Redesigning Modern Portfolio Theory to Improve Spatial Recovery Planning for Oregon Coast Coho Salmon

Photo by Paul Jeffrey, courtesy of Wild Salmon Center

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WILD SALMON CENTER

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Signature Page

As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principle of the school is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Abstract

Oregon Coast (OC) coho salmon (*Oncorhynchus kisutch*) are a federally listed threatened species under the Endangered Species Act. It is integral to conserve this species due to their ecological importance in nutrient cycling and cultural significance to Indigenous peoples. The combination of their threatened status and significance creates a sense of urgency for conservation organizations, like the Wild Salmon Center, to efficiently allocate their budgets. In this project we redesigned Modern Portfolio Theory (MPT) to optimize habitat restoration spending. MPT is traditionally used in finance to inform portfolio managers what the risks and returns are of investing in different portfolios of assets. In our redesigned application, the 21 populations of OC coho salmon are treated as assets, with the increase of salmon abundance and variance directly relating to the amount of money allocated to conserve each population. More specifically, we applied our new approach to mitigating barriers that inhibit salmon from traveling back to their natal streams. We analyzed portfolios under multiple budgets and scenarios that prioritize conservation spending in watersheds important to Indigenous peoples. We found that investing in conservation impacts abundance and variance, even with smaller budgets. We also found that portfolio managers do not need to sacrifice equity when choosing portfolios, because there are efficient portfolios that prioritize environmental justice. This endogenous application is the first of its kind in the conservation field and can be applied to a multitude of species or restoration actions beyond OC coho salmon and barrier mitigation.

Project Objectives

1. Assemble adult abundance data for 21 Oregon Coast coho independent populations and use Modern Portfolio Theory (MPT) metrics to characterize which populations most strongly affect the mean, variance, and covariance of Evolutionary Significant Unit-scale salmon returns.
2. Redesign Modern Portfolio Theory as an endogenous conservation framework for conservation of the Oregon Coast coho salmon.
3. Implement conservation framework to generate optimized portfolios, which maximize returns for a given level of variance, under several budget scenarios.
4. Organize and annotate reproducible code to create a tool for simulating portfolios under different budgets and restoration actions.

Background/Significance

Introduction

The Bren School of Environmental Science and Management and the Wild Salmon Center (WSC) are interested in the conservation of the Oregon Coast (OC) coho salmon (*Oncorhynchus kisutch*). The Wild Salmon Center is a non-profit organization that was founded in 1992 by Pete Soverel and Tom Pero, with the intention of protecting salmon and their habitat. They currently support projects and campaigns that restore salmon habitat or prevent damaging actions from occuring. The OC coho salmon have been classified under the same evolutionarily significant unit ("ESU") assessed by sharing the same naturally spawned location originating from "coastal rivers south of the Columbia River and North of Cape Blanco" (NOAA, 2008). Since it was last listed under the Endangered Species Act ("ESA"), it has become one of the species closest to recovery. Historic anthropogenic activities, including timber production, resulted in the loss of upland and riparian wood, among other anthropocentric activities including splash daming (cut logs that have temporarily stopped rivers) and their abrupt removal has resulted in rapid flooding that removed gravel and other geo-solids required for building suitable salmon spawning and nursing grounds. Habitat restoration efforts, such as mitigating barriers, adding large woody debris, and enhancing riparian vegetation have contributed to the recovery of this species. However, with limited budgets and time, it is integral for conservation managers like the WSC to optimize their spending on restoring OC coho salmon habitat. This collaboration between the Wild Salmon Center and Bren School plans to apply Modern Portfolio Theory (MPT), a quantitative approach, to technically assess the best ways to spatially optimize conservation budgets and recovery of the OC coho salmon.

Salmon Literature

The Oregon Coast coho salmon are widely studied organisms and the conservation of this species is prioritized because of how integral they are for the larger ecosystem. Protecting this species results in positive habitat effects for terrestrial, oceanic, and tribal communities that depend on them. Currently, the Oregon Coast coho salmon is a threatened species listed under the Endangered Species Act (ESA). There are 21 populations that make up the Evolutionary Significant Unit (ESU) of the Oregon Coast coho salmon (NMFS, 2016). The ESU represents a metapopulation, or group of populations, that is "substantially reproductively isolated from other conspecific population units, and represents an important component in the evolutionary legacy of the species" (Waples, 1995). Conspecific populations are populations belonging to the same species. The 21 populations along the coast of Oregon make up the scale and scope of this program. Figure 1 shows the 21 populations of OC coho salmon.

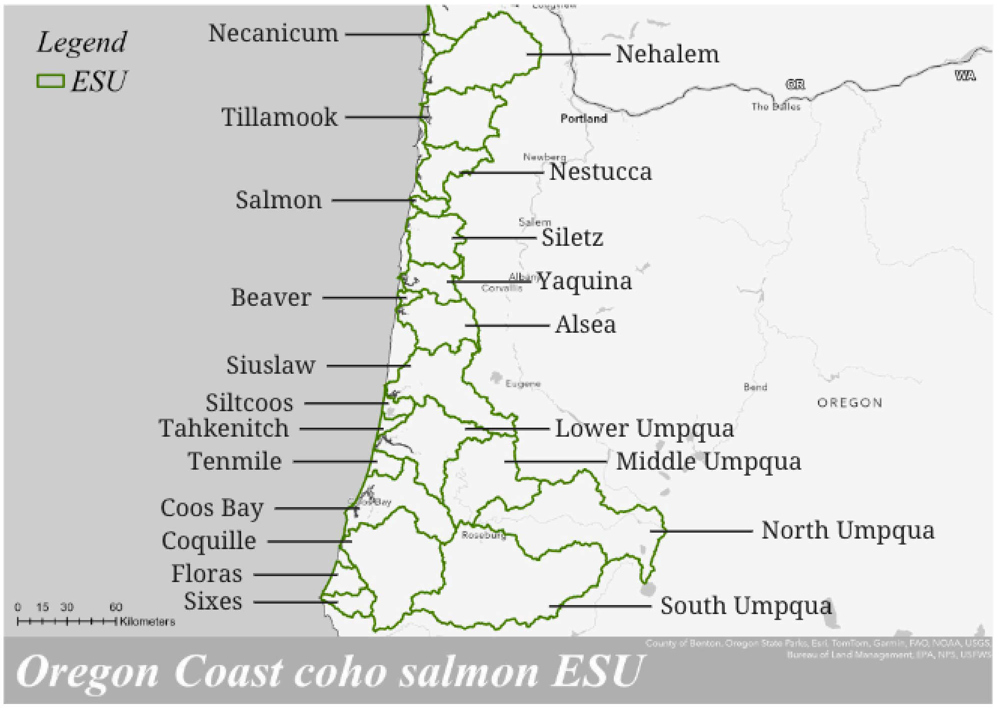

Figure 1. Map of the OC coho salmon ESU in Oregon.

According to the Final ESA Recovery Plan for Oregon Coast coho salmon, created by the National Marine Fisheries Service (NMFS), their populations have greatly declined. It is estimated that predevelopment populations could have exceeded 1-2 million individuals when conditions were favorable. These numbers sharply declined as commercial fishing took off, especially from the 1960s to 1980s where harvest rates ranged from 60-90% of the population (Stout *et al.*, 2012). This caused the number of native spawners to collapse to 14,600 in 1983, and triggered the first petitioning for the OC coho salmon to be listed under the ESA (NMFS, 2016 and NMFS, 1993).

Due to ESA-listing constraints and management agreements, the aggressive harvesting of OC coho salmon has stopped, but their populations are still largely impacted by human development that alters or destroys their native habitat (NMFS, 2016). Salmon are anadromous, meaning they travel from the ocean and up rivers to their natal spawning grounds (Groot and Margolis, 1991). Salmon hatch in cool, freshwater streams with slow moving pools. They rear for almost a year in freshwater through the summer and winter (Groot and Margolis, 1991). In the spring, they begin their migration to estuaries and the ocean. Estuaries are an important part of their habitat that allows them to acclimate to saltwater. Once in the ocean, they stay there until they are 3 years old, or fully mature; then they begin the cycle again by traveling back to their natal streams. This need to unobstructedly move back and forth between different habitats makes them especially vulnerable to development (NMFS, 2016).

Currently, the main factors that impact salmon populations are lost habitat, reduced complexity, degraded water quality, blocked passages, and climate change (NMFS, 2016). Stream complexity is the ability for a stream to provide different habitats for fish through pools or side channels created by wood debris, beavers, and connection to wetlands. In fact, for all 21 OC coho populations, complexity is the primary or secondary limiting factor (NMFS, 2016). In a study done in British Columbia, it was found that these pools help pacific salmon avoid harsh conditions in the winter, provide protection for juvenile salmon from predators and high summer flows, and serve as summer rearing habitat as well (Swales and Levings, 1989). This helps sustain the productivity of salmon populations, even in years where ocean conditions are poor. Stream complexity is reduced by human development including, but not limited to, timber, agricultural, and urban development (Wing and Skaugset, 2002). The prolific timber industry in Oregon reduced stream complexity through widening streams with splash dams and lowering the amount of instream wood or boulders. Agricultural development in Oregon reduces stream complexity by removing vegetation buffers, diverting stream flow, and building dykes and levees (Wing and Skaugset, 2002). Blocked streams are another serious limiting factor because they prevent salmon's migration back to their natal streams. Streams can be blocked by bridges, dams, tide gates, dikes, levees and culverts, as seen in Figure 2 (NMFS, 2016).

Figure 2. A salmon leaping up a culvert (Bernton, 2018).

Improving overall habitat conditions through restoration actions will be essential to attempt to safeguard salmon from the inevitable effects of climate change. One of the likely impacts of climate change on salmon will be changes in water temperature. According to a study observing the John Day River Network in Oregon, an increase in water temperature will likely cause habitat loss for salmon. This study's model predicted that in a moderate climate change scenario, chinook salmon would lose 69–95% of their habitat volume. This is likely because headwater reaches, the home of juvenile and oversummering salmon, are especially sensitive to changes in temperature (Ruesch *et al.*, 2012). As water temperatures rise, predation of introduced non-native fish has potential to increase which would have negative effects on the lake and slow water rearing phases for OC coho salmon (NMFS, 2016).

Salmon are incredibly important to their home ecosystems because they are a keystone species. This is because they have a large impact on the balance of ecosystems as a source of nutrients for a multitude of species. For example, salmon carcasses are predictors of scavenging bird density and diversity. There is also a link between bald eagle presence and salmon carcasses specifically killed by bears and wolves (Field and Reynolds, 2013). Salmon are also an indicator of bears, who's population density can be up to 20 times greater when present (Reimchen, 2000). Without the nutritional input of salmon, these food webs would likely collapse.

Salmon also have a strong significance for Indigenous tribes across the Pacific Northwest. Salmon are considered a first food, which are the essential foods that tribes have been relying on for thousands of years (State of Oregon, 2020). Salmon receive special honors from many tribes because tribal creation stories say that salmon was the first to offer itself to the Creator as food for humans, followed by water. Many tribes also have a First Salmon Ceremony, which celebrates this story and thanks the salmon for returning every year (State of Oregon, 2020). The tribes also understood sustainable fishing practices, and restricted the amount of fish caught during the first couple days of the salmon returning up the stream (State of Oregon, 2020). There are 5 tribes on the Oregon coast who are active partners with the National Oceanic and Atmospheric Administration (NOAA) working on Oregon Coast coho salmon restoration (NOAA, n.d).

In short, Oregon Coast coho salmon are a complex, threatened species that have very specific habitat requirements and lifecycles. A combination of overfishing and human development caused their population to initially collapse, and now the latter is inhibiting their population's recovery. Climate change is also presenting potential future threats to this keystone species. This interconnectedness is what makes salmon such a difficult species to conserve, which leads organizations, such as the WSC, to try to find different frameworks to identify the most useful investments they can make. One way to optimize budgets is to treat investing in salmon populations as a portfolio by utilizing Modern Portfolio Theory.

Modern Portfolio Theory Literature

MPT is a quantitative approach that compares portfolios by minimizing variance of return along an "efficiency curve" that is generated by optimal risk-return ratios (Fabozzi *et al.,* 2002). Figure

3 shows an illustrative example of this efficiency curve, where optimal portfolios with different risk-return ratios fall along the curve, and less optimal portfolios are under the curve. This type of graph is often called an efficiency curve, efficiency frontier, and risk-return graph.

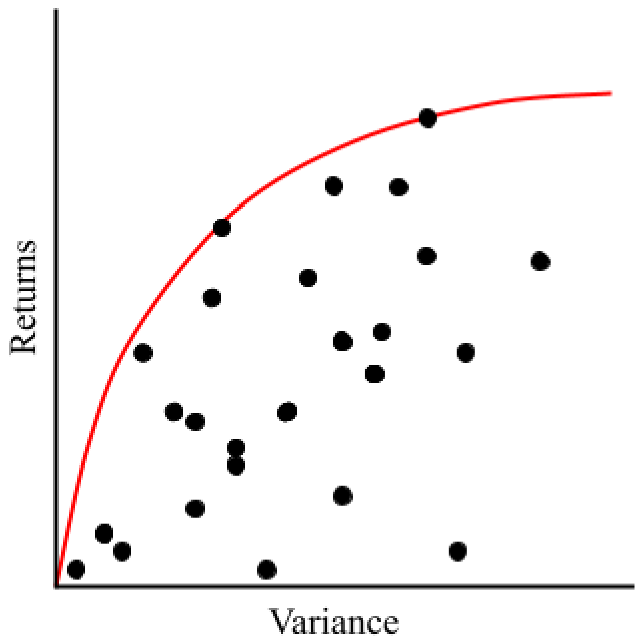

Figure 3. Illustrative Modern Portfolio Theory efficiency curve.

Traditional MPT applications consist of three components: a portfolio, assets, and weights. An investment portfolio is a collection of stocks, bonds, and financial derivatives held by investors or financial organizations to help reduce and spread risk of loss (Xie and Wang, 2022). An asset can be defined as something that is owned or controlled for the purpose of generating value (Ando and Mallory, 2012). Weights determine how much of an investment is allocated to an asset (Alvarez *et al.*, 2017). Portfolio investments are widely practiced in financial decision-making. For example, if we are interested in investing in stocks such as Apple, Google, and Microsoft, MPT can be used to efficiently allocate individual investments made across the companies to optimize overall returns while minimizing risk. For example, a portfolio comprising 3 assets could inform investors the marginal returns and variance of allocating 40% to Facebook, 50% to Microsoft, and 10% to Google. In this situation, the portfolio is the different companies to invest in, the assets are the individual stocks, and the weights are the fraction of a given budget.

Applying Modern Portfolio Theory to Conservation

MPT more recently has been applied in a conservation context as an optimization tool to aid natural resource investment decision making. In natural resource management, this approach is mainly used to understand habitat effects from conservation projects (Alvarez *et al.*, 2017). To translate financial variables to conservation projects, a portfolio and its assets will change depending on the scope of a study. In a conservation context, returns from a portfolio would be the benefits from a conservation investment and risk is losing ecosystem benefits from a conservation investment that did not return as many benefits as expected. Many challenges come with utilizing a financial model in a conservation setting. One major challenge is changing the definition of portfolio weights. This is because, in a strictly financial setting, portfolios with high risk and low return could be viewed as an unreliable investment because they would gain little capital, while taking on high risk. Investors would be more likely to invest in non-risky portfolios that are already showing success in terms of returns. MPT can provide a useful tool for conservation, when managing plant and animal populations with low population abundance and high annual volatility to support population stability.

For example, an organization interested in investing in conservation projects between beaver dam building versus stream stabilization projects can compare the project's variance and the estimated salmon "return." Conservation managers will have the agency to balance whether they prioritize increasing salmon abundance numbers regardless of the variance or risk that may result from the project and vice versa. Modern Portfolio Theory assesses portfolio's return on assets over time, the risk of those returns, and lastly determining the portfolio weights that will grant the lowest risk and highest return.

