table quantifies this relationship, which will only affect fall-spawning Brook Trout in this model. Cutthroat Trout can be indirectly affected by this hydrologic change through a reduction in population strength of Brook Trout and any associated attenuation of biotic interactions.

The Cutthroat Trout BN predicted persistence of a population upstream from existing or potential migration barriers. Model output could be mapped for groups of continuous or connected stream segments, with migration barriers creating discontinuities and changing the extent of habitat available to that population. The BN predicted population persistence 20 years after a management action regarding a barrier (Peterson et al. 2008), so imposing a new set of climate conditions yielded a prediction about the persistence probability of the cutthroat population 20 years later.

Node definitions and rationale

Summer Air Temperature

Summer Air Temperature was defined as mean summer air temperature averaged across the watershed that drains to the stream segment in which the site was located (dtemp following Wenger et al. 2011a). The BN for Cutthroat Trout had five existing states for summer water temperature (Peterson et al. 2008), and we generated air temperature categories corresponding to those water temperature states by examining the relationship between Brook Trout occurrence and the mean summer air temperature at point (ptemp variable from Wenger et al. 2011b), from which we infer that mean summer water temperature is ~0.8 × mean summer air temperature.

States defining *Summer Air Temperature*: *<9^{o}C; 9-13^{o}C; 13-18^{o}C; 18-22^{o}C; >22^{o}C*

Summer Water Temperature

Summer Water Temperature is defined as in Peterson et al (2008): mean summer water temperature over the stream network from 15 July to 15 September. The conditional probability table for *Summer Water Temperature* was based on the air-water temperature conversion described above.

States defining *Summer Water Temperature*: *<7^{o}C; 7-10^{o}C; 10-15^{o}C; 15-18^{o}C; >18^{o}C*

Table C 1. Conditional probability table for *Summer Water Temperature.* Values represent the probability that *Summer Water Temperature* is in particular state, conditioned on the values of the parent node.

Parent node	*Summer Water Temperature*				
Summer Air Temperature	<7 ^{o}C	7-10 ^{o}C	10-15 ^{o}C	15-18 ^{o}C	>18 ^{o}C
<9 ^{o}C	1	0	0	0	0
9-13 ^{o}C	0	1	0	0	0
13-18 ^{o}C	0	0	1	0	0
18-22 ^{o}C	0	0	0	1	0
>22 ^{o}C	0	0	0	0	1

Winter High Flow w95

Winter High Flow w95 was defined as the expected number of days in the "winter" (considered here as December 1-February 28) in which flows are among the highest 5% of all flow days for the year (following Wenger et al. 2010; Wenger et al. 2011a; Wenger et al. 2011b). High flows in the post-spawning period of embryo incubation and pre-emergence are believed to influence the occurrence and productivity of fall-spawning trout species (Nehring and Anderson 1993; Latterell et al. 1998; Fausch et al. 2001; Wenger et al. 2011b), and w95 was negatively related to occurrence of Brook Trout and bull trout in the interior Columbia River basin (Wenger et al. 2011a). The w95 metric is assumed to represent flows with power capable of mobilizing much of the stream bed, displacing and killing embryos and pre-emergent or newly emerged fry under some channel and bed conditions, but not necessarily destroying all embryos and individuals within any stream segment (e.g., Wenger et al. 2011a). We defined three states for w95 based on the range of observed values from Wenger et al. (2011a).

States defining *Winter High Flow*: *<1 time per winter; 1-4 times per winter; >4 times per winter*

Summer Mean Flow

Summer Mean Flow was defined as the mean surface water flow in cubic feet per second (cfs) during the summer (considered here as the first day after June 1 when flows fall below the mean annual value, through September 30; from Wenger et al. 2010, 2011a). *Summer Mean Flow* is used to estimate *Stream Size* (see below), and provides a link between climate-influenced changes in hydrologic conditions and the geomorphic variable (summer wetted width or *Stream Size*) that is most commonly measured in fish distribution studies (Dunham and Rieman 1999). The node definition and derivation of states was identical to that of the *Summer Mean Flow* node in the bull trout model (see Appendix A)

