Economic Valuation of Ecosystem Services Provided by *Nereocystis luetkeana* in Puget Sound.

Meredith Dirkman

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Terrie Klinger

Thomas Mumford

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Abstract

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Chair of the Supervisory Committee:

Dr. Terrie Klinger

School of Marine and Environmental Affairs

Bull kelp (*Nereocystis luetkeana*) is known to provide ecosystem services to Puget Sound in the State of Washington including support of food webs and fisheries, nutrient cycling, mitigation of storm surge and coastal erosion, and cultural services. However, the economic value of these services is largely unknown, making it difficult to conceptualize and communicate the benefits of bull kelp and to justify conservation and restoration investments. This study estimates the contribution of bull kelp to Puget Sound in the form of provisioning services by salmon and herring fisheries and regulating services by temporary nitrate removal. I combined a literature-derived habitat dependency index, a value that represents the proportion of a species' life history that is dependent on bull kelp, with public data to 1) simulate the value of the annual contribution by the current areal extent of bull kelp to non-tribal fisheries and 2) estimate the value of temporary nitrate removal. The contribution of bull kelp to commercial salmon and herring fisheries is valued at \$2.6M ± 0.5M, the contribution to recreational

salmon fisheries is valued at \$2.1M ± 0.2M, and temporary nitrate removal is valued at \$3.1M ± 1M. This means the State of Washington would lose \$7.8M ± 1.7M per year if there were a total loss of bull kelp in Puget Sound from current levels. This value, when combined with estimates of the economic value of other ecosystem services, can inform conservation spending decisions for bull kelp conservation in Puget Sound. This study also provides a foundation for valuing other ecosystem services provided by bull kelp in the region and emphasizes the need for additional data collection with which to improve estimates.

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Introduction

Kelp forests, found on a quarter of global coastlines, are among the world's most productive coastal ecosystems (Wernberg *et al*., 2019). Kelps are 137 species of large brown algae in the family Phaeophyceae, Order Laminariales. They function as foundation species, creating vertically stratified habitat and supporting high biodiversity and productivity (Smale, 2020).

Bull kelp (*Nereocystis luetkeana*) is among the most conspicuous kelp species in Puget Sound (Figure 1), an estuarine system within the Salish Sea. The annual sporophyte phase is canopy-forming and is ecologically and foundationally important in the region. However, bull kelp abundance is declining in southern Puget Sound and other sub-basins, with losses exacerbated in regions experiencing high temperatures and low nutrient concentrations (Berry *et al.*, 2021). Similar losses have been documented worldwide; sixty percent of all macroalgal forests have declined over the past 2–5 decades (Wernberg *et al*., 2019). Changes in the abundance and distribution of multiple kelp species and associated changes in nearshore food webs and ecosystem function are anticipated due to climate change and related impacts.

Arafeh-Dalmau *et al.* (2023) find that only 3.6% of kelp forests are fully protected on the western coast of the U.S. and suggest a 2.5-fold increase in kelp representation in MPAs to meet kelp conservation goals. Conservation efforts in Washington State have included the development of the *Statewide Kelp and Eelgrass Health and Conservation Plan*, which seeks to map areas of concern and identify stressors in collaboration with Tribal Nations and regional partners (Washington State Department of Natural Resources, 2025). Additionally, the plan aims to conserve 10,000 acres of kelp and eelgrass habitat by 2040. Conservation is crucial to enhancing resilience and adaptive capacity, and meeting these conservation goals necessitates additional investments (ibid).

Ecosystem services are defined as the "benefits humans derive from ecosystems" and are commonly categorized into provisioning, regulating, cultural, and supporting services (Millennium

Ecosystem Assessment, 2005). Kelp forests provide services from all four categories through fisheries production, nutrient cycling, shoreline protection, carbon storage, recreation, and cultural values (Eger *et al.,* 2023; Edwards, 2025). They provide habitat for ecologically and commercially important species, facilitate larval dispersal and settlement, buffer wave energy, and may contribute to carbon sequestration through offshore burial of detritus (Hinojosa *et al.,* 2010; Mork, 1995). When valued economically, three key services—fisheries support, nutrient cycling, and carbon sequestration—provided by six canopy-forming kelp genera are valued at an average of $500 billion per year worldwide (Eger *et al.,* 2023).

Ecosystem service valuation provides stakeholders and policymakers with a concrete and comparable value with which to make decisions concerning conservation. Valuation helps prevent ecosystem services from being overlooked and therefore compromised in decisions affecting ecosystem health and function (Zandebasiri *et al.,* 2023). Even data-limited and lower-accuracy valuations serve to create public awareness and establish a priority ranking between conservation actions (Liu *et al.,* 2010).

Both the process and the concept of valuing ecosystem services have been criticized for their anthropocentric framing of conservation. However, ecosystem service valuation serves primarily as a tool for conceptualization and communication. It is not intended to be a comprehensive measure of nature's worth because intrinsic value is not captured by the framework on which this valuation is based (Liu *et al.,* 2010).

My goal was to extend the valuation performed by Eger *et al.* (2023) to services provided by bull kelp in Puget Sound. I applied methods similar to those used by Eger *et al*. (2023) to estimate the value of bull kelp to salmon and herring fisheries in Puget Sound and the value of temporary nitrate removal. Despite increasing concern over bull kelp declines in Puget Sound, the economic value of ecosystem services provided by bull kelp in the region has not yet been quantified. My objective was to begin this process by valuing local and species-specific services from within the provisioning and regulating categories to inform local conservation action.

I used a combination of published literature and publicly available data to estimate the value of bull kelp contributions to non-tribal commercial and recreational salmon and Pacific herring fisheries in Puget Sound. I further estimated the value of temporary nitrate removal by bull kelp in Puget Sound. I performed a series of simulations to estimate the annual value under different scenarios.

The estimates reported here represent an underestimate of unknown magnitude because the cultural value of bull kelp and the investments made by conservation agencies toward bull kelp conservation have not been considered. Moreover, the analysis is affected by data limitations. As the first valuation of its kind in the Puget Sound region, this study is intended primarily to initiate discussion surrounding the value of bull kelp ecosystem services and their importance to regional conservation planning.

