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RESTORING SALMON HABITAT FOR A CHANGING CLIMATE

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ABSTRACT

An important question for salmon restoration efforts in the western USA is 'How should habitat restoration plans be altered to accommodate climate change effects on stream flow and temperature?' We developed a decision support process for adapting salmon recovery plans that incorporates (1) local habitat factors limiting salmon recovery, (2) scenarios of climate change effects on stream flow and temperature, (3) the ability of restoration actions to ameliorate climate change effects, and (4) the ability of restoration actions to increase habitat diversity and salmon population resilience. To facilitate the use of this decision support framework, we mapped scenarios of future stream flow and temperature in the Pacific Northwest region and reviewed literature on habitat restoration actions to determine whether they ameliorate a climate change effect or increase life history diversity and salmon resilience. Under the climate change scenarios considered here, summer low flows decrease by 35–75% west of the Cascade Mountains, maximum monthly flows increase by 10–60% across most of the region, and stream temperatures increase between 2 and 6°C by 2070–2099. On the basis of our literature review, we found that restoring floodplain connectivity, restoring stream flow regimes, and re-aggrading incised channels are most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience. By contrast, most restoration actions focused on in-stream rehabilitation are unlikely to ameliorate climate change effects. Finally, we illustrate how the decision support process can be used to evaluate whether climate change should alter the types or priority of restoration actions in a salmon habitat restoration plan. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: restoration; climate change; decision support; adaptation; salmon habitat; stream flow; stream temperature

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INTRODUCTION

Climate change is predicted to have significant effects on Pacific salmon and their ecosystems in western North America, and several reports suggest that restoring habitats for salmon in some places may be pointless because climate change will make their habitats inhospitable (Lackey, 2003; Nelitz *et al*., 2007). By contrast, recent modelling of the combined effects of climate change and habitat restoration indicates restoration actions are likely to result in a net benefit to salmon populations despite future shifts in temperature and hydrology (Battin *et al*., 2007). This lack of consensus on how climate change will affect salmon populations inhibits the development of clear guidance on how to modify habitat restoration efforts in response to climate change. With millions of dollars spent each year to restore habitats for threatened and endangered salmon in the western USA, there is increasing concern that climate change effects on freshwater habitats may limit the future effectiveness of certain salmon recovery efforts (Lackey *et al*., 2006; Battin *et al*., 2007; Mantua *et al*., 2010) and that the priority or design of specific restoration actions should be altered to accommodate future climate change (Mote *et al*., 2003).

Making the decision to adapt a restoration plan for climate change is not straightforward, as predicted climate change effects vary widely throughout the Pacific salmon range, and some species have life histories that will likely allow them to persist throughout most of their range despite shifts in temperature and precipitation (Waples *et al*., 2009). Stream temperatures are expected to increase in most rivers, and the threat to salmon recovery is high where temperatures are near lethal or sub-lethal thresholds for salmon, but low in many rivers with current temperatures well below those thresholds. Furthermore, some rivers are expected to see large increases in peak flows, whereas other rivers are expected to experience decreased low flows (Arnell, 1999, Mantua *et al*., 2010). However, past land uses and water abstraction have often degraded habitats to a greater degree than that predicted from climate change, presenting substantial

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opportunities to improve salmon habitats more than enough to compensate for expected climate change effects over the next several decades (Battin *et al*., 2007). For salmonids, variation in life history strategies and habitat requirements—along with their demonstrated capacity to adapt to new environments—further complicates the development of general guidance for modifying restoration strategies to accommodate climate change (Quinn, 2005; Beechie *et al*., 2006; Bryant, 2009). This complex interplay of climate effects, restoration opportunities, and potential salmon responses poses a considerable challenge for effectively restoring salmon populations in a changing climate.

In this paper, we present a simple logic framework and data sets to assist managers in adapting salmon habitat restoration efforts to climate change in the Pacific Northwest, USA (PNW). Our approach consists of four components: (1) a set of guiding questions that serve as a starting point for evaluating the potential effects of climate change on freshwater habitat restoration effectiveness; (2) maps showing future stream flow and temperature scenarios; (3) a review of the ability of specific river restoration actions to ameliorate future effects of climate change or to increase salmon resilience; and (4) a simple decision support structure that integrates these three components to help managers evaluate whether salmon restoration actions should be reprioritized or redesigned for a climate-altered future. Together, these components guide decisions on whether and how to adapt or reprioritize actions in light of expected climate-induced habitat changes.

STUDY AREA

The study area encompasses the Columbia River basin and coastal drainages of Oregon and Washington (Figure 1), with climatic and ecological conditions ranging from wet forests in the Cascade Mountains to semi-arid and desert regions in the central plateaus (Omernik and Bailey, 1997). The study area is bordered by the Rocky Mountains to the east, and the Cascade Mountains separate coastal drainages from the interior Columbia basin. Mean annual precipitation ranges from <200 mm/year in the central deserts to 3550 mm/year in the Cascade Range (Daly *et al*., 2002), and elevations range from sea level to over 3700 m in the Rocky Mountains and over 4200 m in the Cascade Mountains. Five anadromous salmon species (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) are found in the study area, along with bull trout (*Salvelinus confluentus*), Dolly Varden char (*S. malma*), and rainbow and

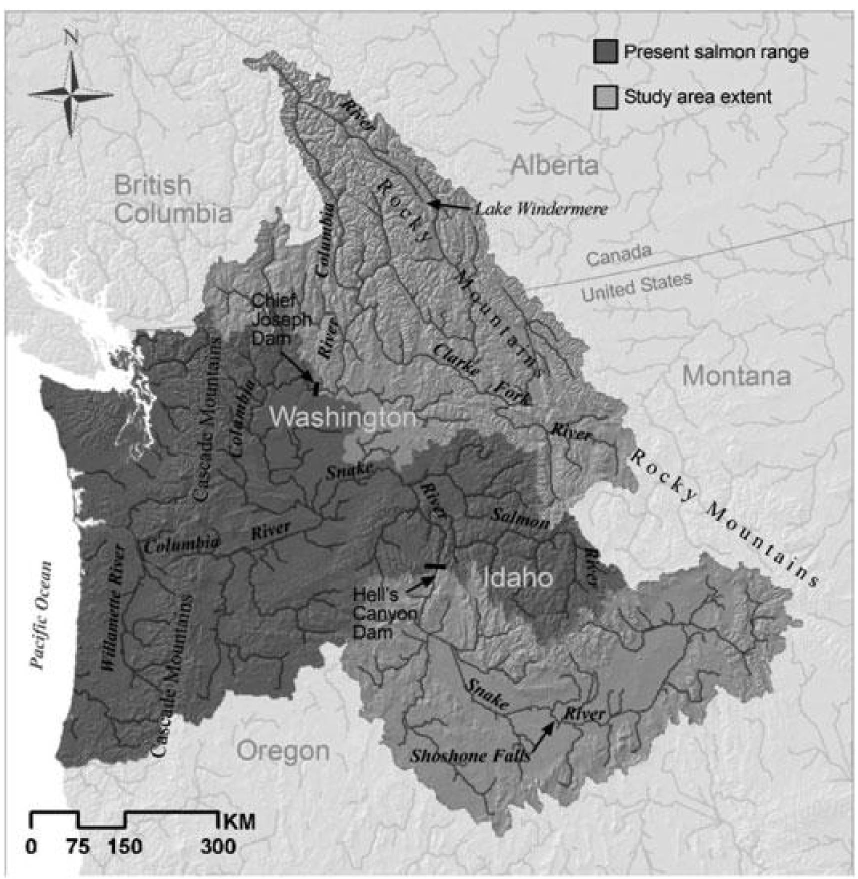

Figure 1. Map of the study area indicating major rivers, mountain ranges, and current and historical ranges of salmon

cutthroat trout (*O. mykiss, O. clarkii*). Current ranges of salmon and steelhead are limited to coastal rivers, the Columbia River basin downstream of Chief Joseph dam and the Snake River basin downstream of Hells Canyon Dam. Historical ranges extended into the upper reaches of the Columbia River (Lake Windermere) and into the Snake River basin up to Shoshone Falls. Resident trout species (rainbow, cutthroat, and bull trout) occupy streams throughout the region, with bull trout generally restricted to colder streams at higher elevations.

FRAMEWORK AND GUIDING QUESTIONS

Determining how a specific change in stream flow or temperature will impact a salmon population depends in part upon species-specific tolerances and life history requirements, and in part upon the expected change in stream flow and temperature relative to those tolerances. The timing of important salmon life history events varies both within and among species (e.g. Groot and Margolis, 1991; Quinn, 2005; Figure 2). For example, salmonids with ocean-type life histories (e.g. pink, chum, and some Chinook) tend to spawn in the fall and winter, do not rear in freshwater during summer, and migrate to sea in the winter or early spring. Salmonids with stream-type life histories (e.g. coho salmon, steelhead, and some Chinook salmon) spawn between fall and late spring, rear in freshwater for 1 or 2 years, and usually migrate to sea in spring or early summer. Hence, each species and life history strategy will encounter a different suite of stream flow and temperature effects because they occupy different habitats and vary in timing of life history events. Climate change effects will also vary among rivers (e.g. Mote *et al*., 2003; Beechie *et al*., 2006; Rieman *et al*., 2007; Crozier *et al*., 2008), adding additional complexity to understanding how climate change will affect salmonid populations.

Because there are many possible combinations of climate change effects and life history responses to evaluate across the study region, we do not attempt a comprehensive review of all possible effects, nor do we use detailed population models to estimate climate change effects on restoration actions (e.g. Battin *et al*., 2007), mainly because many types of restoration actions cannot be modelled with any certainty and evaluation of hundreds of salmon populations is not feasible (Bartz *et al*., 2006; Scheuerell *et al*., 2006). Rather, we summarize key temperature thresholds by species and life history stage, summarize climate change scenarios for stream temperature and flow, and allow local practitioners to relate local climate change scenarios to locally relevant salmonid tolerances. We also review the likely effectiveness of various restoration techniques in a climate-altered future.