States defining *Summer Mean Flow*: *<0.2 cfs; 0.2 to 1.19 cfs; 1.19 to 43.3 cfs; >43.3 cfs*

Stream Width

Stream Width was defined as the mean wetted width over the stream network during base flow, as in Peterson et al. (2008). The state definitions were also identical. Probabilities for *Stream Width* were estimated directly from *Summer Mean Flow* using the linear regression equation $\ln(Stream\ Width) = 0.625 + (0.386 * \ln(Summer\ Mean\ Flow))$ where S*tream Width* is wetted width (m) and *Summer Mean Flow* is in cubic feet per second (cfs) (based on data from Wenger et al. 2011a for N=2197 sites where stream width data were available; R^2=

0.481, Intercept 0.625, SE 0.169; slope 0.386, SE=0.00855). This regression equation was solved for *Stream Width* and encoded directly into the BN.

States defining *Stream Width*: *<3 m*; *3-10m*; *>10m*

Table C 2. Conditional probability table for *Stream Size.* Values represent the probability that *Stream Size* is in particular state, conditioned on the values of the parent node.

Parent node	*Stream Size*		
Summer Mean Flow	< 3m	3-10 m	>10 m
<0.2 cfs	1	0	0
0.2 to 1.19 cfs	0	1	0
1.19 to 43.3 cfs	0	0	1
>43.3 cfs	0	0	0

