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Using Anthropogenic Risks to Inform Salmonid Conservation at the Landscape Scale

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USING ANTHROPOGENIC RISKS TO INFORM SALMONID CONSERVATION AT

THE LANDSCAPE SCALE

by

Andrew W. Witt

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ABSTRACT

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by

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Utah State University, 2018

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Almost every part of the natural world has been altered by human activity. The effects are so resounding (rivaling some of the greatest forces of nature) that many scientists are referring to the modern era of geological history as the "Anthropocene". Of all the world's ecosystems, freshwater systems have been the most impacted and reshaped. To provide for growing human populations, rivers are dammed, diverted, and altered to redirect water's path. As a result, river ecosystems have been manipulated through altering flow, geomorphology, chemistry, or introducing new species whether unintentionally or for recreation. This is especially true for North American freshwater systems, where a 92% increase of threatened, endangered or vulnerable fish taxa has been observed over the last twenty years. Though trout and salmon are highly valued culturally, the historical distribution of native salmonids has been receding because of habitat degradation and the presence of introduced, non-native trout. Compounded by increasing temperatures from future climate projections, stream conditions are likely to change further in the next century. The work described in this thesis addresses several anthropogenic threats facing salmonid conservation, and how threats impact conservation efforts. Systematic conservation planning techniques were implemented as a means for testing how different risk management strategies affect conservation objectives. I examine how risks from an urbanizing basin affect potential protection for five Alaskan salmon species. This process involved applying and integrating several recent advances in systematic conservation planning techniques. Freshwater connectivity rules, and risk simulations were synergized to assess how urbanization and resource extraction affect salmon protected areas. Next, I applied similar methods to multiple basins throughout the entire state of Utah, to examine how anthropogenic, climatological, and ecological risks affect future conservation efforts for two cutthroat subspecies. Results clarify that at a landscape scale, completely avoiding risks associated with human activities reduces conservation resiliency, and leads to low returns on conservation investments, compared to when risks are considered and incorporated into decision making.

(97 pages)

PUBLIC ABSTRACT

Using Anthropogenic Risks to Inform Salmonid Conservation at the Landscape Scale

Andrew W. Witt

The expansion and industrialization of humanity has caused many unforeseen consequences to the natural world. Due to the importance of freshwater for people, rivers have been particularly altered to meet human needs, often at the expense of the natural world. Supplying water for farms, industries, and cities has reshaped the natural state of rivers by altering river paths, chemistry, and species compositions. These changes have harmed many species that prospered before widespread human alterations, including the native trout and salmon of western North America. As human populations continue to grow, new threats will surface for rivers, and the trout and salmon that call rivers home. As a result, many scientists have considered how to assess and counter-act threats to trout and salmon. Often, efforts focus around rehabilitating stretches of river, but do not consider large-scale watershed conditions, which may be responsible for chronic stream degradation. Tools have been developed to guide decision making for coordinating conservation efforts that consider the multitude of risks facing trout and salmon. In this thesis I implemented these tools to help managers and decision makers understand how risks affect their conservation efforts. Two examples are provided, with the first considering development and resource extraction risks to Pacific salmon spawning habitat in Alaska. The second example considers climate, development, and competition risks for cutthroat trout, throughout Utah. Results from both examples clarify that managers who consider risks while conducting conservation yield greater results than managers who attempt to avoid risks. The findings here intend to inform future conservation effort for trout and salmon, and also clarify the importance of risk management in conservation.

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Andrew W. Witt

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CHAPTER 1

INTRODUCTION

1. BACKGROUND

The vast majority of the world's ecosystems have been altered by human activity. The effects are so resounding (rivaling some of the greatest forces of nature) that some scientists are referring to the modern era of geological history as the "Anthropocene" (Steffen, Grinevald, Crutzen, & McNeill, 2011). Whether or not you agree that earth's history has entered the Anthropocene epoch, many natural systems have been unquestionably altered by humanity. In particular, freshwater systems have been incredibly reshaped. To provide for growing human populations, rivers are dammed, diverted, and altered to redirect water's path. As a result, river ecosystems have been manipulated through altering flow, geomorphology, chemistry, or introducing new species whether unintentionally or for recreation. Scientists and planners are starting to address the balance between human needs and conservation (Groves & Game, 2016).

43% of the known fish taxa reside in Earth's freshwater, yet human manipulation of these streams and lakes have greatly impacted these aquatic communities (Helfman, 2007). This is especially true for North American freshwater systems, where the number threatened, endangered and vulnerable fish taxa has noticeably increased (Jelks et al., 2011). Compounded by increasing temperatures from future climate projections, stream conditions are likely to change further in the next century (Keleher & Raher, 1996; Rieman et al. 2007; Wenger et al., 2011). Though trout and salmon are highly valued culturally, the historical distribution of native salmonids has been receding because of habitat degradation and the presence of introduced, non-native trout. Consequently, many populations of native salmon and trout across the western United States have been listed under the U.S. Endangered Species Act (Young, 1995; Williams et al., 2007). The scale of anthropogenic threats facing salmonids range from small stretches of streams, to factors affecting entire drainage basins. Scientists and managers tasked with addressing and minimizing the decline of salmonid populations must consider both small-scale issues as well as landscape issues. In fact, many scientists suggest that regional watershed scale concerns require attention before applying a local in-stream focus (Roper, Dose, & Williams, 1997; Fausch, Torgersen, Baxter, & Li, 2002). Finally, given the range of risks facing future conservation efforts, decision makers must consider their willingness to work in areas containing risks that may lead to failed outcomes (Tulloch et al., 2015).

Many tools have been proposed to assess regional conditions for salmonid populations. Often, such tools implement methods to inventory and assess current conditions, in an effort to guide management (Higgins, Bryer, Khoury, & Fitzhugh, 2005; Thieme et al., 2007; Williams et al., 2007; Haak & Williams, 2013). Unfortunately, several components of these types of techniques bury important assumptions, biases and risk tolerances (Game, Kareiva, & Possingham, 2013). Additionally, when a scoring process contains more than three variables, interpreting the assumptions of the results becomes impossible (Game et al., 2013). Yet, often such tools attempt to inventory a host of important variables (Williams et al., 2007). Though some assumptions may be justified for the regions in which the tools were developed, they may limit widespread applicability. As a counterpoint, systematic conservation planning tools were introduced using heuristic algorithms, to reduce biases (Vanderkam, Wiersma, & King, 2007). Systematic optimization tools, such as Marxan, are now widely used to identify priority protection or management areas (Esfandeh, Kaboli, & Eslami-Andargoli, 2015). Marxan has also been implemented to include risk into its selection process (Foresta, et al., 2016; Hammill, Tulloch, Possingham, Strange, & Wilson, 2016), an essential consideration for coordinating salmonid conservation in the Anthropocene.

The work described in this thesis aims to address several anthropogenic threats facing salmonid conservation, and how threats can impact conservation efforts. The overall goal of the thesis was to use systematic conservation planning techniques to test how different risk management strategies affect salmonid conservation objectives. In Chapter 2, management strategies for protecting Pacific salmon spawning habitat were evaluated. Completing this chapter required specific assessment of anthropogenic risks posed by human development and resource extraction in the Matanuska-Susitna Basin, Alaska. Simulations were then used to determine how management strategies that either ignored, avoided, or incorporated risk would likely perform in terms of salmon conservation. In Chapter 3, the project scope was scaled up to assess several drainage basins that are present in the state of Utah. Strategies for conserving two of Utah's native cutthroat trout subspecies were evaluated. These different strategies considered anthropogenic risks from projected climate change, and human development. Management strategies were developed to address competition risks between cutthroat trout and introduced, non-native trout.

Completing my thesis required me to perform bespoke modifications to available systematic conservation planning tools. The widely used systematic conservation planning tool-Marxan, implemented within my thesis, was not initially designed for lotic freshwater applications, and only recently were useful modifications proposed (Linke et al., 2012). Alterations to Marxan were implemented to better represent stream networks and upstream-downstream habitat connectivity. Pfafstetter topological rules, which clarify how rivers and tributaries relate to each other within a stream network, were applied within Marxan (Hermoso, Linke, Prenda, & Possingham, 2011; Linke et al., 2012). Monte Carlo risk simulations were applied to each management scenario in Chapter 2, clarifying how attitudes towards risk affect conservation outcomes when risk occurs across the landscape (Hammill et al., 2016). Chapter 4 closes with the implications of this work as well as recommendations.

2. STYLE

My thesis was written in a multiple chapter format. I follow style guidelines outlined by *Aquatic Conservation: Marine and Freshwater Ecosystems.* Chapter 2 represents work accepted to *Aquatic Conservation: Marine and Freshwater Ecosystems* by Dr. Edd Hammill and myself.

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CHAPTER 2

USING SYSTEMATIC CONSERVATION PLANNING TO ESTABLISH MANAGEMENT PRIORITIES FOR FRESHWATER SALMON CONSERVATION, MATANUSKA-SUSITNA BASIN, AK, USA

Abstract

1. The Alaskan Matanuska-Susitna Basin (MSB) provides habitat for all five Pacific salmon species, and their large seasonal spawning runs are important both ecologically and economically. However, the encroachment of human development through urbanization and extractive industries poses a serious risk to salmon habitat in the MSB.
2. Using systematic conservation planning techniques, different methods of incorporating anthropogenic risks were assessed to determine how to cost-effectively conserve salmon habitat in the area.
3. The consequences of four distinct conservation scenarios were quantified: no consideration of either urbanization or extractive industries ('Risk ignored' scenario); accounting for the risk of urbanization, and avoiding conservation in all fossil fuel rich areas ('Urbanization accounted, all extraction avoided' scenario); accounting for urbanization and oil and gas development, but avoiding conservation in coal rich areas ('Urbanization accounted, coal areas avoided' scenario); and accounting for all anthropogenic risks to habitat, and allowing conservation in oil, gas, or coal rich areas ('All risks accounted' scenario). To compare conservation success and resiliency, the impact of these risks were

estimated using Monte Carlo simulations. The final cost of each solution was then divided by the number of conservation targets met to determine a return on investment.

4. Results from scenarios that avoided all extractive activities, or just coal, suggest that conservation targets cannot be met by simply avoiding fossil fuel rich areas, and these scenarios resulted in lower returns on investment than when risks from extraction were incorporated into the solution.
5. By providing economically rooted conservation prioritization, this study provides a method for local managers and conservation groups to identify conservation opportunities in MSB river basins.

1. INTRODUCTION

Quantifying and incorporating the uncertainty surrounding the potential success of management actions is crucial to making cost effective conservation decisions. A key source of uncertainty is the risk posed to natural ecosystems by anthropogenic activities, a factor that is critical to incorporate in order to give conservation actions the best chance of success (Bode et al., 2009, Tulloch et al., 2013). For landscapes threatened by events that negatively impact biodiversity, quantifying the spatial distribution of risk sources, and including them into conservation plans can increase the overall return on conservation investments (Hammill, Tulloch, Possingham, Strange, & Wilson, 2016). In many parts of the world, landscapes with high biodiversity are threatened by encroaching housing development, as people seek to live near areas of natural beauty. In addition, growing populations increase the demand of natural resources such as oil, gas, and coal. For areas experiencing both population growth and increased pressure on local natural resources, quantitatively assessing where development should and should not take place is crucial to ensure the survival of local ecosystems and their species (Butt et al., 2013).

The Matanuska-Susitna Basin (MSB) covers over 25,000 square miles (approximately 64,750 square kilometers) of south-central Alaska (Fig. 1). This basin provides habitat for all five Pacific salmon species: Chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*Oncorhynchus kisutch*), coho salmon (*Oncorhynchus keta*), sockeye salmon (*Oncorhynchus nerka*), and pink salmon (*Oncorhynchus gorbuscha*). The ecological importance of salmon spans both aquatic and terrestrial ecosystems. Spawning salmon feed bears, wolves, eagles, and other streamside animals, and after completing their life cycle they provide carbon, nitrogen, and phosphorus to streams and surrounding riparian areas (Juday, Rich, Kemmerer, & Mann, 1932; Shuman, 1950). These crucial nutrients can be distributed hundreds of kilometers inland from streams, even into upland forests (Reimchen, 2000). Estimates of sockeye salmon returns in Bristol Bay, Alaska, predict 20 million salmon during large years, producing over 54 million kilograms of biomass (Gende, Edwards, Willson, & Wipfli, 2002). Their role as agents of nutrient transfer between marine, aquatic and terrestrial systems means that the lives of thousands of individual organisms depend on healthy salmon runs and the resources they provide (Willson, Gende, & Marstron, 1998; Cederholm, Kunze, Murota, & Sibatani, 1999). Additionally, the chinook, coho, and sockeye salmon are of particular importance to commercial and recreational industries (Hughes, 2013). Commercial harvest from the Cook Inlet alone brought in more than $10 million U.S. dollars in 2010 (Shields & Dupuis, 2012). Recreational fishing provides additional revenue, having generated $29 million dollars in 1986, and are estimated to have increased by 15% to

25% between 1986 and 2003, a trend that is expected to continue (Sweet, Ivey, & Rutz, 2003). However, both commercial and recreational revenues are dependent on seasonal spawning returns, which are influenced by the availability of suitable spawning habitat. Within the MSB, the availability of high quality, suitable spawning habitat is threatened by rapid urbanization and extraction of natural resources, both of which have the potential to seriously impact local salmon freshwater life stages (Stromberg & Scholz, 2011; Alderman, Lin, Farrell, Kennedy, & Gillis, 2016).

Anchorage, Alaska's largest city, resides at the confluence of the MSB drainage and the Cook Inlet to the Pacific Ocean. The proximity of this metropolitan region to the salmon-bearing tributaries of the MSB has increased the anthropogenic impairment of salmon habitat. As of 2000, 42% of all Alaskans lived within the Anchorage municipal boundaries (Municipality of Anchorage, 2001). Anchorage accounted for almost half of the state's population growth during the 1990s, and the area's rate of growth is faster than the majority of metropolitan areas in the United States (Municipality of Anchorage, 2001). Between 2001 and 2009, this trend continued; 41.3% of the state's growth occurred in Anchorage, and 34.1% of the state's growth occurred in the MSB (Keith, Erben, & Dapcevich, 2010). Together, the growth of Anchorage and the MSB accounted for 74.4% of the state's growth between 2001 and 2009. Development in the MSB has been 'out not up', with residential buildings sprawling beyond established communities, as many residents desire to make their homes adjacent to streams and lakes. An estimated 31% of MSB residents commute to Anchorage. Due to the rural demand for housing, agricultural land is being converted for residential development and retail (Mat-Su Salmon Partnership, 2013).

With increasing urbanization in the MSB, several anthropogenic impacts on the environment have threatened salmon spawning habitat. Loss of wetlands and riparian habitat, reductions in water quality and quantity, all terrain vehicle (ATV) use within stream channels, and culvert installation, have all concerned the Alaska Department of Fish and Game (ADF&G) as human caused impacts on salmon habitat (Hughes, 2013). Not only are urban land use changes responsible for habitat impairment, but also oil, gas, and mining operations jeopardize freshwater salmon habitat.

Rich, high quality mineral deposits remain an untapped resource for the MSB, with the greatest mining potential being rich coal deposits. Current estimates from the Usibelli Corporation predict an annual yield of 500,000-700,000 tons (approximately 453,000- 635,000 metric tonnes) in coal production spanning twelve years (Metiva & Hanson, 2008). As of September 2016, Alaska Department of Natural Resources Division of Mining renewed Usibelli's mineral lease to this coal deposit (Hollander, 2014), and two additional mine proposals target the same coal deposit. As large mining operations remove mass from a drainage, groundwater flow paths, water quality, sediment transport, and fish access to habitat all become altered (Mat-Su Salmon Partnership, 2013). In addition to mining coal, companies are pursuing coal-bed methane extraction. A 2007 pilot project by Fowler Oil and Gas Corporation started tapping the existing reserves (Metiva & Hanson, 2008). Installation of well pads, roads and pipelines can lead to habitat fragmentation and sedimentation. Furthermore, accidental spills present unpredictable environmental risks associated with extractive resource development (Brittingham, Maloney, Farag, Harper, & Bowen, 2014). The presence of extractive industries in the landscape make necessary to quantify how different attitudes towards risk affect the chances of conservation success. Specifically, conservationists need to address whether effective conservation of salmon habitat can take place by just avoiding areas where extractive industries are present.