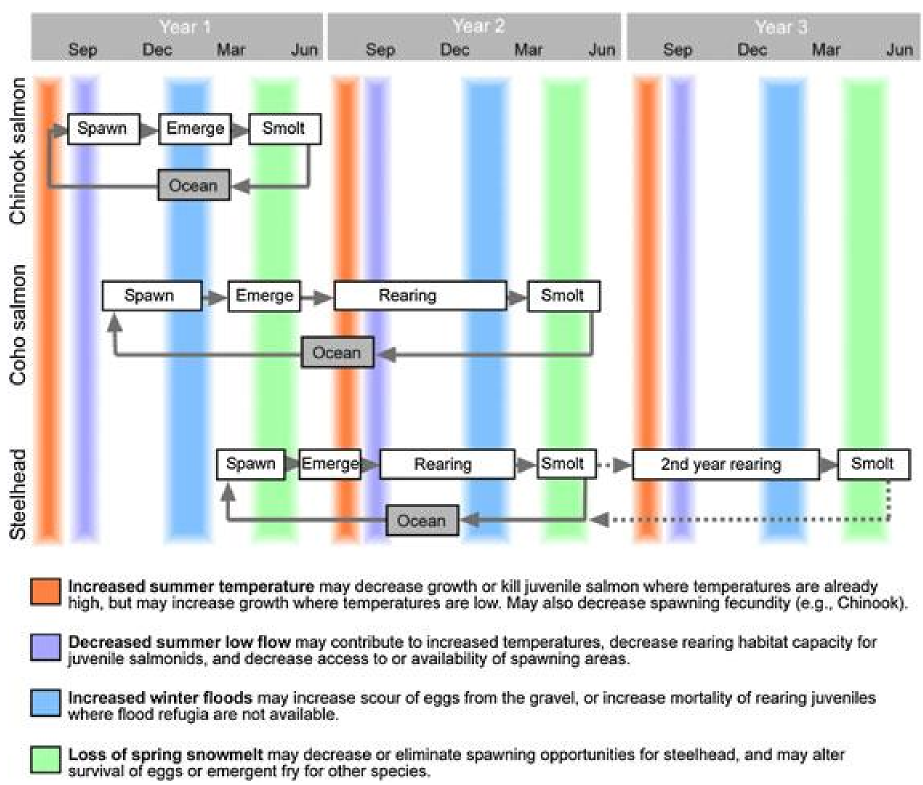

Figure 2. Timing of climate change effects on stream flow and temperature by life history stages of ocean type Chinook salmon, coho salmon, and steelhead

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For example, actions that create new summer rearing habitats in an area expected to exceed upper lethal temperature limits will not likely improve salmonid populations over the long term. By contrast, actions that significantly reduce stream temperature or create thermal refugia for the same species are more likely to retain their effectiveness in a future with increasing temperatures. Therefore, we reviewed recent literature to evaluate whether specific restoration action types will likely ameliorate climate change effects on flood flows, low flows, or stream temperature.

We also developed four guiding questions to evaluate the potential impacts of climate change on project prioritization and design:

(1) What habitat restoration actions are necessary for recovery of local salmon populations?
(2) Do future stream flow and temperature scenarios alter the types of habitat restoration actions that are necessary for recovery?
(3) Does the restoration plan or action ameliorate a predicted climate change effect on stream flow or temperature?
(4) Will the restoration plan or action increase habitat diversity and salmon population resilience?

Systematic consideration of these questions will help determine whether restoration objectives or priorities should be altered to accommodate future climate change. Answering the first question requires local information about restoration plans and objectives, which restoration planners and practitioners can acquire from salmon recovery plans developed under the Endangered Species Act. However, information required to answer the last three questions is rarely readily available to restoration groups. Therefore, in the following sections, we summarize information needed to address questions 2–4 for salmon restoration actions in the PNW.

SCENARIOS FOR CLIMATE CHANGE EFFECTS ON STREAM FLOW AND TEMPERATURE IN THE PACIFIC NORTHWEST

Recent climate change scenarios modelled for the PNW suggest a clear warming trend, but the magnitude of estimated temperature increase varies with choice of climate model and emissions scenario (Elsner *et al*., 2010). By contrast, even the sign of future precipitation changes is not consistent among different scenarios, with some predicting precipitation increases and others predicting decreases (e.g. Elsner *et al*., 2010). A multi-model averaged climate change scenario under A1B emissions indicates an average temperature increase in the PNW of 3.5°C by 2080, with wetter winters, drier summers, and an increase in average annual precipitation of 5% (Elsner *et al*., 2010; Mote and Salathé, 2010). Because all the future climate scenarios evaluated by Elsner *et al*. (2010) predict warming trends, the models predict that more precipitation will fall as rain and less as snow and that this effect will be most pronounced in mid-elevation areas (Hamlet and Lettenmaier, 1999). In this paper, we use this multi-model average from Elsner *et al*. (2010) to drive a coupled stream flow and temperature model (Whited *et al*., in press) to produce scenarios of stream temperature and flow regimes that may have significant impacts on salmon populations and food webs that support them.

Although the A1B multi-model average is commonly considered to be an informative future climate scenario (i.e. it is closest to most model estimates and the weighting scheme discounts extreme values; Mote and Salathé, 2010), there remains considerable uncertainty around any estimate of future precipitation or air temperature. Uncertainties around future temperature and precipitation predictions have three main sources: (1) the factors that force climate change (including future greenhouse gas and aerosol emissions), (2) global climate model (GCM) errors, and (3) 'natural' variability in the climate system (Deser *et al*., 2010; Hawkins and Sutton, 2011). In general, the variation in temperature or precipitation predictions among different emissions scenarios is smaller than the variation among different GCMs (Mote and Salathé, 2010). For example, the multi-model average predictions of PNW climate for three emissions scenarios in the 2040s indicate a temperature increase of 1.7–2.4°C and a precipitation increase of 1–2% (Figure 3); the 2080s simulations indicate a 2.7–4.7°C increase in temperature and 3–6% increase in precipitation. However, the variation among GCMs for the 2040s is roughly 2°C for each emissions scenario (compared with a range of <1°C among emission scenarios) and as high as 3.5°C among GCMs in the 2080s (compared with ~2°C among emissions scenarios). Variation among GCMs is even greater for precipitation predictions, with a range as high as −8% to +23% for precipitation by the 2080s (compared with 3–6% between emissions scenarios). The combined emissions scenario, model uncertainties, and natural variability for air temperature in the PNW suggest an increase of 1–3°C by the 2040s and 2–6°C by the 2080s (multi-model averages of 2°C and 3.5°C, respectively). The combined uncertainties for precipitation suggest a −6% to +14% change in precipitation by the 2040s and a −8% to +23% change by the 2080s (multi-model averages of +2% and +5%, respectively). Finally, both air temperature and precipitation are expected to continue increasing through the end of the 21st century regardless of the GCM used, and our use of climate scenarios for the 2080s is not intended to suggest a stable future climate.

Stream flow and temperature methods

Changes in stream flow and temperature were simulated using a two-step modelling process that (1) predicted daily

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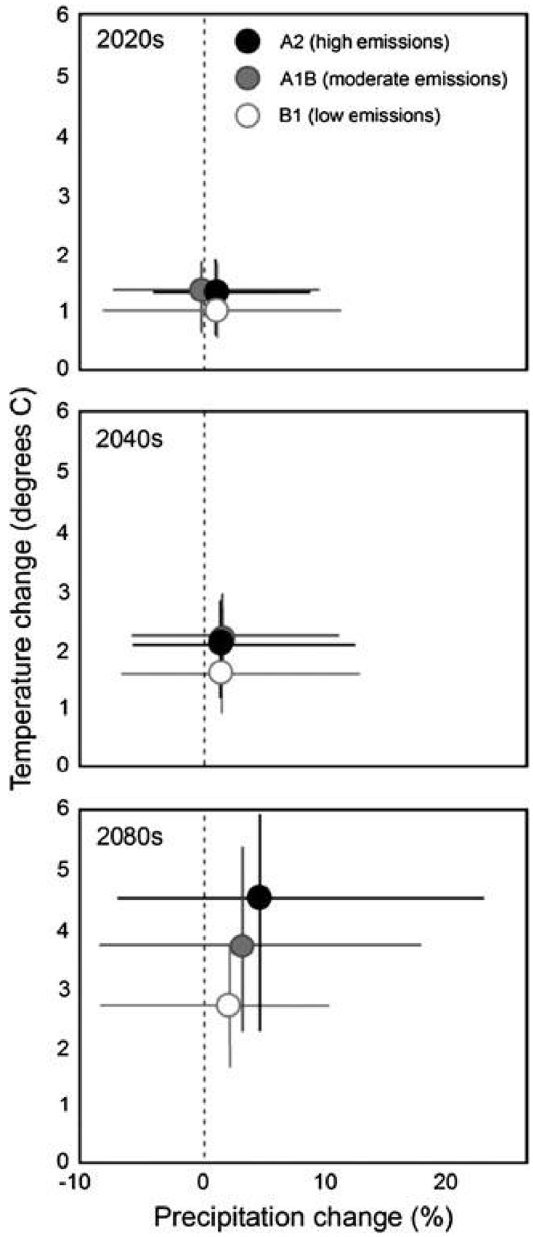

Figure 3. Variation in global climate model (GCM) predictions of precipitation change (%) and temperature increase (°C) in the Pacific Northwest. Circles indicate ensemble model averages for each of three emissions scenarios, and lines indicate range of predictions from 20 different GCMs for each emissions scenario. Based on data from Mote and Salathé (2010)

runoff using the macroscale variable infiltration capacity (VIC) model and (2) dynamic runoff routing, stream flow and stream temperature simulations based on VIC that estimate water balance, energy balance, and runoff outputs. The VIC model produces daily runoff and soil moisture, as well as associated forcing variables including incoming short-wave and long wave radiation that are used later in the stream temperature model. The coupled stream flow and temperature model was based on a hierarchical dominant river tracing algorithm that defines the underlying hydrography for stream flow and temperature calculations (Wu *et al*., 2011). The coupled model, called the dominant river tracing-based stream flow and temperature model, produces gridded daily stream flow and stream temperature data on the basis of water and heat transport in river networks, thermal dynamics of stream water and the surrounding environment, and the coupling of hydrologic routing processes and associated thermal dynamics (Whited *et al*., in press). Stream flow and temperature scenarios were based on the multi-model average future climate scenario described previously that provided daily gridded precipitation and air temperature data at one-sixteenth degree resolution (Elsner *et al*., 2010). Only cells with flow accumulation areas greater than six upstream cells (equivalent to a drainage area of approximately 200 km^2) were included in the regional mapping because smaller drainage areas were not considered reliable for future scenarios (Wu and Kimball, unpublished data).