Applying Modern Portfolio Theory to Salmon and Fisheries

More specifically, MPT has been applied to different salmon populations in a limited number of studies, such as Moore *et al.,* 2009, Alvarez *et al.*, 2017, and Griffiths *et al.,* 2014. While the definition of an asset, investment, and portfolio will differ between ecological and economic applications of MPT, they both share the common goal of optimizing portfolios to maximize returns, while minimizing risk (Griffiths *et al.,* 2014). Investments typically depend on the objective and perspective from which MPT is being applied. For example, applying MPT with the goal of increasing fish counts for fisheries will lead to vastly different investments than if the goal was to increase fish counts for ecosystem services.

"Synchronization and portfolio performance of threatened salmon" by Moore *et al*. is an application of MPT that seeks to understand the effects of synchronization of sockeye salmon in the Snake River Basin. In this study, the portfolio was the Snake River ESU, the assets were populations, and weights were the proportional contribution of each asset (Moore *et al.,* 2009). Their results show that synchronization among populations has a negative effect on portfolio performance, leading to increased vulnerability of the ESU (Moore *et al.,* 2009). A unique aspect of this study is that they integrate a population model, specifically the Ricker model. They also used the Sharpe ratio to evaluate the performance of different portfolios. The Sharpe ratio standardizes returns by their variance and covariance. This is an example of applying MPT to salmon to try to understand population dynamics (Moore *et al.,* 2009).

“Optimizing provision of ecosystem services using modern portfolio theory” by Alvarez *et al*. utilizes MPT to assess the Colombian Pacific Fishery. In this study, the portfolio was the fishery, assets were fish grouped by economic significance, and returns were measured by the biomass of fish caught (Alvarez *et al.*, 2017). The goal was to be able to set catch limits at the ecosystem level. A unique aspect of this study is they run three different scenarios to see how they fall along the efficiency frontier, a baseline scenario with historical catch levels, a sustainability scenario with decreased yields, and an equity scenario where artisanal fish are harvested more than industrial (Alvarez *et al.*, 2017). They also explain how applying Modern Portfolio Theory to natural resources management requires careful consideration of who the portfolio manager is, definitions of assets, how risks and returns are measured, and what constraints apply to the system (Alvarez *et al.*, 2017).

“Performance of salmon fishery portfolios across western North America” by Griffiths *et al*. utilizes MPT to characterize portfolio reliability to inform management goals and conservation efforts. Their portfolio was populations of chinook and sockeye salmon at different latitudes, assets were the total salmon runs in these different locations, and weights were the relative contribution of each asset (Griffiths *et al.,* 2014). Similar to Moore *et al.*, this study also uses the Sharpe ratio to evaluate portfolios. They found that portfolios at higher latitudes were more reliable, where habitats were less degraded by anthropogenic impacts (Griffiths *et al.,* 2014).

These studies emphasize the tradeoffs between applying MPT outside of the traditional finance application. All had different methods of determining their portfolios, weights, and how they evaluated these portfolios. In a fisheries’ setting, maximizing the overall harvest of salmon is the main goal, and a weight of zero is inconsequential because it would equate to not fishing a population. So far, applications of MPT to salmon and fisheries have been comparing different portfolios against each other by using the Sharpe ratio, and have not tried making the weight allocations endogenous to the returns and variance. By manipulating the original MPT framework, we can include more unique constraints so that there are no harmful consequences from divesting in a population.

Methods

Data

Oregon Coast Coho Abundance Dataset

This dataset includes the adult spawner abundance of all 21 populations from 1994-2019. It was retrieved from the WSC. This information was originally collected by the Oregon Department of Fish and Wildlife (ODFW) from annual spawning ground surveys. These surveys are conducted every year between October and January, before the coho start spawning. Fish are counted by technicians who walk up and down the stream, counting fish as well as noting qualitative stream conditions (Lewis *et al*., 2012). A limitation of this dataset is that it only includes adult spawners, and does not have data regarding coho salmon at different life stages.

Barriers Dataset

The Oregon Fish Passage Barrier Data Standard was originally created by the ODFW and was published by Conservation Biology Institute on DataBasin in 2017. This dataset shows barriers that inhibit salmon passage, which informs where restoration actions can occur. It was collected from 2008-2016, and has over 40,000 barrier features, making it the most comprehensive barriers dataset in Oregon. Organized as a point feature class layer, each individual point representing a unique barrier as well as relative tabular information. Figure 4 shows all barriers present in the ESU, not delineated by type. Barrier types include culverts, dams, tide gates, bridges, fords, weirs, and cascades/falls. Some barriers also have the level of passability for salmon. Limitations include barrier presence and passability. This dataset is a snapshot in time, so it is unknown if some of these barriers have been removed, or if more have been added. The passability attribute is also limited because not every barrier has a passability status, and it is unknown if it has changed since the data was collected.

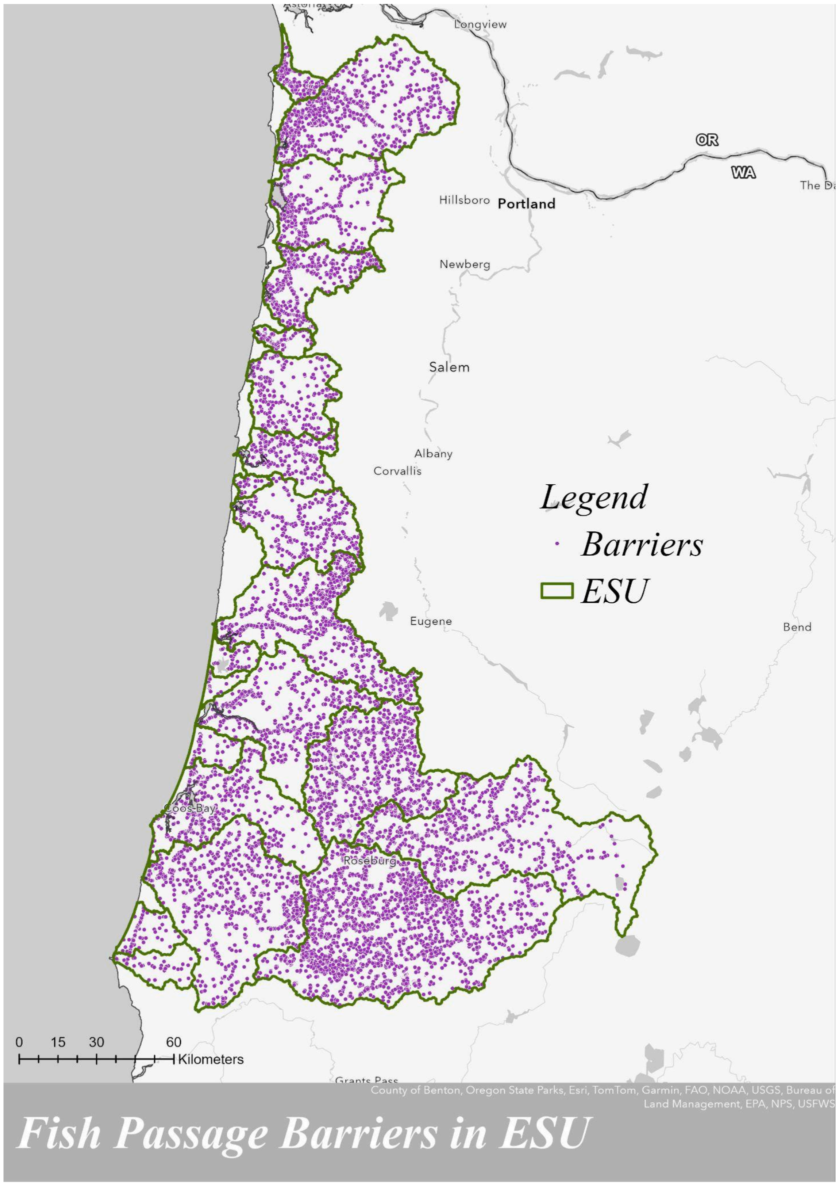

Figure 4. Fish Passage Barriers in the OC coho ESU. Each purple dot represents a fish passage barrier, such as culverts, dams, tide gates, weirs, fords, bridges, and falls.

Barrier Mitigation Cost Dataset

The Oregon Watershed Restoration Inventory (OWRI) was created by the Oregon Watershed Enhancement Board and is updated every year. It is a collection of over 19,000 watershed restoration projects since 1995. This information is stored as an Excel spreadsheet, and has in-depth details about every project, such as when it was completed, the project location, actions taken, as well as how much the project cost. The project cost could be viewed as a limitation because it is self reported and the cost breakdown is unknown.

Reach Dataset for Assessing Stream Passability

The National Hydrography Dataset (NHD) was created by the United States Geological Survey and retired in 2023. It is a geodatabase that consists of the water drainage network in the US, with features like rivers, streams, canals, lakes, ponds, and more. It was processed and sent to the team by Jon Hart at the WSC, who narrowed it down to the reaches and added the stream level attribute. A limitation of this dataset is that it is no longer being updated as of October 2023, so any changes in streams since then will not be reflected. As an example of this data, the Floras population's streams are visualized in Figure 5.

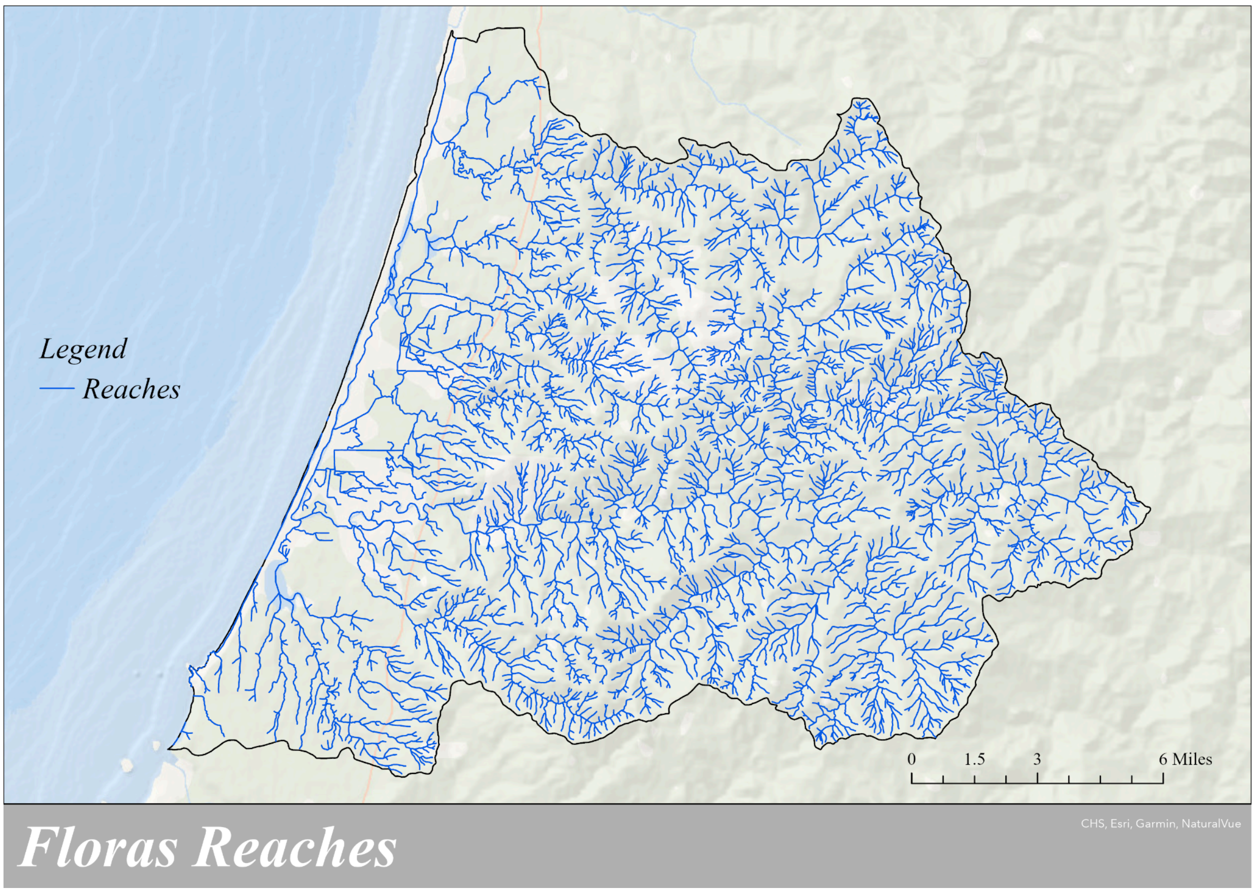

Figure 5. Reaches in the Floras population.

Apply a Direct Approach to MPT

In the early stages of understanding how to apply MPT to salmon conservation, the team conducted a preliminary analysis of a one-to-one, direct application of MPT on the OC coho salmon abundance data using RStudio. Portfolio Theory is commonly represented by Equation 1, where γ is risk tolerance, μ is the vector of mean population returns, w is a vector of portfolio weights, Σ is summation of the weights, and T shows that we are multiplying arrays. $\mu^T w$

represents the expected returns of the portfolio and $w^T\Sigma w$ represents the variance of a portfolio return, which are visualized on a traditional MPT risk-return graph, as shown in Figure 2.

$$\gamma\mu^T w - w^T \sum w \tag{1}$$

This can be solved with a closed form solution by constraining to a given return and minimizing variance, as seen in Equation 2. In Equation 2, $min\ V(w_i)$ represents minimizing variance, $\sum_i$ is taking the sum of the weights across populations, i is the population, w_i represents the weight allocated to population i, μ_i is the mean return for population i, and R is the mean return constraint across the ESU.

$$\begin{gathered} \min_{w_i} V\left(w_i\right) \\ \text{subject to} \sum_i w_i \mu_i \geq R \end{gathered} \tag{2}$$

This equation is widely used to define MPT and can be re-defined to include other constraints and be applied to different contexts (Markowitz, 1952). In this direct approach, the portfolio is the OC coho salmon ESU, the assets are individual populations, and the weights are the proportion that a population contributes to the overall ESU. To implement Equation 2, we solve for an optimized weight that is allocated to population i in the ESU based on the constraint of salmon returns for population i that minimizes variance. In this approach, the annual salmon returns for a population directly influences the weight of a population. The weight given to a population represents a proportion of the overall contribution to the ESU. Utilizing the R package "quadprog," we generated portfolios and the efficiency frontier visualized in Figure 6. In Figure 6, the baseline scenario portfolio is plotted against an efficiency frontier to demonstrate the inefficiency of the current ESU portfolio because of its location below the curved frontier. To optimize that portfolio, the ESU would either need to maintain the current level of risk for a higher amount of return to travel to the red data point, or the ESU would need to maintain the current level of returns for a smaller amount of variance. In MPT, a portfolio manager must choose between maximizing returns or minimizing variance because of the inevitable tradeoffs of the efficiency frontier.