To maximize conservation efforts in landscapes facing anthropogenic development, systematic landscape planning software can be applied to provide cost effective, prioritized conservation solutions to optimize conservation investments. Systematic landscape planning software originally focused on conservation in terrestrial and marine ecosystems, however applications to lotic ecosystems require additional modifications. By applying existing terrestrial and marine procedures, protected areas may be clustered across catchment boundaries, not defined by stream networks. Failing to include the flowing nature of lotic ecosystems means that the solutions generated do not account for the connective habitat requirement of some riverine species, especially species with large ranges (Fausch, Torgersen, Baxter, & Li, 2002). Fortunately, several authors have clarified topological rules to better represent the connectivity between upstream and downstream habitats, increasing systematic landscape planning applications to lotic ecosystems (Hermoso, Linke, Prenda, & Possingham, 2011; Esselman & Allan, 2011; Linke et al., 2012).

In this study, I aimed to incorporate freshwater connectivity rules and risk assessment into a systematic conservation planning process to test the hypothesis that salmon protection areas are more resilient (less chance that risk will drastically threaten salmon) when risk is accounted for while identifying potential management priorities. Using Marxan with probability (a systematic conservation planning tool), I developed a series of scenarios to determine management priorities for salmon spawning habitat conservation, including how spawning habitat is impacted by urbanization, and oil and gas, and coal related risks. Four distinct scenarios were developed to test how different risk sources influence spawning habitat conservation priorities:

- Ignoring all anthropogenic risks to habitat, both urbanization and fossil fuel extraction ('Risk ignored')
- Accounting for risk associated with urbanization, avoiding all areas with fossil fuel extraction and deposits ('Urbanization accounted, all extraction avoided')
- Accounting for risk associated with urbanization, avoiding all areas with coal extraction and deposits ('Urbanization accounted, coal areas avoided')
- Accounting for risks associated with both urbanization and fossil fuel extraction, all areas are however available for conservation ('All risks accounted')

Naidoo et al. (2006) established that incorporating economics into conservation plans yield greater biological gains over plans ignoring costs. Therefore, land use data was also used to calculate opportunity costs of designating areas for conservation. Land costs were then combined with data for spawning habitat locations, and risks to identify areas that represent conservation priorities under each scenario.

2. METHODS

2.1 Conservation Planning Overview

Marxan with probability optimization software was used in conjunction with environmental risk surface (ERS) models to identify priority salmon spawning habitat. (Fig. 2). Marxan software offers conservation planners decision support by optimizing which areas should be set aside for conservation to achieve a desired conservation goal (Possingham, Wilson, Andelman, & Vynne, 2006; Moilanen, Wilson, & Possingham, 2009). Within a Marxan analysis, the landscape is initially divided into ‘planning units’, areas at which management actions are undertaken. Marxan then selects a number of planning units from the total available and calculates whether pre-determined conservation targets (i.e. 30% of a species’ distribution) have been met. Using a simulated annealing optimization algorithm, Marxan then changes some of the selected planning units and calculates whether the change represents an improvement either in terms of conservation targets met or cost. If the newly selected planning units represent an improvement, the process is repeated. If the new planning units do not represent an improvement, the algorithm returns to the previous set of planning units and the process is repeated. Through this iterative process, Marxan can arrive at a set of planning units that achieve all conservation targets at a low cost. Additionally, by implementing Marxan with probability, risks are added as an extra data layer within the analysis, and can be independently minimized, similar to how costs are minimized. By including risks into the Marxan selection process, the risk of failure can be included into how Marxan identifies an output reserve network (Tulloch et al., 2013), making the eventual solution more resilient to potential detrimental processes (Hammill et al., 2016). In this study, each Marxan scenario consists of 100 repeat runs, with 1,000,000 iterations being undertaken in each run, where solutions offer 95% certainty. While recent advances in freshwater systematic conservation planning present methods for implementing multiple zones, multiple actions, and multiple action and threat combinations (Moilanen, Leathwick, & Quick, 2011; Cattarino, Hermoso, Carwardine, Kennard, & Linke, 2015; Hermoso, Cattarino, Kennard, Watts, & Linke, 2015; Cattarino et al., 2016), these methods do not include protocols for incorporating the risk of conservation actions failing. In my study, understanding and simulating the risk of conservation actions failing was critical to comparing how scenarios that accounted for risk perform compared to scenarios that ignored risk.

2.2 Study Area

The MSB was subdivided into tributary sized basins, each of which represented a single planning unit (n=519) within the Marxan analysis. Tributary basins were derived from hydrologic unit code (HUC 12) basins. The HUC system uses a hierarchical system for assigning catchment sizes. HUC 12 basins capture tributary systems, which can be grouped into larger HUC 8 subbasins, representing medium-sized river basins. The system scales up to HUC 2 regions, outlining large river drainages (EnviroAtlas, 2017). Both the HUC 12 basins, and the distributions of Pacific salmon spawning habitat were obtained through the Alaska Department of Natural Resources and spatially correlated to identify salmon habitat within each basin (Fig. 3) (Alaska Department of Natural Resources, 2017, http://www.asgdc.state.ak.us/#30). Next, I derived the financial costs associated with setting aside a planning unit for conservation based on both available land costs and land cover data, provided by the 2011 National Land Cover Database (NLCD) (Homer et al, 2015, https://www.mrlc.gov/nlcd11_data.php). Land costs associated with urban, agricultural, and undeveloped areas were derived from existing parcel costs, as cost per acre, then correlated to corresponding land cover types in the United States Geological Survey Land Cover dataset to determine the spatial distribution of costs (Fig. 4a). Parcel data was obtained from Land Watch, and Land and Farm, sources listing current prices for available land in the MSB (Appendix A) (LandWatch, 2017, https://www.landwatch.com/Alaska_land_for_sale/Matanuska_Susitna; Land and

Farm, 2017, https://www.landandfarm.com/search/Alaska/Undeveloped-Land-for-sale). Five distinct economic categories of available land were identified as urban, agricultural, undeveloped land with intent to build, forestry, and remote undeveloped land. Urban parcels included land for sale with existing building, agricultural land for sale included farming land, and undeveloped land with intent to build included land for sale with pasture, building hook ups or wells, forestry lands included forested areas with potential considerations of timber harvest, and natural lands included remote undeveloped land with potential for recreation access. Additional cost considerations were applied for forested lands, to account for potential lost revenues from timber harvest. Identifying forested lands with potential benefits for salmon conservation could lead to a halt on timber harvesting; therefore the opportunity costs of lost timber revenue were added into the cost per acre of forested lands (Tiegs et al., 2008). The National Association of Conservation Districts (NACD) released a report in 2016 highlighting the available woody biomass for harvest within the MSB at 2.1 million green tons of wood at $82/dry ton, across 49,044 operable forest land acres (Ashton, McDonell, & Barnes, 2016). Over 105,175 total acres, at one dry ton/acre/year I calculated the timber opportunity cost per acre at $1,637/year. This value was added to the forested cost/acre value. Finally, per acre costs were correlated to NLCD land categories to derive costs across the entire MSB study area. Costs per acre were transformed into costs per raster cell, based on the NLCD dataset (30m x 30m, 900m^2). The economic urban category was aligned to the NLCD developed medium intensity and high intensity categories. The economic agricultural category was aligned to the NLCD cultivated crops category. The economic undeveloped land was aligned to the NLCD developed open space category, and pasture/hay category.

The economic forestry category was aligned to the NLCD deciduous forest, evergreen forest, and mixed forest categories. Finally, the economic remote undeveloped land category was aligned to NLCD dwarf shrub, shrub/scrub, grassland/herbaceous, sedge/herbaceous, woody wetlands, and emergent herbaceous wetlands categories. Other NLCD categories: open water, perennial ice/snow, and barren land, were assigned values of one dollar per acre. Though these types of lands likely have values greater than my assignment, no better information was available. A value of one dollar/acre was used to ensure these land types were still considered in the Marxan analysis. A summary of the cost derivation is compiled in Table 1. The best available data was used within this study to determine opportunity costs for converting existing land uses to reflect conservation needs, however economic values are vulnerable to market fluctuations, and long-term economic trends.

Anthropogenic risks to salmon habitat were assessed using an ERS model (Fig. 4c). ERS models synthesize relevant land uses based on impact intensity, and impact distance to clarify the extent of human caused impacts on the environment (McPherson et al., 2008, http://maps.usm.edu/pat/). This process integrates into Marxan to minimize risks when identifying priority conservation areas (Lessman, Muñoz, & Bonaccorso, 2014; Evans, Schill, & Raber, 2015). Risk sources were compiled from urbanized landscape features included residential development, roads, and the threat posed by agriculture. Where applicable, these risks were combined with site-specific risks from mining and oil and gas development (Fig. 4b). These risk sources were again obtained through the Alaska Department of Natural Resources (Alaska Department of Natural Resources, 2017, http://www.asgdc.state.ak.us/#30). ERS models require settings to specify the influence distance and intensity of each risk source. I followed the settings used by Esselman and Allan (2010) and McPherson et al. (2008) to construct my ERS model (Table 2). Schill and Raber (2008) incorporated risk accumulation in stream networks by applying an ERS models to a flow accumulation simulation, as stressors to freshwater ecosystems may originate in distant upstream sources (Fig. 4c) (Lake, 1980; Skelton, Cambray, Lombard, & Benn,1995; Moyle & Randall, 1998; Pringle, Scatena, Paaby-Hansen, & Nunez-Ferrera, 2000). This process specifies the path that risk flows across the landscape. Esselman and Allan (2011) successfully implemented this modification to address risks to streams in Mesoamerican streams, representing an early application of risk assessment within freshwater systematic conservation planning, offering guidance for this study. Following this previous work, the ERS risk layer was fed into a flow accumulation tool in ArcGIS 10.4, specifying the path risk takes across the landscape (Jensen & Dominigue, 1988; Tarboton & Rodriquez-Iturbe, 1991; ESRI 2013; Esselman & Allan, 2011). This procedure produces the final risk flow accumulation layer input into Marxan.

2.3 Marxan with probability Setup

Protected area connectivity may be customized within the Marxan software. In the most basic form of Marxan, connectivity is customized using a boundary length modifier (BLM), which regulates the compactness of the resulting conservation network based on the perimeter of selected priority areas (Ball, Possingham, & Watts, 2009; Fischer et al., 2010). Adjusting BLM values influences the fragmentation or continuity of the output conservation network, where lower BLM scores produce less connected output networks and vice versa. Despite the customization of these variables, applications of systematic conservation planning across varying ecosystems presents issues. Originally designed for terrestrial and marine conservation, applications of systematic conservation planning to lotic freshwater systems have been plagued by several shortcomings (Abell, Allan, & Lehner, 2007; Ball, Possingham, & Watts, 2009). First, calculations of boundary lengths based on an entire study area do not account for hierarchical stream orders within a river basin. By applying existing terrestrial and marine procedures, protected areas may be clustered across catchment boundaries, not defined by stream networks. Several authors have proposed modifications for integrating the linear nature of freshwater connectivity into existing systematic conservation planning software (Hermoso, Linke, Prenda, & Possingham, 2011; Esselman & Allan, 2011; Linke et al., 2012). Of these, Esselman and Allan subdivided natural catchment boundaries into planning units and then calculated neighboring boundary lengths at a larger basin size (2011). By identifying boundaries within subbasins, then reconnecting subbasins within a study area, BLM values identify neighboring planning units within each subbasin for all subbasins across the landscape of interest (Esselman & Allan, 2011). However, this reconnection of small basins within a larger basin still does not distinguish between upstream and downstream connections. Hermoso, Linke, Prenda, and Possingham et al. (2011) first established the connectivity rule for distinguishing connectivity. Next, Linke et al. (2012) improved to the field by clarifying more strict topological rules, utilizing the Pfafstetter stream classification scheme to refine stream network relationships and minimize distances between protected areas. I obtained and compiled the Pfafstetter topological rules for stream networks from the World Wildlife Fund’s HydroBASIN database and joined to the study area’s HUC 12 catchments (Lehner & Grill, 2013, http://www.hydrosheds.org/page/hydrobasins). The

Pfafstetter rules for stream network connectivity were applied to assess connectivity while defining management priority areas, allowing for the crucial distinction between upstream and downstream connectivity.

2.4 Scenario Design

After establishing Marxan inputs and connectivity rules for the analysis, I tested BLM modifiers through a sensitivity analysis to determine the most cost effective and connective matrix of management priorities. Before splitting the analysis into four scenarios, the best BLM value for the connectivity rules was determined. When BLM values equaled one, the Pfafstetter settings had more connections and a cheaper cost than when no connectivity settings were applied. Therefore, a BLM value of one was held constant for testing all scenarios. For each of the four scenarios, a range of conservation targets were tested, ranging from 10% to 40% of each species' current distribution, at 10% increments (Figure 5). Ultimately, a conservation target of 30% was selected for the final comparison following Betts and Villard (2009), and due to increasingly missed targets above the 30% threshold. In the Risk ignorant scenario, Marxan was set to ignore anthropogenic risks to salmon spawning habitat and had no aversion to identifying priority conservation areas where oil, gas, and coal deposits were abundant, meaning that conservation decisions were based solely on cost and species distributions. In the Urbanization accounted, all extraction avoided scenario, Marxan was set to account for the anthropogenic risks associated with urbanization identified through the ERS model, while completely avoiding areas rich in oil, gas and coal deposits. Similar to the extraction-avoiding scenario, the Urbanization accounted, coal areas avoided scenario, Marxan was set to account for the anthropogenic risks associated with urbanization, while completely avoiding areas rich in coal deposits. In the All risks accounted scenario, Marxan was set to account for all anthropogenic risks identified through the ERS, including urbanization and fossil fuel extraction. This scenario specified that areas where oil, gas, and coal deposits were abundant were available for inclusion in a conservation network, but the risks to salmon habitat associated with these areas were accounted for in the selection process. Each scenario therefore represents a different attitude towards the different risks present on the landscape, and as a result, threats to the conservation success of each scenario are dependent on how threats manifest.

To compare the conservation success and resiliency of each scenario, risk was simulated for each scenario's best solution from Marxan to determine how each scenario would likely perform in the face of conservation threats. I simulated risk across the landscape-level conservation solutions generated from each of the four scenarios using Monte Carlo numerical simulations (Hammill, Tulloch, Possingham, Strange & Wilson, 2016). Risk was simulated over 1000 iterations, where for each iteration a random number was assigned to each planning unit. If the random number was less than the existing risk assigned to that unit (as defined by the ERS model) the planning unit was deemed 'lost' and removed from the scenario's conservation solution. As a result, the removal of planning units subtracts from the total area protected over the landscape, potentially meaning insufficient planning units remain 'not lost' to meet the conservation target. By comparing the ratio of conservation targets met after risk simulation to the cost of implementing the conservation solution, a return on investment was calculated for the landscape solutions generated from each of the four scenarios.