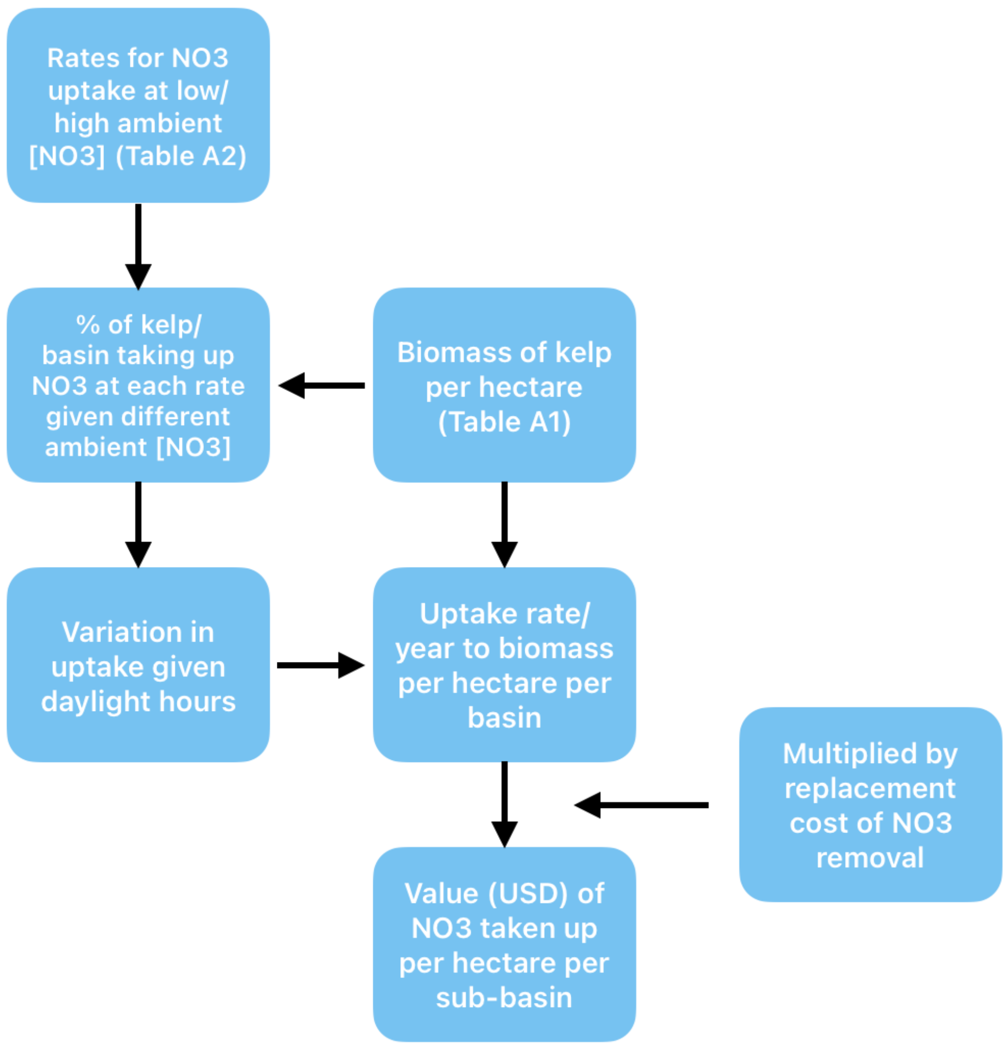
Figure 1. Map of Puget Sound, Claar et al., 2025.

Methods

Extent of Puget Sound Floating Kelp

To estimate the current extent of bull kelp distribution and abundance in Puget Sound, I used data from Department of Natural Resources' (DNR) *Floating Kelp Forest Indicator* (Claar *et al*, 2025). Bull kelp is the only species of floating kelp that occurs in Puget Sound east of Port Townsend, so all canopy cover was recorded as bull kelp. I included North Puget Sound, San Juan Islands, Saratoga/Whidbey, Admiralty Inlet, Central Puget Sound, and South Puget Sound sub-basins in this analysis (Figure 1). I excluded Hood Canal due to the lack of bull kelp in the sub-basin and I did not consider the Eastern and Western sub-basins of the Strait of Juan de Fuca as part of Puget Sound in this analysis.

There is no exact value for total area of floating kelp canopy in Puget Sound. The Floating Kelp Forest Indicator estimates the number of hectares of nearshore habitat between -15 m to -1 m MLLW (typical depths for bull kelp) in each sub-basin (Claar *et al*, 2025). The indicator also estimates the percentage of nearshore habitat monitored in the sub-basin and the percentage of Washington floating kelp beds in the sub-basin (ibid). I used this information to estimate the area, in hectares, of floating kelp in each sub-basin (Table A1).



To convert hectares of bull kelp to an estimate of dry grams of bull kelp per hectare, I estimated standing biomass per hectare using the average density (individuals per m^2) of bull kelp from 42 different kelp beds in Puget Sound (Reef Check, 2025) and the geometric mean dry weight in grams per individual of bull kelp from four of these beds (Roethler, 2026). All analysis was performed in R version 4.5.2.

Valuation of Temporary Nitrogen Removal

To estimate the value of the temporary nitrate removal by bull kelp in Puget Sound (Figure 2), I used published data from laboratory experiments estimating the average uptake of nitrate by bull kelp at differing ambient nitrate conditions (Fales *et al.*, 2023). I only included uptake values at 16°C temperature conditions. Fales *et al*. (2023) tested only high (>10μM) and low (1-3 μM) ambient nitrate concentrations. For more complete coverage, I averaged uptake rates across all observations under 16°C to create a third category representing estimated uptake under intermediate ambient nitrate conditions of 3-10 μM. I combined the averages of uptake rates in low, medium, and high ambient nitrate conditions (Table A2) with data reporting proportional differences in nitrate uptake in the day versus night (Weigel & Pfister, 2021). I used data on the average length of daylight per day to average uptake of nitrate per month of the growing season by one hectare of bull kelp. I defined the primary

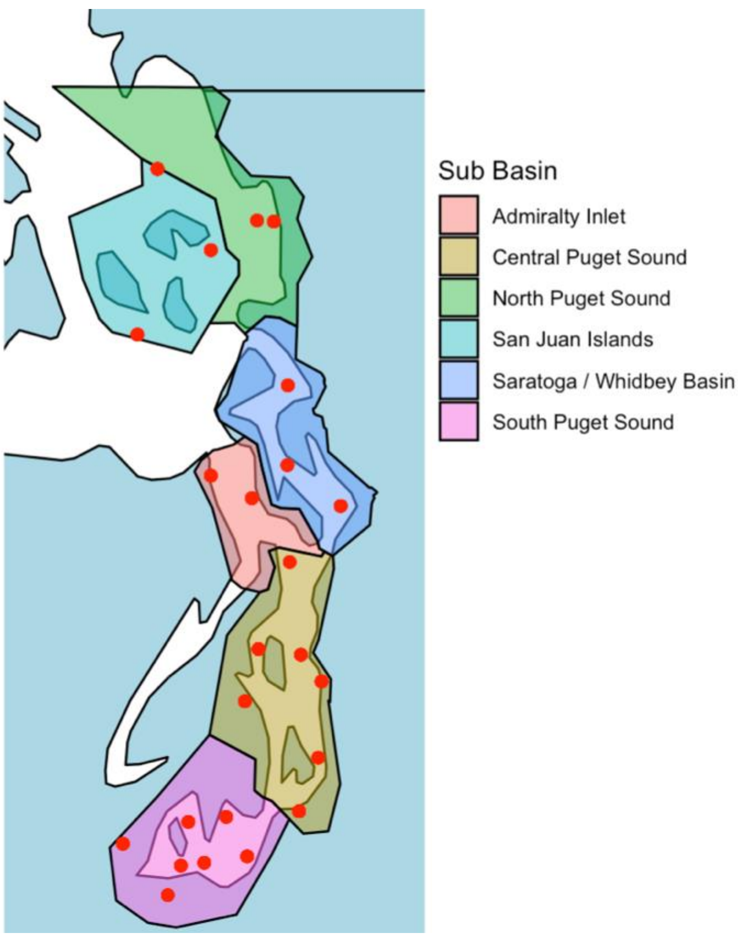


Figure 3. Map of six sub-basins within Puget Sound, overlain with Dept. of Ecology sampling locations (red points) for surface ambient nitrate concentration (Washington State Department of Ecology, 2023, 2024, 2025).