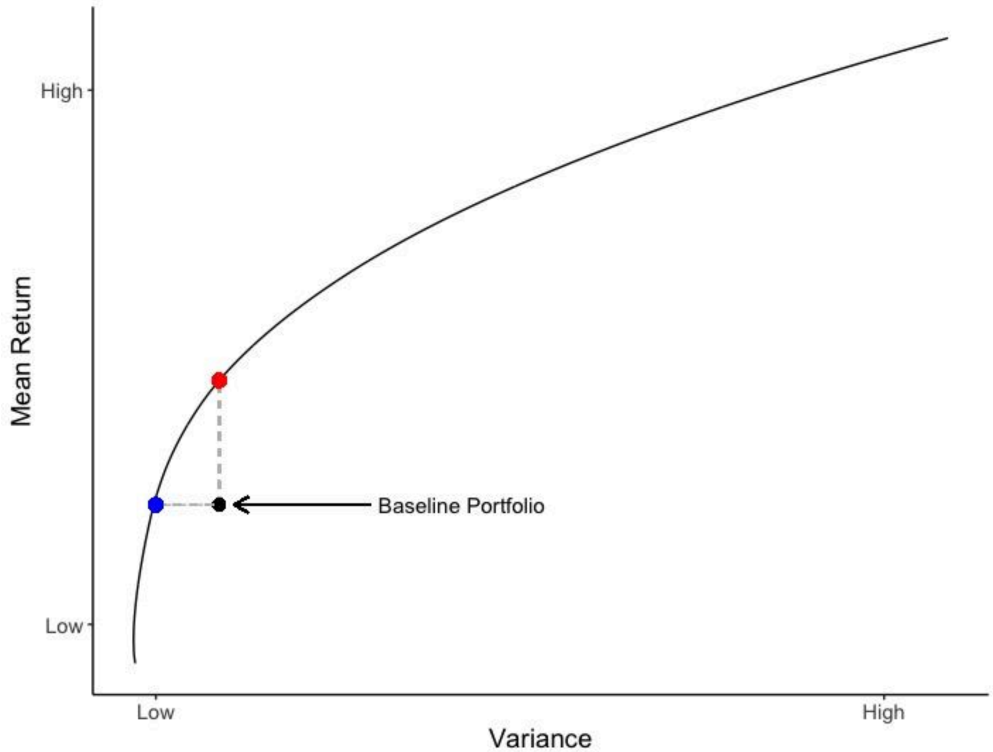

Figure 6. Efficiency frontier of the OC coho salmon ESU under a direct application. The black point denoting the 2019 mean and variance ("current" conditions of the ESU as this is our most recent data) and how much change is required if we wanted to maximize the return, shown in red, or minimize variance, shown in blue.

Using this direct approach, numerous populations receive a weight of '0' as referenced in Table 1. In this application, populations that receive a weight of '0' are populations that are unproductive to increasing the overall salmon return to the ESU. Portfolios that optimize overall fish returns while reducing variance will fall along the efficiency frontier, and have the highest possible returns. Traditional application of MPT would eliminate all populations that receive a weight of '0' because they do not aid in maximizing returns. Effectively, traditional MPT would inform portfolio managers to completely eliminate all salmon populations that recieve a weight of '0' because they do not contribute in maximizing overall return of salmon. This is a major limitation of the direct approach and the main reason why redesigning MPT is essential to properly use MPT for OC coho salmon conservation.

Population	*Optimized Weights 1*	*Optimized Weights 2*
Alsea	*0.206*	*0.180*
Beaver	*0.000*	*0.000*
Coos	*0.028*	*0.047*
Coquille	*0.000*	*0.000*
Floras	*0.000*	*0.000*
Lower Umpqua	*0.000*	*0.000*
Middle Umpqua	*0.000*	*0.000*
Necanicum	*0.000*	*0.000*
Nehalem	*0.000*	*0.000*
Nestucca	*0.193*	*0.000*
North Umpqua	*0.000*	*0.000*
Salmon	*0.000*	*0.240*
Siletz	*0.000*	*0.000*
Siltcoos	*0.000*	*0.000*
Siuslaw	*0.007*	*0.000*
Sixes	*0.173*	*0.120*
South Umpqua	*0.150*	*0.213*
Tahkenitch	*0.114*	*0.200*
Tenmile	*0.119*	*0.000*
Tillamook	*0.000*	*0.000*
Yaquina	*0.000*	*0.000*

Table 1. The weights of the portfolios along the efficiency frontier in Figure 3. Red point on graph represented by "Optimized Weights 1". Blue point on graph represented by "Optimized Weights 2".

Redesign MPT as an Endogenous Portfolio Theory Application

To determine a more meaningful way to interpret investment weights in a conservation context, the team developed an endogenous portfolio theory application of MPT. Using our alternative MPT approach, the portfolio remains the OC coho salmon ESU, the assets remain the 21 individual populations, but the weights are now conservation dollars. Similar to a finance portfolio where investments are allocated across different assets, conservation dollars are allocated to each population for conservation. In this endogenous portfolio theory application, returns and variance are endogenous to the weight allocated to a given population. Weight allocations lead to changes in returns, which in turn lead to changes in variance for the portfolio. These changes in returns and variance of a population are plotted as portfolios on a similar MPT risk-return graph, as shown in Figure 6. This endogenous application can be used to understand how to differentially allocate a budget across the ESU, while balancing aggregate returns and variance.

Weight allocations lead to improvements in both returns and variance, shown by $S(w_i)$ in Equation 3, where w_i is the weight allocated to a population. In Equation 3, i is population, $S(w_i)$ is salmon returns after investment, w_i is conservation dollar investment, ∑ is summation, n is total populations, σ is standard deviation, σ^2 is variance, j represents any population that is not population i, γ is risk aversion, and COV represents covariance. To further break down Equation 3, $max_{w_i} \sum_{i=1}^{n} S(w_i)$ is salmon abundance after conservation dollar investment and $\sum_{i=1}^{n} \sigma_1^2 S(w_i)^2 + \sum_{i=1}^{n}\sum_{j\neq 1}^{n} \sigma_i S(w_i) \sigma_j S(w_j) COV_{i,j}$ is the variance and covariance after conservation dollar investment. Equation 3 shows how conservation investment (w_i) directly impacts abundance and variance across the ESU.

$$\max_{w_i} \sum_{i=1}^{n} S(w_i) - \gamma\left[\sum_{i=1}^{n} \sigma_i^2 S(w_i)^2 + \sum_{i=1}^{n}\sum_{j\neq 1}^{n} \sigma_i S(w_i)\, \sigma_j S(w_j)\, COV_{i,j}\right] \quad (3)$$

Using this approach, portfolio managers will be able to choose between a suite of portfolios along an efficiency frontier. Each portfolio represents unique weight allocations and the portfolio manager can decide how much variance they are willing to accept based on their risk tolerance along the efficiency frontier. A portfolio manager, then, with a fixed budget can better determine where to most effectively allocate conservation dollars across the ESU by maximizing salmon returns for a given level of variance. First, the portfolios need to be simulated and $S(w_i)$, the salmon returns after investment, needs to be calculated. $S(w_i)$ is difficult to calculate, and to do so we need to estimate the returns at baseline, the impact on returns from investments, the cost of investments, and how investments impact carrying capacity and productivity. These steps are shown in Figure 7, where each box is a step and section of this report. In the following 4 sections, we detail how this framework is developed and then in *Applying Endogenous Portfolio Theory* we incorporate the specific restoration actions and how they tie back into calculating $S(w_i)$ in Equation 3.

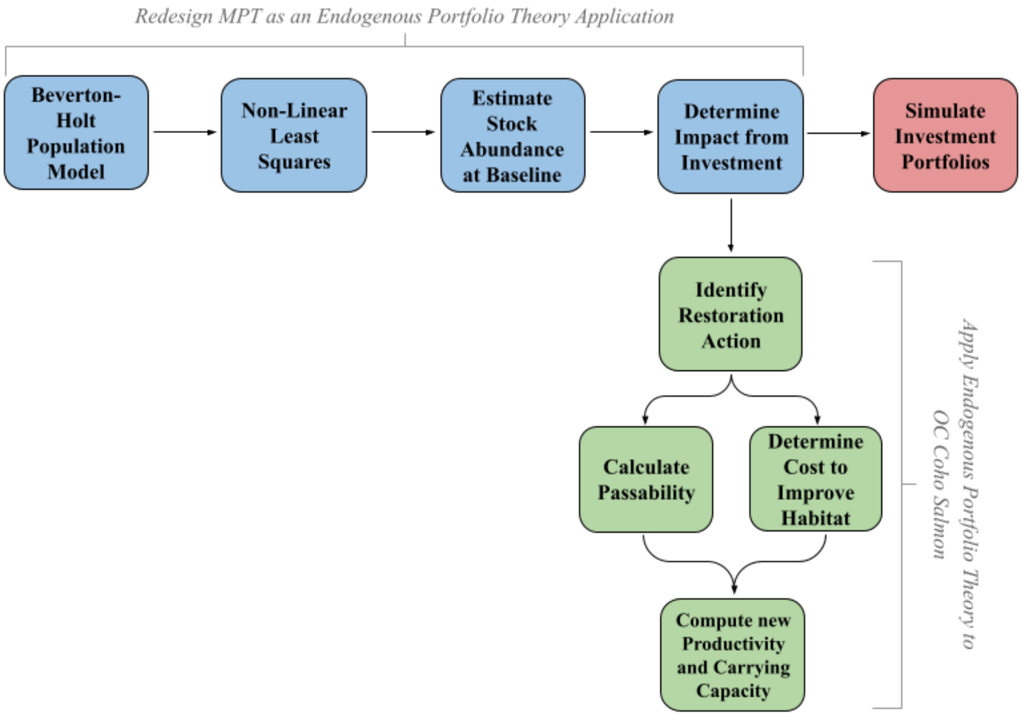

Figure 7. Endogenous portfolio theory application of MPT conceptual diagram.

Beverton-Holt Population Model

The goal is to be able to predict how a population will respond to habitat changes from conservation investments, written as $S(w_i)$ in Equation 3. By incorporating a population model into the framework, we can estimate the impact on salmon returns from conservation investment. In order to integrate habitat impacts across the multiple life stages, lifecycle models (LCMS) can aid in diagnosing habitat impairments inhibiting recovery and population building of pacific salmon (Jorgensen *et al.*, 2021).

There are different types of population models that characterize habitat impacts and the life-stages of salmon, such as multi-stage lifecycle models and single-stage lifecycle models. A multi-stage lifecycle model for coho salmon captures six freshwater life stages: adult upstream migration, spawning, egg incubation, fry colonization, summer rearing, and winter rearing (Jorgensen *et al.,* 2021). The advantage of a multi-stage lifecycle model such as the Habitat Assessment and Restoration Planning (HARP) model is that it quantifies degradation and potential improvements in habitat conditions, while incorporating life-stage parameters of a species. Second is that it can evaluate a change in population size as a function of habitat changes for each life stage in order to understand habitat effects throughout the six freshwater life stages. However, utilizing this type of model requires abundance data for every life-stage, which is not possible for the scope of this project. Our data is limited to annual adult spawner abundance data, therefore utilizing a single-stage lifecycle model is a viable alternative.

The Beverton-Holt Model is a single-stage lifecycle model which is linked to specific age-structures like improving probability for egg incubation of salmonid eggs (Jorgensen *et al.*, 2021). The Beverton-Holt model operates according to Equation 4, where $N_{stage+1}$ represents the abundance of fish at the end of a life stage, p is productivity of the stage, N_{stage} is abundance of fish at the beginning of a lifecycle stage (eggs), and c is the carrying capacity for the stage (Jorgensen *et al.,* 2021).

$$N_{stage+1} = \frac{p \cdot N_{stage}}{1+(\frac{p}{c}) \cdot N_{stage}} \quad (4)$$

Equation 4 can be adapted to the variables for our project into Equation 5, where $S_{t+1,i}$ represents the number of return spawners for population i at time $t+1$, $S_{t,i}$ is the number of current spawners for population i at time t, p_i is the productivity coefficient for population i, and c_i is the carrying capacity coefficient for population i.

$$S_{t+1,\, i} = \frac{p_i S_{t,\, i}}{1 + \frac{S_{t,\, i}}{c_i}} \quad (5)$$

Using Equation 5*,* we derive the equilibrium stock abundance, shown by the steps presented in Equation 6, where salmon returns are the same every year, which is a time independent measure of salmon abundance. In Equation 6, S_i is the equilibrium stock abundance for population i, p_i is the productivity coefficient for population i, and c_i is the carrying capacity coefficient for population i. Estimating the equilibrium stock abundance allows us to quantify what the population should be under given conditions. We can then use this to determine the impact from investment by comparing the stock abundance and variance prior to investment with the stock abundance and variance after investment.

$$S_{t+1,\,i} = \frac{p_i S_{t,\,i}}{1 + \frac{S_{t,\,i}}{c_i}}$$

Divide both sides by $S_{t,i}$

$$1 = \frac{p_i}{1 + \frac{S}{c_i}}$$

Multiply both sides by denominator

$$1 + \frac{S}{c_i} = p_i$$

Subtract both sides by 1 and multiply by denominator

$$S_i = \left(p_i - 1\right) c_i \tag{6}$$

Non-Linear Least Squares

Equilibrium stock abundance, as shown in Equation 6, is a function of productivity and carrying capacity, which can be improved by conservation investments, because they are a function of w_i as seen in Equation 3. To estimate the equilibrium stock abundance for each population prior to conservation intervention, we performed a non-linear least squares (NLS) regression to estimate productivity and carrying capacity coefficients for each population using the annual adult spawner abundance data. Tahkenitch and Sixes were excluded from this analysis due to computational errors when estimating productivity and carrying capacity coefficients using nonlinear least squares regressions on the adult spawner abundance data. Both Tahkenitch and Sixes are small watersheds, and removing them reduced the overall portfolio to 19 populations from 21. Nonlinear least squares allows us to best fit a set of observations to a nonlinear model with multiple unknown values. The estimated productivity and carrying capacity coefficients, shown as $\widehat{p_i}$ and $\widehat{c_i}$ in Equation 7, were then used to estimate equilibrium stock abundance, shown as $\widehat{S_i}$.

$$\widehat{S_i^*} = \left(\widehat{p_i} - 1\right) \widehat{c_i} \tag{7}$$

Estimating equilibrium stock abundance prior to conservation, allows us to understand how stock abundance is improved with conservation investments.

Estimate Stock Abundance at Baseline

The equilibrium stock abundance in Equation 7 represents our baseline scenario, prior to conservation investment. Restoration interventions improve productivity and carrying capacity of the populations. Therefore, as we improve productivity and carrying capacity with conservation investments, equilibrium stock abundance will increase. Using equilibrium stock abundance at baseline, $\widehat{S}_{i}$, we can model the impact from restoration interventions, shown by $S(w_i)$ in Equation 3 by linking investment weights to the productivity and carrying capacity coefficients.

Determine Impact from Investment

To determine the impact from investment on populations, we need to determine how our investment weights impact stock abundance. Once values have been estimated for the productivity and carrying capacity coefficients for each population at baseline, prior to investment, we then determine how conservation investment will impact our productivity and capacity coefficients. To determine the stock abundance and variance response from investment, we need to determine the cost of a given conservation intervention and the impact of that intervention on overall salmon returns. More simply, we need to estimate the number of fish that return for each dollar invested in conservation. Using available data we can compute an informed estimate of the cost of identified conservation interventions and using the literature we can determine the impact of identified conservation interventions on salmon returns (Jorgensen *et al.*, 2021). Jorgensen *et al*. describes the impact of habitat improvements, specifically imperviousness and passage, on productivity and capacity on return spawning salmon. This is seen in Equation 8 and 9, where p is productivity, β_{imperv} is the imperviousness of roads for a population, $\beta_{passage}$ is the passability for a population, w_{spawn} is spawning capacity weight, c is carrying capacity, A_h is area of habitat, and d_h is density of habitat. We then use this relationship to inform the impact from conservation investment from the baseline scenario at equilibrium. Utilizing Equation 8 and 9, the impact of investment will be directly influenced by β_{passage} , the passability for a population. With our known estimated p and c coefficients and β_{passage} value, we treat the variables 0.95, β_{imperv}, and w_{spawn} in Equation 8 as a constant. In Equation 9, A_h and d_h are both habitat indicators, but since our application is aggregating at the watershed level we can treat them as a constant. This is because we are not taking differentiating habitat types into account when calculating the change in stock abundance.

$$p = 0.95\beta_{imperv}\beta_{passage}w_{spawn} \tag{8}$$

$$c = A_h d_h \beta_{passage} \tag{9}$$

Because conservation interventions are financially costly, at the ESU level the impact from conservation investment must be a function of the budget. Within our endogenous application of MPT, weight allocations are defined as a proportion of an overall fixed budget, or the number of dollars invested in a given population for conservation. To understand the impact from these dollars invested, we need to know the cost of an intervention and how much an intervention impacts a population. These two factors are combined to represent α in Equation 10, which represents the impact from investment on productivity and carrying capacity. Equation 10 indicates how the equilibrium stock abundance (S_i) for population i is a function of the weight allocated (w_i) to population i. Productivity of population i (p_i) is a function of the habitat impact for a given allocated weight ($\alpha(w_i)$). Carrying capacity for population i (c_i) is a function of the habitat impact for a given allocated weight ($\alpha(w_i)$).

$$S(w_i)_i = \left(p_i(\alpha(w_i)) - 1\right) c_i(\alpha(w_i)) \tag{10}$$

For a fixed budget, we can allocate weights (w_i) to each population in the ESU, as described in more detail in *Apply Endogenous Portfolio Theory to OC Coho Salmon.* Equations 5-10 allow us to translate each population's budget allocation into a change in equilibrium stock abundance resulting in $S(w_i)$ from Equation 3. The equilibrium stock abundance responds to the impacts of conservation interventions that are invested in with the allocated budget funding. With a change in equilibrium stock abundance computed for each population *i,* the unique $S(w_i)$ computes unique variance values that are aggregated to the ESU level. This allows the portfolio manager to estimate many possible combinations of variance and stock abundance returns which together, can be plotted to reveal the efficiency frontier. In *Apply Endogenous Portfolio Theory to OC Coho Salmon,* we detail how we model conservation interventions with simulated budget allocations.