3. RESULTS

Each scenario addressed conservation risks differently, demonstrating the importance of attitude to risk on conservation success. The Risk ignored scenario identified management priorities without accounting for threats from anthropogenic activity or avoiding areas rich in extractive resources (Fig. 7a). In the absence of landscape level risk, the Risk ignored scenario would meet the defined 30% conservation targets for all five Pacific salmon species, at an estimated cost of $45,000 (Fig. 6a). However, when the predicted impact of anthropogenic activities was simulated, the predicted loss of planning units suggests that the solution would only protect 1.67 [SD, 0.08] species (Fig. 6b) due to the number of planning units predicted to be impacted by human encroachment, or extractive resource development. The Risk ignored scenario would therefore yield a return on investment of 0.39 [SD, 0.02] targets met per $10K spent (Fig. 6c). Under an Urbanization accounted, all extraction avoided scenario (Fig. 7b), where risks associated with urbanization are accounted for in the Marxan analysis but areas with fossil fuels are unavailable for selection, 0 [SD 0.0] targets would be met (Fig. 6a), at an estimated cost of $98,000 (Fig. 4b). The Urbanization accounted, all extraction avoided scenario would therefore yield a return on investment of 0 [SD, 0.0] targets met per $10K spent (Fig. 6c). Under an Urbanization accounted, coal areas avoided scenario (Fig. 7c), where risks associated with urbanization are accounted for in the Marxan analysis but areas with rich in coal resources are unavailable for selection, 0.97 [SD, 0.02] targets would be met (Fig. 6a), at an estimated cost of $113,000 (Fig. 6b). The Urbanization accounted, coal areas avoided scenario would therefore yield a return on investment of 0.085 [SD, 0.002] targets met per $10K spent (Fig. 6c). Following a simulation of landscape level risks, the All risks accounted scenario (Fig. 7d) would meet an average of 4.73 [SD, 0.05] conservation targets (Fig. 6a) at an estimated cost of $58,000 (Fig. 6b). The All risks accounted scenario is therefore predicted to yield the greatest return on investment of 0.81 [SD, 0.009] targets met per $10K spent (Fig. 6c). Additionally, risk simulations were conducted for each scenario at 10%, 20%, and 40% targets. At a 10% target all scenarios performed best, reaching the greatest return on investment. However, as targets were increased, the ability for each scenario to meet the targets decreased, and costs increased.

The All risks accounted scenario was the only scenario able to maintain the number of targets met after risk was simulated onto the solution. However, the cost of the solution increased as the size of each target increased, leading to overall decreases in return on investment, even for the All risks accounted scenario (Fig. 5). Once targets reached 40%, both the Coal areas avoided, and All extraction avoided scenarios missed targets for all species and return on investment dropped to 0. These results support my hypothesis that salmon protection areas are more resilient (less chance that risk will drastically threaten salmon) when risk is accounted for while identifying potential management priorities.

4. DISCUSSION

With increasing anthropogenic stresses being placed on formally pristine habitats, it is critical to investigate how risk of human encroachment should be incorporated into conservation planning (Goudie & Viles, 2003). My results demonstrate that simply choosing to ignore anthropogenic risk, and base conservation decisions solely on costs and species’ distributions represents a poor attitude towards risk as losses incurred prevent conservation targets being met. In addition, simply choosing to avoid locations containing potentially catastrophic threats means that large portions of the landscape would be excluded, making conservation targets impossible to meet. This was seen as targets increased from 30% to 40%, the Coal areas avoided and All extraction avoided scenarios, all targets were missed. I propose that when making landscape-scale conservation decisions, the best attitude towards risk appears to be a willingness to accept risk (i.e. do not simply avoid potentially risky areas) but incorporate this risk into conservation decisions (Hammill, Tulloch, Possingham, Strange & Wilson, 2016).

Under a Risk ignorant scenario, landscape decisions were based solely on cost and biodiversity data alone. While the solution generated through the Risk ignorant scenario at a target of 30% had the lowest up front cost, the number of conservation targets met following a risk simulation (1.67) was lower than the All risks accounted scenario (4.73) that incorporated risks into the decision-making process. This low number of targets met is due to selected planning units being deemed ‘lost’ meaning that insufficient areas remain to meet conservation targets. Also, the low number of targets met mean that a Risk ignorant strategy had a lower overall return on investment (0.39 targets met per $10K spent) than the All risks accounted scenario (0.81 targets met per $10K spent).

Under the Urbanization accounted, all extraction avoided scenario, and the Urbanization accounted, coal areas avoided scenario, large numbers of available planning units were locked out from possible solutions. Simply avoiding areas with fossil fuel development excludes a large portion of the landscape, making it impossible to meet conservation targets (Fig. 7bc). In addition, although the solutions generated under the extraction avoided, and coal areas avoided scenarios did not meet all targets even before risk was simulated, both incurred higher upfront cost than the remaining scenarios. These high costs may be because the exclusion of large areas substantially reduces the options available, forcing the software to include expensive, sub-optimal planning units in the solution in an attempt to meet at least some conservation targets. These high costs also mean that the return on investment predicted to be obtained through the extraction avoided, and coal areas avoided scenarios were the lowest.

Finally, under the All risks accounted scenario landscape decisions incorporated cost, biodiversity data, while minimizing risks. Unlike the scenarios that merely excluded areas with extractive resources present, the All risks accounted scenario accepted risk associated with extractive regions and included that risk into the optimization process. Therefore, the resulting solution maximized return on investment as well as minimizing landscape risk, providing ‘risk proofing’ for the scenario. Due to the initial ‘risk proofing’ of the All risks accounted scenario, the Monte Carlo risk simulation affected this scenario less than the other three scenarios. The risk simulation for the All risks accounted scenario removed fewer planning units from desired targets, compared to the other three scenarios. Though the All risks accounted scenario incurred a greater upfront cost than the Risk ignored scenario, the All risks accounted scenario met more targets and yielded the greatest return on investment than the other three scenarios tested. Though the All risks accounted scenario was 29.8% more costly than the Risk ignorant scenario at a 30% target, the return on investment for under the All risks accounted scenario was twice as large. By including potential anthropogenic risk factors, the All risks accounted scenario identified priority areas of increased resiliency compared to priority areas identified when risks are ignored. As targets were increased from 10% to 40%, the All risks accounted scenario was the only scenario able to maintain the number of met targets following simulated risk across the study area. The high number of missed targets under both the Urbanization accounted, all extraction avoided scenario and the Urbanization accounted, coal areas avoided scenario suggests that coordinating effective freshwater salmon conservation in the MSB cannot be achieved by attempting to completely avoid areas rich in extractive resources. Managers may be pre-disposed to adopting risk averse attitudes towards conservation due to fear of failure (Maguire & Albright, 2005; Lennox & Armsworth, 2011; Tulloch et al., 2015). However, results indicated that greater returns are obtained when managers accept certain risks into their salmon conservation strategies, and acknowledge that future energy extraction will influence freshwater salmon conservation.

Future efforts to improve the resiliency of salmon conservation in the MSB would be improved through increased data resolution. This study does not clarify how conservation priorities would change from fluctuations to yearly spawning returns. Spawning data provided by Alaska Department of Natural Resources clarified the spatial extent of spawning habitat, but did not clarify the density of redds in spawning areas. Nonetheless, in years with low spawning returns, fish use the same habitat as spawners from greater returning years, but in lower frequency. Therefore, the spatial priorities identified within this study apply for both high and low spawning return years, however the absolute magnitude of spawners is not included. Oceanic conditions have great influence on salmon productivity and mortality; driven by the Pacific Decadal Oscillation (Hare & Francis, 1995; Beamish et al., 2010). This work does not suggest that the pelagic life stages of Pacific salmon are less vital for salmon conservation, but instead focused on the novel threats to freshwater salmon habitat from rapidly increasing human activity.

Mineral rights and values were excluded from cost derivations for this study to as conservation groups often pursue land acquisition for conservation purposes. However, mineral rights are independently regulated from surface rights. It would be possible to own property without the ability to restrict extraction on the property. Therefore, this same analysis conducted under a larger state run land planning endeavor, aimed at balancing socio-economic development and their impacts on biophysical systems, may need to include revenue considerations to accommodate for profit requirements on state lands. Though few functioning mines and oil and gas wells are currently productive within the MSB, changes in political climate, policies, or market values of resources may entice future extraction of minerals or oil and gas deposits.

4.1 Management Recommendation

Commercial and sport fishing represent multi-million dollar industries for Alaska, and the MSB is no exception. Fishing industries are bound by the success of seasonal salmon spawning runs and the health of freshwater salmon habitat. Meanwhile, human activities threaten critical freshwater salmon habitat. By providing economically-rooted conservation prioritization, this study intends to provide local managers and conservation groups with useful information to identify conservation opportunities in local river basins conflicted by land uses. The Urbanization risk included scenario suggests that risk adverse management techniques are impractical. The All risks accounted scenario highlights how including anthropogenic risks identify management priorities. The cost increase associated with accounting for All Risk (estimated $13,000.00) suggests that including risk into management decisions is achievable at a known price. Local non-profit Great Land Trust has been independently developing salmon conservation priorities for the MSB using different prioritization methods. Going forward, Dr. Edd Hammill and I hope to share the results from this study with both Great Land Trust and other local agencies, to work towards integrating conservation strategies for MSB salmon.

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Table 2.1. Table overview of the cost derivation used in Chapter 2.

NLCD Land Cover Grouping	Economic Grouping	Acquisition Cost/Acre	Opportunity Cost/Acre	Final Cost/Acre	Final Cost/Cell	Source
open water	natural	$ 1.00	$ -	$ 1.00	$ 0.22	NA
perrennial ice/snow	natural	$ 1.00	$ -	$ 1.00	$ 0.22	NA
developed open space	Land	$ 23,420.70	$ -	$ 23,420.70	$ 5,208.65	(LandWatch, 2017)
developed low intensity	Housing	$248,371.39		$ 248,371.39	$ 55,236.56	(LandWatch, 2017)
developed medium intensity	Housing	$248,371.39		$ 248,371.39	$ 55,236.56	(LandWatch, 2017)
developed high intensity	Housing	$248,371.39		$ 248,371.39	$ 55,236.56	(LandWatch, 2017)
barren land	natural	$ 1.00	$ -	$ 1.00	$ 0.22	(Land and Farm, 2017)
deciduous forest	natural+forestry	$ 6,984.27	$ 1,637.27	$ 8,621.54	$ 1,917.39	(Land and Farm, 2017; Ashton, McDonnell, & Barnes, 2016)
evergreen forest	natural+forestry	$ 6,984.27	$ 1,637.27	$ 8,621.54	$ 1,917.39	(Land and Farm, 2017; Ashton, McDonnell, & Barnes, 2016)
mixed forest	natural+forestry	$ 6,984.27	$ 1,637.27	$ 8,621.54	$ 1,917.39	(Land and Farm, 2017; Ashton, McDonnell, & Barnes, 2016)
dwarf shrub	natural	$ 7,649.80	$ -	$ 7,649.80	$ 1,701.28	(Land and Farm, 2017)
shrub/scrub	natural	$ 7,649.80	$ -	$ 7,649.80	$ 1,701.28	(Land and Farm, 2017)
grassland/herbaceous	natural	$ 7,649.80	$ -	$ 7,649.80	$ 1,701.28	(Land and Farm, 2017)
sedge/herbaceous	natural	$ 7,649.80	$ -	$ 7,649.80	$ 1,701.28	(Land and Farm, 2017)
pasture/hay	Land	$ 23,420.70	$ -	$ 23,420.70	$ 5,208.65	(LandWatch, 2017)
cultivated crops	Ag	$ 5,741.02	$ 70.68	$ 5,811.71	$ 1,292.49	(LandWatch, 2017)
woody wetlands	natural	$ 6,984.27	$ -	$ 6,984.27	$ 1,553.27	(Land and Farm, 2017)
emergent herbaceous wetlands	natural	$ 6,984.27	$ -	$ 6,984.27	$ 1,553.27	(Land and Farm, 2017)

Table 2.2. Overview of the ERS model settings for this study. Freshwater intensity and impact distances were both specified based on previous works that implemented similar methods.

Risk Element	Class	Freshwater Intensity (relative score)	Freshwater Influence Distance (m)	Source
Mining Sites	All	60	5000	(Esselman & Allan, 2010)
Oil/Gas Wells	All	60	5000	(Esselman & Allan, 2010)
Paved Roads	All	10	60	(Esselman & Allan, 2010)
Dirt Roads	All	10	15	(Esselman & Allan, 2010)
Agriculture	All	30	3000	(McPherson et al., 2008)
Pipelines	All	60	60	(Esselman & Allan, 2010)
Urban Areas	Low Density	70	5000	(Esselman & Allan, 2010)
Urban Areas	Mid Density	80	7000	(Esselman & Allan, 2010)
Urban Areas	High Density	90	10000	(Esselman & Allan, 2010)

Figure 2.1. Overview map of the MSB and Chapter 2 study area (Mat-Su Salmon Partnership, 2013).

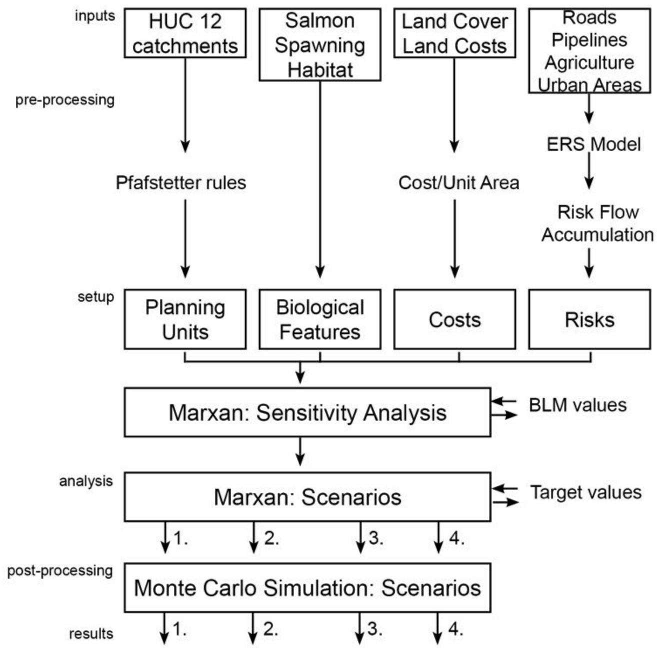

Figure 2.2. Flow chart of the methods implemented in this study. Four distinct scenarios were tested, 1) Risk ignored; 2) Urbanization accounted, all extraction avoided; 3) Urbanization accounted, coal areas avoided; 4) All risks accounted.

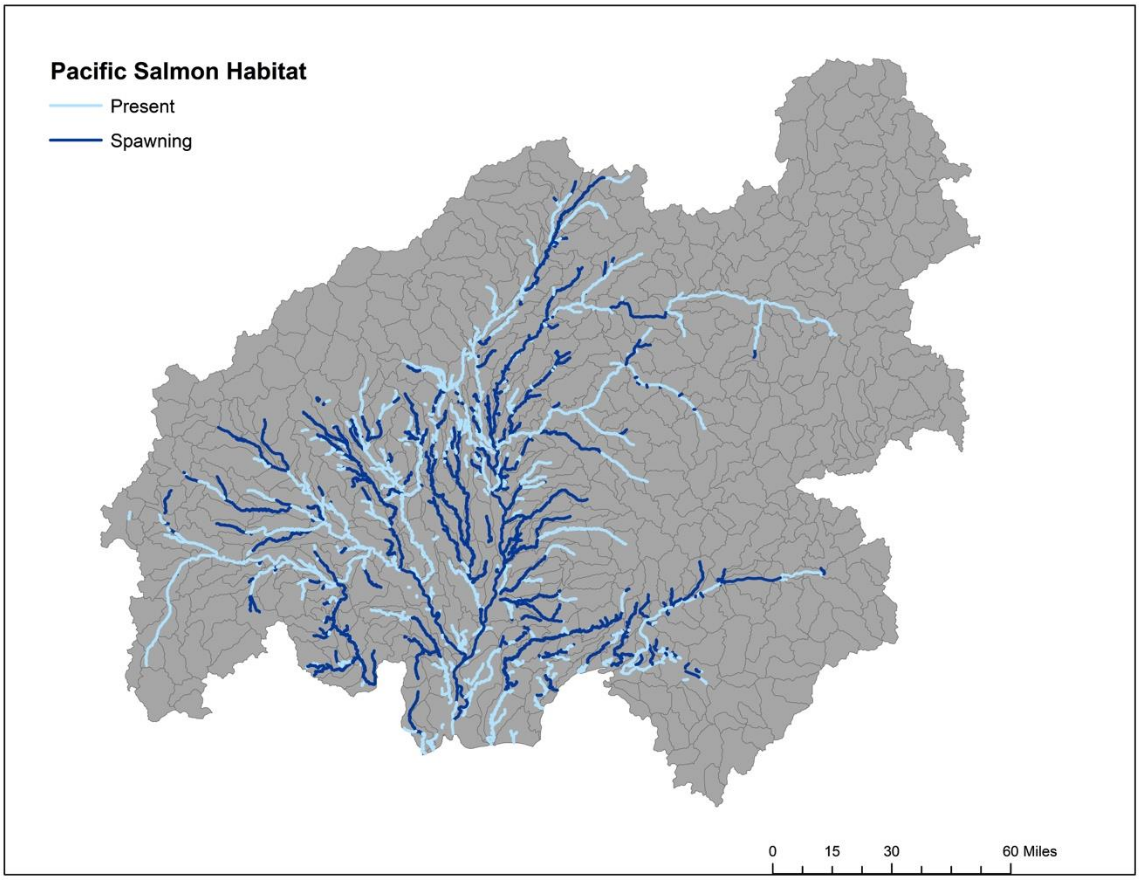

Figure 2.3. Map of Pacific salmon distribution in the MSB. Spawning habitat, and overall presence of salmon are both documented. HUC 12 catchments are outlined within the extent of the MSB drainage.