growing season for bull kelp as May through September, and so restricted this estimation of yearly nitrate uptake to daylight/night hours that occur within this range (Pontier *et al.*, 2024).

I filtered nitrate concentration measurements from the Washington State Department of Ecology (2023, 2024, 2025) to include only surface samples (<1m) taken within the bounds of the 6 sub-basins considered (Figure 3). I binned these ambient surface nitrate concentrations into low (1–3 µM), medium (3–10 µM), and high (>10 µM) (Table A2). For each sub-basin, I calculated the percentage of samples in each bin and multiplied these percentages by the total bull kelp area (ha) within the sub-basin (Table A1). I applied the corresponding nitrate uptake rates reported by Fales *et al.* (2023) to the kelp area in each bin to estimate the annual nitrate uptake per sub-basin. To find the average uptake per hectare within each sub-basin and the overall value of nitrate uptake by sub-basin, I combined this annual nitrate uptake per sub-basin with the replacement cost of nitrate uptake (Eger *et al.*, 2023).

Phosphorus removal was not valued because it is not limiting in Puget Sound (Newton & Van Voorhis, 2002). Additionally, carbon sequestration was not valued because long-term sequestration depends primarily on the export of kelp detritus to the deep ocean (Krause-Jensen & Duarte, 2016), a process unlikely in Puget Sound because of its fjord-like circulation and limited offshore export (Cannon, 1990). Consequently, carbon sequestration was assigned a value of zero for Puget Sound, although additional research may demonstrate that this is an undervaluation.

Valuation of Contribution to Non-Tribal Fisheries

Habitat Dependency Indices

To estimate the contribution of bull kelp to commercial and recreational fisheries in Puget Sound, I amended a previously published formula to assign dependency classes to the six species of fish considered in this analysis: Pacific Herring (*Clupea pallasii)*, Pink Salmon (*Oncorhynchus gorbuscha*), Coho Salmon (*Oncorhynchus kisutch*), Chinook Salmon (*Oncorhynchus tshawytscha*), Sockeye Salmon

(*Oncorhynchus nerka*), and Chum Salmon (*Oncorhynchus keta*). This formula was based on Piñeiro-Corbeira *et al.* (2025) and generates a habitat dependency index or HDI. An HDI is an evidence-based measure of the contribution of a given habitat to a species at various life stages and habitat usages. When used in combination with valuations of commercial or recreational harvests, this HDI can scale these valuations to reflect the value attributable to the presence and health of the habitat (ibid).

I conducted a literature review using key words: "salmon," "habitat," "bull kelp," "juvenile" and the various species names of interest and binned papers into respective dependency categories based on the relationship they described. There are only records of juvenile salmon usage of bull kelp habitats (Miller, 1976; Simenstad *et al.*, 1977; Murphy *et al.*, 2000; Duffy *et al.*, 2005; Schroeder *et al.*, 2019; Shaffer *et al.*, 2020; Johnson *et al.*, 2023; Shaffer *et al.*, 2023; ByrneStrong & Shaffer, 2024; Domke *et al.*, 2025). Consequently, if a paper mentioned the presence of the species in the habitat, but not a description of use, I assigned a dependency value of "low" to "habitat for juveniles." However, because Pacific herring, depending on the specific stock, can remain in Puget Sound for extended periods, I also considered adult and larval stages in their dependency analysis (Miller, 1976; Simenstad *et al,* 1977; Haegele & Schweigert, 1985; Dean *et al.*, 2000; Johnson, 2003; Thornton *et al.*, 2010; Fox, 2013; Shelton *et al.*, 2014; Heath *et al.*, 2015; Fox *et al.*, 2018; Zuercher *et al.*, 2019; Shaffer *et al.*, 2020; Shaffer *et al.*, 2023; ByrneStrong & Shaffer, 2024).

I assigned a dependency value of "low" to a paper that described an infrequent or low abundance of a species in the habitat. I assigned a dependency value of "medium" when presence was observed, and a certain habitat usage was suspected but not directly observed. I assigned a dependency value of "high" to papers that directly observed the type of habitat usage, usually during snorkel surveys or through camera footage, and those that reported a high abundance of the species in the area.

There is a numerical bias in literature reports towards presence/absence surveys, especially those conducted on the outer edges of kelp forests, due to the increased ease of sampling in these locations. Camera and/or snorkel surveys are much more infrequent, resulting in what is likely an underestimate of habitat dependency. Additionally, the reports of the association between juvenile salmon and bull kelp are relatively limited (Shaffer, 2004), and therefore the body of literature is likely to increase as more information becomes available, changing the habitat dependency value.

I did not observe any instances of "total" dependency for any species of interest in this study, nor did I consider any species that had zero dependency. To convert dependency categories to numeric values, I used the following conversion from Piñeiro-Corbeira *et al.* (2025): "total" = 1, "high" = 0.75, "medium" = 0.5, "low" = 0.25, to convert categorical to interval data. After filtering by species, I took the mean of all values associated with the habitat usage category to generate habitat dependency indicators for each species (Table A3).

Commercial Fisheries

To calculate species-specific fisheries value (Figure 4), I combined data on average wet weight per fish by species (Highland Economic, LLC, 2022), average numbers of fish landed (individuals) from 2023 (WDFW Puget Sound Commercial Salmon Team, 2024), and average dressed price for trolled fish (Pacific Fishery Management Council, 2025) (Table A4; Table A5). Because the price represented trolled fish and excluded gillnet or purse-seined fish, this value may be slightly inflated and would change if fish caught by other means were included. I then multiplied this value by the species-specific habitat dependency indices (Table A3).