Apply Endogenous Portfolio Theory to OC Coho Salmon

Identify Restoration Action

Using this endogenous portfolio theory application of MPT, we applied it to the conservation of OC coho salmon. In this report, we identified mitigating barriers that impact salmon passage as our restoration action. Barriers within stream channels impact salmon passage, therefore we wanted to determine how mitigating these barriers can improve salmon abundance. Barrier mitigation was chosen because barriers directly impact passage for adult spawner populations, specifically the removal of barriers has shown an increase in adult coho spawning populations by 6% in Washington (Jorgensen *et al*., 2021). Passage impacts productivity and carrying capacity of a watershed, as seen in Equations 8 and 9 (Jorgensen *et al*., 2021). There is comprehensive data on barriers that impact salmon passage in Oregon from the ODFW, and includes an estimate on how much barrier mitigation costs (Jorgensen *et al*., 2021). However, this framework can be utilized for different types of habitat restoration as well, depending on available data and a connection to adult spawner abundance.

Calculate Passability

To compute the current passability before conservation investment, shown as $\beta_{passage}$ in Equation 8 and 9, we need to identify the current barriers present within each population's watershed, the passability of each barrier, and where each barrier is located throughout the watershed. The barriers dataset from the Oregon Department of Fish and Wildlife shows all barriers in the ESU as well as what kind they are. Barriers denoted as "unknown" or "other" were removed since they could not be assigned a cost. Barrier passability was denoted as passable, blocked, partial, or unknown in the dataset. Following a similar method to Beechie *et al.,* 2023, we assigned numerical values to these qualitative descriptions to quantify the passability in a population. Passable barriers were assigned a value of .9, blocked barriers were assigned a value of .1, partially blocked barriers were assigned a value of .5, and assumptions were made for barriers classified as unknown based on their barrier type. Barriers that had unknown barrier passability were assigned passability scores based on barriers with the same classification and known passability. Table 2 shows assigned barrier passability for all barriers with unknown passability.

Barrier Type	Passable/Blocked/Partial	Passage Score
Bridge	Passable	.9
Cascade gradient falls	Blocked	.1
Culverts	Blocked	.1
Dams	Blocked	.1
Falls	Partial	.5
Ford	Partial	.5
Tide Gates	Partial	.5

Table 2. Barrier analysis assumptions. Passability scores assigned for barriers with unknown passability.

By combining the barriers dataset with the National Hydrography Dataset (NHD) from the United States Geological Survey (USGS) in ArcGIS Pro, every barrier is assigned a stream identification (ID) number and stream level, which is then used to compute overall passability ($\beta_{passage}$) for each population in Equation 11. Because of their upstream migration, spawning salmon are impacted by barriers lower in the watershed, along the main channel, before they reach barriers higher up in the watershed. This is incorporated into our equation to compute passability shown in Equation 11, where the impact of removing a barrier is directly related to its stream level and location within the stream level. Stream level is a spatial-added attribute provided in the NHD. Stream level identifies a hierarchy for streams from 1-8, ranking streams that flow directly into the ocean a 1, then connecting streams and small tributaries a higher score (USGS, n.d.). There are many individual streams within a stream level. To identify those streams, we allocated stream ID values. The stream ID values are not in numerical order, but they represent a continuous segment of a stream. For example, the mainstem of a watershed would have its own ID as far as it goes, and every stream that branches off would also have their own individual IDs. Assigning each barrier to a stream ID helps to further prioritize the barrier mitigation based on location within a stream. We created a ModelBuilder[1] flow for all 19 populations to connect these layers. After combining barrier type, barrier passability (Passable/Blocked/Partial), a numerical passibility score, stream level, stream ID, and cost to mitigate the barrier in every watershed into a single layer for each population, the Excel files were exported from ArcGIS, transformed into .csv files, and imported into RStudio.

Passability (β_{passage}) is calculated using Equation 11, where R is the number of stream levels within a population, r is stream level, S_r is the number of stream IDs within stream level r, s_r is a stream ID within stream level r, p_b is the passability of barrier b, and f_{r,s_r} is the weight specific to stream level r and stream id s_r. This equation allows us to incorporate spatial elements into computing passability. Equation 11 shows how passability is computed for each watershed by taking into account the passability of each barrier, the number of barriers within each watershed, and the location of those barriers within a watershed.

$$\beta_{passage} = \sum_{r=1}^{R} \sum_{s_r=1}^{S_r} \prod_{b \in r, s_r} p_b \cdot f_{r,s_r} \qquad (11)$$

The location of a barrier in a watershed directly impacts the overall passability for salmon. Because of this, the passability of a barrier (p_b) is multiplied by a weight (f_{r,s_r}) that is influenced by location, as shown in Equation 11. Equation 12 calculates the weight that is specific to stream level r and stream id s_r (f_{r,s_r}) where G_{s_r} is the total number of barriers in a given stream ID, G_r is the total number of barriers in a stream level, R is the number of stream levels within a population, and r is stream level. Equation 12 calculates a heavier weight toward lower stream levels since main channels impact passibility more than small tributaries. This means that barriers in lower stream levels have a greater impact on overall watershed passability than barriers at higher stream levels. With the incorporation of the amount of barriers located on each stream ID within the same stream level, we are able to target streams with many barriers that hinder the overall passability of the watershed.

[1] See appendix for ModelBuilder flow

$$f_{r,s_r} = \frac{1}{r\sum_{r=1}^{R}\frac{1}{r}} \cdot \frac{G_{s_r}}{G_r} \tag{12}$$

Determine Cost to Improve Habitat

To improve stream passability with conservation interventions, we need to estimate the cost to mitigate barriers. The cost to mitigate a barrier is essential because it determines how many conservation actions can occur for a given budget and will factor into α for Equation 10. The cost analysis was grounded in the Oregon Watershed Restoration Inventory (OWRI), published by the Oregon Watershed Enhancement Board (OWEB). OWRI is a collection of 19,000 watershed restoration projects since 1995, with details about what restoration actions were taken, how long the project took, and how much the project cost to complete. The cost data was organized in Google Sheets. The cost of mitigation for every barrier type was then adjusted for inflation, by using the consumer price index for each year as seen in Equation 13, where $CPI_{project\ year}$ is the consumer price index for whatever year the project of interest is in, CPI_{2023} is the consumer price index for 2023, and the cost is the cost of the restoration project (Bureau of US Labor Statistics, n.d.).

$$\textbf{Inflation Adjusted Cost} = \frac{\left(CPI_{2023}\right)}{\left(CPI_{project\ year}\right)} \cdot cost_{project\ year} \tag{13}$$

With the costs adjusted for inflation, we averaged the cost for each project type to get the final cost per type of restoration project. More information regarding assumptions regarding cost calculations is referenced in the appendix. Some assumptions were made based on the availability of data. Culverts and fords have the same estimated cost because they are very similar types of structures (Williams, 2005). The cost for bridge removal was calculated by taking the standard deviation of the cost for culvert removal. This made the cost similar to culverts but a single order larger. This is because, according to the barriers data set, bridges are structures with openings bigger than 20 feet and culverts on state highways with openings as little as 6 feet (Oregon, 2017). This means that these are very similar or the same as culverts, but larger and thus more costly to remove. We also assumed the cost to mitigate falls or cascades would be the same, as they are similar features. Lastly, these are only estimated costs, real life projects would likely have more variability due to location, scope, and cost of labor. However, having an estimated cost for barrier mitigation shows what actions can be done under a particular budget allocation.

Compute New Productivity and Carrying Capacity
For each population, we individually computed new productivity and carrying capacity coefficients by incorporating our investment weights (w_i). To do so, we used the baseline passability ($\beta_{passage}$) values that were computed using Equation 11, and inserted the values into Equations 8 and 9. In addition, using the output from the nonlinear least squares regression for each population, we inserted the productivity (p) values into Equation 8 and the carrying capacity (c) values into Equation 9. We then solved for the constant in Equation 8 and 9, as mentioned in the *Determine Impact from Investment* section. Each of these steps were completed individually for each population within the ESU. Once the constants were defined for Equation 8 and 9 for each population, we then created portfolio weights to compute new productivity and carrying capacity coefficients for each population within the ESU.

To simulate a portfolio, we defined an overall conservation budget and created randomized weight allocations to determine the number of conservation dollars (w_i) allocated to each population (i). For each population, we independently extracted the population's list of sorted barriers with the associated barrier mitigation costs, and identified the number of barriers to be improved by moving through the sorted list of barriers until the allocated budget is spent. Each barrier that was improved, received an improved passability score of 1. Then, using the list of barriers with the improved list of passability scores, we computed passability after investment, known as $\beta_{passage}$ using Equation 11. We then incorporated the improved passability ($\beta_{passage}$) score into Equations 8 and 9, and used the previously calculated constant for each population in Equation 8 and 9 to compute productivity and carrying capacity coefficients after investment. Each of these steps were repeated for each population within the ESU to compute new productivity and carrying capacity coefficients.

Simulate Investment Portfolios

Using the improved productivity and carrying capacity coefficients, we used Equation 5 to compute stock abundance for each population after investment, shown by $S(w_i)_i$ in Equation 10. To compute aggregate returns for the ESU, shown as $S(w_i)$ in Equation 3, we took the sum of returns for all populations within the ESU for a portfolio. The result of this is the equilibrium stock abundance after investment $S(w_i)$. Lastly, using the aggregate stock abundance after investment $S(w_i)$, we computed variance for the ESU using Equation 3. These two values represent the stock abundance and variance of one investment portfolio.

Using this application, we generated over 10,000 simulations for three defined budgets: $3.5 million, $13.1 million, and $23 million. Weights were randomly allocated across the 19 populations within the ESU, to understand how differential weight allocations lead to differential results using this endogenous portfolio theory application. Portfolios were simulated for each defined budget and portfolio results were plotted on a traditional risk-return MPT graph, with total ESU salmon returns on the Y axis and variance on the X axis. An efficiency frontier was created for each defined budget by taking the cumulative ranking of returns. The cumulative ranking of returns was found by taking the maximum returns for a given level of variance. Any portfolio that falls along the efficiency frontier, is an optimized portfolio. An optimized portfolio is one that maximizes total ESU salmon returns for a given level of variance.

Prioritize Budget Allocations Based on Equity

In addition to weighting the barriers to be removed, we incorporated the option to prioritize by presence of tribal harvests. Ensuring that Indigenous people continue to have access to ample salmon to harvest is an example of environmental justice (EJ). Environmental justice seeks to address environmental injustice, where people of color are disproportionately impacted by pollution and environmental issues (Gilio-Whitaker, 2021). To incorporate environmental justice, we increased the likelihood that populations that are actively being harvested by tribes will be allocated a larger proportion of the budget. This was implemented by upweighting populations that practice tribal harvests, such as Siletz, Salmon, and Yaquina. When generating the EJ conservation investment weights Siletz, Salmon, and Yaquina each had three times the probability of receiving a weight allocation than all other populations in the ESU. We generated 2000 simulated portfolio weights for each of our three budgets: \$3.5 million, \$13.1 million, and \$23 million and used our endogenous portfolio theory application to simulate results.

Deliver Framework as Reproducible Tool

Although this analysis has specific results, this framework can be used by the Wild Salmon Center, or any portfolio manager, to apply different budgets, different restoration interventions, or even to a different species. The framework is accessible on GitHub, with annotations explaining the steps detailed in this report. If interested in still applying the framework to OC coho salmon and barrier mitigation, the portfolio manager could run the model with different budgets, or weigh tribal harvest populations differently. If they were interested in applying different restoration actions to OC coho salmon, they could manipulate the framework to focus on a different action than barriers. However to achieve this, they must be able to link productivity and carrying capacity coefficients to abundance as was done in Jorgensen *et al.*, 2021. They also would need the cost of the type of restoration action, so the weights can be allocated among populations. If they still wanted to analyze OC coho salmon, but had abundance data at different life stages, then they could incorporate a multi life-stage model rather than a single-stage Beverton-Holt model as we did. Lastly, if they wanted to apply it to another species, they would need to change all of these components and ensure they have data on abundance, a life cycle model matching the life stage of that abundance, a restoration action, the cost of the restoration action, and a link between the restoration action and the species in interest's productivity and carrying capacity.

Results

Endogenous portfolio theory provides insight into how to differentially allocate a fixed budget for conservation by maximizing returns for a given level of variance. Conservation interventions increase salmon abundance by improving habitat quality *(*Jorgensen *et al.,* 2021*)*. Using this endogenous portfolio theory application, we make the assumption that as conservation interventions increase ESU abundance, they also increase ESU variance. In theory conservation interventions may lead to a reduction in variance by decreasing volatility in annual stock abundance through habitat improvements. While our model currently assumes a positive relationship between returns and variance, as shown in Equation 3, more evidence on the impact of conservation interventions on variance could lead to more nuanced interpretations of variance. Using this framework, we applied this endogenous portfolio theory application using three budgets: $3.5 million, $13.1 million, and $23 million.

Portfolio Results under Different Budgets

A $23 million investment in conservation for OC coho salmon leads to a substantial increase in ESU abundance and ESU variance from baseline, as shown in Figure 8. Each point on the graph shown in Figure 8 represents a single portfolio, made up of investments across 19 populations. The results illustrate how differential budget allocations using a fixed budget lead to differential impacts in returns and variance across 19 populations within the ESU. The efficiency frontier shown in red in Figure 8, represents optimized portfolios. An optimized portfolio is one that maximizes abundance for a given level of variance. The steepness of the efficiency frontier illustrates that there are large improvements in salmon abundance with relatively low changes in variance. For example, there are investments that increase abundance by ~25% while only raising variance by ~32%. This implies that even the most risk averse portfolio manager will still see improvements in salmon returns after investment.