Stream flow and temperature were calibrated to measured stream flow and temperatures at seven US Geological Survey sites in the Columbia River basin and then validated against an independent 10-year record of daily stream flows at 12 gauges and a 7-year record of daily stream temperatures at 11 gauges. Model validation indicated strong correlation between measured and simulated stream flow and temperature at the majority of gauges (Figure 4). Although there was no consistent positive or negative bias in either stream flow or temperature, some deviations between modelled and measured stream flow or temperature are likely due to differences between the way VIC models runoff, groundwater, and stream flow compared with local physical processes. For example, in the Willamette basin, groundwater discharge

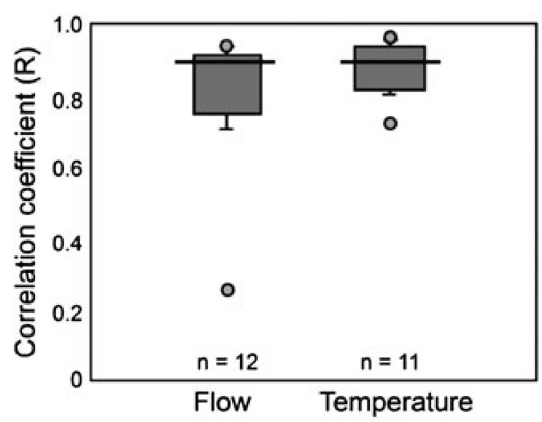

Figure 4. Summary of dominant river tracing-based stream flow and temperature model validation results, illustrating distribution of correlation coefficients (R) for modelled versus measured stream flow and temperature. Heavy horizontal line indicates median R, box indicates 25th and 75th percentiles, lines indicate 10th and 90th percentiles, and circles indicate range of values. (Wu and Kimball, unpublished data)

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from the fractured basalts of the Cascade Mountains leads to higher summer stream flow and lower summer temperature than predicted by the dominant river tracing-based stream flow and temperature model, primarily because the VIC model does not effectively model deep groundwater storage and its influence on flow. Therefore, the VIC model underestimates summer stream flow, which in turn leads to an overestimate of summer stream temperature. Other studies have found regional biases in mean annual runoff associated with arid regions or snowmelt systems and showed overall underestimation of mean annual stream flow in the PNW from VIC modelling (Gangopadhyay and Pruitt, 2011). However, validation of stream flows for this study did not suggest a clear spatial pattern of positive or negative biases.

We focused our flow analysis on mean monthly flows for four periods: 1970–1999, 2000–2029, 2030–2069, and 2070–2099. We calculated change in magnitude of the maximum and minimum monthly flows between periods for each stream cell, as well as the change in timing of maximum and minimum monthly flows between periods. We focused on predicted *change* in flow relative to the modelled historical baseline rather than absolute stream flows to minimize impacts of errors in the flow model on our results. That is, we assume that biases in the stream flow model will be in the same direction for all periods within a grid cell and that using the change in flow as our primary metric will reduce the impact of those biases on our analysis. Finally, we used cluster analysis to map three flow regimes (rainfall-dominated, snowmelt-dominated, and transitional) during each period (Beechie *et al*., 2006).

We chose to map temperature predictions directly to allow the greatest flexibility in biological interpretations. That is, we avoided selection of specific thermal limits because thermal tolerances vary considerably among species for each life stage. To aid in biological interpretation of these temperature maps, we provide both species-specific and generalized salmonid thermal limits (Table I), as well as published temperature criteria that are recommended for protection of Pacific salmon from negative temperature effects (Table II). Most upper lethal limits are between 20 and 24°C and recommended temperature thresholds for the 7-day average daily maximum range from 13 to 18°C. In the absence of local data on thermal tolerances of salmonids (which vary among species and environments), these data can be used to gauge the likelihood that stream temperature changes will be significant for local species.

Results: stream flow change scenario

Areas of the PNW with a snowmelt-dominated hydrologic regime (in which the maximum monthly flows are during the spring snowmelt) shrink considerably under the ensemble climate change scenario as snow level rises across the region (Figure 5). By 2070–2099, the snowmelt hydrologic regime no longer exists in the north Cascades and upper Snake River basin, and the only remaining snowmelt-dominated area is in the Canadian Rockies. The transitional regime, which has

Table I. Temperature thresholds (°C) for critical parts of the salmonid life cycle, including general and species specific information

Life stage	Chinook (*O. tshawytscha*)	Chum (*O. keta*)	Coho (*O. kisutch*)	Pink (*O. gorbuscha*)	Sockeye (*O. nerka*)	Steelhead (*O. mykiss*)
Adult migration						
Optimal threshold			15.6			
Lethal threshold	22	21	21			
Thermal blockage						22
Adult holding and spawning						
Optimal threshold	14.5	12.8	15.6			12.8
Detrimental to internally held gametes			20			
Incubation and early fry development						
Upper threshold	14.5	10	12	12	12.5	12
Juvenile rearing						
Optimal threshold	14.8[a]	15	17			19
Lethal threshold		21	23		20	
UZNG[b]	24	19.8	23.4	21		24
Smoltification						
Impairment threshold	12–17		15			13

Temperatures cited are for constant exposure, unless otherwise noted. Data compiled from Bjornn and Reiser (1991), Eaton and Scheller (1996), McCullough *et al*. (2001), and Richter and Kolmes (2005).
[a]Natural rations level
[b]Upper zero net growth (UZNG) temperature: maximum weekly temperature at which fish can live for several days but at which they do not ingest enough food to gain weight

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Table II. Recommended temperature criteria (upper thresholds; °C) for Pacific salmon and steelhead

	Life stage						Reference
	Adult migration	Spawning	Incubation	Juvenile rearing	Smoltification (non-steelhead)	Steelhead smoltification	
7-DADM	18	13	13	16	16	14	Richter and Kolmes, 2005; US EPA, 2003
Weekly mean	16	10	10	15	15	12	Richter and Kolmes, 2005

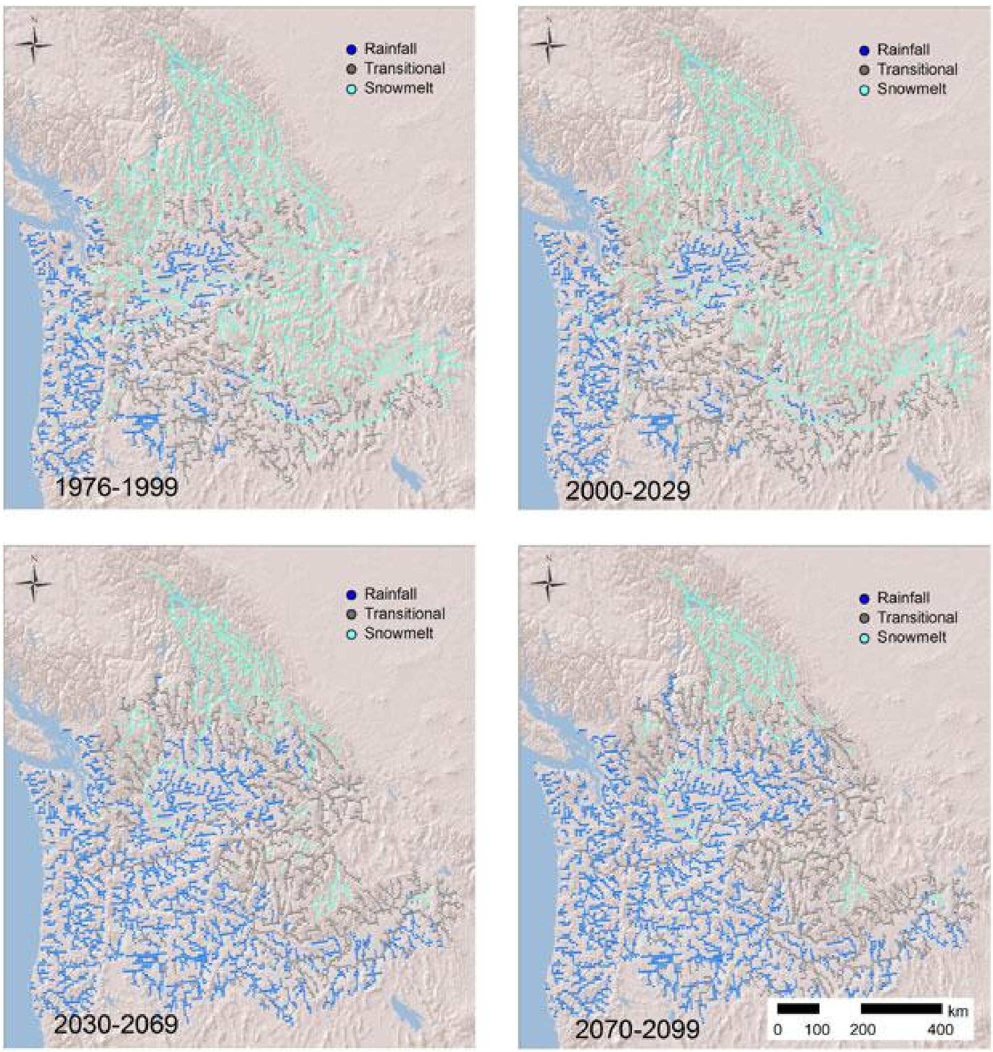

Figure 5. Modelled hydrologic regime through time, based on cluster analyses of mean monthly flows for each period

both spring snowmelt and fall–winter high flows, shifts inland and northwards, leaving only small areas of the transitional regime in the north Cascades and the Rocky Mountains. The rainfall-dominated regime, which has the highest flows during fall–winter floods, has historically been limited to the maritime climate west of the Cascades and small low-elevation portion of the interior Columbia basin. By 2070–2099 however, the rainfall-dominated regime expands to nearly the entire interior Columbia basin in this climate change scenario.