To vary numbers of commercial fish landed within reasonable ranges, I used data from WDFW on Puget Sound Non-Tribal Commercial Salmon Catch from 2018 through 2023 (WDFW Puget Sound

Commercial Salmon Team, 2024). I used the formula below to find the standard deviation for the catch of each species, where *a* is the minimum of the data, *b* is the maximum, and *c* is the mean:

$$SD = \sqrt{\frac{a^2 + b^2 + c^2 - ab - ac - bc}{18}}$$

For Pacific herring (*Clupea pallasii*) I used an estimate of the per-pound landed value of herring reported from southeast Alaska (Abelman *et al.*, 2023). Southeast Alaska is reasonably comparable to Puget Sound in species caught, hatchery contribution, and commercial management (Clark *et al.*, 2006). Pacific Herring catch size was determined from published data on annual landings from 2021-2025 (Washington Department of Fish and Wildlife, 2026).

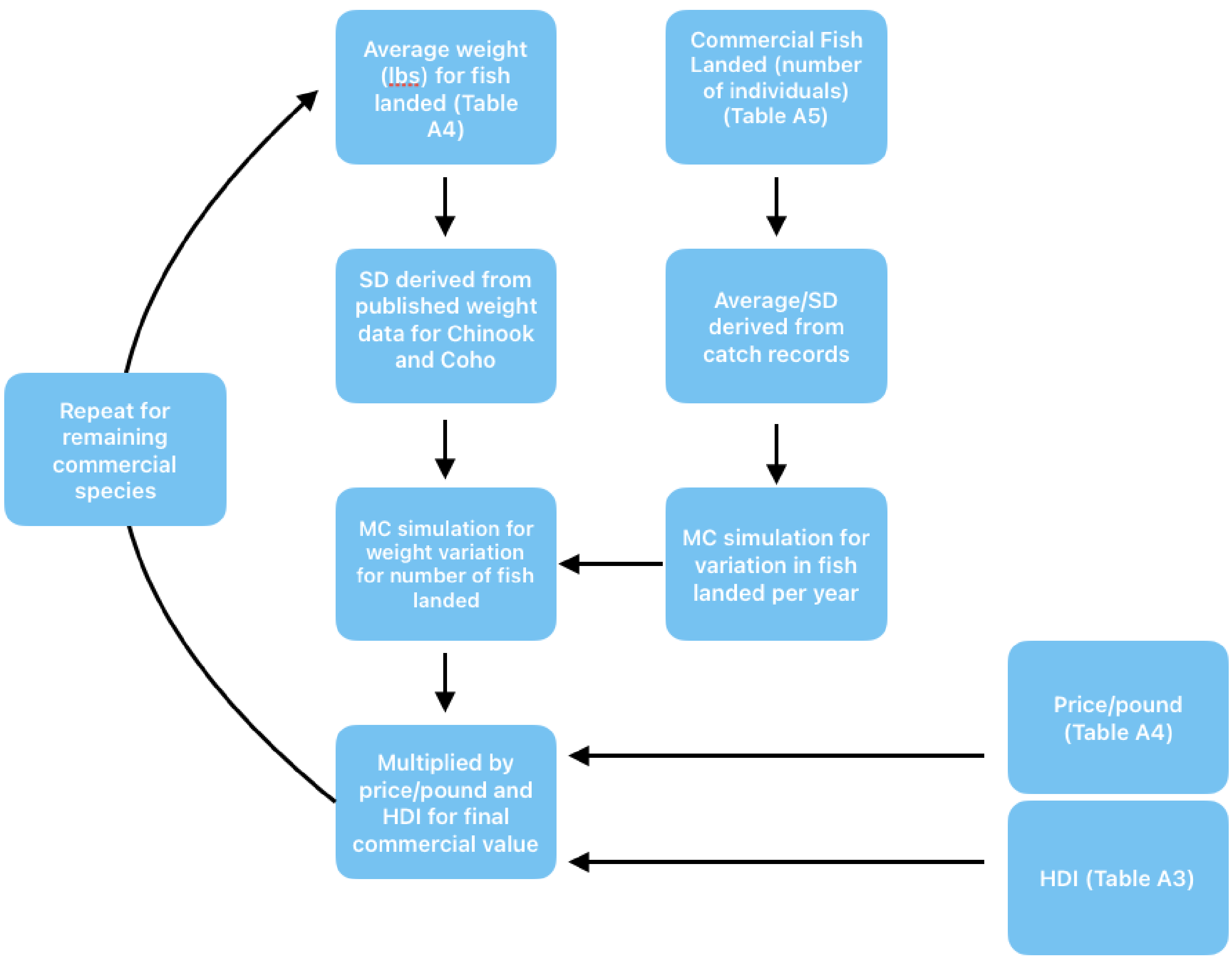


Figure 4. Flowchart displaying methods for commercial valuation. MC refers to Monte Carlo statistical simulation methods, SD refers to standard deviation, HDI refers to Habitat Dependency Index (Piñeiro-Corbeira et al. 2025).

I varied yearly average weight for Chinook and Coho using standard deviations calculated from 2021-2025 (Pacific Fisheries Management Council, 2025). I chose to restrict subsequent weight distributions to one standard deviation from the mean to avoid unusually large or small average weights. In each iteration of my Monte Carlo simulation, I sampled one annual average weight and one commercial catch size, again restricted to one standard deviation to avoid unusual variation, multiplied these values, and multiplied by the respective price per pound and HDI to obtain total contributions of bull kelp to each commercial fishery considered. After simulations revealed the minimal impact of annual average fish weight on the value of commercial fisheries per year, and due to lack of publicly accessible data, I chose to exclude this variation from simulations for Chum, Sockeye, and Pink salmon. I also chose not to simulate variation in price per pound, largely because this value is relatively stable apart from inflation, in part because of interactions with the aquaculture salmon market.

Recreational Fisheries

I valued recreational fisheries using a method similar to those used for commercial fisheries. I sourced values for marginal willingness-to-pay (WTP), the amount a consumer is willing to pay for a given quantity of a good, given a set of conditions, per species by Puget Sound anglers from the literature (Anderson & Lee, 2013; Plummer *et al.*, 2013) and from Anderson (pers. comm., 2026) and adjusted for inflation from 2009 to 2023 (Table A6). These data estimated WTP for hatchery-origin vs wild, catch-and-release vs. catch-and-keep, and small vs. medium vs. large fish, finding that anglers will pay more for large wild fish that they are able to keep (Anderson & Lee, 2013).

To convert this WTP data to a usable metric, I used a Monte Carlo simulation to simulate a normal distributions of fish weights using the average reported sizes for Puget Sound Chinook and Coho (Highland Economic, LLC, 2022). I calculated standard deviations for these values using Chinook and Coho weights per fish from 2021-2025 (Pacific Fisheries Management Council, 2025). I did not vary the weights for Pink Salmon due to a lack of publicly available data and a lack of variation in WTP for different weights.