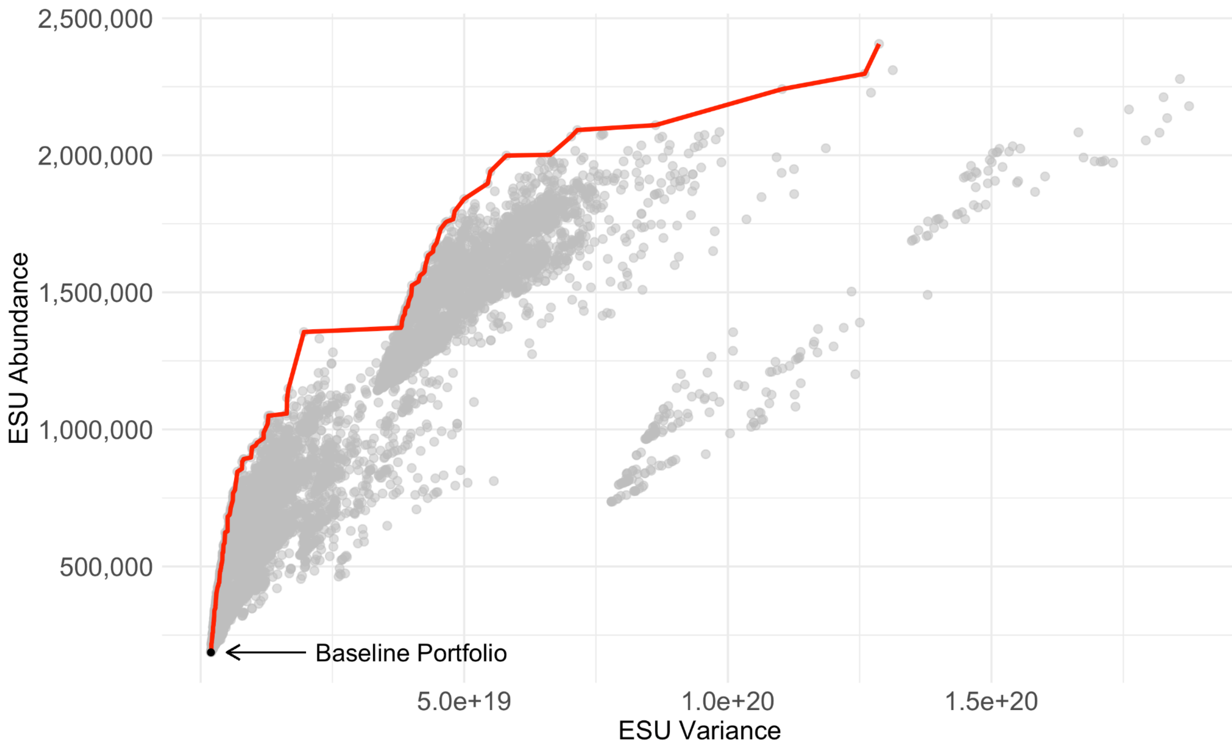

Figure 8. Portfolio results and efficiency frontier under a conservation budget of $23 million. The efficiency frontier for an application of endogenous portfolio theory represents optimized portfolios, where ESU returns are maximized for a given level of variance.

A budget of $23 million represents the award from the Oregon Watershed Enhancement Board, given to the Coast Coho Partnership, which is a statewide coalition of watershed teams managed by the nonprofit Wild Salmon Center (DeNies, 2022). This scenario informs how the Wild Salmon Center can effectively invest their budget into the conservation of OC coho salmon. Based on the simulated portfolio results, we see that as the total conservation dollar budget increases, both the abundance and variance of the ESU increase drastically from the baseline portfolio.

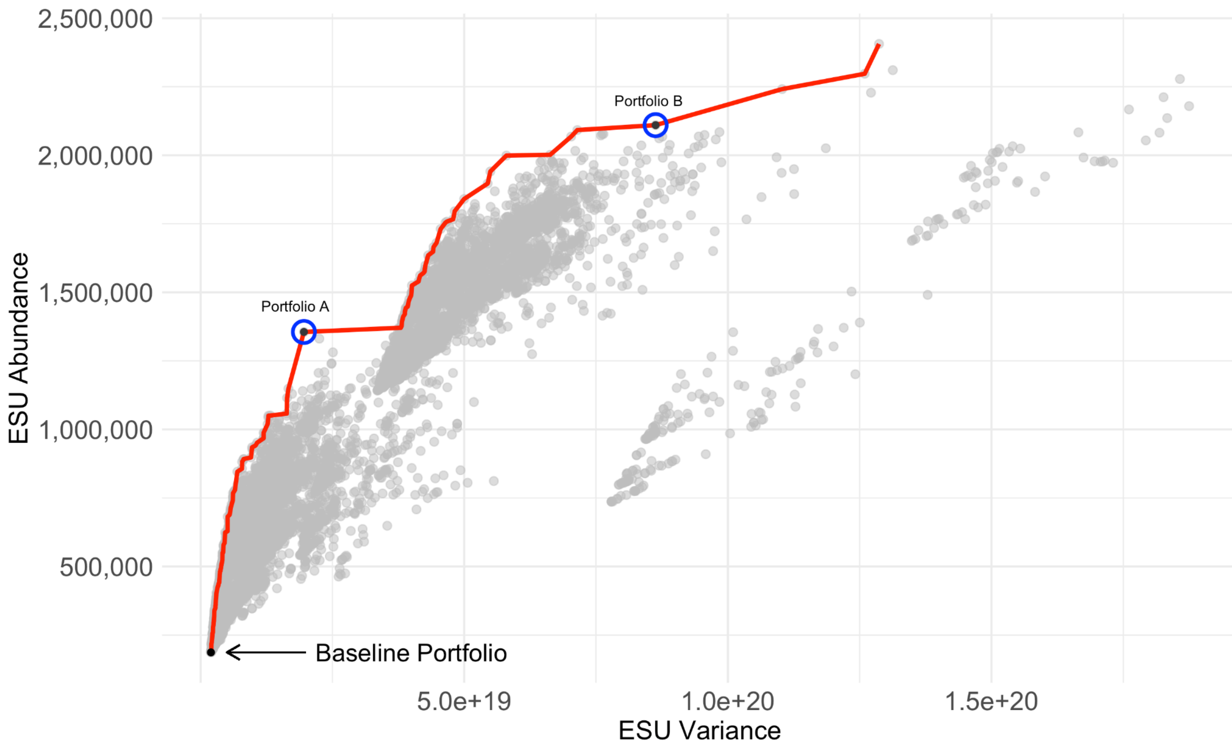

Figure 9. Identified optimal portfolios under a conservation budget of $23 million. Optimal portfolios selected are indicated in blue labeled 'Portfolio A' and 'Portfolio B' on the efficiency frontier shown in red.

Figure 9 is the same efficiency frontier as Figure 8, but two portfolios along the efficiency frontier were selected. The associated conservation budget allocations are shown in Figure 10 and 11.

Figure 10 illustrates how the conservation budget allocations for Portfolio A prioritized larger investments in two populations and smaller investments in the remaining 17 populations. The choropleth map in Figure 10 provides a spatial illustration of where the budget is being allocated. In Portfolio A, over $7 million were allocated to Floras for conservation, nearly $3.5 million were allocated to North Umpqua, and 17 populations received less than $2 million of the budget. In addition, Floras is a small population, geographically, when compared to other populations in the ESU. These results indicate that when proportionally large budget allocations are invested in fewer populations, the portfolio performs well, leading to high salmon abundance, but relatively low variance.

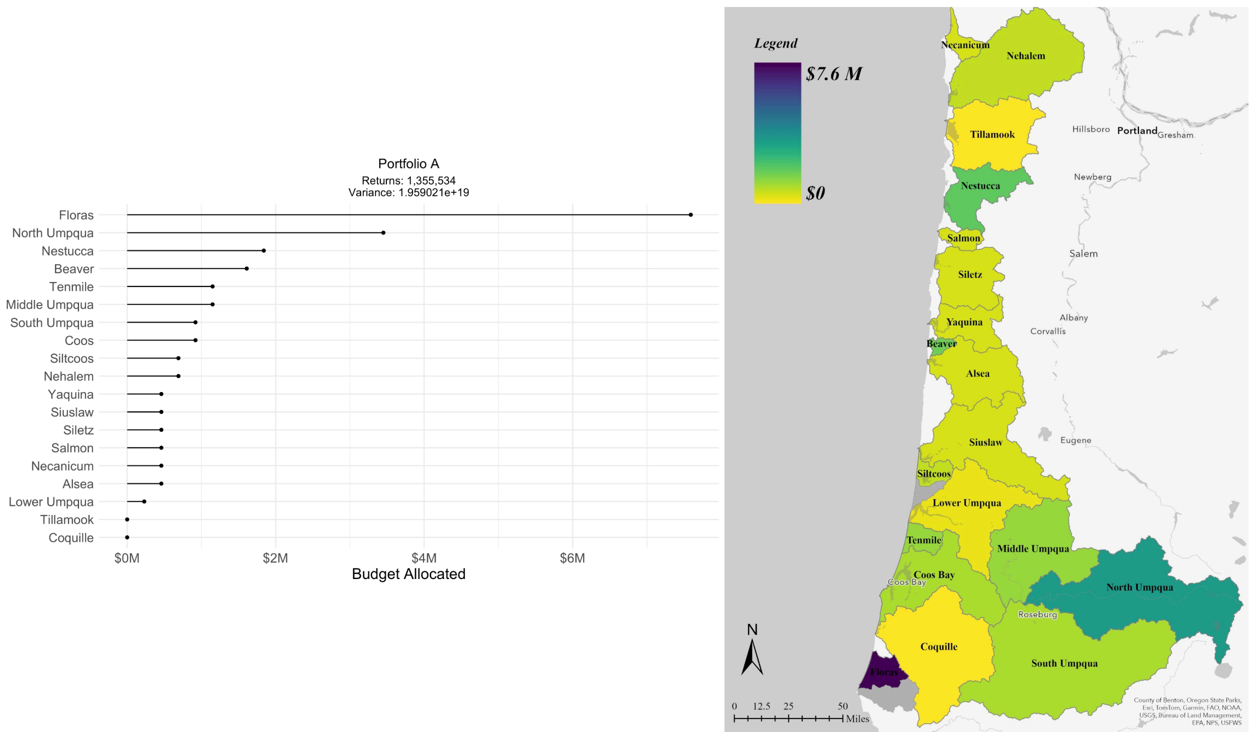

Figure 10. Conservation budget allocations for optimal Portfolio A.

In Figure 11, the conservation budget allocations in Portfolio B are more evenly distributed, when compared to Portfolio A. In Portfolio B, the populations receiving the highest budget allocation are Tenmile and Siltcoos. While there is still a large distribution in the budgets allocated across the ESU in Portfolio B, there are more intermediate budget allocations. Similar to Portfolio A, the population receiving the largest budget allocation is a relatively small population, geographically. While Portfolio B results in greater aggregate returns than Portfolio A, variance drastically increases, as shown in Figure 9. Both portfolio A and B are optimal, so it would be up to the portfolio manager to decide between the two depending on their priorities and knowledge of local dynamics.

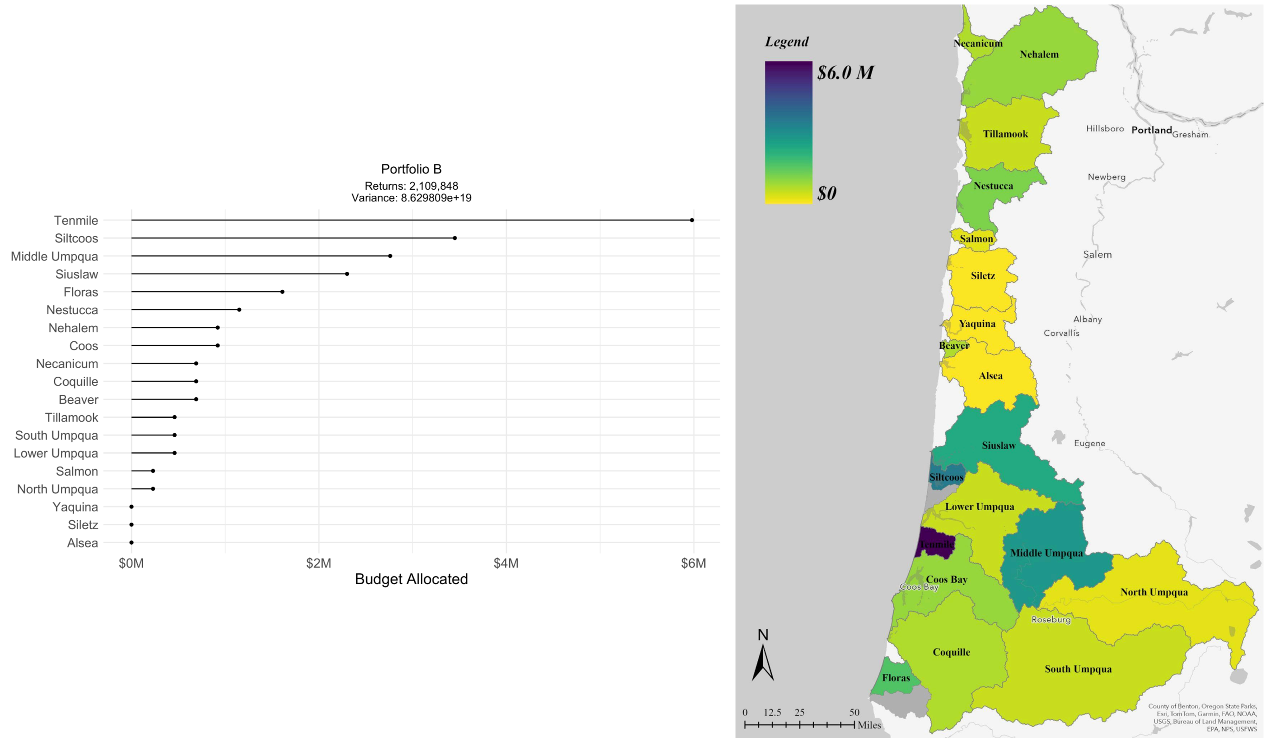

Figure 11. Conservation budget allocations for optimal Portfolio B.

A map of Tenmile is shown in Figure 12, illustrating which barriers were mitigated for the Tenmile population in Portfolio B and which barriers are still impacting stream passage. In Portfolio B, Tenmile received $6 million, the highest budget allocation in the portfolio. Each red point in Figure 12 is an identified barrier that is still impacting stream passage and each blue point represents a barrier that was mitigated with conservation investment, and no longer impacts fish passage. The removed fish passage barriers are spatially distributed across all of the major streams shown in blue; however, the map indicates that there is a high number of fish passage barriers near the mouth of the river closest to the oceans to begin with. With this in mind, spatial recovery planning to increase salmon fish passage may begin with prioritizing barrier removal at the mouth of the river while moving deeper in the watershed. Under the team's endogenous application of MPT, Tenmile will see the highest budget allocation across the 19 populations, and approximately 16 barriers that could be up for removal.