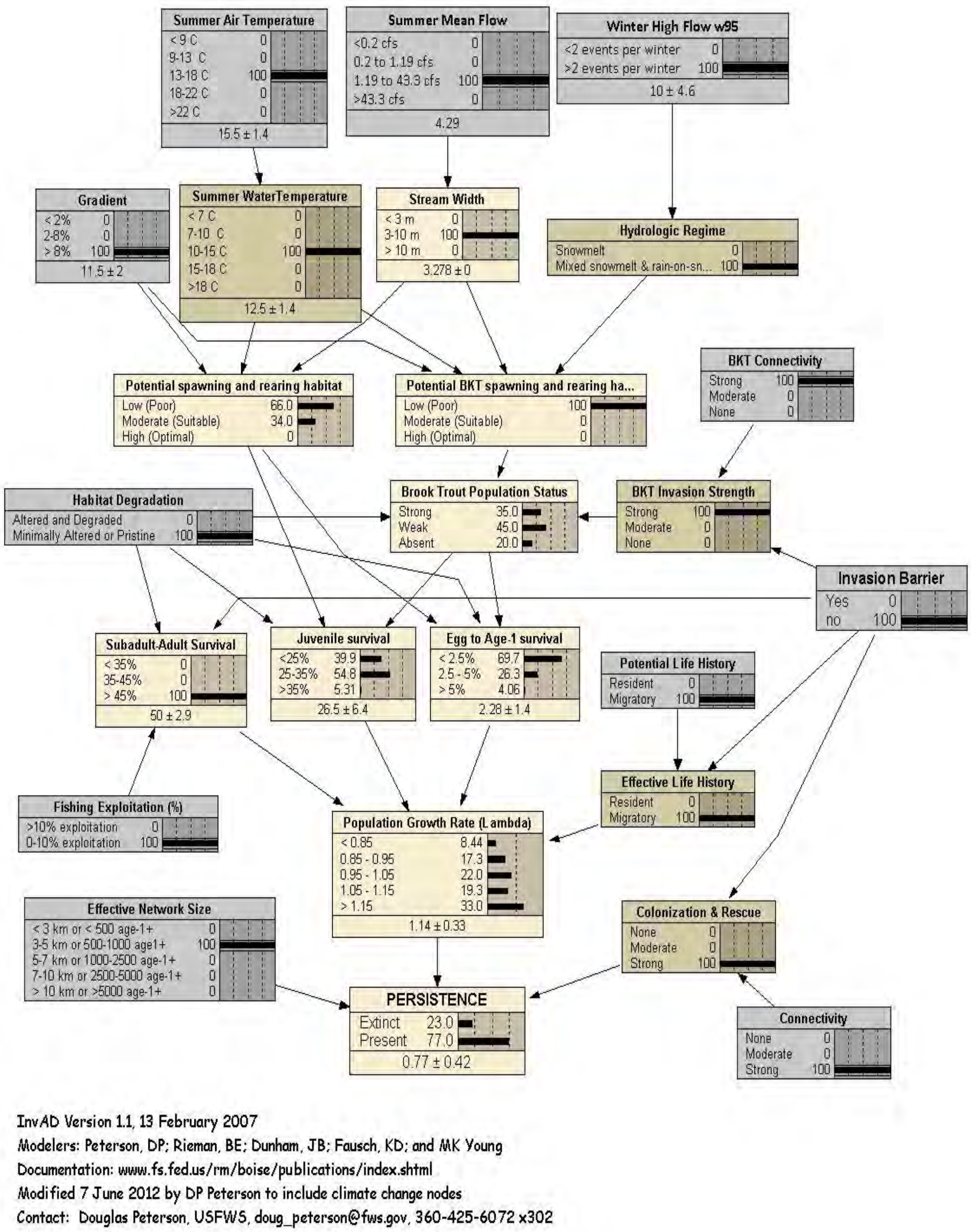

Figure C 1. Bayesian network (BN) used to analyze barrier removal decision for Westslope Cutthroat Trout. This is a version of the BN presented in Peterson et al (2008) expanded to include three new nodes (*Summer Air Temperature, Summer Mean Flow*, *Winter High Flow w95*) to model factors anticipated to respond strongly to climate change. The BN was implemented using Netica, and represents the parameterized version of the conceptual model presented in Figure 4 (Peterson et al. Unpublished ms).

II. Detailed results for three examples analyzed with the Cutthroat Trout BN (Figure B1)

Silver Creek

In Silver Creek, barrier removal maximized probability of persistence Cutthroat Trout population in future climate scenarios (Figure B2, Table B 3). Persistence probability decreased from 0.87 to 0.76 between historical and 2040s time periods if the population remained isolated by a barrier, but persistence was predicted to be ≥ 0.96 in both time periods if the barrier was removed.

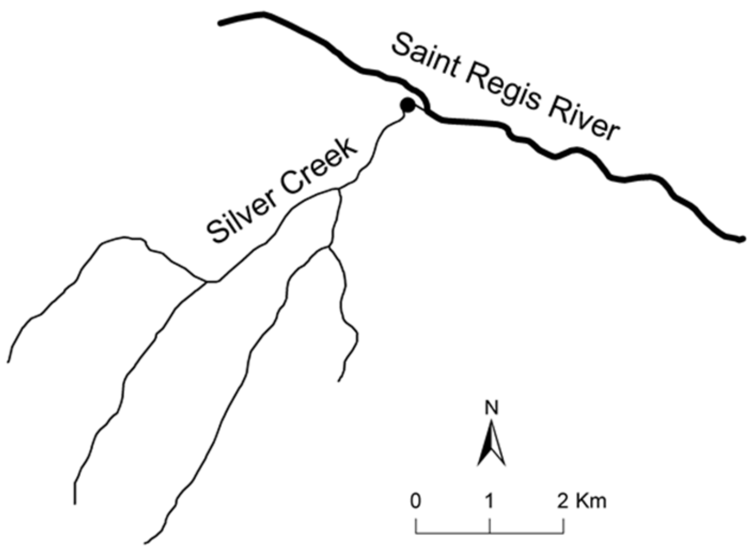

Figure C 2. Schematic of Silver Creek showing location of existing fish migration barrier (•).

Table C 3. Input conditions and results for Silver Creek example. Columns 2-5 contain results for the four scenarios considered (barrier or not, historical or future environmental conditions). State values for input (root) nodes that did not differ among scenarios were: Habitat degradation = Minimally Altered or Pristine, Fishing = 0-10% exploitation, BKT_connectivity = Moderate, Effective network size = > 10 km or >5000 age-1+, Life History Potential = Migratory, CT_Connectivity = Strong, and Gradient = 2.7%.