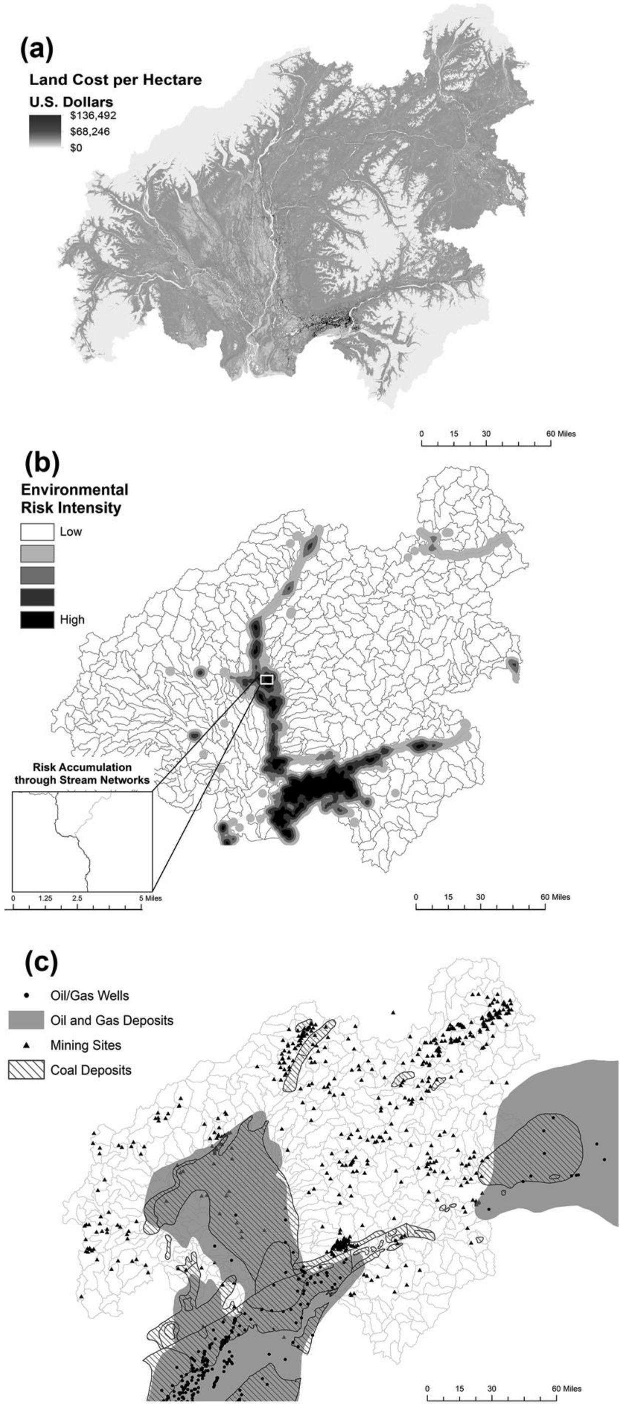

Figure 2.4. Spatial distributions of data incorporated into Marxan analysis. (a) Land costs based on available land cover data, land costs are calculated per hectare in US dollars. (b) Distribution of environmental risks derived from ERS model. Inset describes how risk accumulation flows through stream networks. (c) Fossil fuel resources within the MSB.

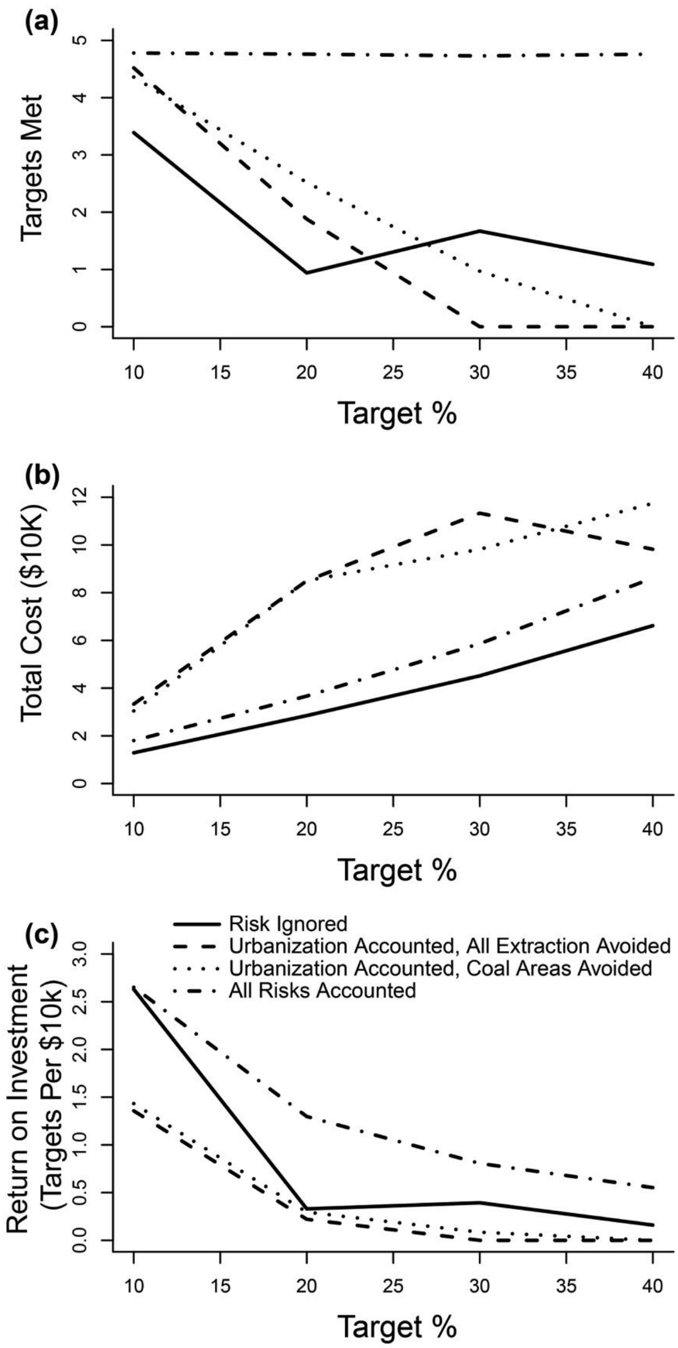

Figure 2.5. Results summary for the four different risk scenarios following simulation of the impacts of environmental risk tested at targets from 10% to 40%, (a) Number of conservation targets met, (b) Cost of best solution, (c) Return on investment.

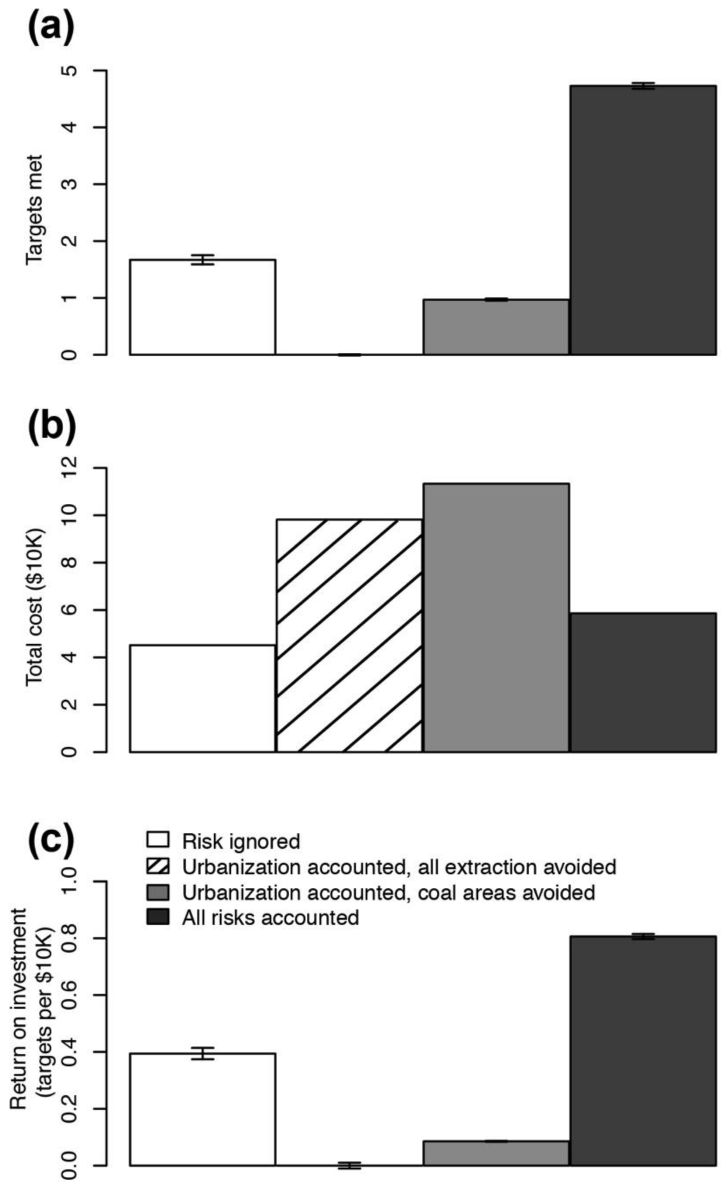

Figure 2.6. Results for the four different risk scenarios following simulation of the impacts of environmental risk at a 30% target (a) Number of conservation targets met. (b) Cost of best solution. (c) Return on investment.

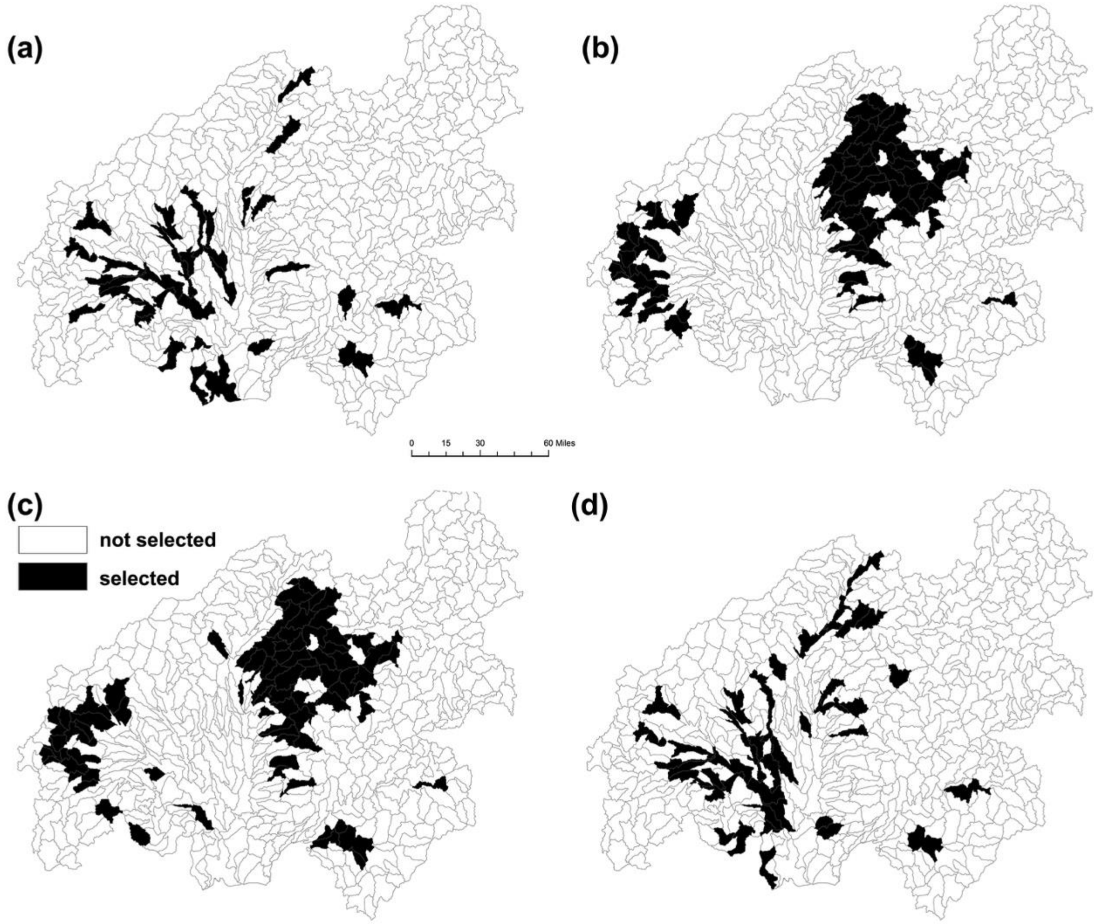

Figure 2.7. Planning units selected in the best solution for each of the four scenarios, out of 100 Marxan runs. (a) Risk ignored scenario. (b) Urbanization accounted, all extraction avoided. (c) Urbanization accounted, coal areas avoided. (d) All risks accounted.

CHAPTER 3

USING SYSTEMATIC CONSERVATION PLANNING TO ASSESS MANAGEMENT STRATEGIES FOR TWO OF UTAH'S NATIVE CUTTHROAT TROUT SUBSPECIES

Abstract

1. Widespread historical distribution of North American native salmonids has been on the decline due to habitat degradation and the introduction of non-native trout, resulting in the listing of many salmon and trout across the western United States under the U.S. Endangered Species Act.
2. Local stream restoration projects usually target improving in-stream features, though some argue that these restoration projects are merely treating the symptoms and not the cause. Both abiotic and biotic upstream conditions throughout a river basin are influential on the downstream environment, suggesting basin-wide efforts are prerequisite to addressing issues at a local habitat scale.
3. Using systematic conservation planning techniques, I identified priority conservation watersheds for Bonneville (*Oncorhynchus clarki utah*) and Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) testing three differing management strategies for incorporating anthropogenic risks to identify priority watersheds. Climatological risks, anthropogenic risks, and ecological risks from non-native trout were considered to address the various scales and issues facing native trout in Utah.

4. When watersheds with non-native trout were eliminated from selection, overall cutthroat conservation objectives were not achieved. Conversely, goals were achieved when accepting and minimizing all risks in basins shared by native cutthroat and non-native trout.
5. These results indicate that opting to work with isolated populations of native cutthroat trout increased exposure to climatological and anthropogenic risks, despite eliminating competition risk from non-native trout.