The ensemble climate scenario suggests the largest decreases in summer low flows will be west of the Cascade Mountains, where minimum monthly flows decrease by 10–70% over the

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course of the 21st century (Figure 6). The largest changes are in basins that currently have a transitional hydrologic regime (with both a fall/winter storm peak and a late spring snowmelt peak), and large decreases in minimum monthly flows result from a nearly complete loss of the spring snowmelt peak and a concomitant decline in late summer flows. More modest decreases in low flow (10–35%) are predicted in the Rocky Mountains south of the US–Canada border and in the Blue Mountains of northeastern Oregon. In these areas, the hydrologic regime shifts from snowmelt to transitional, and the decline in snowpack results in earlier spring melt and a decrease in late summer stream flows (Figure 6). Minimum monthly flows in the Canadian Rockies increase by 10% or more, largely as a result of a predicted increase in precipitation and snowpack. Increased minimum flows are also predicted in the upper Snake River basin, caused by a shift in minimum monthly flows from the cold January–February period to minimum flows in summer following spring snowmelt. In this region, there is little predicted change in summer low flows, but the minimum winter flows increase significantly.

Simulated maximum monthly flows increase by 10–50% across most of the region as a result of an increasing fraction of precipitation falling as rain rather than snow (Figure 7). The few areas where maximum monthly flows are expected to increase by more than 50% are located in the Cascade Mountains and in the middle and lower Snake River basin. The large increases in the Cascade Mountains are predominantly a result of a shift from transitional to rainfall-dominated hydrographs, with future flood flows in the fall and winter being considerably larger than at present. Large predicted increases in the monthly average peak stream flow in the Snake River tributaries result mainly from large increases in spring precipitation. Overall, the ensemble scenario suggests increasing volume of winter runoff and increased flooding in transitional basins and increasing spring flows in snow-dominant basins. Reductions in summer low flows are projected to be largest in the transitional basins in the Cascade and Olympic Mountain ranges.

Results: stream temperature change scenario

Increased air temperatures will lead to increased water temperatures on both the west and east sides of the Cascade Mountains, and the scenario indicates a 1–4°C increase in stream temperatures (maximum weekly mean temperature) across the region by the 2030–2069 period and a 2–6°C increase by the 2070–2099 period (Figure 8). Highest mean weekly water temperatures vary significantly across the region in all periods, with highest temperatures in reaches of the Snake and Willamette River basins (Figure 9). Because these areas are close to or exceed published thermal tolerances of most salmon species even during the historical period (1970–1999), they are most likely to shift to stressful or lethal thermal conditions in the future. Notably, many rivers within the current salmon range have modelled temperatures above published lethal or protective thresholds (Tables I and II), yet salmon currently occupy the majority of these rivers. Stream temperatures in the northern part of the Columbia basin are currently within thermal tolerances of most rearing juvenile salmonids, and under this climate change scenario, projected temperature increases remain the lowest in the region and within thermal tolerances. This area is outside the current salmon range because of blocked migration by dams, but within their historical range. Most coastal river systems and rivers originating on the west slope of the Cascade Mountains are likely to remain within published thermal tolerances even in the 2070–2099 period. These river systems have the smallest projected temperature increases, whereas the largest increases are expected in the main stem Columbia River and tributaries in the middle and lower Columbia basin.

REVIEW OF RESTORATION ACTIONS AND CLIMATE CHANGE

We grouped restoration actions on the basis of the watershed processes or functions they attempt to restore (Beechie *et al.*, 2010) and then classified them as either likely or not likely to ameliorate a climate change effect on high stream flows, low stream flows, and stream temperatures (Table III). We classified actions on the basis of a literature review of restoration action effectiveness and watershed processes to develop a comprehensive summary of each action's likelihood of ameliorating climate change effects. Our basic rules were to (1) classify an action as likely to ameliorate an effect if we could find literature support for that response and (2) avoid including effects that were theoretically possible but not supported by data. In a few cases, the literature was sparse and suggested mixed effects depending on the context. In those cases, we classified the action as having a context-dependent effect on stream flow or temperature to indicate that the ability of the action to ameliorate a climate effect depends on the situation in which the action is employed. Although these rules may omit a few effects, we felt that it was more important to provide clear guidance on the dominant effects and avoid including actions that only rarely would ameliorate the climate change effect. Nevertheless, this review is not intended to imply that less robust actions should be avoided in all circumstances. For instance, where summer rearing habitats constrain population recovery and summer stream flow and temperature are not expected to change significantly, any action that addresses causal factors for habitat and population declines should be implemented even if it does not ameliorate a climate change effect. Only in cases where

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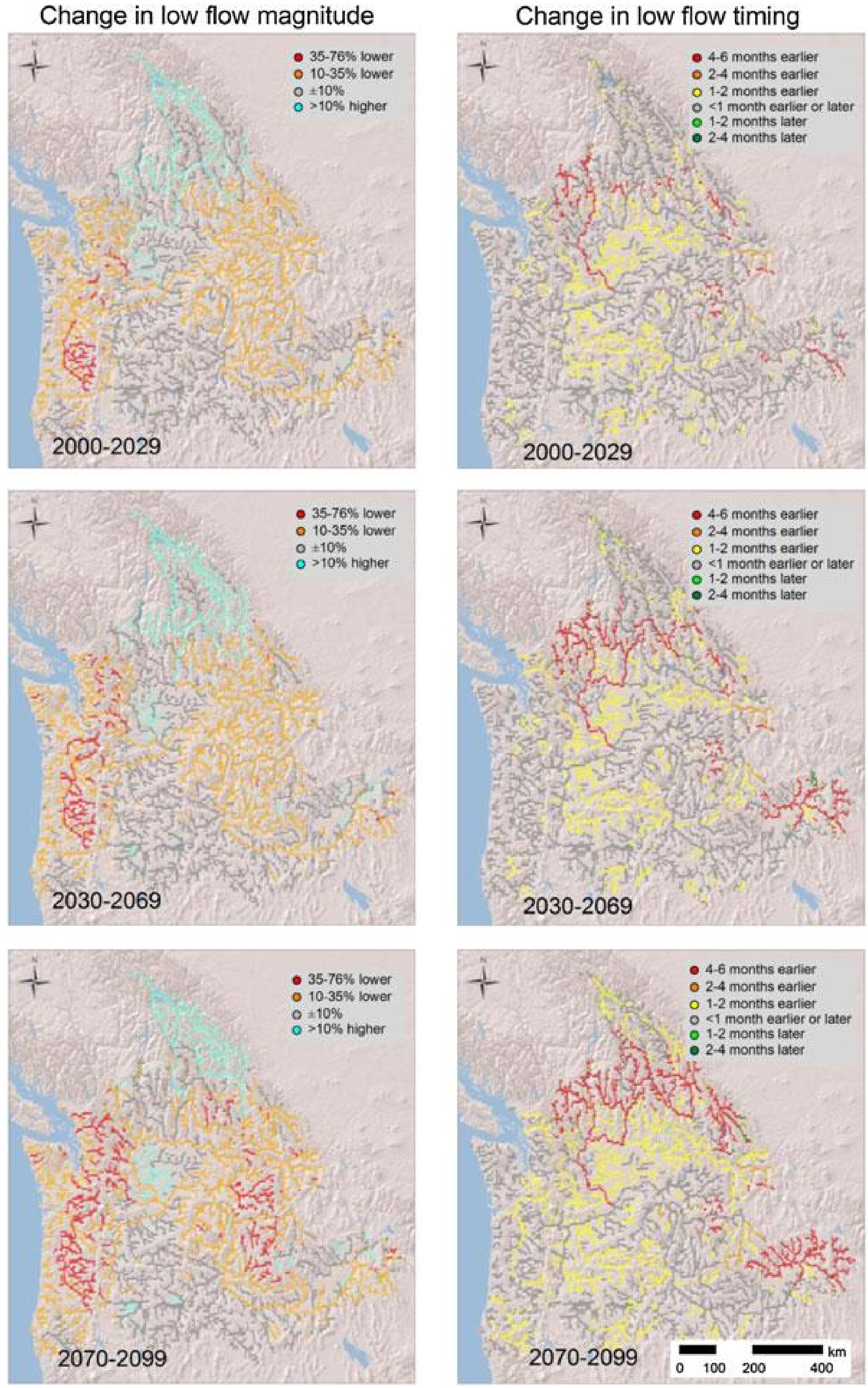

Figure 6. Modelled change in the minimum mean monthly flow and shift in timing of minimum mean monthly flow. Ratio is minimum mean monthly flow from the future period divided by the minimum mean monthly flow from the period 1970–1999. For shift in low flow timing, areas mapped in red indicate a shift from minimum flow in winter (usually February) to minimum flow in August. Areas in yellow predominantly indicate a shift from minimum monthly flow in September to August