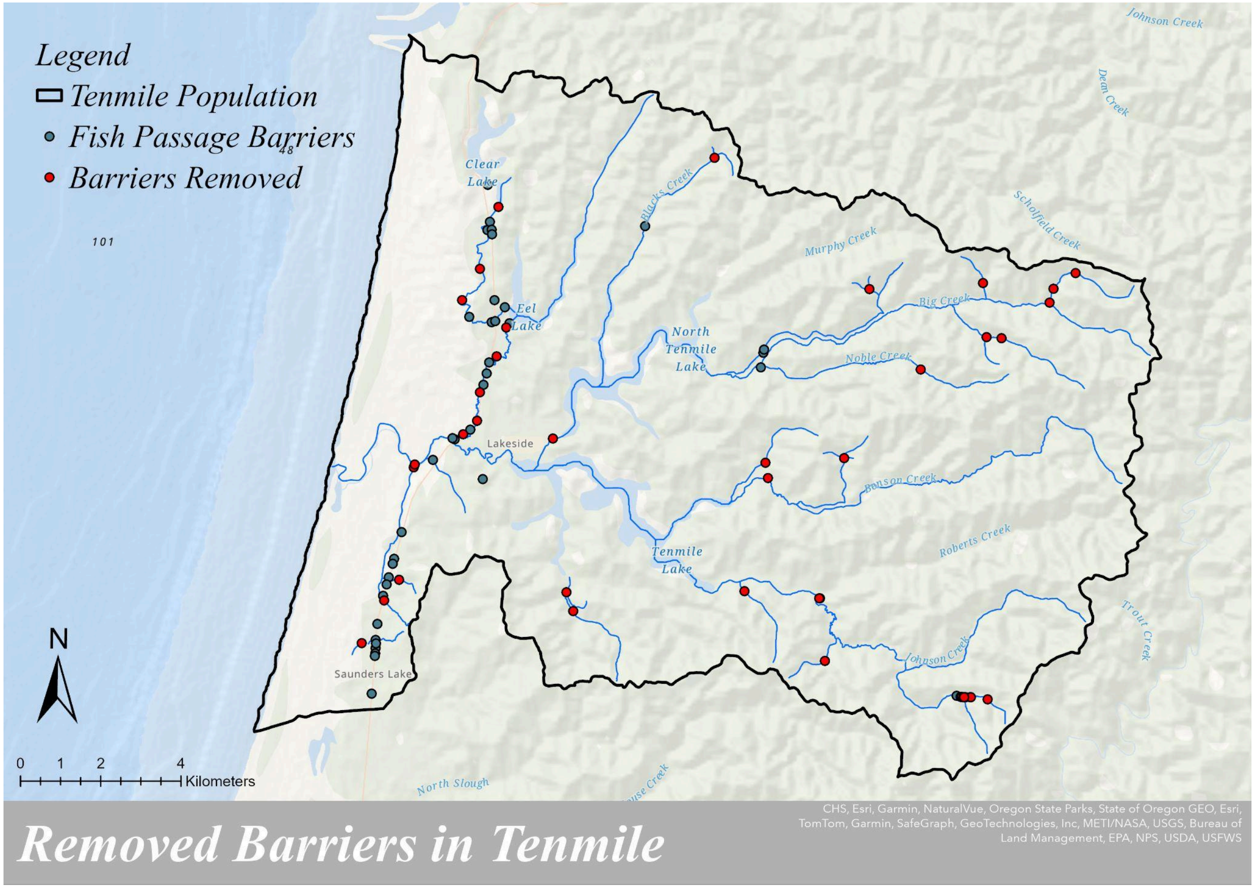

Figure 12. Identified barriers for removal in Tenmile under a budget of $23 million for Portfolio B.

Figure 13 provides a direct comparison of allocated budgets between Portfolio A and Portfolio B. Optimized Portfolio A is shown in teal, while optimized Portfolio B is shown in indigo. The budget allocations between the two portfolios greatly differ for salmon populations Floras, Tenmile, Siltcoos, Middle Umpqua, and North Umpqua. While both portfolios consistently allocate a budget evenly to the geographically larger watersheds, including Tillamook, Coos, Salmon, Necanicum, and South Umpqua. Figure 10 and 11 indicate that in Portfolio A, the highest overall budget allocation to a population reached $7.6 million while in Portfolio B, the highest overall budget allocation to a population reached $6.0 million. These results show that differential weight allocations using a fixed budget, lead to differences in ESU abundance and ESU variance. Using these results, a portfolio manager can directly compare the differential weight allocations between portfolios for a fixed budget. By directly comparing portfolios in this way, a portfolio manager can better understand the tradeoffs of their investments.

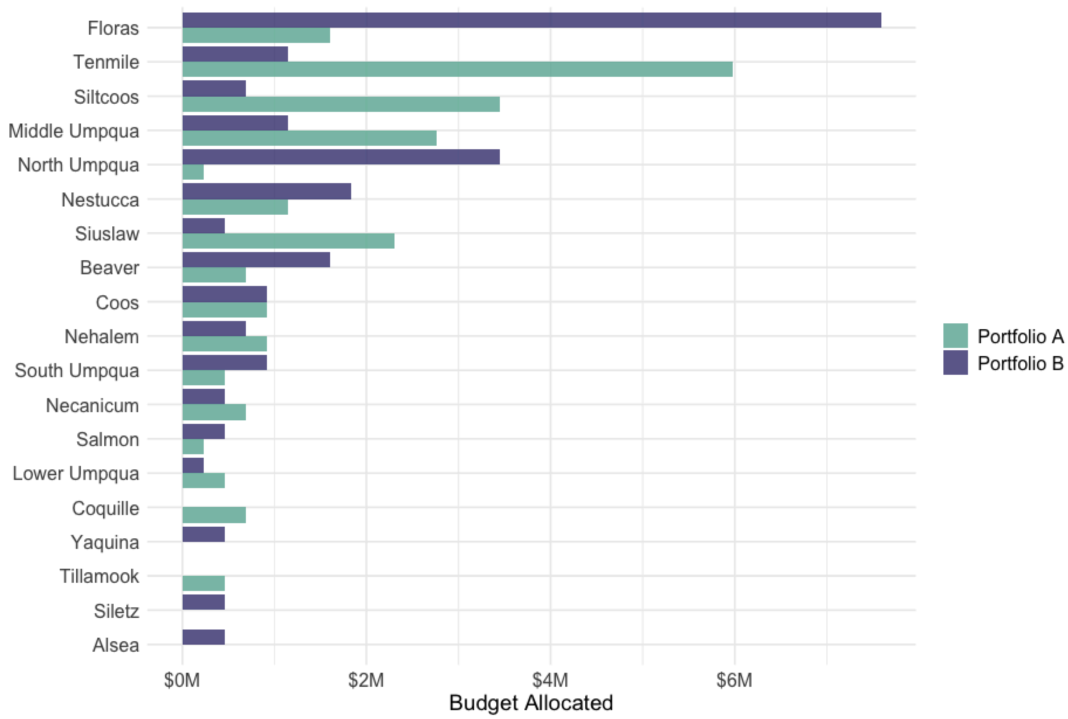

Figure 13. A comparison of budget allocations between Portfolio A and B.

Figure 14 shows a suite of portfolio options for a $13.1 million budget. The figure illustrates how differentially allocating a fixed budget can lead to varying impacts on ESU abundance and ESU variance. Each point on the graph represents a portfolio of differentially allocated conservation dollar weights across the 19 populations, using the same overall fixed budget. The efficiency frontier, shown in red, represents the most efficient portfolios for a fixed budget. Similar to Figure 8, many portfolios have greater stock abundance, despite having a lower budget. An efficient, or optimal portfolio, maximizes salmon returns for a given level of variance. Figure 14 depicts a steeper efficiency frontier compared to Figure 8. This means that the marginal impact of conservation interventions under a fixed budget of $13.1 million leads to an increase in ESU abundance, which allows for smaller changes in the ESU variance. While the scale of ESU abundance is lower than in the $23 million budget scenario in Figure 8, there is also lower ESU variance in the $13.1 million scenario.

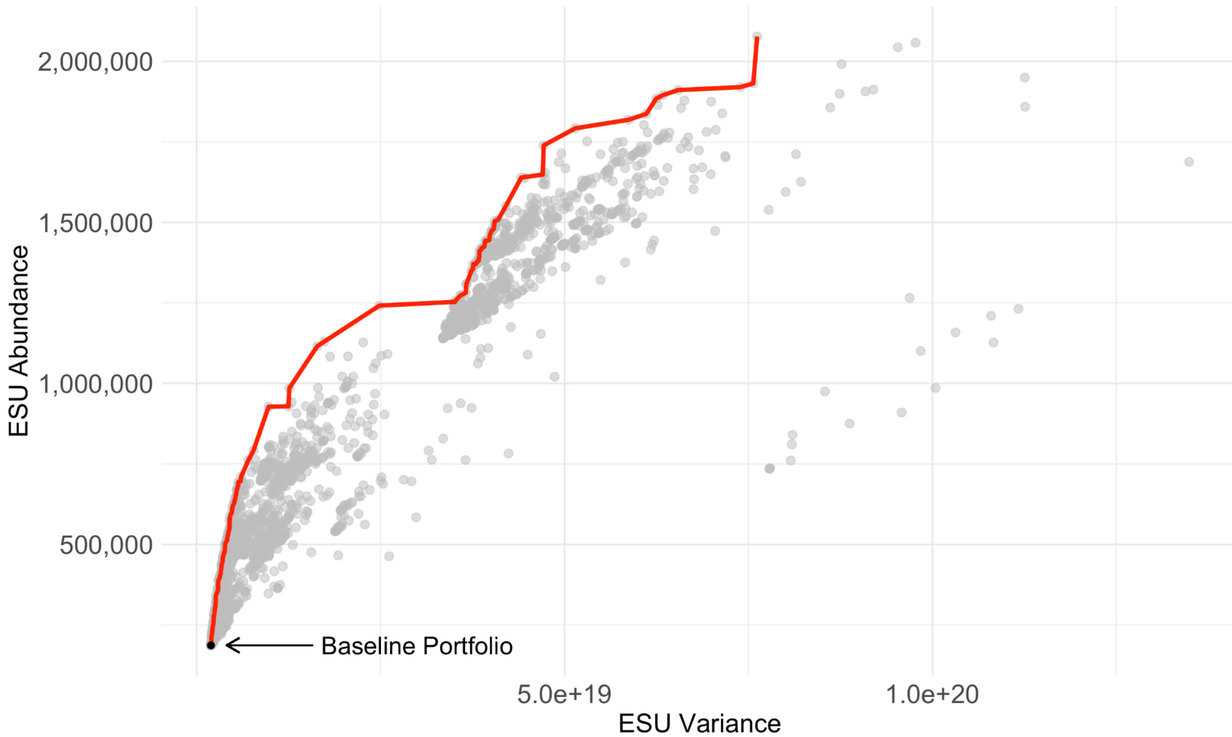

Figure 14. Efficiency frontier under a conservation budget of $13.1 million.

Our endogenous application of portfolio theory can be applied using any defined budget. Figure 15 shows a suite of portfolio options for a $3.5 million budget, where the cost of interventions is defined by the type of barrier. In this scenario, we simulate the impact of a $3.5 million budget, which represents an estimate of the amount of money the Wild Salmon Center invested in Oregon Coast coho conservation over a 5-year period. This scenario informs how the Wild Salmon Center can most effectively invest their money into the conservation of OC coho salmon, despite having a smaller budget. Figure 16 represents the same efficiency curve, but it is zoomed in to better show the individual points. There is a significant overlap of points and despite it only appearing as though ~30 points are visible, there are ~9,900 individual portfolios in Figure 16.

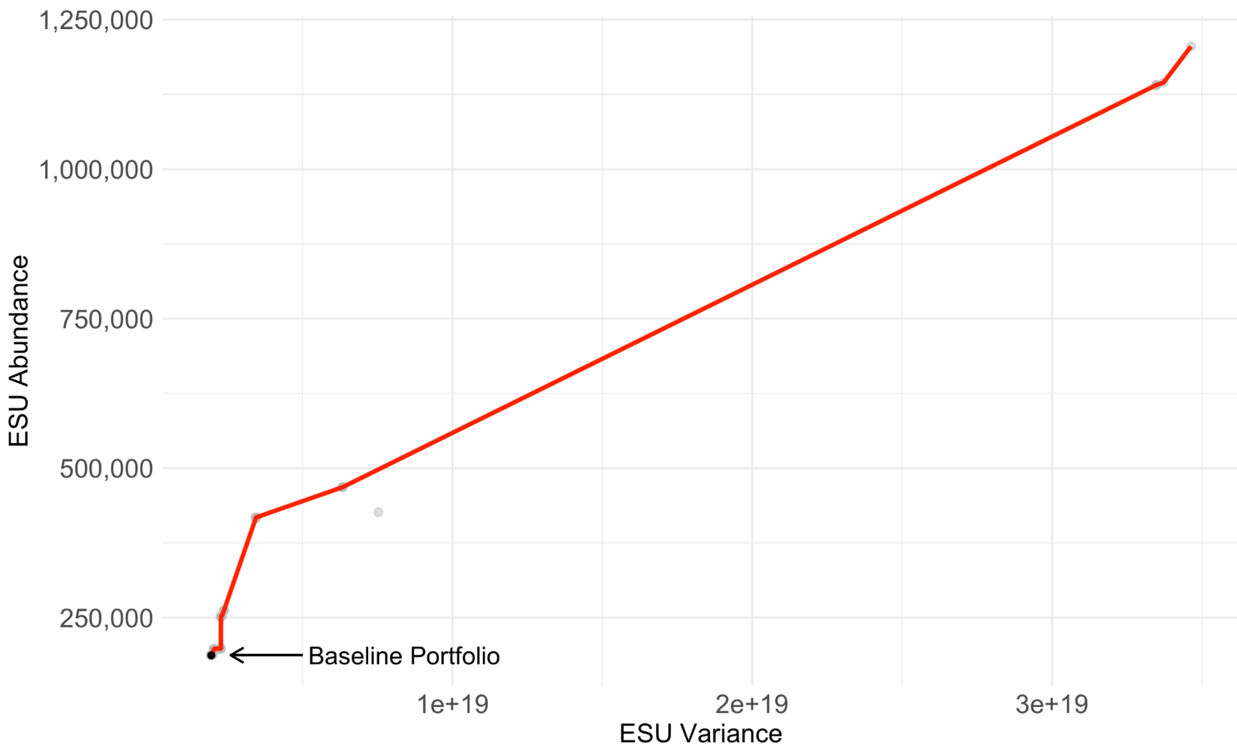

Figure 15. Overall efficiency frontier under a conservation budget of $3.5 million.

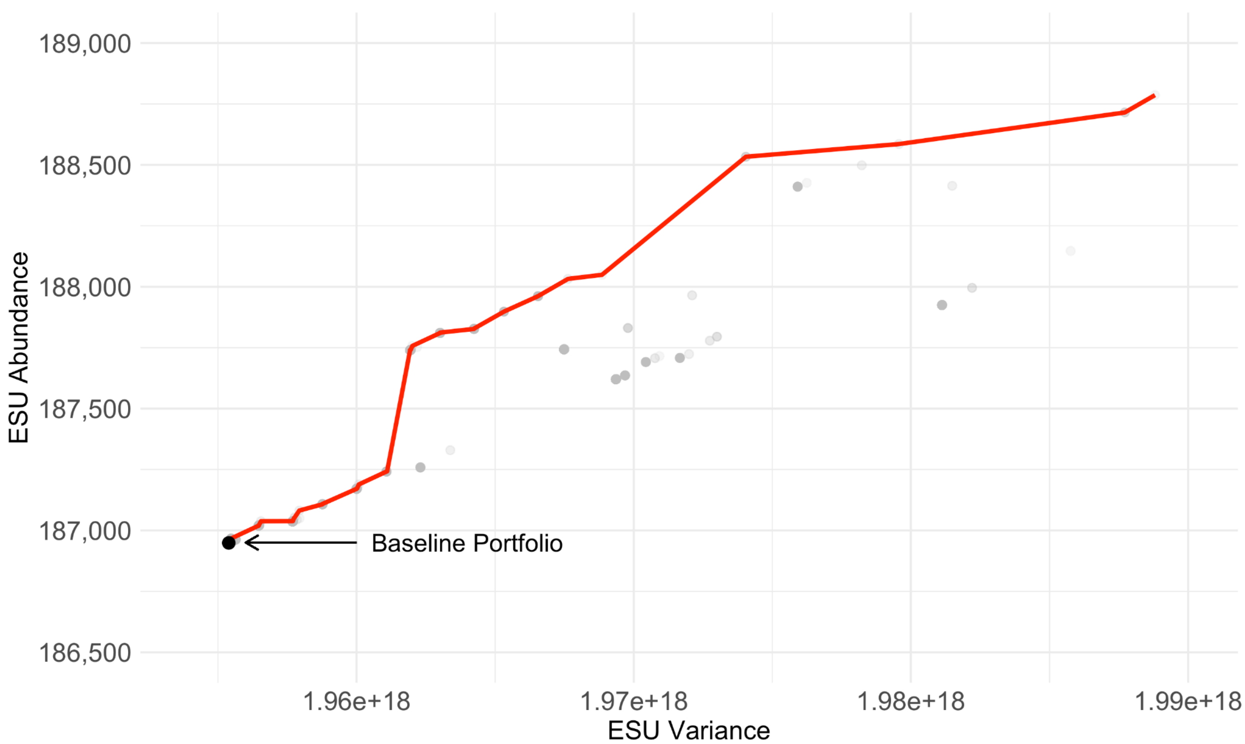

Figure 16. Zoomed in efficiency frontier under a conservation budget of $3.5 million. Overall frontier distribution was zoomed in to show clustering of ~9900 portfolios at ESU abundance 186,500-189,000.