Because fish weighing 0lbs cannot be caught, I constrained the sample to within one standard deviation of the mean. In each iteration of my simulation, I generated a yearly average weight from this distribution for the number of each species caught in 2023 from catch areas located within Puget Sound (Washington Puget Sound Creel reports) (Table A7). Because there were only 32 Chum and nine Sockeye recreational catches reported in 2023 (comprising 0.07% of the total catch), I chose to exclude them from this valuation. To account for the variation in catch sizes, I simulated a normal distribution, restricted to one standard deviation to avoid unrealistic variation in catch size, based on the catches from 2021 through 2025 for Chinook and Coho. Due to the two-year run cycle of Pink salmon, I only included catch data for 2021, 2023, and 2025 for the species. This is a relatively small range, but due to changes in population sizes and fishing regulations, and the impact of the COVID-19 pandemic, I opted not to use records from prior to 2021. I defined Puget Sound catch areas as Areas 7 through 13, plus Bellingham Bay, Commencement Bay, Inner Elliot Bay Fishery Area, Nisqually River, Dabob Bay, Sinclair Inlet, and Tulalip Terminal Area. I used this catch data to calculate a mean and standard deviation over this five-year period and used this simulated catch data to vary the number of fish caught per year for each species.

I then assigned each simulated yearly average weight to a given WTP as indicated in Table 6, generated from published data (Anderson *et al*., 2013). Due to data limitations, I assigned the same WTP to all Pink salmon weights. I assumed all fish caught were kept, not released, and that all fish were of hatchery origin, due to the estimation that 70% of saltwater salmon caught in Washington State are of hatchery origin (Highland Economic, LLC, 2022). WTP values represent values for the first fish caught per trip, so this valuation does not assume that fish are worth less as more are caught per fishing trip.

After applying the appropriate WTP to each simulated fish, I summed all values to obtain a total value for recreational salmon catch by species and multiplied this number by the respective HDI to estimate the contribution of bull kelp to the value of yearly recreational salmon harvest.

Results

Nutrient Cycling

The estimated total value of nitrate removal by bull kelp in Puget Sound is \$3,103,831± 1,034,405 g (dry weight)/nitrate/year. This result is largely dependent on the best estimate of the number

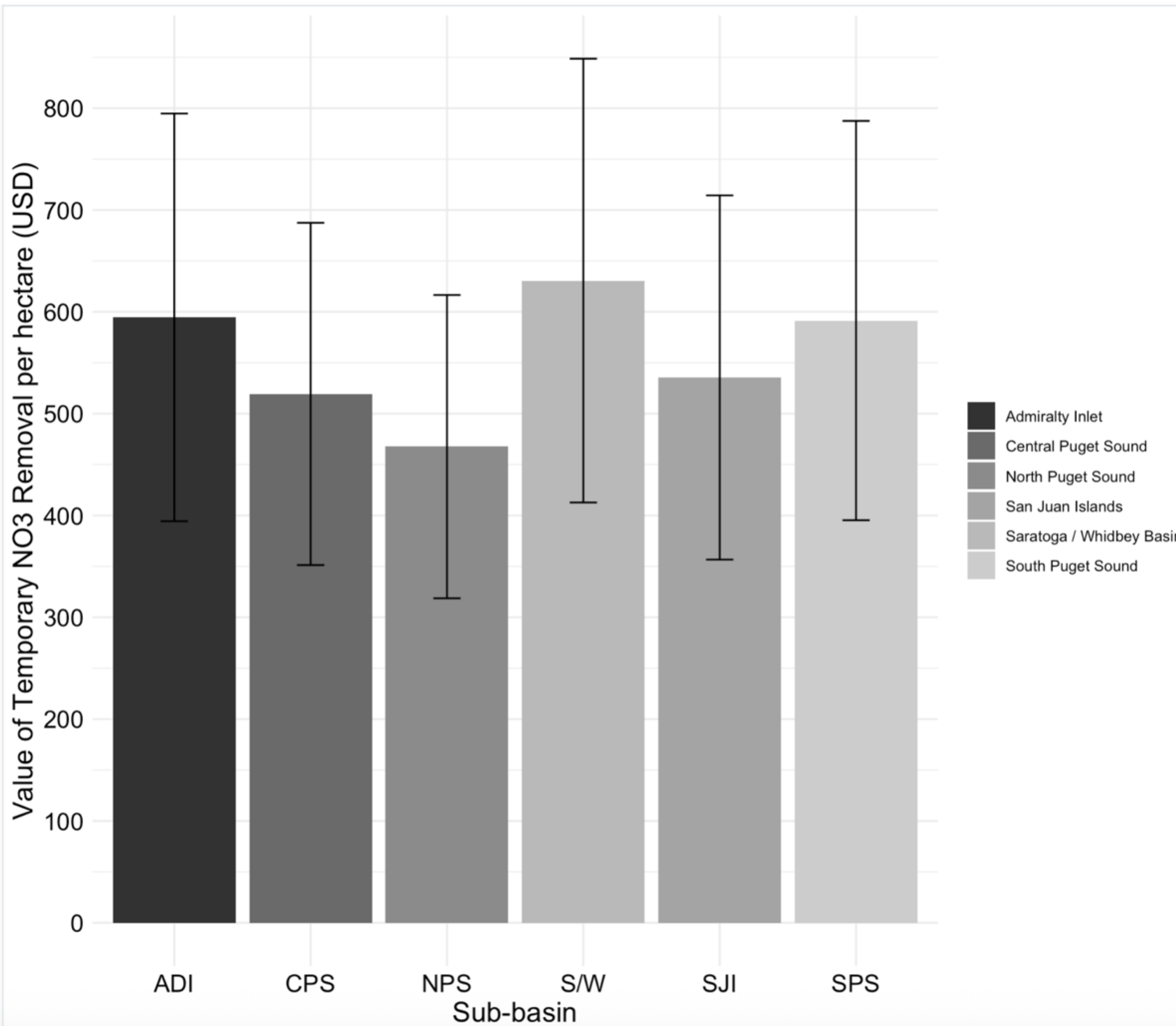


Figure 5. Value (USD) of annual temporary nitrogen removal per hectare of bull kelp by Puget Sound sub-basin.

of hectares of bull kelp per sub-basin; sub-basins with more bull kelp have higher values of nitrate removal. On a per-hectare basis (Figure 5), the mean value of temporary nitrate removal was similar across sub-basins, as indicated by the overlapping error bars. Saratoga/Whidbey had the highest mean per-hectare value, while North Puget Sound had the lowest. When per hectare uptake values are applied to estimates of number of hectares of bull kelp per sub-basin, San Juan Islands has the highest proportion of the overall value of nitrate removal, at \$2,893,980 ± 966,342 g/nitrate/year, 93.24% of the overall value. The average value of nitrate removal per gram (dry weight) of tissue per hectare per year is \$532.93 ± 177.61 g/nitrate/Ha/year.