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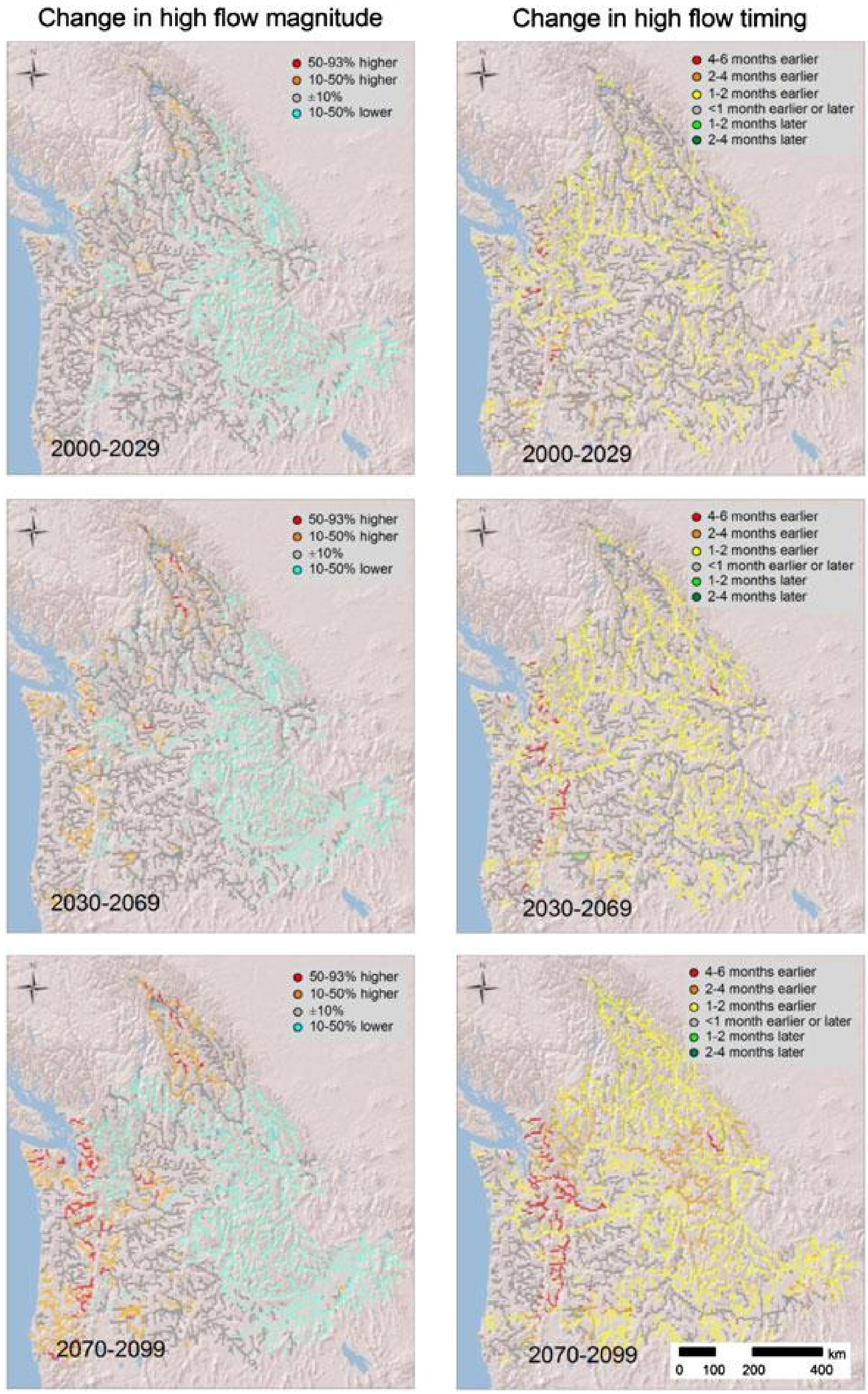

Figure 7. Modelled change in the maximum mean monthly flow and shift in timing of maximum monthly flows. Ratio is maximum mean monthly flow from the future period 2070–2099 divided by the maximum mean monthly flow from the period 1970–1999. For timing of maximum monthly flows, areas mapped in red indicate a shift from maximum monthly flow during spring snowmelt (usually April or May) to maximum flows during December and January winter storms. Areas in yellow indicate areas with maximum monthly flow remaining in late winter or spring, but shifted 1–2 months earlier (generally April–May to February–March)

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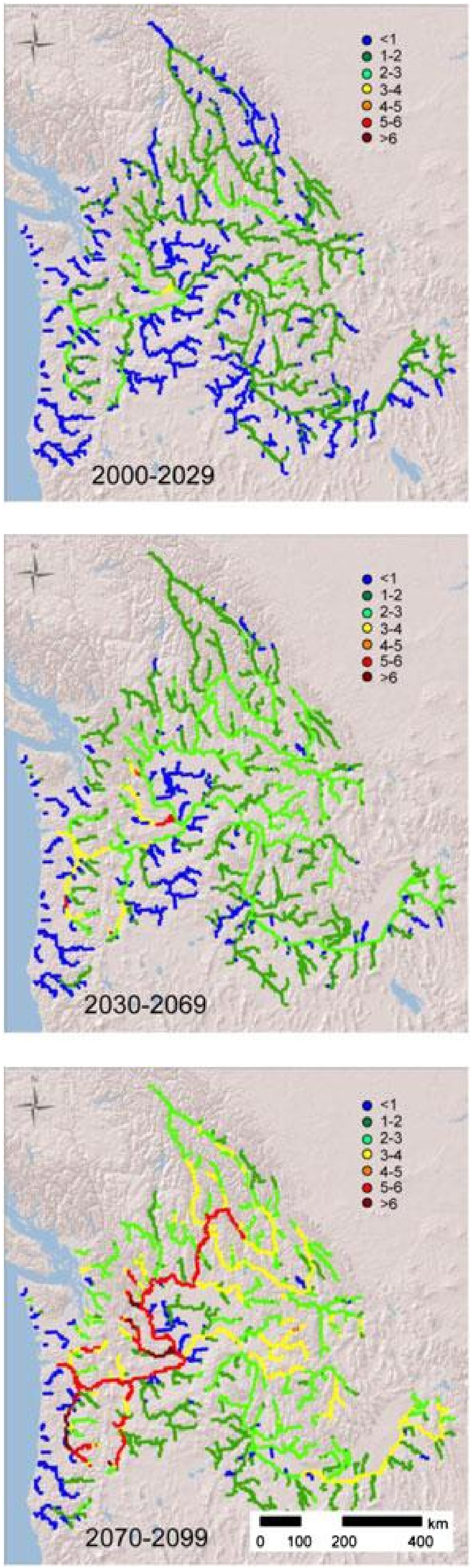

Figure 8. Modelled increase in maximum average weekly temperature through time in the Columbia River basin

climate effects are expected to impact a project's or plan's effectiveness within a few decades do we suggest adjustments to project priorities or designs.

We also review restoration actions in the context of their ability to maintain or increase resilience of river ecosystems and salmon populations (Waples *et al*., 2009). We define resilience as the ability of a system to absorb change and still maintain its basic ecosystem functions and relationships, even though the balance of habitat types or species may shift slowly through time (Holling, 1973; Waples *et al*., 2009). Pacific salmon are adapted to wide array of natural disturbance regimes by virtue of their life history diversity, and restoration actions designed to reduce constraints on life history diversity allow Pacific salmon a broader range of options by which to respond to climate change (Waples *et al*., 2008, 2009)—conferring resilience to both populations and meta-populations (Greene *et al*., 2010; Schindler *et al*., 2010). That is, restoration actions that increase habitat diversity to the point that salmon have the ability to express alternative life history strategies are considered to potentially increase population resilience. For example, restoring diverse floodplain habitats or reconnecting cold-water tributaries to main stem habitats by barrier removals offers salmon a variety of physical and thermal conditions, allowing multiple species to persist and to express varied life history strategies within species (Poole *et al*., 2008; Waples *et al*., 2009). In contrast, creation of pools by adding wood to a small stream generates a small increase in habitat diversity but does not offer an array of habitats that allow expression of alternative life histories. Hence, we consider the former action to potentially increase resilience but not the latter.

Restoring connectivity

Restoring connectivity (longitudinal, lateral, and vertical) typically improves both physical and biological functions of river systems. Restoring longitudinal connectivity for salmon is primarily intended to reestablish salmon migration to diverse habitats that have been lost through construction of artificial barriers such as dams or culverts, but it often also restores downstream transport of essential flows, sediment, and wood or organic matter. Restoring lateral connectivity generally refers to reconnection of rivers to their floodplains by removal of levees or bank armouring. These actions restore the ability of the river system to create and sustain diverse habitats and to allow migration of salmon into those habitats. Actions that aim to restore vertical connectivity seek to aggrade incised or scoured channels, which increases the connection between surface and subsurface flows and increases floodplain connectivity over time.

Longitudinal connectivity (barrier removal). The primary aims of restoring longitudinal connectivity by removal of dams or other blocking structures are to (1) reestablish upstream and

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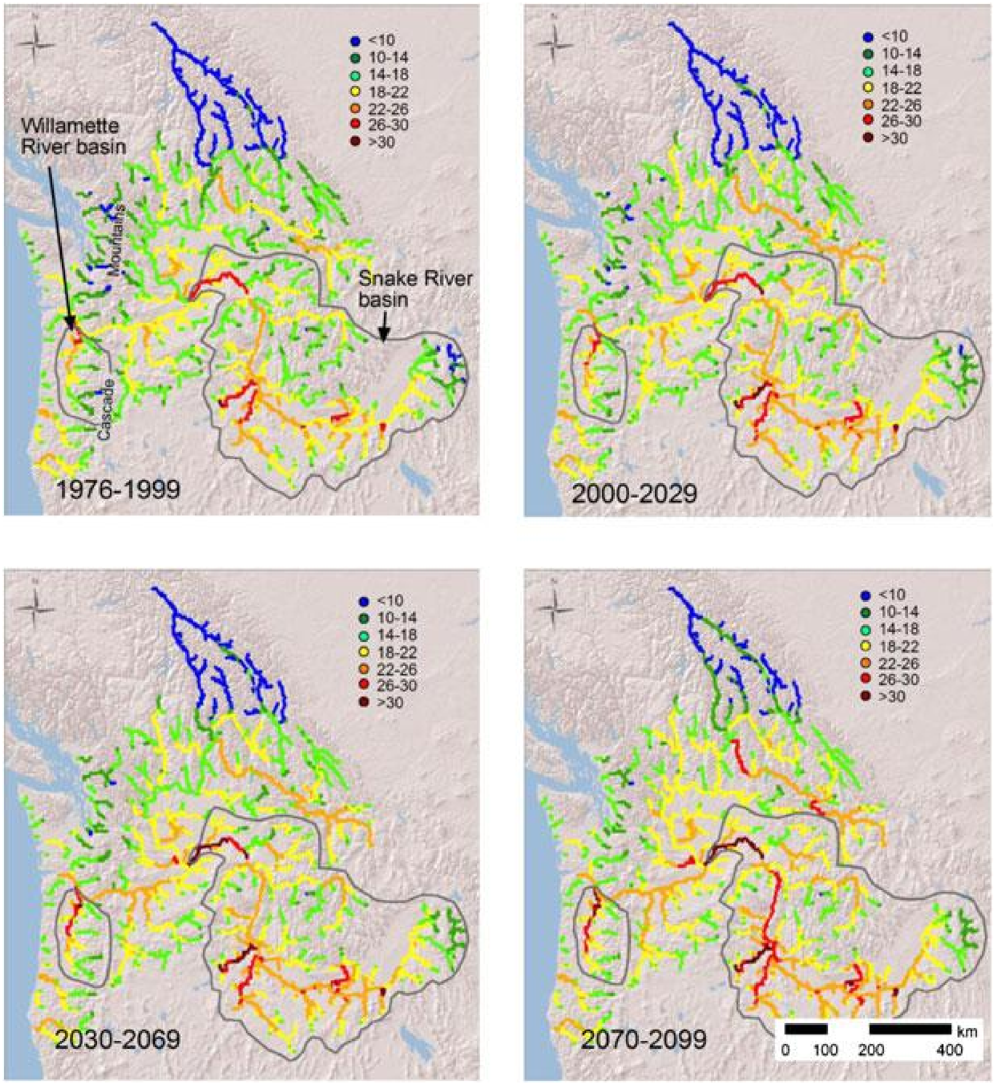

Figure 9. Modelled maximum weekly temperature through time in the Columbia River basin

downstream fish migration pathways and (2) restore natural stream flow, sediment, and organic matter transport (Pess *et al*., 2005). Removal of dams or providing fish passage on dams that cannot be removed will allow fish to access important upstream cool water habitats when downstream areas become too warm (McClure *et al*., 2008; Pess *et al*., 2008), thereby increasing habitat and life history diversity at the population and meta-population scales (Beechie *et al*., 2006; Waples *et al*., 2009). Where dams or other structures contribute to reduced low flows or increased stream temperature, dam removal can also ameliorate low base flow and high temperature problems by restoring downstream movement of sediment and water (Burroughs *et al*., 2009).