1. INTRODUCTION

Trout are among the most well-known and culturally valued fish throughout North America (Behnke, 2002). For scientists, the presence of trout species in streams often aids in assessing both stream conditions and larger scale watershed conditions, as trout are sensitive to alterations in habitat, flow and water chemistry, making them important indicator species (Lee et al., 1997; Williams, Haak, Gillespie & Colyer, 2007). Stable trout populations indicate not only suitable local environmental conditions, but also favorable upstream conditions due to the highly connected nature of a river basin. However, the historical distribution of native salmonids has been on the decline due to habitat degradation and the presence of non-native trout (Fig. 1), resulting in the listing of many populations of salmon and trout across the western United States under the U.S. Endangered Species Act. (Young, 1995; Williams et al., 2007). Since local trout habitat directly depends on upstream conditions, considering a variety of geographic scales is necessary for scientists tasked with conserving and restoring trout habitat, ranging from local reach scale (within a single basin), to historic distribution across a landscape (spanning multiple river basins). Local stream restoration projects typically target improvements to in-stream structures, habitat connectivity, culvert alteration or removal, bank stabilization, and replanting efforts. However, many scientists suggest that these restoration projects fail to address the root causes of degraded habitat (Roper, Dose, & Williams, 1997; Fausch, Torgersen, Baxter, & Li, 2002). Both abiotic and biotic upslope conditions throughout a basin are influential on downstream environments, suggesting basin-wide efforts are prerequisite to addressing issues within local habitat (Lichatowich, Mobrand, Lestelle, & Vogel, 1995; Roper et al., 1997).

Shifts to watershed scale conservation have prompted the development of spatial methods to assess and guide conservation action. Developed by Williams et al. (2007), the conservation success index (CSI) aims to synthesize landscape scale fisheries data to analyze salmonid status, habitat condition, and simplify protection and restoration efforts. Based on four scoring categories; range-wide condition, population integrity, habitat integrity, and future scarcity; tributary-sized watersheds are scored from low to high quality (Appendix C). Each score is based on a set of rules, simplifying quantitative measures into distinct categories. Each category’s score is summed and then coupled with geographic data, which provides management prioritization across a landscape. Adapted by Trout Unlimited (TU), the CSI method has been used throughout the United States to develop freshwater fish conservation strategies. Though the categories cover a wide range of variables, quantitative measurements are distilled into equal groups used to produce a final score (Appendix C). However, some variables may not be best represented through such equal divisions. Certain variables may be more important, or function on non-linear scales, different from the scoring breakdown within the CSI. In fact, rules within the CSI, and other similar scoring procedures carry the values, beliefs, assumptions, biases, and even acceptable risk tolerances of the developers. Further, it can become impossible to interpret the values and assumptions when these scoring processes contain three or more variables, as in the case with the CSI framework (Game, Kareiva, & Possingham, 2013). Such hidden assumptions can undermine transparency during the prioritization process. Game et al. (2013) go as far as to say scoring and combinatory rules actually obscure the planning objectives by concealing judgments within a numerical system. Though hidden judgments are not inherently bad, many landscape scale freshwater conservation plans rely on classification schemes similar to the CSI framework, including the Freshwater Classification Approach to Biodiversity Conservation Planning, Freshwater Conservation Planning in Data-Poor Areas, and the 3-R Framework (Higgins, Bryer, Khoury, & Fitzhugh, 2005; Thieme et al., 2007; Haak & Williams, 2013).

Conversely, quantitative prioritization methods require an explicit setting of assumptions in an effort to reduce biases, and increase transparency (Game et al., 2013). Tools like Marxan, which is the most widely used systematic conservation planning program in the world, incorporate such quantitative methods to prioritize conservation actions. Further, recent advancements in freshwater applications of Marxan provide appropriate adaptations to assess reproducible prioritization, applicable to salmonids (Hermoso, Linke, Prenda, & Possingham, 2011; Esselman & Allan, 2011; Linke et al., 2012; Witt & Hammill, in press). Therefore, quantitative prioritization methods offer a new transparent approach to landscape scale salmonid conservation across Utah.

The state of Utah is home to several native salmonid subspecies, including the Bonneville cutthroat trout *(Oncorhynchus clarki utah),* Colorado River cutthroat trout *(Oncorhynchus clarki pleuriticus),* and Yellowstone cutthroat trout *(Oncorhynchus clarki* *bouvieri)*. Once widespread throughout Utah, Bonneville cutthroat trout currently occupy only around 35% of their historic range, and Colorado River cutthroat occupy much less, around 15% (Haak & Williams, 2013). The decline of native cutthroat trout populations in Utah is the culmination of several factors. During the 1950s, Bonneville cutthroat trout were thought to be extinct, due to stocking, and competition with non-native brook trout, brown trout, and rainbow trout (Behnke, 2002). Though managers were able to re-establish Bonneville cutthroat trout through stocking and protection programs, competition from non-native trout, even at similar fish sizes, continue to threaten cutthroats (McHugh & Budy, 2005; Shemai, Sallenave, & Cowley, 2011; Wang & White, 2011). Colorado River cutthroat trout are similarly affected by competition from non-native trout, and are also facing issues concerning genetic hybridization with rainbow trout (Young, 1995). Though both Bonneville and Colorado River cutthroat have evolved in some highly fluctuating and unstable stream environments, erosion from livestock grazing has further destabilized cutthroat habitat over the last 100 years (Behnke, 2002). Current day cutthroat trout face additional risks throughout Utah; human population growth, additional land use changes, increasing water diversions, and warming climate all threaten existing and future habitat availability.

In 2016, Utah's population experienced the greatest percent growth increase of any state in North America (U.S. Census, 2016), and as populations surge, so does the demand for water. Utah has one of the highest per capita diversion rates in the United States, despite diverting less total water than many other western states (Utah Division of Water Resources, 2010). Further, climate projections suggest that in-stream flows and water temperatures are already being altered throughout North America, as indicated by earlier snowmelt, shorter spring runoff, and increasing late summer water temperatures (Mote, Hamlet, Clark, & Lennenmaier, 2005; Stewart et al., 2005; Kaushal et al., 2010; Isaak et al., 2011). Aquatic communities are evolutionarily tied to natural flow regimes, and temperature gradients strongly dictate species distribution and abundances (Bunn & Arthington, 2002; Wenger et al., 2011). Yet alterations to flow from earlier snowmelt and rapidly warming streams force trout to migrate according to their temperature preferences (Heino, Virkkala, & Toivonen, 2009).

To address the various issues facing cutthroat trout conservation in Utah, methods appropriate to address climatological risks, anthropogenic risks, as well as ecological risk from non-native trout competition are required. Quantitative methods of spatial prioritization relevant to cutthroat conservation can address the relevant risks at the watershed scale (Game, Watts, Wooldridge, & Possingham, 2008; Carvalho, Brito, Crespo, Watts & Possingham, 2010). In this study I implemented the Marxan systematic conservation planning tool, following the connectivity rules and risk assessment techniques discussed in Chapter 2, to develop conservation prioritization for both Bonneville and Colorado River cutthroat trout in Utah. By incorporating conservation objective outlined by Utah's Division of Wildlife Resources (UDWR)—to restore and maintain at least 52 conservation populations, protect 294 stream miles for Bonneville cutthroat, 537 stream miles for Colorado River cutthroat, and to eliminate or minimize threats to each species—I developed several Marxan prioritization plans for both subspecies (UDWR, 1997; UDWR, 2008). In this study, I aimed to take the freshwater connectivity rules and risk assessment techniques from Chapter 2, and implement them into a systematic conservation planning process. The goal was to test the hypothesis that feasible cutthroat conservation targets can be met by completely avoiding tributaries that also contain non-native trout presence, while also considering both anthropogenic and climatological risks. This hypothesis represents an ideal outcome to the UDWR goals. To test this hypothesis three scenarios were developed. First, areas where non-native trout and native trout coincide were excluded from selection, eliminating risk from non-natives (a) ‘Only native populations’. The other scenarios minimized risks from non-native trout competition by limiting the number of watersheds where native cutthroat and non-native trout were both present into a solution, minimizing the risks from non-natives. This was conducted at two separate targets (b) ‘Native and 10% of coexisting populations’ and (c) ‘Native and 20% of coexisting populations’. Here, coexistence refers to the spatial overlap of native and non-native trout within catchments. All three scenarios considered and minimized climatological and anthropogenic risks.

2. METHODS

2.1 Conservation Planning Overview

Following similar procedures to Chapter 2, Marxan optimization software was used in conjunction with several risk models, including aquatic temperature exposure models as well as existing models on human impacts to watersheds. These were combined to determine priority areas for cutthroat trout conservation. Chapter 2 discussed the importance of considering and incorporating risks when identifying protected areas for freshwater applications with Marxan. Therefore, Marxan was implemented to minimize risks, treated as a cost, using a simulated annealing optimization algorithm. Through this iterative process, Marxan can arrive at a set of planning units that achieve defined conservation targets with least risk. By including risks in the Marxan selection process, the risk of failure is included in how Marxan identifies an output reserve network (Tulloch et al., 2013), making the ultimate solution more resilient to probable damaging activities (Hammill et al., 2016). As with Chapter 2, Pfafstetter topology rules were applied to the Marxan selection process to effectively account for water's course through stream networks from headwaters to larger streams and rivers. The construction of an Environmental Risk Surface model and flow accumulation simulation was not necessary, as input risk data had been constructed specifically for freshwater streams by other sources and compiled (Esselman et al., 2011; Haight & Hammill, 2017).

2.2 Study Area

The state of Utah was subdivided into tributary sized basins, each of which represented a single planning unit (n=1864) within the Marxan analysis. Tributary basins were derived from hydrologic unit code (HUC 12) basins. HUC 12 basins were obtained with Pfafstetter topological rules for stream networks from the HydroBASINS database, and used to define the planning units within Utah (Lehner & Grill, 2013, http://www.hydrosheds.org/page/hydrobasins). Unlike in Chapter 2, where the entire study area was contained within one enclosed basin, the state of Utah drains into the Upper Colorado Basin to the East, the Great Basin to the West, as well as the Lower Colorado Basin to the South (Fig. 2). Therefore each basin was separated to apply the Pfafstetter topological rules, and then recombined before use in Marxan. This process ensures that no watershed boundaries can be crossed during the selection of priority areas. Next, distribution data on both Bonneville Cutthroat trout and Colorado River Cutthroat trout were provided by Trout Unlimited and spatially correlated by population density to each planning unit. Though present in Utah, Yellowstone Cutthroat trout are restricted to a small geographic extent, occupying only the Raft Creek drainage in the northwest corner of the state. Due to their limited statewide distribution, this subspecies was omitted from the Marxan analysis, as prioritization efforts would be uninformative.

Several risk sources were integrated into Marxan to consider potential risks to cutthroat trout in Utah. First, Haight and Hammill (2017) developed an aquatic climate exposure model assessing the landscape-scale effects of climate change on freshwater systems for Utah (Fig. 3). Their model integrates climate projections via the AdaptWest Project and several alternative future climate scenarios, and when fed through a flow accumulation based on projected temperature changes, the model predicts future aquatic ecosystem vulnerability relevant to cutthroat trout habitat (AdaptWest Project, 2015; Wang, Hamann, Spittlehouse & Carroll, 2016; Haight & Hammill 2017). Haight and Hammill (2017) caution that though aquatic climate exposure may represent long-term large-scale risks, other short-term smaller-scale vulnerabilities threaten aquatic systems, namely pollution and water diversions. To address such anthropogenic risks, cumulative disturbances to river fish habitats were compiled based on data produced by Esselman et al. (2011). As part of the 2010 National Fish Habitat Action Plan, Esselman et al. established criteria for human disturbances based on land use, land cover types, population density, proximity to roads, presence of dams as diversions, and pollutant sources such as mine tailings and discharge sites (Appendix B). A composite risk of both climate risk and anthropogenic risks was calculated as a raster layer to assess both potential stressors within one Marxan analysis based on the following calculation:

$$1 - [\left(1 - \frac{climate\ risk\ score}{max\ climate\ risk\ score}\right) * \left(1 - \frac{anthropogenic\ risk\ score}{max\ anthropogenic\ risk\ score}\right)]$$

This equation calculates the probability of each planning unit being impacted by either, or both of the two risk sources. The scores from the composite risk calculation were then assigned to each HUC 12 basin in Utah.

2.3 Marxan Setup

The desired level of connectivity among planning units is customizable within the Marxan software. Connectivity amongst protected areas is manipulated through a boundary length modifier (BLM) regulating the compactness of a Marxan conservation network, based on the total perimeter of selected priority areas (Ball, Possingham, & Watts, 2009; Fischer et al., 2010). Adjusting BLM values influences the fragmentation or continuity of the output conservation network, with lower BLM scores producing less connected output networks and vice versa. Following protocols outlined in Chapter 2, adaptations of BLM values for lotic systems were applied to account for the hierarchical stream orders within catchment basins (Hermoso, Linke, Prenda, and Possingham et al., 2011; Linke et al., 2012).

Species targets were established for both Bonneville Cutthroat trout as well as Colorado River Cutthroat trout based on the presence of non-native trout species living within the same habitats as these native trout. Targets were established for Bonneville Cutthroat trout in the absence of non-native species, and also in the presence of non-native species. The same process was conducted for Colorado River Cutthroat trout. Data on the presence of non-native species within cutthroat trout habitat were provided in conjunction with cutthroat trout distribution data, made available through Trout Unlimited. Under the scenario excluding non-native trout from selection ‘Only Native Populations’, waters home to non-native trout were deemed unavailable. Targets for cutthroat were tested between 10% and 90%, in 10% increments. Additionally, two scenarios were developed where the selection process could include streams with non-native trout and cutthroat trout coexistence. Under the ‘Native and 10% of coexisting populations’ scenario, cutthroat trout targets were tested from 10% to 90%, while targets for coexisting populations of cutthroat trout and non-native trout were held constant at a 10% target. The ‘Native and 20% of coexisting populations’ scenario functioned similarly, but held a 20% target. Finally, the stream miles, and relative population sizes identified by the solution of each scenario were summed, to compare the results to UDWR’s conservation goals.

3. RESULTS

Each scenario addressed risk from non-native trout differently. When forced to avoid selecting watersheds with non-native trout (‘Only native populations’), targets failed to adequately represent the goal of 30% of cutthroat distributions protected, or the UDWR goals for protected stream miles for each species. At the defined 20% target, the scenario identified approximately 130 stream miles of Bonneville cutthroat habitat for protection, and approximately 154 stream miles for Colorado River cutthroat for protection (~282 combined), short of the collective UDWR goal of 831 miles (Table 1a). Under both scenarios where the selection process could include non-native trout living within cutthroat trout catchments, targets were met at all intervals ranging from 10% to 90%. As targets increased, the accepted risk, and number of catchments in the solution also increased. For the ‘Native and 10% of coexisting populations’ scenario, approximately 190 stream miles of Bonneville habitat and 135 stream miles of Colorado River cutthroat habitat were selected, at a 20% target (Table 1b). The combined total stream miles at 20% under this scenario exceeds the amount of stream miles identified in the ‘Only native populations’ scenario, ~324 vs. ~283, respectively. At a 30% target, the stream miles protected for Bonneville cutthroat habitat met the stream miles goal. As targets were increased to 50%, the ‘Native and 10% of coexisting populations’ scenario protected approximately 955 combined stream miles of habitat, meeting the UDWR goals for each species. However, to meet the stream miles goal for Colorado River cutthroat trout, an 80% target was required. Similar trends were seen for the ‘Native and 20% of coexisting populations’ scenario. Approximately 315 combined stream miles of habitat were identified, at a 20% target. Stream mile goals were met for Bonneville cutthroat at a 30% target. At a 50% target, the scenario identified approximately 1008 stream miles of habitat, exceeding the combined goals for each species, as well as the ‘Native and 10% of coexisting populations’ scenario (Table 1c). Finally, an 80% target was required to meet stream mile goals for Colorado River cutthroat trout. Along with calculating the amount of stream miles identified for each scenario, relative population size was calculated at each target in each scenario (Table 1). Meeting steam mile goals for Bonneville cutthroat trout at a 30% target included approximately 15% of the state’s Bonneville population. For Colorado River cutthroat, approximately 26% of the state’s population was identified at an 80% target.