Habitat Dependency Indices

According to the Habitat Dependency Indices (Table A3), juvenile Coho, Chum, and Pink have roughly the same dependency on bull kelp, while juvenile Chinook have a slightly lower dependency. Juvenile Sockeye have the lowest dependency of the salmon species considered, with only 25% of the fishery's value being attributable to the presence of bull kelp. By extension, Coho, Chum, Chinook, and Pink salmon populations are at a higher risk of population decline given a total loss of bull kelp compared with Sockeye or Pacific Herring.

Non-Tribal Commercial Value

Overall, bull kelp contributes an estimated \$2,565,021 ± 457,044 to commercial salmon and herring fisheries in Puget Sound. However, the contribution of bull kelp to these fisheries depends heavily on the species and the number of fish landed annually. Bull kelp contributes most to the overall fisheries value through Chum and Sockeye salmon fisheries (30% and 24% of the total annual value respectively) and least through Coho fisheries (2.4%) (Figure 6). This is largely because more Sockeye and Chum are caught annually than other species, making their fishery values higher despite Sockeye having a lower HDI. The number of fish caught per year, the biggest contributor to overall biomass harvested, is the largest contributor to the value of bull kelp contribution to a given fishery. Therefore, Coho, despite being more highly dependent on bull kelp than other salmon species, have the lowest fisheries value due to a decline in Coho populations and subsequent regulations on harvest (Puget Sound Partnership, 2025).

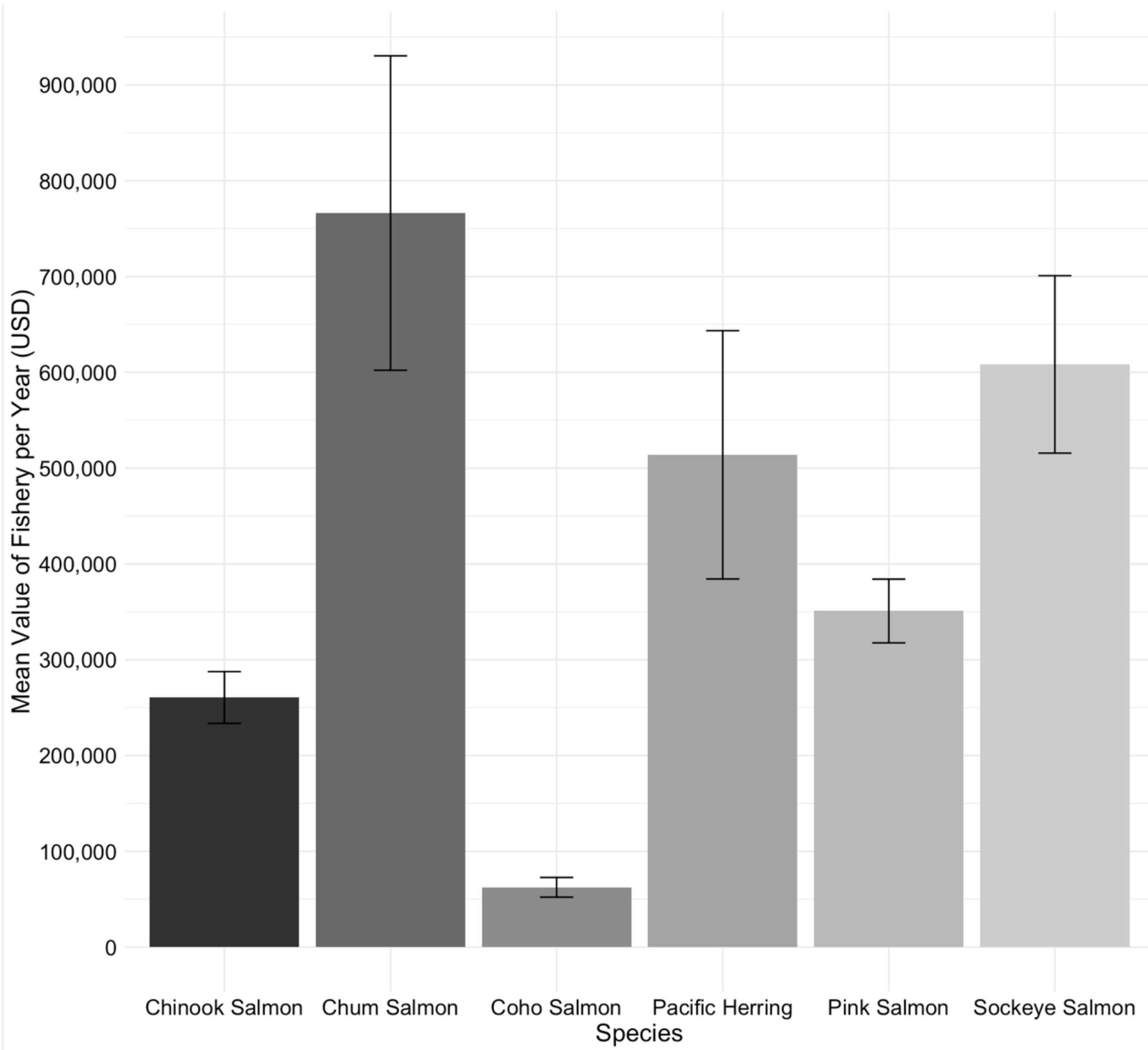


Figure 6. Annual value (USD) of the contribution of bull kelp to Chinook, Coho, Chum, Sockeye, and Pink salmon and Pacific Herring commercial fisheries in Puget Sound.

The average combined value for all species considered per hectare is $440 annually. This valuation assumes a year in which all salmon species are caught; alternative years may exhibit lower values if regulations are changed, or other factors inhibit fishing of the species.

When catch size is fixed and only annual average weight is varied, the estimated overall contribution of bull kelp to the fishery shows relatively little variation (Figure 7). In contrast, varying catch size while the annual average weight is fixed results in a larger distribution of possible overall values due to the greater variability in total biomass landed. This indicates that interannual variation in the number of individuals landed contributes more to uncertainty in the estimated contribution of bull kelp to commercial fishery value than variation in annual average weight.