Lateral connectivity (floodplain reconnection). The aims of re-establishing lateral connectivity between river channels and floodplains are often twofold: to restore river floodplain dynamics that create diverse habitats and to restore fish access to floodplain habitats (Pess *et al*., 2005; Waples *et al*., 2009). These actions, which typically include reconnection or creation of side channels and sloughs, removal or set back of levees and dikes, and re-meandering of dredged or straightened channels, can ameliorate peak flow increases by storing flood water and reducing flood peaks (Sparks *et al*., 1998; McAlister *et al*., 2000) or by increasing the availability of velocity and thermal refugia (Sommer *et al*., 2001; Morley *et al*., 2005; Jeffres *et al*., 2008; Poole *et al*., 2008). Similarly, removing levees or re-meandering channels can ameliorate temperature increases by increasing length of hyporheic flow paths beneath the floodplain, which can cool water during the summer (Arrigoni *et al*., 2008; Konrad *et al*., 2008; Poole *et al*., 2008; Opperman *et al*.,

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Table III. Summary of restoration action types and their ability to ameliorate climate change effects on peak flow, low flow, stream temperature, or to increase salmon population resilience

Category	Common techniques	Ameliorates temperature increase	Ameliorates base flow decrease	Ameliorates peak flow increase	Increases salmon resilience
Longitudinal connectivity (barrier removal)					
	Removal or breaching of dam	●	●	○	●
	Barrier or culvert replacement/removal	○	○	○	●
Lateral connectivity (floodplain reconnection)					
	Levee removal	●	○	●	●
	Reconnection of floodplain features (e.g. channels, ponds)	●	○	●	●
	Creation of new floodplain habitats	●	○	●	●
Vertical connectivity (incised channel restoration)					
	Reintroduce beaver (dams increase sediment storage)	●	●	●	●
	Remove cattle (restored vegetation stores sediment)	●	●	●	○
	Install grade controls	●	●	●	○
Stream flow regimes					
	Restoration of natural flood regime	●	●	○	◒
	Reduce water withdrawals, restore summer baseflow	●	●	○	○
	Reduce upland grazing	○	◒	◒	○
	Disconnect road drainage from streams	○	○	●	○
	Natural drainage systems, retention ponds, other urban stormwater techniques	○	◒	●	○
Erosion and sediment delivery					
	Road resurfacing	○	○	○	○
	Landslide hazard reduction (sidecast removal, fill removal)	○	○	○	○
	Reduced cropland erosion (e.g. no-till seeding)	○	○	○	○
	Reduced grazing (e.g. fencing livestock away from streams)	◒	○	○	○
Riparian functions					
	Grazing removal, fencing, controlled grazing	●	○	○	○
	Planting (trees, other vegetation)	●	○	○	○
	Thinning or removal of understory	○	○	○	○
	Remove non-native plants	◒	◒	○	○
Instream rehabilitation					
	Re-meandering of straightened stream, channel realignment	◒	○	○	◒
	Addition of log structures, log jams	◒	○	○	○
	Boulder weirs and boulders	◒			
	Brush bundles, cover structures	○	○	○	○
	Gravel addition	○	○	○	○
Nutrient enrichment					
	Addition of organic and inorganic nutrients	○	○	○	○

Actions are grouped by major processes or functions they attempt to restore: connectivity (longitudinal, lateral and vertical), watershed-scale processes (stream flow and erosion regimes), riparian processes, instream rehabilitation, and nutrient enrichment. Filled circles indicate positive effect, empty circles indicate no effect, and partially filled circles indicate context-dependent effects. See text for supporting citations.

2010). Increasing habitat diversity by restoring lateral connectivity generally allows for increased life history diversity within a population (Waples *et al*., 2009), which has been linked to increased population resilience (Greene *et al*., 2010; Schindler *et al*., 2010). Floodplain reconnection actions generally do not ameliorate base flow decreases.

Vertical connectivity (restoring incised channels). Channel incision (or downcutting) has degraded stream and riparian habitats in many rivers of the PNW by lowering water tables, reducing exchange between surface and subsurface flows, and decreasing late summer stream flows. Associated losses in riparian vegetation lead to reduced shading

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and organic matter inputs to streams and increased stream temperatures (Elmore and Beschta, 1987; Poole and Berman, 2001). Moreover, incised streams rarely access their floodplains, high flows are concentrated within the incised channel, and fish have no access to slow-water refugia during floods (Harvey and Watson, 1986; Elmore and Beschta, 1987; Shields *et al*., 1995). Efforts to restore incised streams by increasing sediment storage and aggrading the channel aim to restore floodplain aquifer storage, increase summer base flow and decrease summer stream temperature, and increase availability of flood refugia (Pollock *et al*., 2007; Beechie *et al*., 2008b). Some restoration techniques, such as use of beaver dams to increase sediment storage, have the added effects of increasing summer base flows, locally decreasing or buffering stream temperature and increasing habitat diversity and productivity (Ponce and Lindquist, 1990; McRae and Edwards, 1994; Pollock *et al*., 2003; Pollock *et al*., 2007). Hence, restoration of incised channels has the potential to ameliorate climate-induced increases in stream temperature, effects on peak flows and low flows, and also to increase life history diversity through creation of off-channel and pond habitats. We emphasize that ameliorating climate change effects through aggradation techniques is specific to incised channels and that the same techniques may have different responses in other settings. For example, water may be warmer in a beaver pond within an otherwise closed canopy system, although stream cooling may still occur downstream of the pond (Robison *et al*., 1999).

Restoring stream flow regimes

Flood flows are increased to a moderate degree by logging and forest roads (Jones and Grant, 1996), grazing effects (Belsky *et al*., 1999), and to a much greater degree by impervious surfaces in urban areas (Booth *et al*., 2002). The primary mechanism by which logging roads increase peak flows is interception of subsurface flow through soils (which moves relatively slowly) and rapid routing of water to streams through ditches (Furniss *et al*., 1991; Jones and Grant, 1996). Road rehabilitation actions to decrease peak flow effects generally focus on addition of cross-drains to reduce routing of water directly from road ditches to the stream (Furniss *et al*., 1991). In an urban environment, the primary focus is to reduce the impacts of impervious surfaces by creating additional stormwater retention structures or modifying impervious surface areas so that rapid runoff is routed into groundwater storage rather than storm drains (e.g. Booth and Leavitt, 1999). In many cases, increased runoff and flood flows cause summer baseflows to decrease due to loss of infiltration and water storage in soils (e.g. Belsky *et al*., 1999). Hence, reductions of grazing or logging effects on flood flows may also increase low flows in summer.

Low stream flows are often reduced by withdrawal of water from streams for irrigation or consumptive uses (Poff *et al*., 1997; Myers *et al*., 1998), and both peak and low flows may be dramatically reduced by water storage behind dams (Stanford *et al*., 1996; Poff *et al*., 1997). Restoring some or all of abstracted water to streams through purchase of water rights or increased irrigation efficiency can dramatically increase low flows to streams (Poff *et al*., 2010) and directly ameliorate climate-induced decreases in low stream flow or increased stream temperature. In some cases, flow regulation has decreased peak flows to the point that many geomorphological and ecological functions of streams are lost (Olden and Poff, 2004). Moreover, low flows may be reduced in summer, which can also lead to increased stream temperature. In such cases, restoring 'environmental flow regimes' can ameliorate not only low stream flows, but can also increase habitat diversity by restoring channel-forming flows that maintain habitat diversity and other ecological functions (Stanford *et al*., 1996; Poff *et al*., 2010). Hence, where water storage or withdrawal has decreased low flows, purchase of water rights or use of water conservation measures that leave more water in the stream can ameliorate predicted decreases in low flows. Some dams can release cool water from deep in the reservoir, allowing dam operations to ameliorate stream temperature increases. Where water storage has decreased peak flows, restoration of channel forming flows can increase habitat diversity through restoration of physical functions that create diverse habitat features in streams and across the floodplain and also maintain riparian functions (Poff *et al*., 1997)—thereby increasing resilience of river ecosystems to climate change.

Reducing erosion and sediment delivery

In forested environments of the PNW, sediment supply to stream channels is typically increased through surface erosion on unpaved roads or by increased landsliding from roads or clearcuts (Reid and Dunne, 1984; Sidle *et al*., 1985). Therefore, sediment reduction efforts in forest environments commonly focus on road rehabilitation to decrease landslide hazards and surface erosion (Beechie *et al*., 2005; Roni *et al*., 2008). Landslide hazard reduction is typically achieved by removing or abandoning roads, or rebuilding stream crossings to avoid fill failures when culverts become blocked (Madej, 2001; McCaffery *et al*., 2007). Despite these efforts, future increases in storm intensity and a shift from snow to rainfall may drive more frequent mass wasting in forest environments, especially where road management has not yet achieved reductions in landslide hazard. Effects of increased surface erosion on roads can be abated by resurfacing the road or adding cross drains or water bars to prevent delivery of eroded sediments to streams (Furniss *et al*., 1991).