	Node value or state, by scenario			
Node name [1]	1	2	3	4
Barrier removed	No	Yes	Yes	No
Time Period & Global Climate Model	Historical	Historical	2040s_PCM	2040s_PCM
P(Persistence)	0.866177	0.972961	0.760724	0.966423
E[Lambda]	1.06898	1.26389	0.919525	1.21025
std-dev Lambda	0.317956	0.340305	0.269615	0.336853
Air Temperature	17.2411	17.2411	19.2968	19.2968
Water Temperature - ^{o}C	10-15	10-15	15-18	15-18
SummerMeanFlow – cfs	7.63	7.63	5.42	5.42
WinterHighFlow95 – frequency	3.45	3.45	7.35	7.35
finding InvasionBarrier	Yes	no	Yes	no
Colonization & Rescue	None_Isolated	Strong	None_Isolated	Strong

[1] Column provides node names and value or statistic calculated for that node; “P” indicates a probability calculated by the model for discrete nodes, “E” indicates a probability (or expected value) calculated by the model for continuous nodes, and “std-dev” indicates Gaussian standard deviation calculated for continuous nodes.

Dominion Creek

In Dominion Creek, we considered scenarios involving removal of the upper barrier (with and without Brook Trout removal) and removal of both barriers (Figure B3). For all comparisons there was no difference between historical conditions and the 2040s climate; removing the upper barrier and eradicating Brook Trout increased the predicted cutthroat population persistence in the longer segment from 0.25 to 0.41 for both periods (Table B4). Removing both barriers produced an identical estimate of 0.77. The lack of difference is attributed to the counteracting effects of temperature and stream flow on Cutthroat Trout survival. Between the historical period and the 2040s, increased air temperature caused water temperature to shift from the optimal (10-15^{o}C) to the high (15-18^{o}C) categories which made conditions less amenable to recruitment and survival (of Cutthroat Trout). Concurrently, projected changes in summer base flow caused the stream size variable to change from the 3-10 m state to the <3 m state, which improved spawning and rearing conditions for Cutthroat Trout. The choice of state values in the nodes representing temperature, mean flow, and stream size contributed to this cancellation effect. A small change in temperature and flow resulted in a shift between state categories and the crossing of a biologically-significant threshold or inflection point encoded in the model; in this case, the effects were simply in opposite directions.

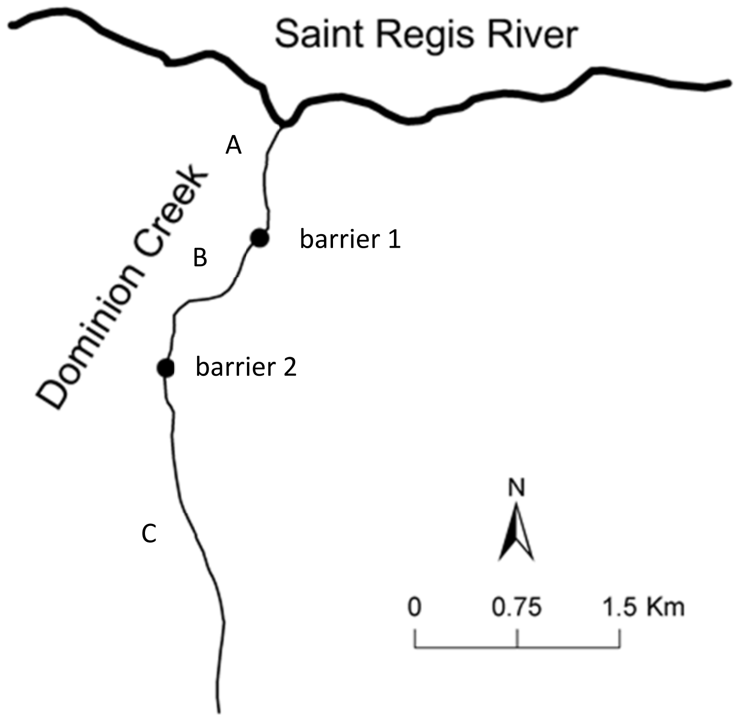

Figure C 3. Schematic of Dominion Creek showing location of two existing fish migration barriers (•).   Stream reaches between existing barriers are designated by letters A, B and C.

Table C 4. Input conditions and results for the Dominion Creek example. Stream reaches (Reach) are depicted in Figure B3. State values for input (root) nodes that did not differ among scenarios were: Habitat degradation = Minimally Altered or Pristine, Fishing = 0-10% exploitation, and Gradient = 9.6%; values for other root nodes are given in the table. The table shows results for 16 different scenarios numbered 2-20 (scenarios 1, 5, 13, and 16 were not of interest for this analysis).