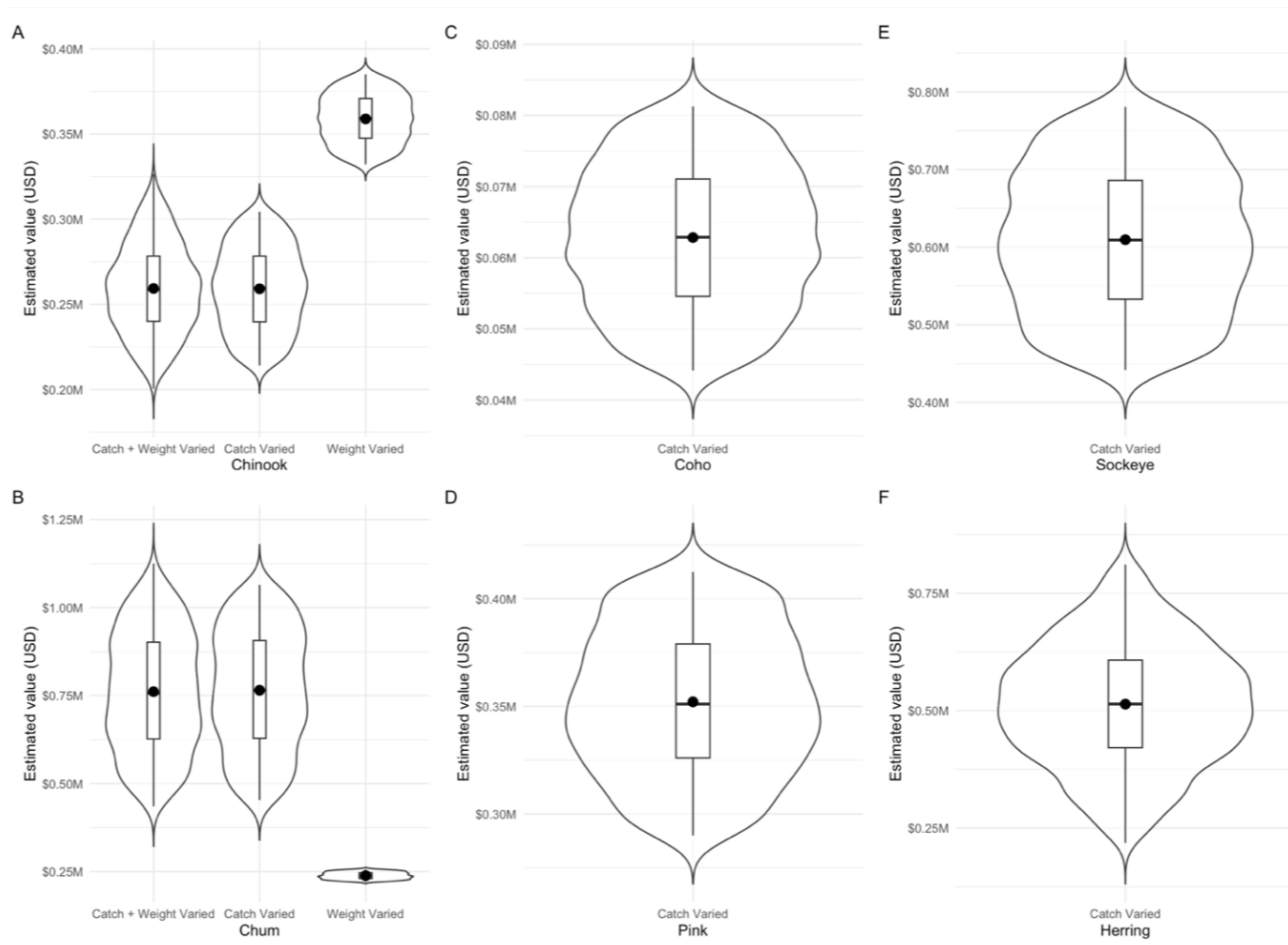


Figure 7. Variation in simulated overall estimated value of the contribution of bull kelp to the following commercial fisheries: A. Chinook salmon, B. Chum salmon, C. Coho salmon, D. Pink Salmon, E. Sockeye Salmon, F. Pacific Herring. Values on Y-axis vary.

Recreational Value

To estimate the value of bull kelp to fisheries, I determined that, on average, bull kelp contributes around $2,133,771 ± 198,638 to the value of recreational fisheries for Chinook, Coho, and Pink Salmon in Puget Sound (Figure 8). There is no recreational catch of Pacific Herring, and the recreational catch of Sockeye and Chum salmon can be effectively valued at $0.

The range of possible values is due both to the number of fish caught in the given year and on the average weights of the fish caught, because that affects the value of the fish to anglers. The frequency of each observed simulation result for the estimated contribution of bull kelp to each recreational salmon fishery is displayed in Figure 9. The value of contribution of bull kelp to Coho salmon ($1,127,161