Direct comparison of Improvements from Fixed Budgets

The results shown in Figure 17 illustrate the distribution of the portfolios under three conservation budgets: $3.5 million, $13.1 million, and $23 million. To support habitat improvement for the OC coho Salmon ESU, it is evident that the allocation of the largest budget yields more impact, since there are more opportunities to implement more restoration interventions. The results show that larger budgets also lead to increased portfolio diversity, shown by the increased area of the contour lines represented by the $23 million budget versus the smaller budgets. The results illustrate a $3.5 million budget, but in comparison to the other budget scenarios, it shows a relatively small impact on salmon abundance and variance. However, this is expected because conservation actions are financially costly. When the budget is increased to $13.1 million, the results show that conservation actions have positive impacts in increasing ESU abundance. Under each respective budget scenario, the portfolios are clustered together, with the exception of a subset of portfolios that lead to substantially higher returns and variance. In addition, by increasing the conservation budget to $23 million, the results show even greater impact from conservation interventions on abundance. There is a greater distribution of portfolio results, where many portfolios lead to much higher returns and accept more risk. Evaluating the distribution of portfolio results provides insight into the degree of impact from each budget. Portfolio managers, such as the Wild Salmon Center, can use this to inform conservation budgets.

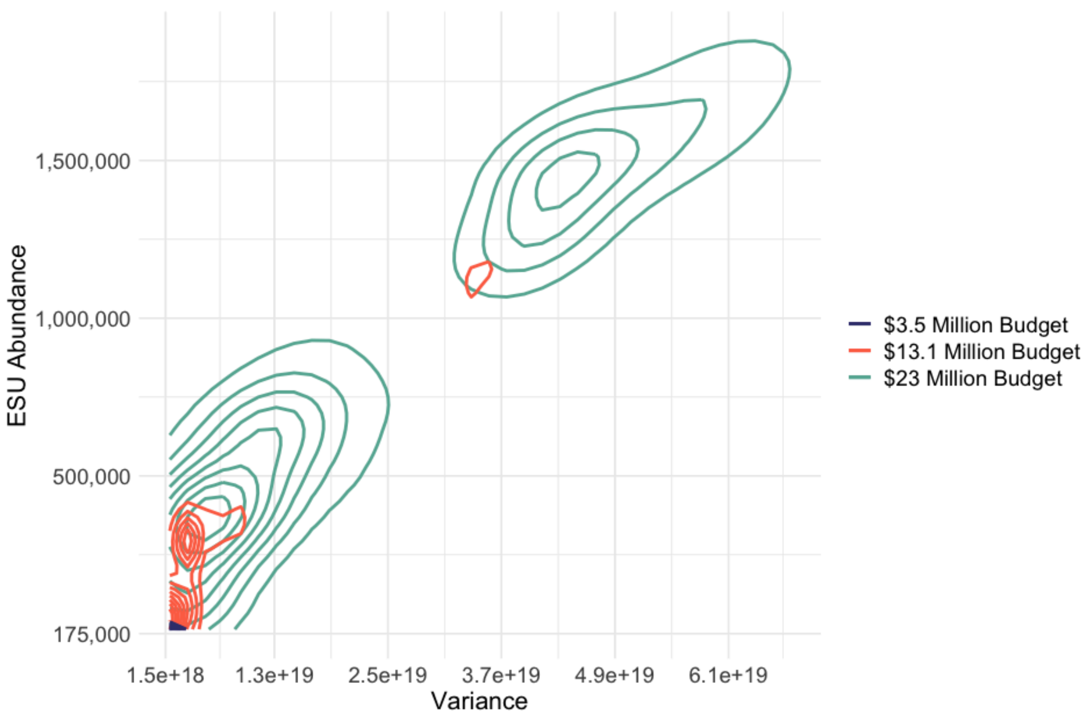

Figure 17. Density plot across all three budget scenarios. Density plot showing the distribution of returns and variance for all three budget scenarios: $3.5 million depicted in purple, $13.1 million depicted in orange, and $23 million depicted in teal.

Environmental Justice Scenario Results

An endogenous application of MPT can be used to prioritize environmental justice and equity in spatial recovery planning for OC coho. Figure 18 identifies three salmon populations that are currently known to be harvested by tribes, shown in green. Incorporating environmental justice in our analysis, we created portfolios that prioritized weight allocations for these three populations. Excluded populations from the analysis are shown in dark gray, while populations that received a randomized weight allocation are shown in light gray. These three populations were used to generate investment portfolios, while emphasizing environmental justice, using a fixed budget of $3.5 million, $13.1 million, and $23 million.

As a general trend across our EJ results, we see the EJ portfolios and the randomized portfolios cluster and form two separate clouds of points. This may imply that there is a significant change in marginal return of ESU abundance when the budget has allocated barrier removal across different stream levels. While the overall passability score of the ESU is being increased by barrier removal, the team theorized that the marginal return of ESU abundance will level off once all of the barriers on stream level 1 are removed. However, removing barriers on stream level 2 further leads to an increase in overall ESU return, as indicated in the second cloud of points clustered higher up on the efficiency frontier. At that point, portfolio managers can decide to either increase the budget allocated further to remove all barriers blocking salmon passage, or prioritize barrier removal at the stream level.

Figure 18. Map of populations harvested by tribes. A GIS map highlighting the location of populations to be prioritized for investments to improve EJ.

Figure 19 shows a suite of portfolios for a fixed budget of $23 million with green portfolios that represent the EJ portfolios. The results show that the majority of the green portfolios fall below the red efficiency frontier for this budget, identifying them as inefficient portfolios. However, some green EJ portfolios are located along the efficiency frontier. This means that there are portfolio options where EJ populations can be prioritized and belong to efficient portfolios. In Figure 19, the scale of abundance for those efficient EJ portfolios are relatively low when compared to the gray standard portfolios, however the variance for the portfolios are also low.

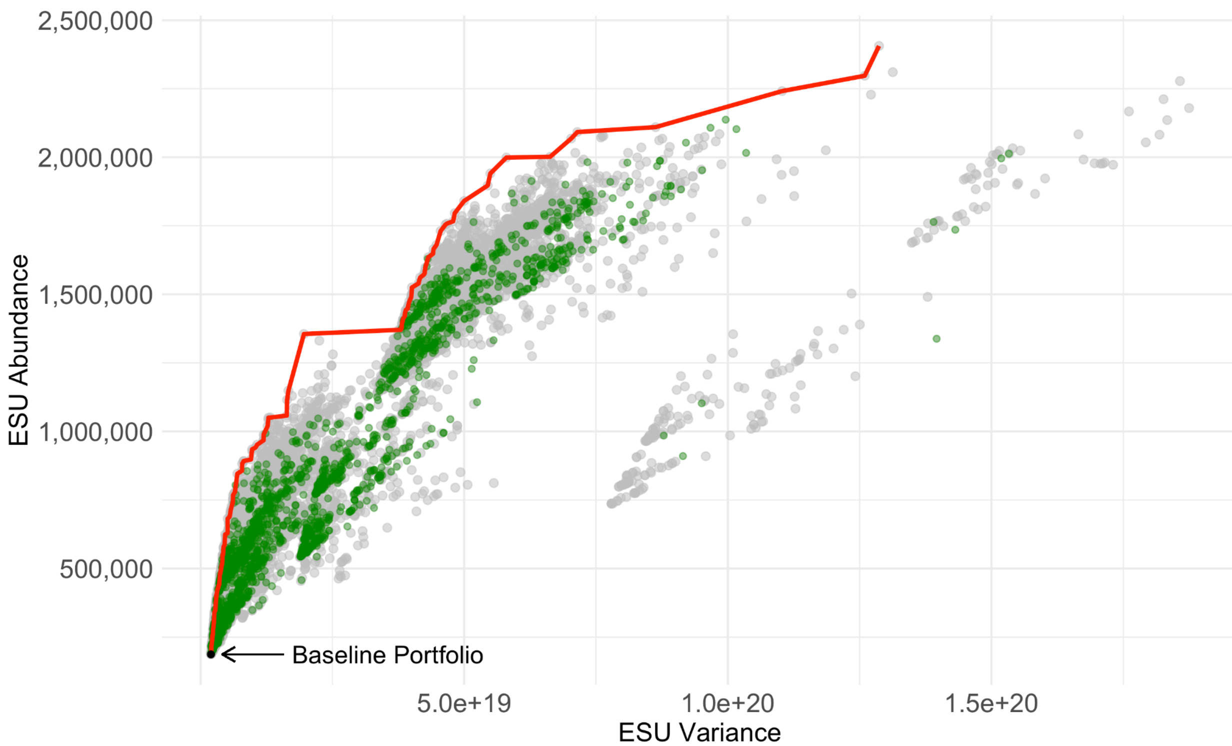

Figure 19. Efficiency frontier with EJ weights under a conservation budget of $23 million. The green data points represent portfolios prioritizing EJ populations Salmon, Siletz, and Yaquina.

Figure 20 shows a suite of portfolios for a fixed budget of $13.1 million, with green portfolios that represent the EJ portfolios. Similar to the EJ results for a budget of $23 million, nearly all EJ portfolios fall below the efficiency frontier, when compared to the regular portfolios. While in the traditional sense, this may mean that these portfolios are not optimal, if conservation managers prioritize equity over salmon returns, then they would be seen as optimal in this way. There are, however, optimal EJ portfolios that maximize ESU returns while balancing equity for tribal harvests, so including environmental justice scenarios is possible under a budget allocation of $13.1 million.

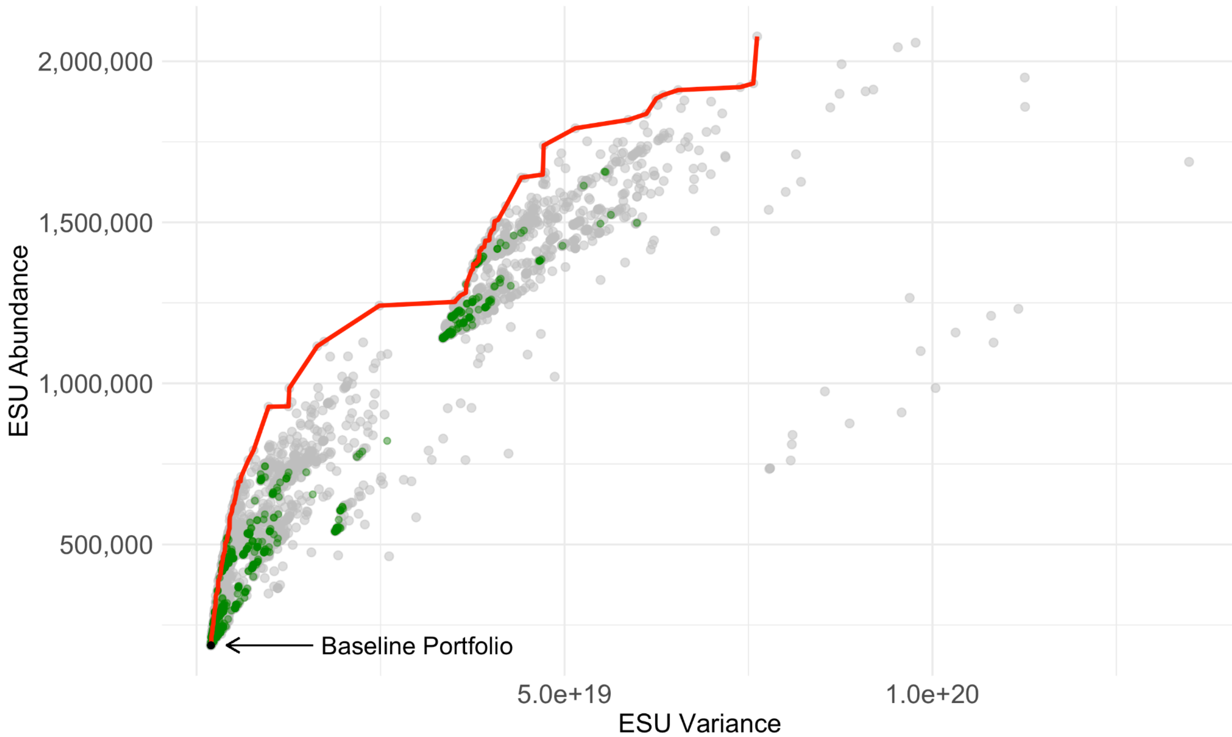

Figure 20. Efficiency frontier with EJ weights under a conservation budget of $13.1 million. The green data points represent portfolios prioritizing EJ populations Salmon, Siletz, and Yaquina.

Figure 21 shows a suite of portfolios under a fixed budget of $3.5 million with green portfolios that highlight the EJ populations and zoomed in to see the distribution of the portfolios. This figure displays ~9900 standard portfolios and ~1900 EJ portfolios displaying major overlap of portfolios. Some EJ portfolios fall under the red efficiency frontier; however, the majority fall along the efficiency frontier. With a smaller fixed budget of $3.5 million, the marginal improvements to stock abundance are especially small because of the limited budget allocation to each population. Due to this, the variance of these portfolios do not increase drastically. While this budget results in more efficient EJ portfolios along the frontier improving equity to those populations, the scale of which the abundance increased from the baseline portfolio is insignificant. Investments across the EJ portfolios under $3.5 million are not as impactful as the results from Figure 19 with a larger conservation dollar budget.

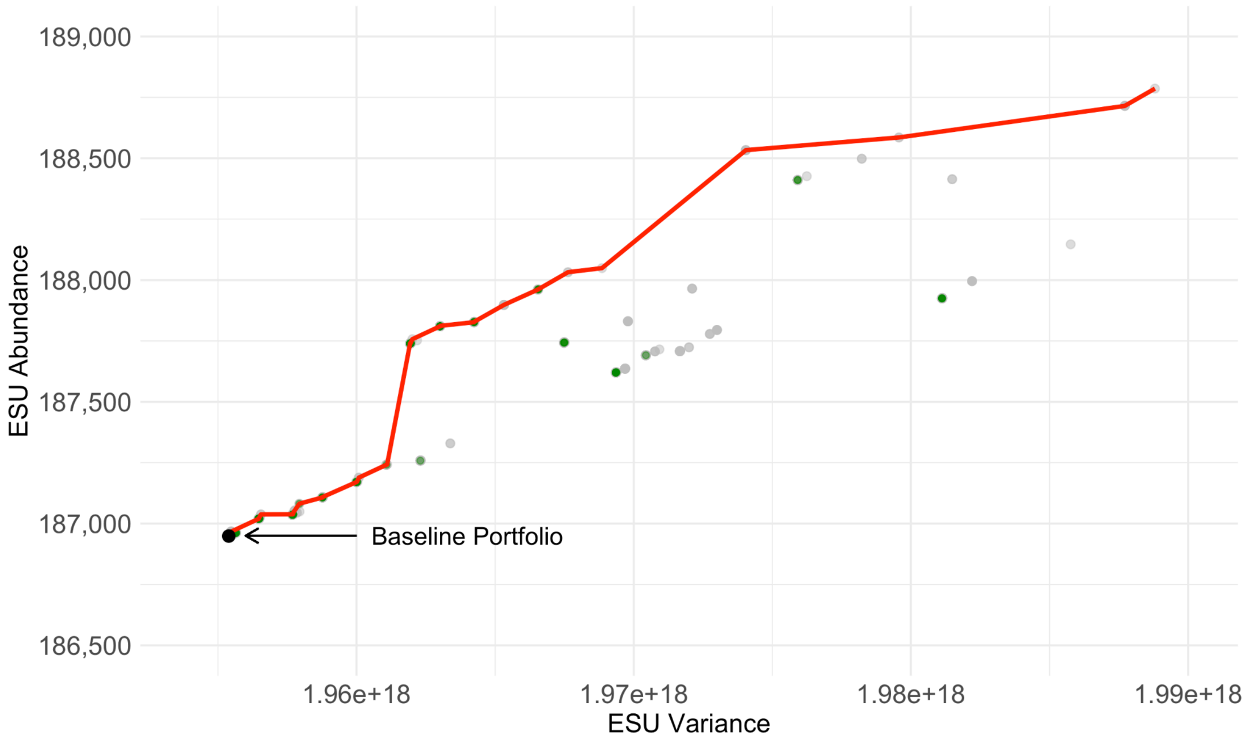

Figure 21. Efficiency frontier with EJ weights under a conservation budget of $3.5 million. Approximately ~9900 standard portfolios and ~1900 EJ portfolios are shown.