4. DISCUSSION

Fisheries managers are increasingly burdened with including future conditions into their decision-making processes, namely climate change and anthropogenic influences (Esselman et al., 2011; Peterson, Wegner, Rieman, & Issak, 2013). Future climate change predictions suggest western U.S. cutthroat trout will lose an additional

58% of their existing habitat by 2080 (Wenger et al., 2011). Increasing temperatures will impact cutthroat trout's thermal tolerances, and perpetuate competition with other species, further restricting their range. Increasing temperatures also have significant indirect effects on stream habitat, as the frequency and intensity of disturbances (such as forest fires) are likely to increase, which leads to increased erosion and turbidity following fires (Williams, Haak, Neville, & Coyler, 2009). Such studies are calling for urgent action to recognize resilient populations of cutthroat trout with targeted mitigation efforts (Williams et al., 2009; Wenger et al., 2011). My results acknowledge this call for action by identifying basins where cutthroat trout are least exposed to climatological and anthropogenic risks. Further, the solutions identified within this Marxan analysis clarify how different risk management strategies affect the resiliency of conservation plans for Utah's cutthroat subspecies. Though it is well recognized that non-native trout have largely displaced cutthroat trout subspecies throughout the Western U.S., conservation actions cannot simply avoid streams where cutthroat and non-natives both reside. The 'Only native populations' scenario was unable to achieve targets above 20%, but at a 20% target the scenario did not identify as many stream miles for protection as the other scenarios (Fig. 4a). These results suggest that management strategies avoiding competitive risk between cutthroat and non-native trout cannot meet goals as successfully as strategies where competitive risks are considered. Further, opting to avoid competitive risks between cutthroat trout and non-native trout increased the climatological and anthropogenic risks in areas identified by Marxan (Fig. 4b). Conversely, both Native and coexisting population scenarios achieved all defined targets ranging from 10% to 90%. The length of steam miles identified, and risk scores, of each scenario followed similar trends as targets increased (Fig. 4). The 'Native and 10% of coexisting populations' scenario protected fewer stream miles per target, but also incurred less risk in each solution. Most importantly, risks from non-native and cutthroat trout interactions can still be minimized to constant 10% targets and achieve greater protections than through attempting to eliminate these risks. Meaning only 10% of cutthroat populations that coexist with non-native trout were required to meet overall targets. To meet the stream mile goal for Colorado River cutthroat trout, a higher target was needed (80%) compared to Bonneville cutthroat (30%), suggesting that meeting conservation goals for Colorado River cutthroat trout would require greater efforts than for Bonneville cutthroat.

Geographically, both Native and coexisting populations scenarios repeatedly selected priority watersheds at high elevations throughout the Wasatch and Uinta ranges, including many headwaters of the Weber, Ogden, and Provo rivers. Additionally, many streams draining from the north-slope Uinta Mountains into Wyoming were repeatedly selected (Fig. 7). Areas identified for selection vary between my results and prior work done within the CSI framework of Trout Unlimited (Appendix C). Though Trout Unlimited was only identifying areas relevant to Bonneville Cutthroat trout the differences were noticeable. Interestingly, Trout Unlimited identified important areas in the Wasatch and Uinta range and close to Salt Lake City and Ogden, similar to my results when targets were set at 20%. My results also identify areas in the Uinta Mountains not identified by the CSI results, possibly due to the inclusion of Colorado River cutthroat trout. Further, my results were more centralized than the CSI framework, likely resulting from the importance of connectivity and risk accumulation downstream. These considerations were more explicitly considered than the broad classification scheme of the CSI framework (Williams et al., 2007). Therefore, my results highlight the importance of the upper Weber, Ogden and Provo rivers, along with the Uinta Mountains, to future Utah cutthroat conservation.

Though accepting some non-native trout competition within conservation strategies yielded better results than avoiding basins with competition risk, in-stream habitat restoration still presents difficulties. Habitat restoration efforts can be complicated through the presence of non-native species, as efforts to improve habitat connectivity can open new pathways for non-native species expansion. Subsequently, fish barriers have been installed to isolate native cutthroat from downstream threats. Isolating cutthroat trout in headwater tributaries can limit competition from non-native species, hybridization risks, and contact with pathogens, such as whirling disease (Kondratiff & Richer, 2017). Interestingly, my results indicate that identifying only isolated cutthroat populations may limit non-native competition risks; other climatological and anthropogenic risks increase. Though fish barriers in many cases are artificially manufactured, naturally produced beaver dams offer similar benefits, and have been shown to more passable to native Bonneville cutthroat than invasive brown trout (Lokteff, Roper, & Wheaton, 2013). Additionally, beaver dams can increase the residence time of water passing through river systems, offering means to offset shortened spring runoff (Majerova, Neilson, Schmadel, Wheaton, & Snow, 2015). Yet, barriers are not always impassible for non-native species (Lokteff et al., 2013; Robets, Fausch, Hooten, & Peterson, 2017). Non-native fish removal has also been implemented, to physically eliminate unwanted species within stream segments. Though some success has been documented in small streams, removal efforts are often time-consuming, expensive, and not feasible for larger river systems

(Sheperd, Spoon, & Nelson, 2002; Roberts et al., 2017). Appropriate, in-stream techniques for habitat improvements are essential to the success of conservation efforts within the Marxan identified areas for protection.

Nonetheless, the quantitative method implemented through this work offers a transparent approach for coordinating Utah cutthroat conservation while accounting for various risks factors. Further, Marxan targets were easily re-portrayed as UDWR goals for stream mile protection, offering future integration between systematic conservation planning techniques and management objectives. Goals for stream mile protection for both Bonneville and Colorado River cutthroat trout were clarified as Marxan targets as well as relative population size. Future work with UDWR would greatly benefit from this translation between their intentions and the data requirements for Marxan. Also, the methods applied herein would easily translate to include additional cutthroat subspecies, providing greater insight throughout the entire western range. Finally, specific scenarios should be developed to assess additional risks, including disease risk, hybridization or genetic risks, and future invasion risks. Such specific scenarios would further clarify the types of on-the-ground action required for successful conservation.

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Table 3.1. Marxan scenario results for Bonneville and Colorado River Cutthroat conservation in Utah, a) Only native populations scenario, b) Native and 10% coexisting populations scenario, c) Native and 20% coexisting populations scenario

a)

Only Native Populations							
Targets	Risk Score	Catchments in Solution	Missed Species	Miles Identified Bonneville	Miles Identified ColoRiv	Relative Population Size Bonneville	Relative Population Size ColoRiv
10	5.6	13	0	88.17	111.52	5.11%	1.96%
20	11.9	26	0	129.76	153.71	7.89%	4.69%
30	26.1	55	2	206.82	218.33	11.51%	5.92%
40	26.1	55	2	206.82	218.33	11.51%	5.92%
50	26.1	55	2	206.82	218.33	11.51%	5.92%
60	--	--	--	--	--	--	--
70	--	--	--	--	--	--	--
80	--	--	--	--	--	--	--
90	--	--	--	--	--	--	--

Target (%)	
0	Bonneville Present With Non-natives
(10 - 90)	Bonneville Present Without Non-natives
0	Colorado River Present With Non-natives
(10 - 90)	Colorado River Present Without Non-natives

294 miles: Goal Bonneville	Met Goal
537 miles: Goal Colorado River	Missed Goal

Table 3.1. (cont.)

b)

Native and 10% of coexisting populations							
Targets	Risk Score	Catchments in Solution	Missed Species	Miles Protected Bonneville	Miles Protected ColoRiv	Relative Population Size Bonneville	Relative Population Size ColoRiv
10	4.2	9	0	68.29	76.28	3.68%	5.52%
20	8.1	18	0	189.63	134.96	6.74%	7.85%
30	15.7	32	0	428.66	211.56	14.77%	12.34%
40	19.8	41	0	432.68	246.5	21.16%	14.21%
50	25.8	53	0	633.46	322.29	32.77%	15.66%
60	34.4	68	0	895.34	405.61	42.47%	18.48%
70	37.2	77	0	941.56	493.88	47.81%	21.07%
80	51.4	106	0	1075.15	585.98	54.04%	26.04%
90	55.3	110	0	1323.27	656.19	64.10%	31.25%

Target (%)	
10	Bonneville Present With Non-natives
(10 - 90)	Bonneville Present Without Non-natives
10	Colorado River Present With Non-natives
(10 - 90)	Colorado River Present Without Non-natives

294 miles: Goal Bonneville	Met Goal	(yellow)
537 miles: Goal Colorado River	Missed Goal	(gray)

Table 3.1. (cont.)

c)

Native and 20% of coexisting populations							
Targets	Risk Score	Catchments in Solution	Missed Species	Miles Protected Bonneville	Miles Protected ColoRiv	Relative Population Size Bonneville	Relative Population Size ColoRiv
10	5.5	12	0	75.57	135.53	3.82%	7.66%
20	10.4	21	0	169.89	145.84	9.41%	8.72%
30	14.2	30	0	516.52	211.56	17.81%	12.33%
40	20.4	43	0	500.18	248.06	24.17%	14.20%
50	26.9	55	0	684.88	323.86	30.63%	15.66%
60	34.1	67	0	881.9	405.61	42.29%	18.48%
70	39.2	80	0	1013.21	493.89	49.68%	21.01%
80	47.3	98	0	1090.81	585.98	54.88%	26.04%
90	54.1	111	0	1275.95	618.62	60.93%	27.99%

Target (%)	
20	Bonneville Present With Non-natives
(10 - 90)	Bonneville Present Without Non-natives
20	Colorado River Present With Non-natives
(10 - 90)	Colorado River Present Without Non-natives

294 miles: Goal Bonneville	Met Goal	(yellow)
537 miles: Goal Colorado River	Missed Goal	(grey)

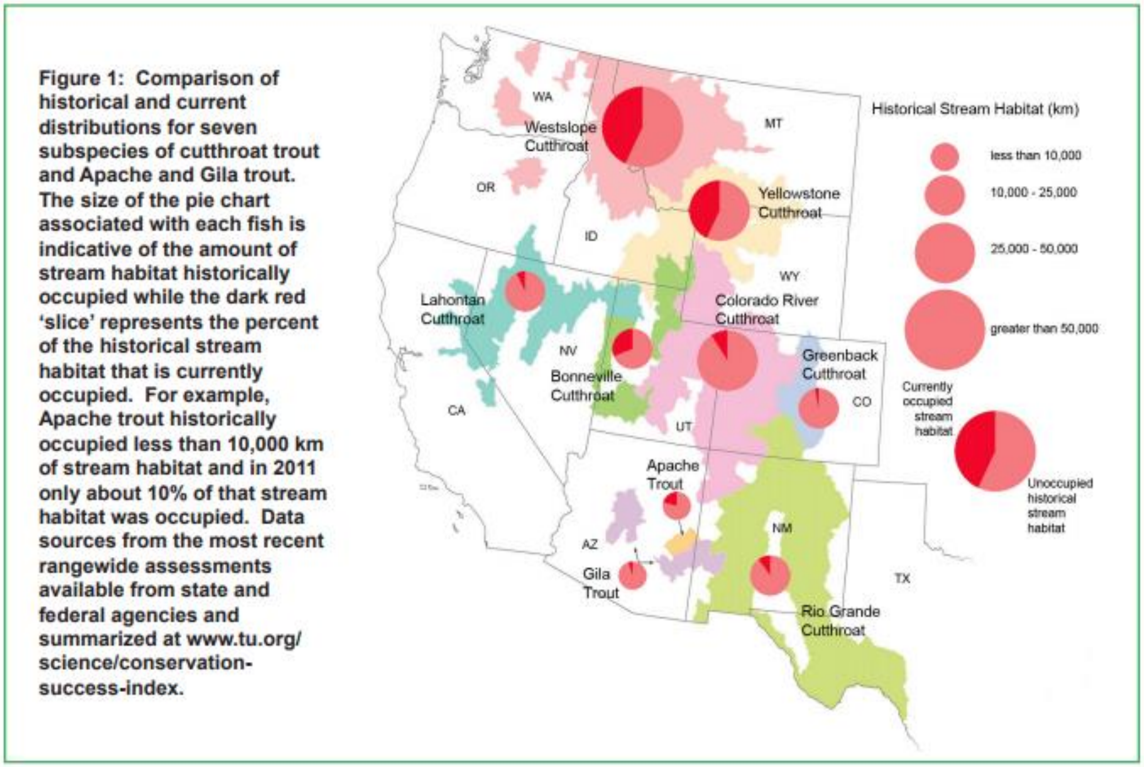

Figure 3.1. Historical vs. current stream habitat for native cutthroat trout subspecies in the Interior Western United States (Haak & Williams, 2013). Within the pie chart, dark red represents currently occupied stream habitat, while pale red indicates unoccupied historical stream habitat.

Figure 3.2. Water Resource Regions of the United States (Utah State University Extension & U.S. Geological Survey, 2018). The three main regions within Utah are the Upper Colorado, Lower Colorado, and Great Basin.

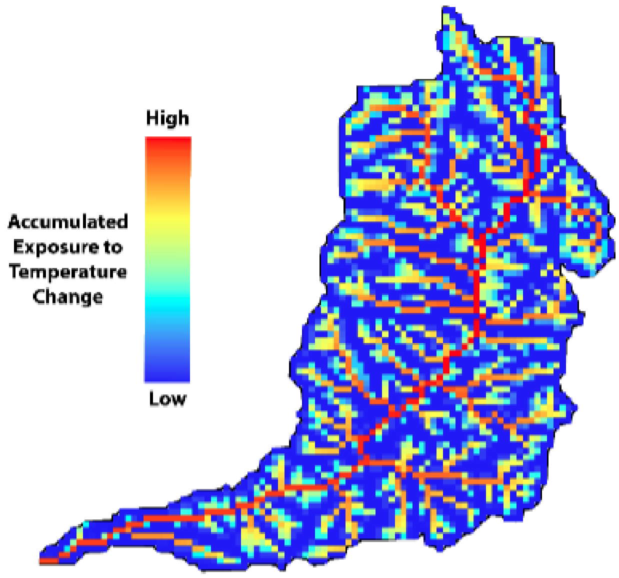

Figure 3.3. Example watershed from the aquatic climate exposure risk data (Haight and Hammill, 2017). This data source depicts the increase in accumulated exposure to temperature change through a drainage network, under projected climate change.