	Node value or state, by scenario				
Node name[1]	2	3	4	6	7
Barrier removed	None	None	None	None	None
Brook Trout	Present	Remove	Absent	Present	Remove
Reach	B	B	C	B	B
Time period & GCM	Historical	Historical	Historical	2040s_PCM	2040s_PCM
P(Persistence)	0.079794	0.11847	0.11847	0.079794	0.11847
E[Lambda]	0.775388	0.937053	0.937053	0.775388	0.937053
std-dev Lambda	0.23553	0.269435	0.269435	0.23553	0.269435
finding Temperature_Air - ^{o}C	17.6787	17.6787	17.6787	19.7369	19.7369
finding SummerMeanFlow - cfs	4.29	4.29	4.29	2.99	2.99
finding WinterHighFlow95 - freq	0.65	0.65	0.65	3.85	3.85
finding BKT_Connectivity	Strong	None	None	Strong	None
finding InvasionBarrier	no	no	no	no	no
finding LifeHistory_Potential	Resident	Resident	Resident	Resident	Resident
finding CT_Connectivity	None	None	None	None	None
finding EffectiveNetsize	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+
Water Temperature – ^{o}C	10-15	10-15	10-15	15-18	15-18
E[StreamWidth] – m	3.27765	3.27765	3.27765	2.8513	2.8513
Stream Width - m	3-10	3-10	3-10	<3	<3
Hydrologic Regime	Snowmelt	Snowmelt	Snowmelt	Mixed	Mixed
Invasion Strength	High	None	None	High	None
Life History	Isolated_Resident	Isolated_Resident	Isolated_Resident	Isolated_Resident	Isolated_Resident
Colonization & Rescue	None_Isolated	None_Isolated	None_Isolated	None_Isolated	None_Isolated

Table C 4 (continued).

Node name[1]	Node value or state, by scenario				
	8	9	10	11	12
Barrier removed	None	1	1	1	1
Brook Trout	Absent	Present	Absent	Present	Absent
Reach	C	A_B	C	A_B	C
Time period & GCM	2040s_PCM	Historical	Historical	2040s_PCM	2040s_PCM
P(Persistence)	0.11847	0.309153	0.11847	0.309153	0.11847
E[Lambda]	0.937053	1.14361	0.937053	1.14361	0.937053
std-dev Lambda	0.269435	0.326884	0.269435	0.326884	0.269435
finding Temperature_Air - ^{o}C	19.7369	17.6787	17.6787	19.7369	19.7369
finding SummerMeanFlow - cfs	2.99	4.29	4.29	2.99	2.99
finding WinterHighFlow95 - freq	3.85	0.65	0.65	3.85	3.85
finding BKT_Connectivity	None	Strong	None	Strong	None
finding InvasionBarrier	no	no	no	no	no
finding LifeHistory_Potential	Resident	Migratory	Resident	Migratory	Resident
finding CT_Connectivity	None	Strong	None	Strong	None
finding EffectiveNetsize	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+
Water Temperature – ^{o}C	15-18	10-15	10-15	15-18	15-18
E[StreamWidth] – m	2.8513	3.27765	3.27765	2.8513	2.8513
Stream Width - m	<3	3-10	3-10	<3	<3
Hydrologic Regime	Mixed	Snowmelt	Snowmelt	Mixed	Mixed
Invasion Strength	None	High	None	High	None
Life History	Isolated_Resident	Migratory	Isolated_Resident	Migratory	Isolated_Resident
Colonization & Rescue	None_Isolated	Strong	None_Isolated	Strong	None_Isolated

Table C 4 (continued).