The endogenous portfolio theory application allows for the incorporation of environmental justice by using procedural justice. Procedural justice is the practice of ensuring fairness and equity in the processes and procedures of environmental decision making ("Procedural Justice," n.d.). Through the Wild Salmon Center's relationship with indigenous tribal communities they have the opportunity to further expand on incorporating more populations that participate in tribal harvest. This process enhances the voices of tribal communities that are directly impacted by the improvements stock abundance and variance has on the ESU. Emphasizing environmental justice in this way is essential to having a more comprehensive implementation of conservation efforts within the ESU.

Depending on the WSC's approach, the implications of these results may vary. For instance, if the WSC were to compare highly efficient portfolios with portfolios that enhance their partnerships with tribal communities, their decision would be guided by the alignment of their current goals and objectives. This is just one example of how, through this endogenous portfolio theory application, investments can be directly implemented to prioritize budget allocations that emphasize equity and environmental justice using a desired budget for conservation.

Conclusions

OC coho salmon require specific habitat conditions to accommodate their complex lifecycle. Intense anthropogenic activities have shown to damage their habitat conditions needed to rear the next generation of fish. There are many different restoration actions the WSC can implement in order to improve salmon habitat. However, it can be difficult to know where to meaningfully implement restoration actions to make the greatest impact. WSC has looked toward Modern Portfolio Theory as a way to quantitatively measure how to effectively spend their money across the ESU, in order to maximize salmon returns, for a given level of variance. Traditionally, MPT is used in finance to maximize returns on investment of a given portfolio by allocating a fraction of a budget across different assets within a portfolio based on calculated optimized weights. MPT has been applied to different species of salmon as a conservation strategy to understand ecosystem performance as a function of salmon returns and variance of a portfolio.

Applying MPT to coho salmon needs to have a conservation application where the understanding of a portfolio, asset, and associated weights ties back to the performance of the ESU. The traditional approach of MPT would be challenging to implement a conservation application because of the weighting system. In the traditional approach, a weight of '0' given to a population is interpreted as being optimal to remove from the ESU in order to maximize overall returns. Instead, an endogenous portfolio theory application better aligns with the WSC's conservation efforts. In an endogenous application, the portfolio is the ESU, the assets are the 21 populations, and the weights are conservation dollars. In this application, the weights are interpreted differently, where a weight of '0' means that zero conservation dollars will be allocated to that population. With the endogenous application, the WSC will be able to effectively distribute a fixed budget across the ESU based on the weight allocation system. In this approach, returns and variance are endogenous to the weight allocated to each population and are aggregated to the ESU level.

The endogenous portfolio theory application can be used as a potential tool for conservation managers. While the current application assesses coho salmon populations, endogenous portfolio theory could be applied to other species to determine how to effectively allocate a conservation budget. This application utilizes a single-stage lifecycle that is informed by the impact of restoration actions. In order to apply an adapted version to a different species, the conservation manager would need to choose a restoration action and know the impacts it has on the population.

Using this endogenous portfolio theory application, simulated portfolios were generated using fixed budgets of \$3.5 million, \$13.1 million, and \$23 million. In Figure 15, Figure 14, and Figure 8 we visually see the impacts barrier mitigation has on the ESU abundance and variance. Increased conservation dollar investment leads to both increases in stock abundance and variance. Due to the amount of budget available for barrier mitigation across the ESU, the fixed budget of $23 million led to the highest amount of increased stock abundance while also an increase of variance for the ESU.

Discussion

Process for Redesigning Application of MPT

A direct application of MPT in a non-fishery setting is incompatible with conservation projects, and a direct application of MPT may result in harm done to the population that do not receive a portion of the overall conservation budget.

The team evaluated several habitat conservation projects that were shown to directly improve adult coho population abundance. Jorgensen *et al.* writes about a variety of habitat interventions that have been shown to improve adult coho population abundance numbers. From the extensive list, barrier intervention and improving overall barrier passability became the most promising avenue for the team to incorporate in redesigning MPT to have an endogenous application. This was due to having extensive cost of barrier mitigation and barrier location data. The second is that the team can calculate a baseline passability score for all of the 19 salmon populations, and understand how investing in the populations using the endogenous framework can directly improve that passability score.

An organization or group that is interested in seeing how a conservation intervention is expected to change the functionality of an ecosystem can use an endogenous application of MPT to make spatial management decisions while operating under a budget constraint. If there is a lifecycle model, known habitat restoration actions, as well as the cost and impact of those actions, then this analysis is suitable for other species or a combination of species. Overlapping habitat or conservation projects may yield dual benefits for multiple species. Applying the team's endogenous application of MPT for multiple species belonging to the same ecosystem allows conservation managers to understand the magnitude of how beneficial a habitat intervention may be. Not only can this endogenous application be used for more than just different species, it can be used for different conservation actions. For organizations that are interested in efficiently investing their budgets to habitat restoration projects, the team's endogenous application of MPT allows conservation managers to understand the scale of habitat impacts from conservation interventions. Portfolio managers will also have the agency to choose between portfolios that maximize returns, reduce variance, or include equitable outcomes. This spatial management tool can be used towards species management while efficiently allocating budgets that the team believes it can be useful for both small and large organizations to adopt. This can be an especially valuable tool for conservation managers who often operate under limited budgets, to help decide where to allocate their money most effectively.

Limitations to Endogenous Application of MPT Analysis

Limitations of our analysis include utilizing a single-stage lifecycle model, only having access to adult spawner data, the barriers dataset, and assumptions made in calculating cost. Implementing a single-stage lifecycle model versus a multi-stage lifecycle model will broaden or narrow the applications of habitat interventions using MPT. One of the biggest limitations of the team's approach includes being data limited to only adult coho spawner data. Part of our assumption to parameterize our model was to assume salmon return every year when in reality they return to their natal streams every 2-3 years. To truly understand the variance of salmon populations, we would need to use a multi-stage lifecycle model, abundance data for all life stages, and how much impact conservation intervention has on salmon. The barriers dataset is a limitation of this study because it is a snapshot in time. The data reflects the status of barriers when the data was collected, which could have changed between then and now. Furthermore, the passability of many barriers was unknown, leading us to make assumptions about their passability to include them in the analysis. Lastly, the calculation of cost was based off of the inflation-adjusted average of barrier mitigation projects. While the average is informative to give a general idea of how much these types of projects would cost, there are unique factors, like barrier size, environmental conditions, and location, that would impact the cost. This makes our cost an estimate of how much these projects would cost, and it would likely vary in real life. While these are limitations of our project, they are also opportunities for it to improve. As more data of salmon abundance and barriers is collected, conservation managers can incorporate this into the framework and make it more robust.

Equity and MPT

Equally as important is the team's approach in incorporating equity into the endogenous application of MPT. Salmon are not treated as just an investment, but also as an essential part of Indigenous tribes' culture. Salmon is intrinsically connected to Indigenous tribes being able to perform tribal harvests and build a strong sense of connection to their home and ancestors. As a result, the WSC worked with the Biological Program Director of Siletz Tribe to identify key populations to prioritize to ensure continued exercise of tribal harvests.

Thus far, populations that have been identified to have the highest use of tribal harvests are Siletz, Salmon, and Yaquina. These populations were upweighted, which means that they have a higher likelihood of receiving a bigger portion of a fixed budget. Approximately 2,000 portfolios, incorporating the new upweighting system, were generated under a budget of $3.5 million, $13.1 million, and $23 million respectively. Figure 17 and 18 shows the scattering of EJ portfolios in green, with many of the portfolios lying just under the efficient frontier. While some portfolios are under the efficiency frontier, some are along the curve, meaning a portfolio manager would not need to make a tradeoff between efficiency and equity if they chose an EJ portfolio on the curve. Allocating more conservation investments to these populations also opens the opportunity for collaboration with or leadership on restoration projects by tribes.

The team's framework allows for other types of equity approaches to be pursued based on the portfolio manager choice. The team identified three salmon populations, but alternative equitable approaches may include adding more populations to prioritize based on other concerns, not just tribal harvests. In addition, each portfolio can be observed in closer detail to understand which population experiences an increase in salmon abundance as opposed to others. Under this endogenous framework, portfolio managers are able to implement a welfare equivalent approach based on equitable salmon returns across the EJ populations. For portfolio managers that want to prioritize equity, the team's endogenous application of MPT allows for managers to balance equity and return.

Broad Applications for MPT

Individuals interested in the conservation of other taxonomic groups are able to adopt and apply this approach. With many of its applications being diverse and inclusive, MPT can be used to understand how to increase overall returns for a given level of variance at expansive spatial scales. While the team's model is developed as a single-staged lifecycle model specifically for the Oregon Coast coho salmon, conservation managers that have access to multi-staged lifecycle data for terrestrial or aquatic species are able to alter and apply MPT to understand how to spatially recover species.

Figure 17, which shows all of the portfolios under three budget scenarios, all show positive impacts on ESU abundance after investment. Applications of MPT can clearly indicate how to effectively allocate conservation funds in a relatively cost-effective manner. For organizations that are budget constrained, the team believes that applications of MPT can strategically help stakeholders make spatial land management decisions that require large investments with great amounts of flexibility.

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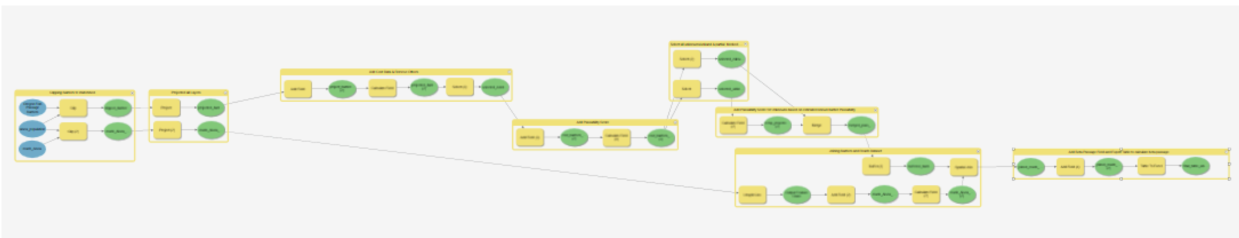
Data Appendix

Type of Restoration Action/ Barrier Mitigation	Average Cost of Mitigation	Justification
Cascades/Falls	$455,041.93	Cascades and falls combined, definitions are extremely similar and required restoration actions would also be similar. Restoration action: installing fish ladders. Deleted one project that was $13 million and two projects that were $0, and took the mean cost
Bridge	$370,171.00	Bridge definition from barriers dataset: "A bridge is defined as a structure having an opening measured along the center of the path of more than 20 feet. Bridges include culverts on the state highway system that have an opening of as little as 6 feet. For city and county bridges, all structures with an opening of 20 feet are included. Some cities and counties provided information on structures with an opening of less than 20 feet." Essentially these are large culverts, so will have larger cost than culverts. We looked at the cost distribution of culverts and then added the mean + standard deviation to arrive at estimated cost for bridges (261324 +108847)

Culvert	$108,847.20	Took the mean of projects removing culverts, rounded up from .16
Ford	$108,847.20	Very similar to culverts (Boubée and Smith, 2005), just on smaller roads so made the same cost as culverts
Tidegate	$77,617.39	Took the mean of projects removing tide gates
Weirs	$190,097.21	Searched for "weir barrier removed" as restoration action and took the mean
Dam	$487,195.20	Took the mean of projects removing dams, rounded down from .23

Table 3. Estimated cost for barrier mitigation by barrier type.



Modelbuilder[1]. ModelBuilder processes for barrier calculations.

Equation Appendix

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1. **Traditional Modern Portfolio Theory**

$$\gamma\mu^T w - w^T \sum w$$

2. **Modern Portfolio Theory Closed Form Solution**

$$\min_{w_i} V(w_i)$$

$$\text{subject to } \sum_i w_i \mu_i \geq R$$

3. **Endogenous Portfolio Theory**

$$\max_{w_i} \sum_{i=1}^{n} S(w_i) - \gamma\left[\sum_{i=1}^{n} \sigma_i^2 S(w_i)^2 + \sum_{i=1}^{n}\sum_{j\neq 1}^{n} \sigma_i S(w_i)\sigma_j S(w_j) COV_{i,j}\right]$$

4. **Beverton-Holt Population Model**

$$N_{stage+1} = \frac{p \cdot N_{stage}}{1+(\frac{p}{c}) \cdot N_{stage}}$$

5. **Beverton-Holt Population Model Adapted to our Project**

$$S_{t+1,\ i} = \frac{p_i S_{t,i}}{1 + \frac{S_{t,i}}{c_i}}$$

6. **Equilibrium Stock Abundance**

$$S_i = \left(p_i - 1\right) c_i$$

7. **Estimated Equilibrium Stock Abundance**

$$\widehat{S_i} = \left(\widehat{p_i} - 1\right) \widehat{c_i}$$

8. **Carrying Capacity Equation**

$$c = A_n d_h \beta_{passage}$$

9. **Productivity Equation**

$$p\ =\ 0.95\beta_{imperv}\beta_{passage}w_{spawn}$$

10. **Stock abundance from investment**

$$S\left(w_i\right)_i = \left(p_i\left(\alpha\left(w_i\right)\right) - 1\right) c_i\left(\alpha\left(w_i\right)\right)$$

11. **Beta Passage**

$$\beta_{passage} = \sum_{r=1}^{R} \sum_{s_r=1}^{S_r} \prod_{b \in r, s_r} p_b \cdot f_{r, s_r}$$

12. **Barrier Prioritization**

$$f_{r, s_r} = \frac{1}{r \sum_{r=1}^{R} \frac{1}{r}} \cdot \frac{G_{s_r}}{G_r}$$

13. **Inflation**

$$\text{Inflation Adjusted Cost} = \frac{\left(CPI_{2023}\right)}{\left(CPI_{project\ year}\right)} \cdot\ cost_{project\ year}$$

Methods Appendix

Non-Linear Least Squares

We used Equation 6 to calculate the equilibrium stock abundance, and ran NLS to calculate the productivity coefficient and carrying capacity coefficients for each of the 21 populations in the ESU. We started by taking the reciprocal of the recruits and abundance based on the abundance data given to us by WSC. Recruits are adult spawners that came back to a given population, i from the previous year and abundance are current adult spawners for population, i.

$$Recruit\ Reciprocal = \frac{1}{Recruits}$$
$$Abundance\ Reciprocal = \frac{1}{Abundance}$$

Then we ran regressions based on the reciprocal values to get an intercept and coefficient for each population, with recruits as a function of current abundance (1/recruits ~ 1/abundance). Because coefficients were in the flipped form we un-flipped the coefficients to get the true guess vectors for productivity and carrying capacity coefficients, which were later fed into the NLS algorithm.These vectors will help train the data in order to produce a more accurate output.

$$guess\ p = \frac{1}{coefficient}$$
$$guess\ c = \frac{1}{(intercept \cdot \frac{1}{coefficient}}$$

Running NLS as a part of our population model allowed us to establish our baseline coefficients for the ESU. These coefficients were used to calculate the equilibrium stock abundance before conservation investment and after investment.