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In croplands, surface erosion is often increased by erosion of exposed soil in fallow fields (Wendt and Burwell, 1985; Ebbert and Roe, 1998). An increasingly common strategy to manage surface erosion in agricultural lands is no-till seeding, which preserves vegetative cover on croplands and dramatically reduces erosion and sediment delivery to streams (Wendt and Burwell, 1985; Ebbert and Roe, 1998). Grazing effects on sediment supply include removal of hillslope vegetation and erosion of exposed soils, as well as trampling of banks and increased bank erosion (Medina *et al*., 2005). Grazing impacts can be controlled either by removal of livestock from key areas (especially stream banks and riparian areas) or by grazing rotations that retain sufficient vegetative cover to reduce surface erosion (Medina *et al*., 2005). Although each of these actions can improve stream habitat by decreasing fines in the stream bed, increasing pool depth, or narrowing widened channels—none of these actions ameliorate decreased low flows, increased flood magnitude, or increased stream temperature (although increased pool depth may create thermal refugia in rare cases). Moreover, these actions do little to increase habitat or life history diversity except in cases where extremely high sediment supply has filled pools and reduced the diversity of habitat types (see Beechie *et al*., 2005 for examples).

Restoring riparian functions

Riparian rehabilitation actions aim to restore riparian functions such as stream shading, root reinforcement of banks, supply of large wood and organic matter, and trapping sediment or filtering nutrients (Kauffman *et al*., 1997; Pollock *et al*., 2005). In forested environments, restoration of riparian functions commonly focuses on thinning or replanting of riparian forests to restore wood recruitment and shade functions and, secondarily, to restore other functions (Beechie *et al*., 2000; Welty *et al*., 2002; Meleason *et al*., 2003). Restored riparian functions do not directly ameliorate the stream flow changes predicted by climate change models, but may mitigate stream temperature increases via increased shading (Johnson, 2004), or via increased wood recruitment and sediment storage in headwater channels that have been scoured to bedrock (Pollock *et al*., 2009). However, removal of certain non-native species that use more water than native species and provide less shade can ameliorate increased stream temperatures or decreased flows. In non-forest environments, replanting of denuded or managed riparian zones and removal or reduction of livestock grazing typically results in regrowth of riparian vegetation and should also ameliorate increases in stream temperatures through increased shade, bank stability, and narrowing of stream channels (Medina *et al*., 2005). Riparian restoration can lead to modest increases in habitat diversity over the long term via formation of pools or hiding cover (Beechie *et al*., 2000), whereas actions that seek to thin riparian zones are unlikely to affect either stream flow or temperature (Pollock *et al*., 2009). Finally, restoration of normative flow regimes on regulated rivers should help recovery of riparian areas on larger rivers, as seedling establishment for key riparian species is often dependent on flood magnitudes and duration (Stanford *et al*., 1996; Mahoney and Rood, 1998). Riparian restoration can be expected to increase ecosystem resilience in the sense that rivers with intact riparian buffers can buffer ecological functions against changes in stream flow, but it is unlikely to increase life history diversity and salmon resilience beyond the buffering of temperature effects.

Instream rehabilitation

Instream rehabilitation includes restoration actions that seek to improve habitat conditions by actively altering channel habitat structure (e.g. adding wood debris, spawning gravel), reconstructing channel characteristics (re-meandering), or by providing cover for fish (Roni *et al*., 2008). Such fixed structures are susceptible to failure or require maintenance, especially in the face of increased magnitude and frequency of peak flow events as predicted by climate change models. Although instream rehabilitation actions such as wood and boulder placement have been documented to provide quick improvements in both physical habitat and fish production (Cederholm *et al*., 1997; Solazzi *et al*., 2000; Roni and Quinn, 2001), they do not restore the underlying disrupted process (typically large wood delivery) and are unlikely to last more than one or two decades without additional intervention or maintenance (Roni *et al*., 2002). Moreover, instream rehabilitation actions generally do not ameliorate changes in temperature, base flow, or peak flows. For example, some studies have shown that creation of pool-riffle sequences can lead to increased hyporheic exchange and increased temperature variability, but none has shown a significant net decrease in stream temperature (Crispell and Endreny, 2009; Hester *et al*., 2009). This is most likely because the subsurface flow path is too short to significantly affect stream temperature (Poole *et al*., 2008). By contrast, restoring sediment storage to channels that are incised to bedrock may reduce stream temperatures if the loss of sediment has completely eliminated hyporheic exchange and increased stream temperature (Pollock *et al*., 2009). In such cases, use of wood or boulder structures to store sediment may decrease stream temperature. Finally, instream habitat actions can increase local habitat complexity (particularly if a large portion of the stream is treated), but such actions are unlikely to increase life history diversity or resilience of salmon populations.

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Nutrient enrichment

The purpose of nutrient enrichment is to compensate for lack of marine-derived nutrients from reduced salmon returns by adding nutrients and carbon to boost stream or lake productivity, and ultimately fish production (Bilby *et al.*, 1998; Gresh *et al.*, 2000; Kiffney *et al.*, 2005). These exogenous sources of nutrients are important to the productivity of naturally oligotrophic rivers of the PNW where many salmonid populations are food-limited (e.g. Boss and Richardson, 2002). As with instream rehabilitation actions, nutrient additions do not address the ultimate cause of low nutrient levels as a result of reduced salmon runs and, in the absence of increased salmon returns, are dependent on continually adding nutrients to maintain any benefits (Roni *et al.*, 2008). Nutrient additions do not ameliorate climate change effects on stream flow, stream temperature, or habitat diversity. However, an important secondary effect of increased stream temperature is increased metabolism in juvenile fishes, which increases food requirements to maintain positive growth (McCullough *et al.*, 2001; Boughton *et al.*, 2007). Where reduced nutrients and food resources have already compromised growth of juvenile salmonids, rehabilitation actions to increase nutrient supply—thereby increasing invertebrate abundance and prey availability for juvenile salmonids—may indirectly ameliorate temperature effects on salmonid growth rates (Wipfli and Baxter, 2010). However, this would require a consistent, long-term nutrient supplementation programme and would not lead to self-sustaining nutrient levels without continual intervention.

DECISION SUPPORT STRUCTURE TO EVALUATE CLIMATE CHANGE EFFECTS ON SALMON RESTORATION

We proposed four guiding questions to help determine whether restoration plans or actions should be altered to accommodate climate change (first column of Figure 10). We have also provided key maps and information to answer these questions (Figures 3–7, Tables 1–3). However, translation of this information into adaptation of restoration plans or actions can be ambiguous, so we offer two simple decision support tools to assist in evaluating restoration plans or actions in the context of climate change. Both are simple flow charts that illustrate how answers to the guiding questions might lead to logical adaptations of restoration plans or actions. We do not intend these to be rigid protocols with predefined outcomes because there are many possible combinations of future climates, restoration strategies, and species responses, and it is difficult to arrive at a set of rules that will apply to all possible cases. Rather, we intend these tools to illustrate how answers to the guiding questions can be integrated to arrive at management decisions in the context of local goals and objectives, as well as in the context of local climate change scenarios.

Evaluating a salmon recovery plan

In most cases, the first of the guiding questions has been answered in the process of developing local salmon recovery plans (e.g. Shared Strategy Development Committee, 2007). That is, an important component of salmon recovery plans is the identification of habitat impairments that constrain salmon population growth, and which, if addressed, will increase abundance or productivity (population growth rate) of the population (McElhany *et al.*, 2000; Beechie *et al.*, 2003). From this analysis, a list of important habitat recovery actions can be developed and prioritized (Beechie *et al.*, 2008a). However, these lists are commonly developed without consideration of future climate change effects on habitats and therefore have not considered how climate change might alter the suite of restoration actions identified as necessary to achieve salmon recovery.

Evaluating whether potential climate change effects on stream flow or temperature will change the list of restoration actions necessary for salmon recovery (question 2) begins a decision tree that helps restoration planners determine whether a salmon recovery plan should be revised to accommodate future climate change effects (Figure 10). Answering this question requires examination of potential climate change effects on stream flow and temperature (Figures 3–6) and a qualitative assessment of whether future stream flows or temperatures are likely to alter conclusions about which habitat restoration actions are necessary for salmon recovery. If climate change effects on stream flow or temperature are not expected to change the types or priority of restoration actions, then restoration actions may proceed according to the current plan. An important caution is that any assessment using mapped scenarios of flow or temperature changes should recognize that the resolution of the maps is quite low (in our analysis, the smallest grid cell representing a stream is 6×6 km) and that there is considerable variation in predicted stream flow and temperature changes among emissions scenarios and GCMs (Elsner *et al.*, 2010). Therefore, any evaluation of these stream flow and temperature scenarios should acknowledge that uncertainty in the climate scenarios is high.