	Node value or state, by scenario			
Node name[1]	14	15	17	18
Barrier removed	2	2	2	2
Brook Trout	Present	Remove	Present	Remove
Reach	B_C	B_C	B_C	B_C
Time period & GCM	Historical	Historical	2040s_PCM	2040s_PCM
P(Persistence)	0.251003	0.414362	0.251003	0.414362
E[Lambda]	0.775388	0.937053	0.775388	0.937053
std-dev Lambda	0.23553	0.269435	0.23553	0.269435
finding Temperature_Air - ^{o}C	17.6787	17.6787	19.7369	19.7369
finding SummerMeanFlow - cfs	4.29	4.29	2.99	2.99
finding WinterHighFlow95 - freq	0.65	0.65	3.85	3.85
finding BKT_Connectivity	Strong	None	Strong	None
finding InvasionBarrier	no	no	no	no
finding LifeHistory_Potential	Resident	Resident	Resident	Resident
finding CT_Connectivity	None	None	None	None
finding EffectiveNetsize	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+
Water Temperature – ^{o}C	10-15	10-15	15-18	15-18
E[StreamWidth] – m	3.27765	3.27765	2.8513	2.8513
Stream Width - m	3-10	3-10	<3	<3
Hydrologic Regime	Snowmelt	Snowmelt	Mixed	Mixed
Invasion Strength	High	None	High	None
Life History	Isolated_Resident	Isolated_Resident	Isolated_Resident	Isolated_Resident
Colonization & Rescue	None_Isolated	None_Isolated	None_Isolated	None_Isolated

Table C 4 (concluded).

Node name[1]	Node value or state, by scenario	
	19	20
Barrier removed	1_2	1_2
Brook Trout	Present	Present
Reach	A_B_C	A_B_C
Time period & GCM	Historical	2040s_PCM
P(Persistence)	0.769901	0.769901
E[Lambda]	1.14361	1.14361
std-dev Lambda	0.326884	0.326884
finding Temperature_Air - °C	17.6787	19.7369
finding SummerMeanFlow - cfs	4.29	2.99
finding WinterHighFlow95 - freq	0.65	3.85
finding BKT_Connectivity	Strong	Strong
finding InvasionBarrier	no	no
finding LifeHistory_Potential	Migratory	Migratory
finding CT_Connectivity	Strong	Strong
finding EffectiveNetsize	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+
Water Temperature – °C	10-15	15-18
E[StreamWidth] – m	3.27765	2.8513
Stream Width – m	3-10	<3
Hydrologic Regime	Snowmelt	Mixed
Invasion Strength	High	High
Life History	Migratory	Migratory
Colonization & Rescue	Strong	Strong

[1] Column provides node names and value or statistic calculated for that node; "P" indicates a probability calculated by the model for discrete nodes, "E" indicates a probability (or expected value) calculated by the model for continuous nodes, and "std-dev" indicates Gaussian standard deviation calculated for continuous nodes.

Deep Creek

Results for Deep Creek imply that removing all barriers (Brook Trout invade) instead of just the upper two (no Brook Trout) will result in a larger relative increase in persistence under climate change (0.11 to 0.53, an 0.42 absolute increase but 3.7-fold relative increase) compared to historical environmental conditions (0.15 to 0.59, a 0.44 absolute increase but 3.0-fold relative increase). Including habitat remediation provided an even greater relative benefit under climate change (persistence = 0.73, a 5.5-fold increase) than under historical conditions (0.77, a 4.2-fold increase). Conversely, we saw little relative difference in benefit before or after climate change when Brook Trout were absent, we controlled for habitat extent (i.e., upper barriers removed) and then implemented habitat restoration. In this scenario probabilities increased from 0.11 to 0.30 with climate change and 0.15 to 0.40 without; a 1.7-fold increase for both.