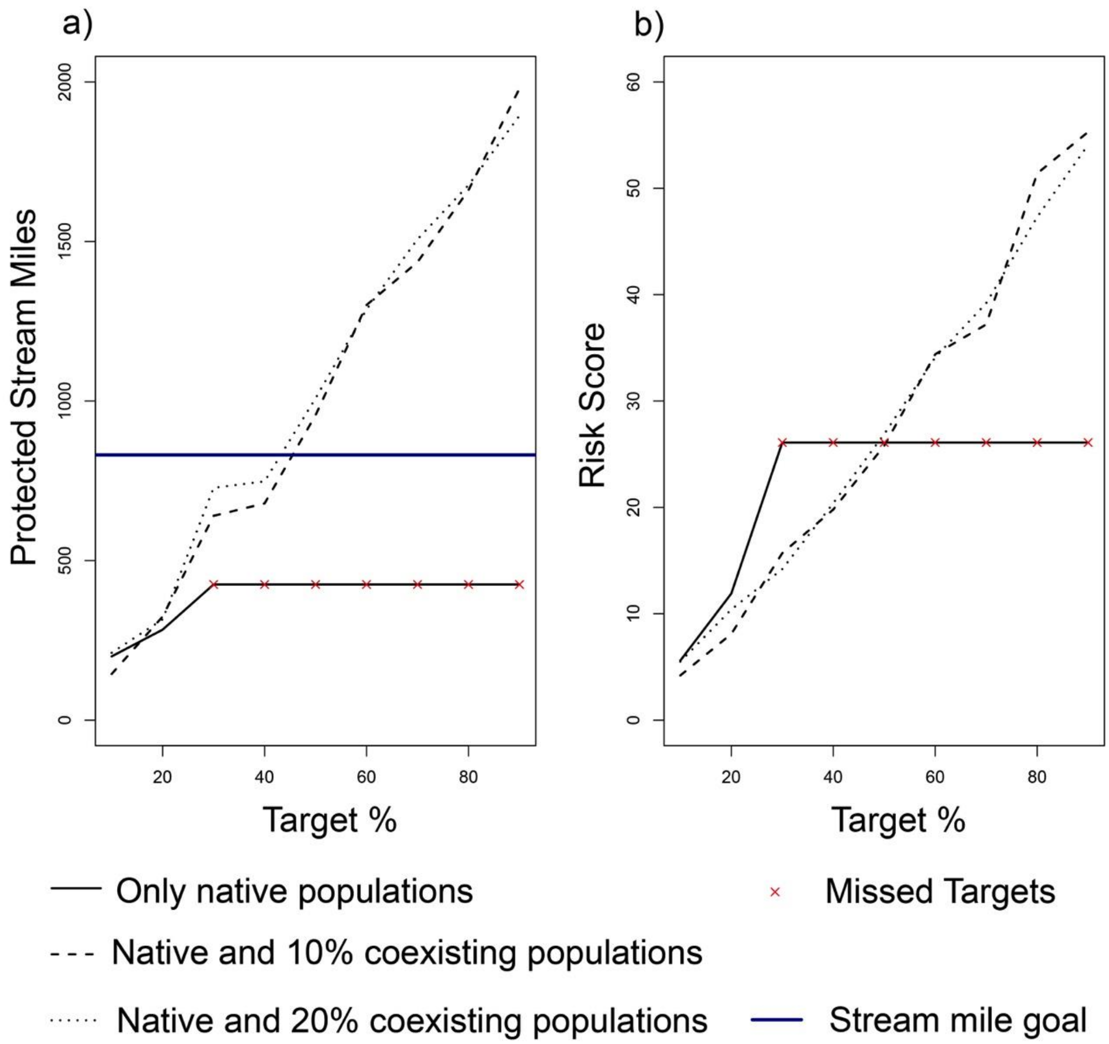

Figure 3.4. Results summary for the three different scenarios at targets from 10% to 90%, (a) Protected stream miles from each scenario, (b) Sum of risk for each scenario

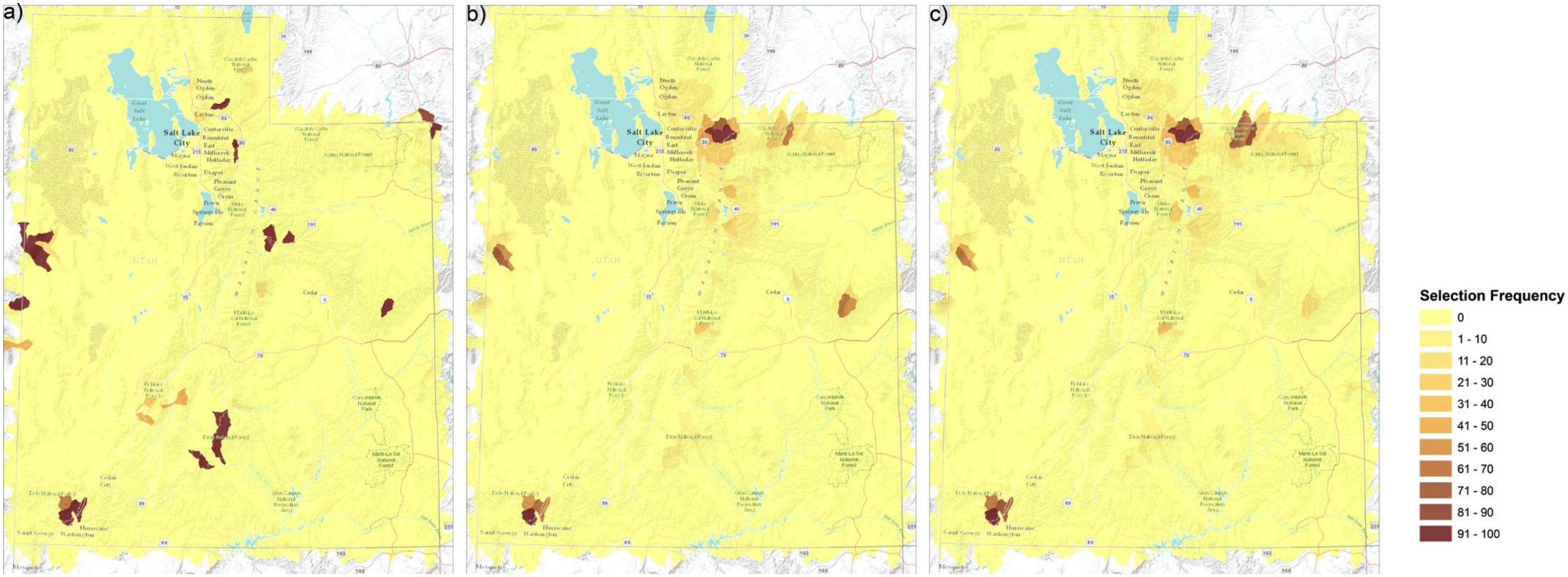

Figure 3.5. Selection frequency results maps from three Marxan scenarios, at 20% native cutthroat targets: a) Only native populations, b) Native and 10% of coexisting populations, c) Native and 20% of coexisting populations

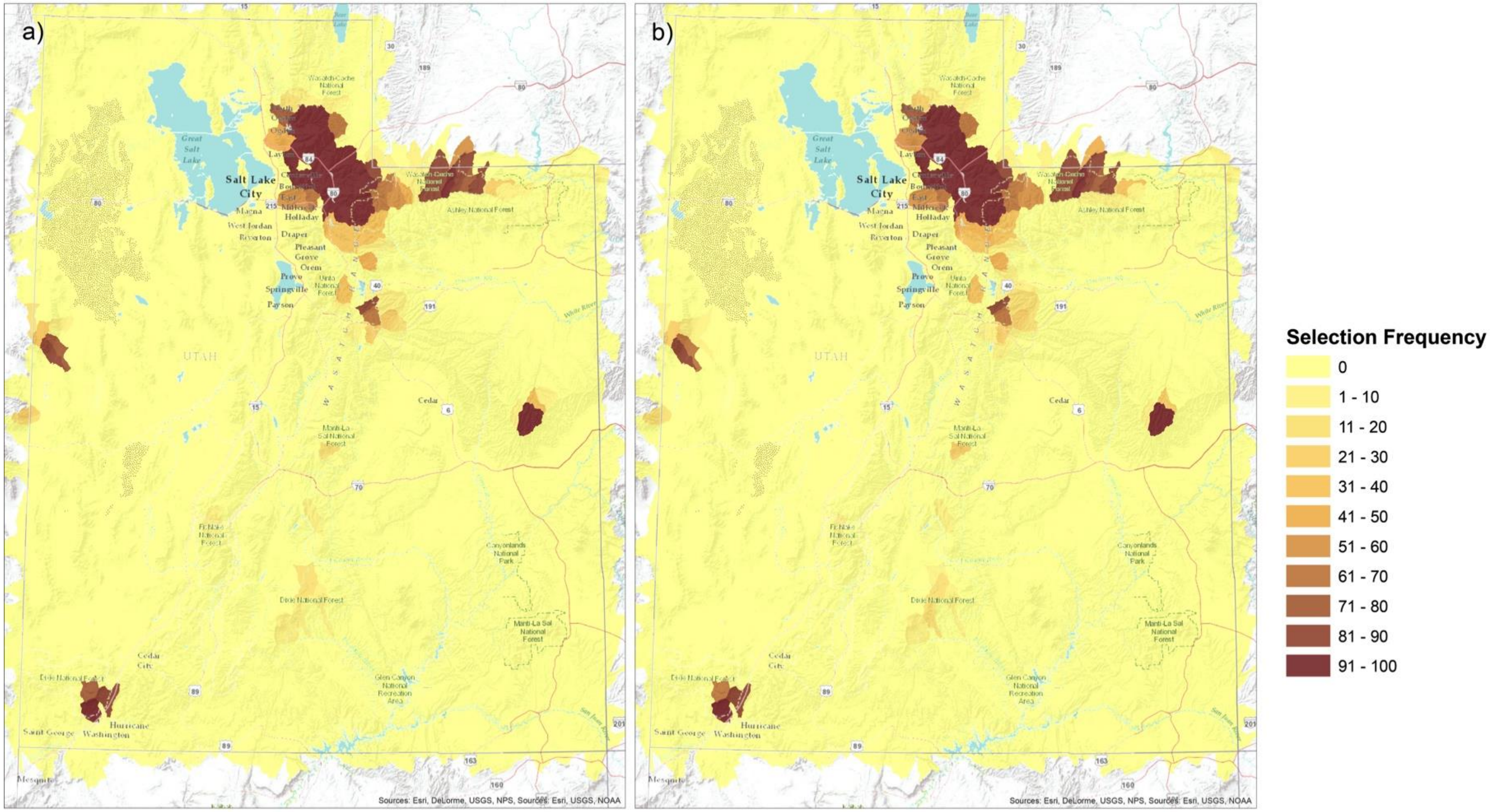

Figure 3.6. Selection frequency results maps from both Native and coexisting population scenarios, at 50% native cutthroat targets: a) Native and 10% of coexisting populations, b) Native and 20% coexisting populations

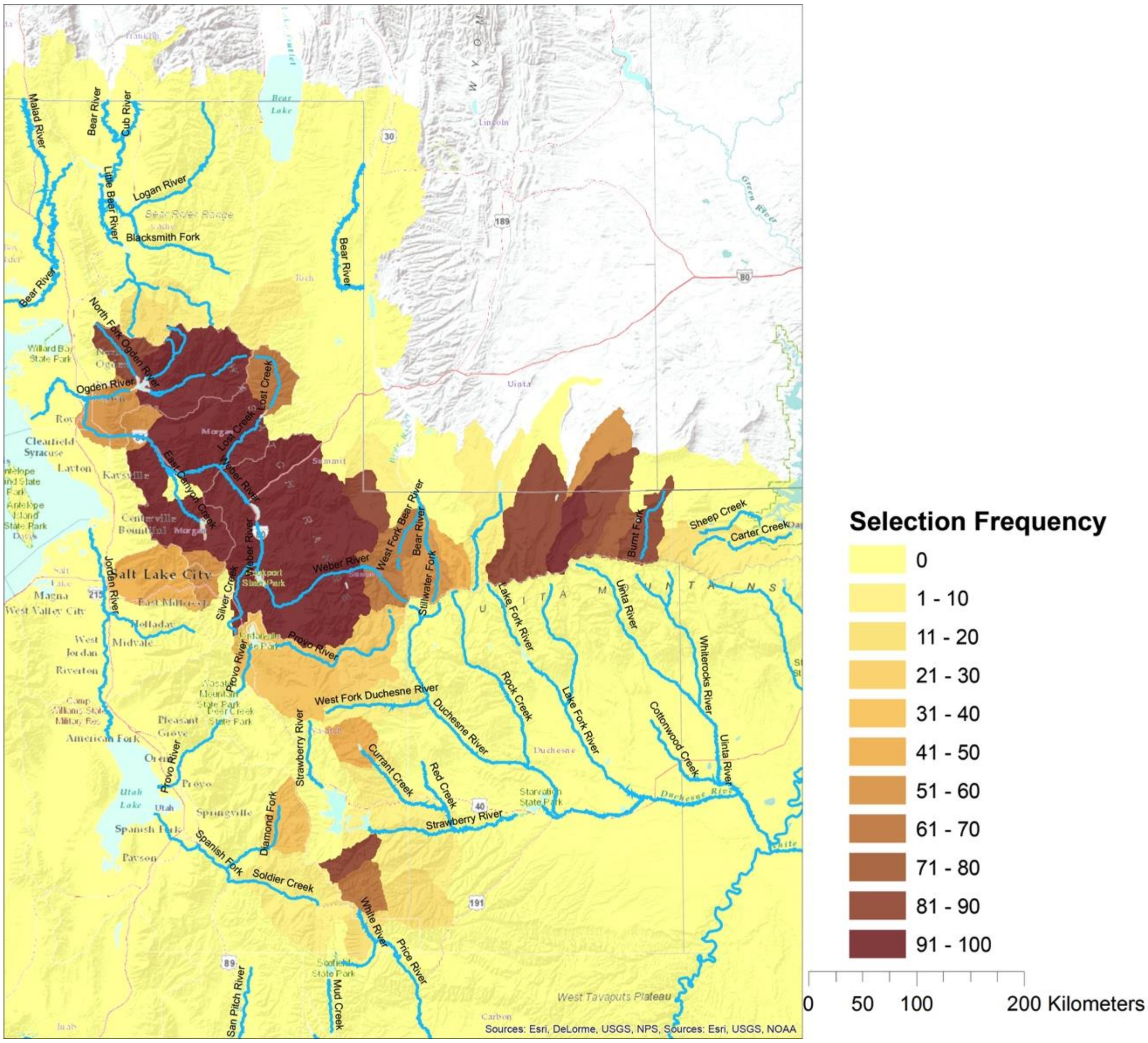

Figure 3.7. Selection frequency results map from 'Native and 10% coexisting population scenarios zoomed in on northern Utah, showing the important rivers identified by the Marxan solution

CHAPTER 4

CONCLUSIONS

Though freshwater accounts for merely 0.01% of Earth's water, lakes and streams provide habitat for over 12,000 documented fish species, and account for approximately 43% of known global fish biodiversity (Dudgeon et al., 2006; Nelson, 2006; Helfman, 2007). In North America, the continent considered to have the greatest temperate freshwater biodiversity on Earth (Abell et al., 2000), the number of threatened, endangered, or vulnerable fish taxa has increased 92% between 1989 and 2011 (Jelks et al., 2011). Five major threats are at the root of the decline: flow modifications, species invasion, habitat degradation, water pollution, and over-exploitation (Dudgeon et al., 2006). Each of these threats can be attributed to human modifications across the landscape. For coldwater fish, these threats are compounded by future climatic changes that have predicted further alteration to geographic distributions (Keleher & Raher, 1996; Rieman et al. 2007; Wenger et al., 2011). But only recently have landscape scale efforts been considered to address the growing number of risks facing freshwater ecosystems (U.S. Forest Service, 2008; U.S. Fish & Wildlife Service, 2010; Peterson et al., 2013). Methods have been proposed and implemented to better direct conservation actions, specifically to address the natural systems most in need of protection. However, many prioritization efforts do not consider possible failures after implementation (Redford & Taber, 2000; Game et al., 2013). Though advancements in quantitative prioritization methods have been refined, additional hurdles are presented when identifying priority areas that best reflect the longitudinal connectivity of streams.

The purpose of my research was to highlight how managers can best consider the risks facing fish biodiversity when identifying important areas for protection that specifically reflect the dendritic nature of stream networks. I examined how risks from an urbanizing basin affect potential protection for five Alaskan salmon species. Part of this process involved applying and integrating several recent advances in systematic conservation planning techniques. Freshwater connectivity rules, and risk simulations were synergized to assess how urbanization and resource extraction affect salmon protected areas. Next, I applied similar methods to multiple basins throughout the entire state of Utah, to examine how anthropogenic, climatological, and ecological risks affect future conservation efforts for two cutthroat subspecies. Results clarify that protected areas identified when completely avoiding risks offer lower returns on investment, and resiliency than protected areas identified when risks are considered and incorporated. This is especially relevant considering most conservation plans are developed to minimize the severity of consequences, should a project fail (Maguire & Albright, 2005; Tulloch et al., 2015). These overly risk adverse strategies can lead to sub-optimal conservation results (Hammill, Tulloch, & Possingham, 2016). Maguire & Albright clarify that excessive risk adverse behavior is common when faced with uncertainty or conflicting objectives (2005). As a result, many individuals working for land management agencies, review boards, and even the public may be prone to risk adverse behavior. This is especially true when conservation plans are integrated into a broader resource planning process, tasked with balancing the needs of multiple biophysical and socio-economic systems (Groves & Game, 2016). Therefore, it is essential to understand the role of risk in conservation decision-making.