If the evaluation of climate change scenarios indicates a change in the types of actions needed for recovery, then planned actions should be evaluated to determine whether they ameliorate the local climate change effects (question 3). For example, a coho salmon population may currently be constrained by winter rearing habitat availability, but potential increases in summer stream temperatures and decreases in summer stream flows (Figure 9) may reduce summer rearing habitat availability to the point that it

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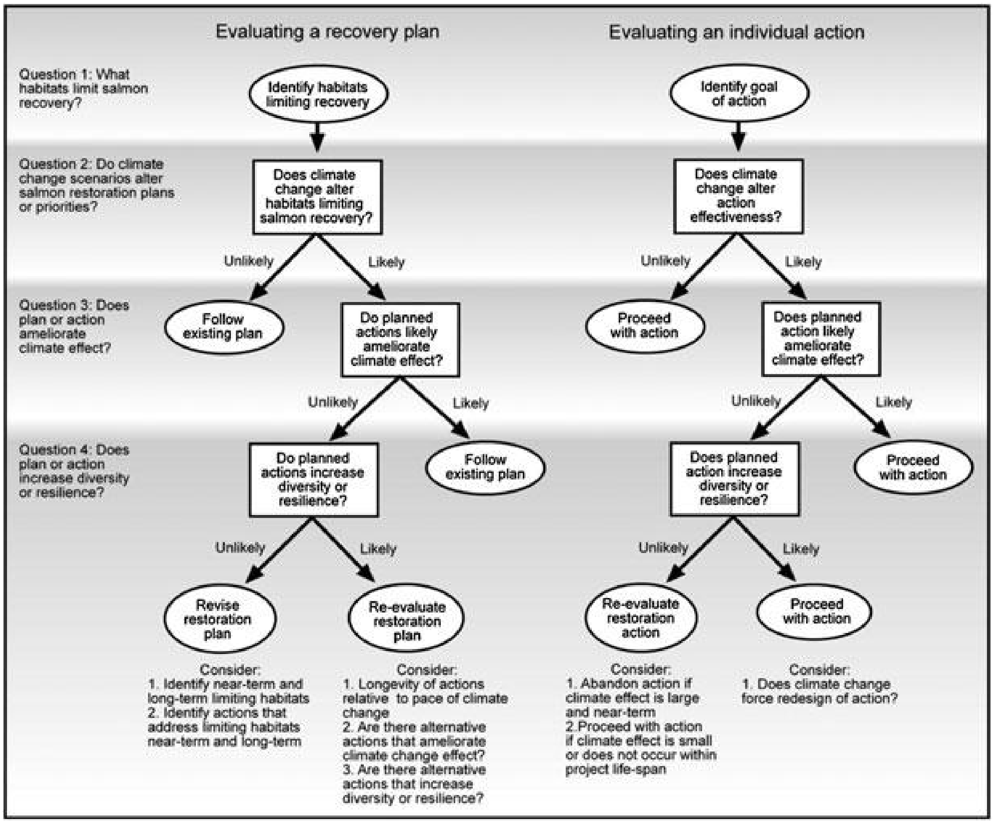

Figure 10. Schematic diagram of the decision-making process for adapting salmon recovery plans or individual restoration actions to climate change, and relationship to the four guiding questions

becomes the primary constraint on a population's recovery. If the planned restoration actions are likely to ameliorate climate change effects on stream flow or temperature (from Table III) and preserve the anticipated effectiveness of the restoration plan, then restoration can also proceed without modification. However, if actions will not ameliorate the climate change effects, revisions to the restoration plan should be considered. We acknowledge that determining whether the plan will ameliorate a temperature effect enough to prevent stream temperatures from exceeding critical thresholds is extremely difficult. In most cases, available data and models are not sufficient to answer this question quantitatively and with confidence. However, most restoration actions are not expected to reduce stream temperatures by more than 1–2°C (e.g. Medina *et al*., 2005; Arrigoni *et al*., 2008), so we suggest as a rule of thumb that restoration actions in areas that are less than 1–2°C below a critical threshold be considered unlikely to ameliorate a climate change effect. Nevertheless, it is possible that some combinations of actions might reduce stream temperature by more than 2°C, and local experience with restoration actions and changes in stream flow or temperature should be considered in management decisions. Moreover, salmon are often adapted to higher temperatures than are typically reported in the literature, and data on local thermal tolerances of salmon should be considered.

When revision of a plan is warranted, the degree to which the plan should be revised depends on whether the proposed actions contribute to increasing resilience of the population (question 4). Where the main habitat restoration actions in a plan contribute significantly to increasing resilience of populations (e.g. by increasing habitat diversity; Waples *et al*., 2009), the plan may be followed with the understanding that climate change may reduce effectiveness of the habitat restoration plan over the long term. There will always be considerable uncertainty about whether the actions can increase resilience enough to allow population recovery. But in any case, restoring diverse habitats will increase resilience of the riverine ecosystem—thereby increasing the likelihood that a salmon population can recover under a warming climate. Where the main habitat restoration actions do not contribute significantly to increasing habitat diversity or resilience of a population, then the restoration plan should be revised to increase the likelihood that actions either ameliorate climate change effects or increase habitat diversity and ecosystem resilience. The re-evaluation should focus on identifying actions that will help the population recover under both existing and future

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limiting habitats, so that climate change effects on habitat conditions and population performance do not hinder recovery of the population. Restoration of key physical and biological processes will allow a river ecosystem to adjust naturally to changes in key ecosystem drivers such as stream flow and temperature and will be more robust to variation in future climate patterns than actions that attempt to control river behaviour or build specific habitat features (Waples *et al*., 2009; Beechie *et al*., 2010). We stress that even where detailed models are used to assess how climate change will affect habitats that limit population recovery (e.g. Battin *et al*., 2007), there will always be considerable uncertainty in both model structure and climate change scenarios. Therefore, we encourage adjustments to recovery plans that broaden the portfolio of actions to accommodate a wide range of potential future climate scenarios.

Although we did not model future stream flow and temperature for multiple emissions scenarios and climate models, previous studies give us some indication of the range of potential outcomes for air temperature and precipitation (e.g. Elsner *et al*., 2010, Mote and Salathé, 2010). On the basis of those studies, it seems prudent to consider a range of potential stream temperature increases at least 2°C higher than those predicted from our A1B ensemble climate scenario (although we recognize that there is not always a strong correlation between air temperature and stream temperature). We cannot suggest a similar range of values for stream flows because no studies have modelled variation in stream flow among GCMs in the PNW (although Elsner *et al*., 2010 modelled stream flow differences among two emissions scenarios). Nevertheless, uncertainty in precipitation predictions is very high, suggesting that a conservative approach might anticipate that changes in stream flow (either high or low) might be considerably larger than our map illustrates.

Finally, population status may also influence management choices. Populations at very low abundance may require an emphasis on near-term habitat recovery actions to stabilize abundance (i.e. longevity of actions may be only 10–20 years), whereas more stable populations may benefit more from restoration of processes that persist for much longer periods. For near-term actions, climate change will likely produce relatively small effects on habitat conditions, and plans that emphasize near-term actions may need little revision regardless of climate change threats. However, this is a relatively rare case (most populations are threatened rather than endangered), and emphasizing restoration of habitat-forming processes is more likely to succeed over the long term (Beechie *et al*., 2010).

Evaluating an individual habitat restoration action

Individual restoration actions are perhaps simpler to evaluate because their future effectiveness is primarily a function of their intended purpose, which can be very narrowly defined. Answering the four guiding questions leads to one of three potential decisions: proceed with the action as planned, redesign the project to accommodate climate change, or abandon the project in favour of other projects that maintain their effectiveness in the face of climate change. The first outcome—proceeding with the action as planned—is appropriate when climate change does not alter effectiveness or longevity of the action, or when the action ameliorates the climate change effect sufficiently to maintain project effectiveness in the future (Figure 10). Redesigning a project to accommodate climate change is most appropriate where the action effectiveness is not reduced but longevity may be reduced as a function of a climate change effect (e.g. if peak flows will increase then the project should be designed to accommodate larger peak flows than observed at present). Finally, it is prudent to consider abandoning a specific project if climate change will likely negate its intended purpose, the action does not ameliorate the effect, and the action does not increase diversity and resilience. In these cases, the action may be abandoned in favour of other actions that will maintain their effectiveness in the face of climate change.

In evaluating the potential effects of climate change on individual restoration projects, it is first necessary to know which species and life stage the restoration action targets in order to evaluate whether climate change alters the effectiveness of the action. For example, if an action is intended to restore a winter rearing habitat, then changes to winter stream flows will be an important evaluation criterion whereas summer stream temperatures may not. Once the purpose of an action is identified, one can ask whether climate change will alter action effectiveness. If the effectiveness is not altered, then the action can proceed pending evaluation of climate change effects on project longevity (Figure 10). If the effectiveness is likely to be reduced, then one should consider whether the action type significantly ameliorates climate-related changes in stream flow and temperature. Evaluating the ecological impacts of different temperature change scenarios is relatively straightforward, as each species and life stage has a relatively specific range of thermal tolerances (Tables I and II), and temperature change magnitudes (Figures 2 and 3) can be compared with those tolerances to judge whether climate change will likely reduce project effectiveness. Finally, it is also important to consider how long the restoration action will last when determining whether it will ameliorate the impacts of climate change. Actions such as restoring floodplain connectivity or removing migration barriers restore underlying watershed processes, can last many decades, and will likely be the most effective long-term strategies for climate change because they both ameliorate climate change effects and increase habitat diversity and resilience. Other actions that may last only two or three decades without continued intervention will only provide

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short-term amelioration for climate change impacts and are unlikely to appreciably increase resilience over the long term.

SUMMARY AND CONCLUSIONS

We developed a set of guiding questions and data to inform adaptation of habitat restoration plans for salmonids in northwestern USA. These same questions are applicable to any salmon restoration effort, and—moreover—generally applicable to restoration of many species or ecosystems. Key elements of adapting any restoration strategy to climate change include (1) understanding the current recovery needs, (2) evaluating whether climate change effects will likely alter those needs, (3) determining whether restoration actions can ameliorate climate change effects, and (4) determining whether restoration actions can increase ecosystem resilience. These components are not specific to salmon, nor are they specific to aquatic species. These same questions can be used for any ecosystem in which restoration actions might need to be adapted to accommodate environmental effects of climate change. The key questions that must be answered for any adaptation strategy are as follows: Does climate change alter restoration needs in the future? And can restoration actions increase ecosystem resilience by reducing climate change effects or increasing habitat diversity? When these questions are applied to other species or environments, data needs include an understanding of current restoration plans, an assessment of how climate change might alter restoration needs, data on likely environmental effects of climate change, and a review of potential restoration actions to evaluate their likely effectiveness under future climate scenarios.

Although habitat restoration can contribute to increasing resilience of salmon populations to climate change, restoration of freshwater habitats alone may not be enough for their recovery. Climate change effects are imposed on top of a long history of insults, including harvest and hatchery effects on population status, a broad array of habitat losses that have dramatically reduced salmon abundance in the western USA, and continuing changes in ocean conditions that are at least partly a result of climate change. These combined constraints have reduced wild salmon populations to the point that many have been listed under the US Endangered Species Act. Hence, recovery of these populations may also require adjustments to hatchery production and harvest levels that impact wild populations, which we did not address here. In combination, such actions will likely increase abundance and diversity in wild populations, allowing them to adapt to a changing climate.

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