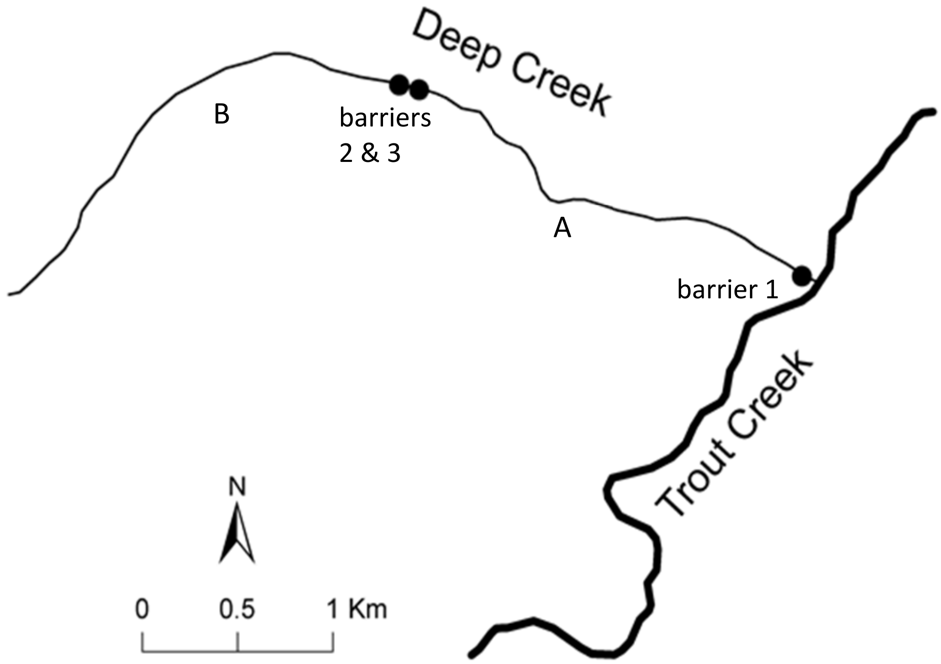

Figure C 4. Schematic of Deep Creek showing location of three existing fish migration barriers (•). Stream reaches between existing barriers are designated by letters A and B.

Table C 5. Input conditions and results for the Deep Creek example. Stream reaches (Reach) are depicted in Figure B4. State values for input (root) nodes that did not differ among scenarios were: Fishing = 0-10% exploitation, Gradient = 9.2%; BKT Connectivity = Strong, CT Connectivity = Strong, and LifeHistory Potential = Migratory; values for other root nodes are given in the table. The table shows results for 16 different scenarios numbered 1-16.

	Node value or state, by scenario			
Node name	1	2	3	4
Barrier removed	None	None	None	None
Brook Trout	Absent	Absent	Absent	Absent
Reach	A	A	A	A
Habitat_Improvement	no	no	yes	yes
Time period & GCM	Historical	2040s_PCM	Historical	2040s_PCM
P(Persistence)	0.0582635	0.0521164	0.114171	0.0890807
E[Lambda]	0.662909	0.623962	0.919525	0.825631
std-dev Lambda	0.181538	0.154831	0.269615	0.222451
finding Temperature_Air - ^{o}C	17.7634	19.7666	17.7634	19.7666
finding SummerMeanFlow - cfs	5.31	4.22	5.31	4.22
finding WinterHighFlow95 - freq	0.8	2.65	0.8	2.65
finding HabitatDegradation	Altered and Degraded	Altered and Degraded	Minimally Altered or Pristine	Minimally Altered or Pristine
finding InvasionBarrier	Yes	Yes	Yes	Yes
finding EffectiveNetsize	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+
Water Temperature - ^{o}C	10-15	15-18	10-15	15-18
E[StreamWidth] - m	3.55894	3.2569	3.55894	3.2569
Stream Width - m	3-10	3-10	3-10	3-10
Hydrologic Regime	Snowmelt	Mixed	Snowmelt	Mixed
Invasion Strength	None	None	None	None
LifeHistory_Effective	Isolated_ResidentOnly	Isolated_ResidentOnly	Isolated_ResidentOnly	Isolated_ResidentOnly
Colonization & Rescue	None_Isolated	None_Isolated	None_Isolated	None_Isolated

Table C 5 (continued).