I propose that the work conducted in my thesis now offers managers and freshwater conservation planners with useful methods to be implemented in other freshwater systems. I documented that risk adverse management strategies fail in comparison to risk inclusive management strategies. In closing, I recommend that future conservation prioritization efforts consider systematic approaches that reflect possible risks of failure, instead of simply avoiding potential risks.

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APPENDICES

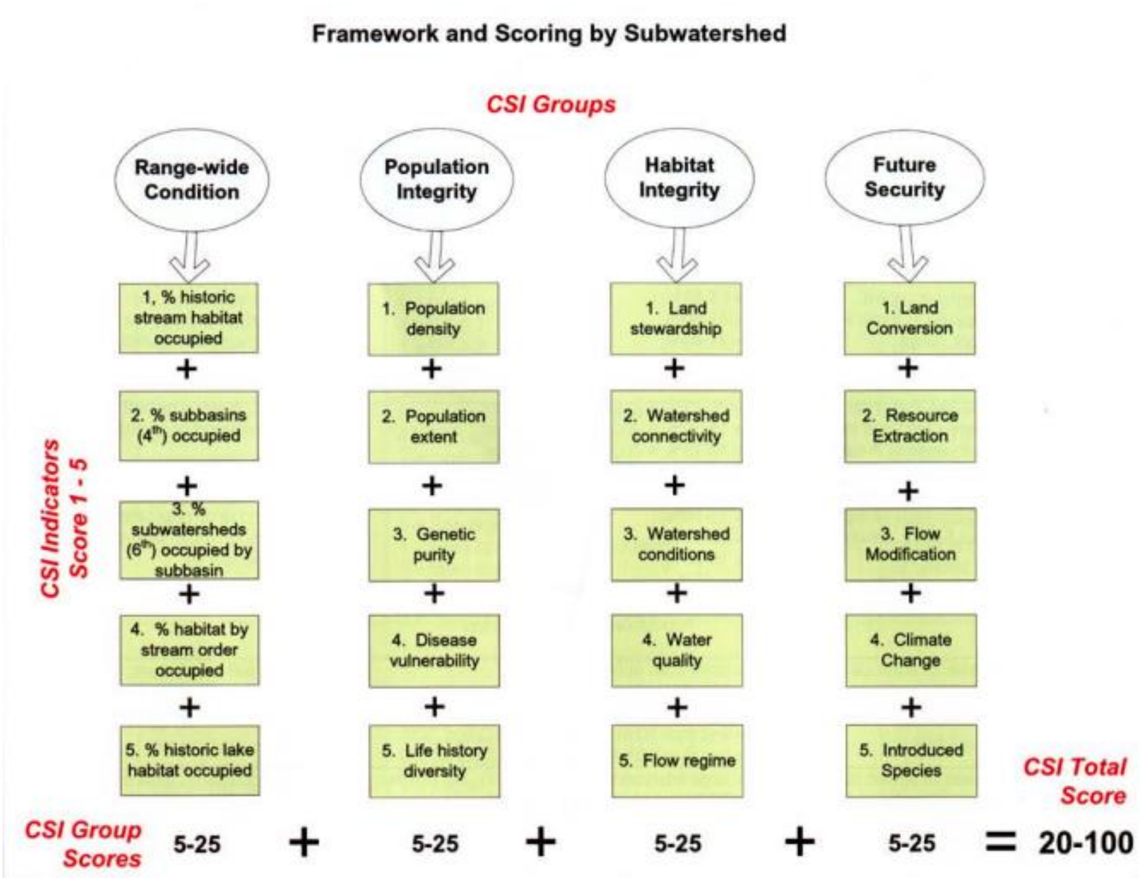
APPENDIX A. Land cost listings used for cost derivation in Chapter 2. Data assembled via LandWatch (2017), and Land and Farm (2017).

Listing Type	Land Type	Cost	Acres	Source
Building included	Housing	698000	5.63	(LandWatch, 2017)
hook ups, wells	Land	75000	50	(LandWatch, 2017)
hook ups, wells	Land	79000	11.5	(LandWatch, 2017)
Building included	Housing	545000	1.14	(LandWatch, 2017)
farming/pasture land	Ag	114000	35.37	(LandWatch, 2017)
Building included	Housing	595000	1.34	(LandWatch, 2017)
hook ups, wells	Land	54000	3.05	(LandWatch, 2017)
Building included	Housing	2500000	315	(LandWatch, 2017)
hook ups, wells	Land	165000	1.32	(LandWatch, 2017)
farming	Ag	560000	80	(LandWatch, 2017)
hook ups, wells	Land	35000	10	(LandWatch, 2017)
hook ups, wells	Land	68000	4.01	(LandWatch, 2017)
hook ups, wells	Land	32500	1.02	(LandWatch, 2017)
hook ups, wells	Land	49500	1.9	(LandWatch, 2017)
hook ups, wells	Land	85000	7.23	(LandWatch, 2017)
hook ups, wells	Land	104000	10.48	(LandWatch, 2017)
hook ups, wells	Land	97500	15	(LandWatch, 2017)
farming	Ag	2240000	320	(LandWatch, 2017)
Building included	Housing	344000	3.25	(LandWatch, 2017)
Building included	Housing	1199000	2.86	(LandWatch, 2017)
Building included	Housing	449950	1.04	(LandWatch, 2017)
Building included	Housing	249900	1.3	(LandWatch, 2017)
Building included	Housing	310000	1.03	(LandWatch, 2017)
Building included	Housing	649900	4.67	(LandWatch, 2017)
Building included	Housing	232000	1.03	(LandWatch, 2017)
Building included	Housing	200000	1.8	(LandWatch, 2017)
undeveloped, recreation access, remote	Natural	44000	3.4	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	69000	3.93	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	80000	4.63	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	13600	18.5	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	25000	5	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	50000	10	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	94900	80	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	75000	50	(Land and Farm, 2017)
undeveloped, recreation access, remote	Natural	24900	15	(Land and Farm, 2017)
forested	forest	45000	5.81	(Land and Farm, 2017)

APPENDIX B. Anthropogenic disturbances used to derive the human disturbance index by Esselman et al. (2011). This data was used as a risk layer in Chapter 3.

Variable (Units)	Scale	Quartile 25%	Quartile 75%	Mean	Source
Natural					
Mean catchment elevation (m)	30 m	189.42	1,108.88	706.93	USGS 2006
Mean catchment slope (°)	30 m	1.04	7.71	5.55	USGS 2006
Mean annual air temperature (10 × °C)	4 km	75.26	150.20	112.14	USEPA & USGS 2005
Mean annual precipitation (mm)	4 km	458.57	1,183.01	866.19	USEPA & USGS 2005
Network catchment area (km²)	1:100,000	26.61	336.59	3,072.14	USEPA & USGS 2005
Anthropogenic Disturbance					
% land use					
Developed, open space	30 m	0	4.52	3.39	USGS 2008
Developed, low intensity	30 m	0	0.38	1.33	USGS 2008
Developed, medium intensity	30 m	0	0	0.43	USGS 2008
Developed, high intensity	30 m	0	0	0.13	USGS 2008
Impervious surfaces	30 m	0.01	0.58	1.08	USGS 2008
Pasture/hay	30 m	0	9.99	8.72	USGS 2008
Cultivated crops	30 m	0	14.72	14.15	USGS 2008
Density (per km²)					
Population	1 km	0.24	6.61	15.69	NOAA 2010
Road crossings	1:100,000	0	1	0.97	U.S. Bureau of the Census 2000
Roads (m/km²)	1:100,000	134.76	4,070.07	3,535.93	U.S. Bureau of the Census 2000
Dams**	NA	0	0	0.03	USACE 2010
Mines or mineral processing plants**	NA	0	0	0.003	USGS 2005
Toxics Release Inventorysites**	NA	0	0	0.02	USEPA 2010
National Pollutant Discharge Elimination System sites**	NA	0	0	0.002	USEPA 2010
Superfund National Priority sites**	NA	0	0	0.001	USEPA 2010

APPENDIX C. Conservation Success Index categories, and results for Bonneville cutthroat trout in Utah (Williams et al., 2007)



APPENDIX C. (cont.)

Indicator	Definition	General Scoring Rules[1]	Relevance to Conservation
Range-wide Condition Indicators			
% Historic stream habitat occupied	% historic stream habitat currently occupied (km) versus historic conditions	5 = >50% historic range occupied; 4 = 35-49%; 3 = 20-34%; 2 = 10-19%; 1 = < 10%	Species that occupy a larger proportion of their historic range will have an increased likelihood of persistence.
% Subbasins (4th level HUC) occupied	% 4th level hydrologic units currently occupied versus those within historic range	5 = 90-100% historic subbasins occupied; 4 = 80-89%; 3 = 70-79%; 2 = 50-69%; 1 = < 50%	Larger river basins often correspond with Distinct Population Segments or Geographic Management Units that may have distinct genetic or evolutionary legacies for the species.
% Subwatersheds (6th level HUC) occupied within subbasin	% 6th level hydrologic units currently occupied compared to those within historic range	5 = 81-100% historic subwatersheds occupied; 4 = 61-80%; 3 = 41-60%; 2 = 21-40%; 1 = 1-20%	Species that occupy a larger proportion of their historic subwatersheds are likely to be more broadly distributed and have an increased likelihood of persistence.
% Habitat by stream order occupied	% current habitat occupied in 1st and 2nd order streams compared to larger stream systems in each subwatershed	5 = > 25% of stream habitat is 2nd order or greater; 4 = 20-25% is 2nd order or greater; 3 = 15-20% is 2nd order of greater; 2 = 10-15% is 2nd order or greater; 1 = < 10% is 2nd order or greater	Species that occupy a broader range of stream sizes will have an increased likelihood of persistence.
% Historic lake habitat occupied	% lake habitat (surface area) currently occupied versus historic condition	5 = > 50% historic lake habitat occupied; 4 = 35-50%; 3 = 20-35%; 2 = 10-20%; 1 = < 10%	Lakes often harbor unique life histories and large populations that are important to long-term persistence of the species.
Population Integrity Indicators			
Population density	Number of adult salmonids per habitat unit area	5 = more than 400/mile; 4 = 151-400/mile; 3 = 50-50/mile; 2 = less than 50 /mile, overall population 500; 1 = less than 50/mile, overall population < 500	Small populations, particularly those below 500 effective population size, are more vulnerable to extirpation.
Population extent	Amount of stream habitat (km or mi) or lake habitat (surface acres) available to population	5 = large interconnected populations, no barriers; 4 = 30-50 km of connected habitat; 3 = 20-30 km connected habitat; 2 =10-20 km connected habitat; 1 = < 10 km connected habitat	Populations with smaller available habitats are more vulnerable to extirpation.
Genetic purity	Measured as percent of fish known or suspected to be hybridized with non-native salmonids, including hatchery fish	5 = no hybridization; 4 = no hybridization known but proximity to non-native trout causes concern; 3 = hybridization < 10%; 2 = hybridization 10-20%; 1 = hybridization > 20%	Hybridization and loss of the native genome via introgression with non-native salmonids are among the leading factors in declines of native salmonids.
Disease vulnerability	Measured as presence of non-native diseases or parasites and/or accessibility of vectors of disease or parasites	5 = no diseases/pathogens; 4 = none present but proximity >10km; 3 = disease/pathogens present but not in target fish; 2 = disease/pathogens present in habitat but not target fish; 1 = disease/pathogens in target fish	Non-native pathogens and parasites, including the myxozoan parasite that causes whirling disease, can infect native trout and reduce their populations.
Life history diversity	Number of life history forms present as compared to presumed historic condition	5 = all life history forms present; 3 = two or more life histories present but at least one absent; 1 = one life history present, others absent	Loss of life history forms, particularly migratory forms, increases risk of extirpation; loss of migratory forms may reduce genetic diversity.

APPENDIX C. (cont.)

Indicator	Definition	General Scoring Rules[1]	Relevance to Conservation
Habitat Integrity Indicators			
Land stewardship	Amount (acres or ha) of federal or state lands with regulatory or congressionally-established habitat protections	5 = 30% or more of subwatershed in protected status; 4 = 20-29% protected; 3 = 10-19% protected; 2 = 1-10% protected; 1 = no protected habitat	Subwatersheds with higher proportions of protected federal and state lands typically support higher quality habitat than do other lands.
Watershed connectivity	Measured by instream barriers, water diversions, and dewatered segments	5 = all streams connected; 4 = streams connected but fragmented at watershed scale; 3 = minor fragmentation within subwatershed; 2 = moderate fragmentation; 1 = high fragmentation	Increased hydrologic connectivity provides more habitat area and facilitates development of multiple life histories, which increase likelihood of persistence.
Watershed conditions	Measured by road density, riparian function, stream habitat complexity, and/or deep pools	if road density is used: 5 = 0-0.1 density; 4 = 0.1-0.7; 3 = 0.7-1.7; 2 = 1.7-4.7; 1 = > 4.7	Habitat conditions as indicated by road density, presence of deep pools, or riparian vegetation, are the primary determinant on persistence of most populations.
Water quality	Measured by presence of 303(d) water quality limited stream segments; number of mines, and point sources of pollution.	5 = high quality, no 303(d) segments; 4 = high quality, minor pollution sources; 3 = moderate to high quality; 2 = moderate quality with significant sources of pollution; 1 = poor quality	Decreases in water quality, including reduced dissolved oxygen, increased turbidity, increased temperature, and the presence of pollutants, reduces habitat suitability for salmonids.
Flow regime	Measured by seasonal fluctuations and total flows, compared to historic regime	5 = flow regime unaltered; 4 = flows approx. 90% of historic; 3 = flows approx. 75%; 2 = flows approx. 50%; 1 = flows highly modified, < 50% of historic	Natural flow regimes are critical to proper ecosystem function. Reduced or altered flows reduce capability of watershed to support native biodiversity.
Future Security Indicators			
Land conversion	Amount of land vulnerable to conversion based on proximity to population centers, slope, land ownership, and road density	5 = amount of land vulnerable to conversion < 20%; 4 = 20-40%; 3 = 40-60%; 2 = 60-80%; 1 = >80%	Conversion of lands from natural habitats will reduce habitat quality and availability.
Resource extraction	Amount of land vulnerable to resource extraction based on energy leases, undeveloped mineral resources, oil, and gas deposits	5 = no potential development; 4 = no active development; low potential; 3 = no active development but recoverable deposits present; 2 = recoverable deposits present, moderate likelihood of active development; 1 = high likelihood of active development	Increased mining and energy development will increase road densities, modify natural hydrology, and increase likelihood of pollution.
Flow modification	Amount of water vulnerable to future diversion, impoundment, or other development	5 = no known vulnerability; 4 = one site or application; 3 = 2 or 3 sites or applications; 2 = multiple sites or applications indicatelikely modifications in significant portion of subwatershed; 1 = multiple applications indicat likely modifications throughout subwatershed	Changes in natural flow regimes are likely to reduce habitat suitability for native salmonids and increase the likelihood of invasion by non-native species.
Climate change	Resistance to climate change impacts as a function of watershed connectivity, habitat conditions, and elevational gradient	5 = high condition; high connectivity; 4 = moderate condition; moderate connectivity; 3 = moderate conditions but low connectivity; 2 = low conditions, low connectivity; 1 = very low conditions	Climate change is likely to threaten most salmonid populations because of warmer water temperatures, changes in peak flows, and increased frequency and intensity of disturbances such as flood and wildlife.
Introduced species	Future vulnerability to introduced species determined as a function of roads in riparian corridors, human population density, and occurrences of introduced species	5 = threats minor or nonexistent; 4 = nonnatives present in larger watershed, chance of spread low; 3 = nonnatives present in watershed, chance of spread moderate; 2 = nonnatives in watershed, chance of spread high; 1 = nonnatives present in subwatershed, chance of spread high	Introduced species are likely to reduce native salmonid populations through predation, competition, hybridization, and the introduction of non-native parasites and pathogens.

APPENDIX C. (cont.)