Node name	Node value or state, by scenario 5	6	7	8
Barrier removed	1	1	1	1
Brook Trout	Present	Present	Present	Present
Reach	A	A	A	A
Habitat_Improvement	no	no	yes	yes
Time period & GCM	Historical	2040s_PCM	Historical	2040s_PCM
P(Persistence)	0.225453	0.19827	0.309153	0.284332
E[Lambda]	0.950894	0.890242	1.14361	1.08919
std-dev Lambda	0.320812	0.282299	0.326884	0.309106
finding Temperature_Air - ^{o}C	17.7634	19.7666	17.7634	19.7666
finding SummerMeanFlow - cfs	5.31	4.22	5.31	4.22
finding WinterHighFlow95 - freq	0.8	2.65	0.8	2.65
finding HabitatDegradation	Altered and Degraded	Altered and Degraded	Minimally Altered or Pristine	Minimally Altered or Pristine
finding InvasionBarrier	no	no	no	no
finding EffectiveNetsize	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+	< 3 km or < 500 age-1+
Water Temperature - ^{o}C	10-15	15-18	10-15	15-18
E[StreamWidth] - m	3.55894	3.2569	3.55894	3.2569
Stream Width - m	3-10	3-10	3-10	3-10
Hydrologic Regime	Snowmelt	Mixed	Snowmelt	Mixed
Invasion Strength	High	High	High	High
LifeHistory_Effective	FullExpression	FullExpression	FullExpression	FullExpression
Colonization & Rescue	Strong	Strong	Strong	Strong

Table C 5 (continued).

Node name	Node value or state, by scenario			
	9	10	11	12
Barrier removed	2_3	2_3	2_3	2_3
Brook Trout	Absent	Absent	Absent	Absent
Reach	A_B	A_B	A_B	A_B
Habitat_Improvement	no	no	yes	yes
Time period & GCM	Historical	2040s_PCM	Historical	2040s_PCM
P(Persistence)	0.146756	0.113161	0.396571	0.301321
E[Lambda]	0.662909	0.623962	0.919525	0.825631
std-dev Lambda	0.181538	0.154831	0.269615	0.222451
finding Temperature_Air - ^{o}C	17.7634	19.7666	17.7634	19.7666
finding SummerMeanFlow - cfs	5.31	4.22	5.31	4.22
finding WinterHighFlow95 - freq	0.8	2.65	0.8	2.65
finding HabitatDegradation	Altered and Degraded	Altered and Degraded	Minimally Altered or Pristine	Minimally Altered or Pristine
finding InvasionBarrier	Yes	Yes	Yes	Yes
finding EffectiveNetsize	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+
Water Temperature - ^{o}C	10-15	15-18	10-15	15-18
E[StreamWidth] - m	3.55894	3.2569	3.55894	3.2569
Stream Width - m	3-10	3-10	3-10	3-10
Hydrologic Regime	Snowmelt	Mixed	Snowmelt	Mixed
Invasion Strength	None	None	None	None
LifeHistory_Effective	Isolated_ResidentOnly	Isolated_ResidentOnly	Isolated_ResidentOnly	Isolated_ResidentOnly
Colonization & Rescue	None_Isolated	None_Isolated	None_Isolated	None_Isolated

Table C 5 (concluded).

Node name	Node value or state, by scenario 13	14	15	16
Barrier removed	1_2_3	1_2_3	1_2_3	1_2_3
Brook Trout	Present	Present	Present	Present
Reach	A_B	A_B	A_B	A_B
Habitat_Improvement	no	no	yes	yes
Time period & GCM	Historical	2040s_PCM	Historical	2040s_PCM
P(Persistence)	0.585083	0.532251	0.769901	0.734126
E[Lambda]	0.950894	0.890242	1.14361	1.08919
std-dev Lambda	0.320812	0.282299	0.326884	0.309106
finding Temperature_Air - ^{o}C	17.7634	19.7666	17.7634	19.7666
finding SummerMeanFlow - cfs	5.31	4.22	5.31	4.22
finding WinterHighFlow95 - freq	0.8	2.65	0.8	2.65
finding HabitatDegradation	Altered and Degraded	Altered and Degraded	Minimally Altered or Pristine	Minimally Altered or Pristine
finding InvasionBarrier	no	no	no	no
finding EffectiveNetsize	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+	3-5 km or 500-1000 age1+
Water Temperature - ^{o}C	10-15	15-18	10-15	15-18
E[StreamWidth] - m	3.55894	3.2569	3.55894	3.2569
Stream Width - m	3-10	3-10	3-10	3-10
Hydrologic Regime	Snowmelt	Mixed	Snowmelt	Mixed
Invasion Strength	High	High	High	High
LifeHistory_Effective	FullExpression	FullExpression	FullExpression	FullExpression
Colonization & Rescue	Strong	Strong	Strong	Strong

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