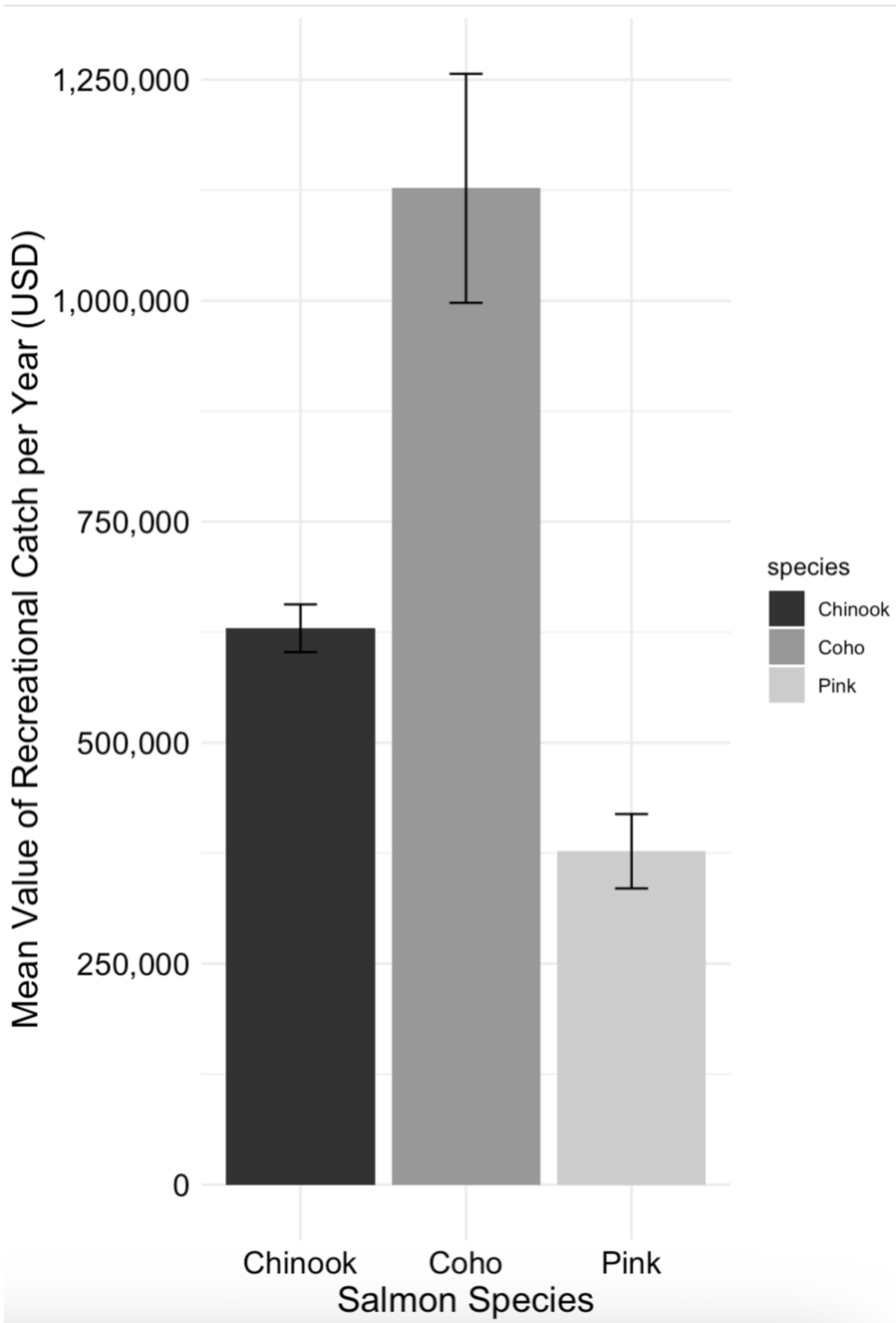


Figure 8. Bar chart displaying the annual value (USD) of the contribution of bull kelp to Chinook, Coho, and Pink recreational fisheries in Puget Sound given estimated Willingness to Pay.

± 129,561) makes up 53% of the overall value of the contribution of bull kelp to recreational salmon fisheries in Puget Sound.

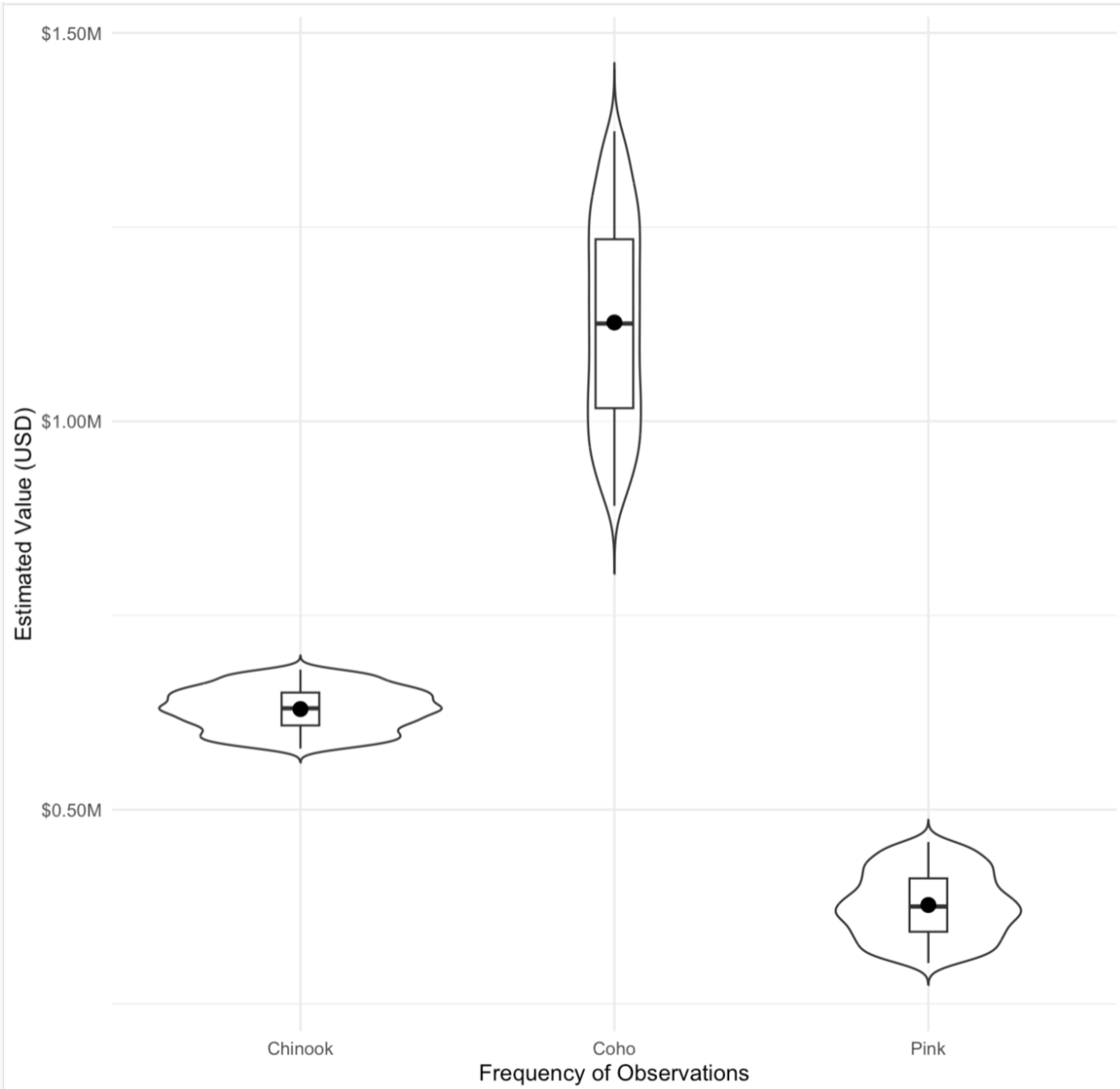


Figure 9. Distribution of the estimated value ($ millions) of bull kelp contribution to Chinook, Coho, and Pink recreational fisheries when the number of fish landed per year is varied.

Overall Value

Overall, bull kelp contributes an estimated $7,802,624 ± 1,690,087 to salmon and herring fisheries and temporary nitrate removal in Puget Sound annually. Of this total value, bull kelp contributes an estimated \$4,698,793 ± 655,682 to combined salmon and herring non-tribal commercial and recreational fisheries in Puget Sound and \$3,103,831 ± 1,034,405 to temporary nitrate removal.

Per hectare, bull kelp contributes an estimated \$807 ± 113 to salmon and herring fisheries and \$533 ± 178 to temporary nitrate removal. In total, the value of ecosystem services provided by bull kelp in Puget Sound can be estimated to be within the range of \$1,340 ± 290 per hectare per year.

Discussion

Interpretation of Results

The estimated value of the contribution (\$7,802,624 ± 1,690,087) of bull kelp to local economies in the Puget Sound region represents the annual value at risk given a total loss of all bull kelp in the region, assuming the services will not be replaced by other kelp species. The contribution of bull kelp to fisheries presents a larger proportion (~60%) of the annual value of ecosystem services considered than temporary nitrate removal in Puget Sound.

This difference is because the valuation of the contribution of bull kelp to fisheries is based on the biomass of fish harvested, while the valuation of nitrate removal is dependent on the area of the kelp canopy. Moreover, fisheries are sizable sources of income for the region (Puget Sound Partnership, 2025), while nitrogen is not traded on a market within the Puget Sound region and therefore does not have an associated monetary value that represents its true local worth.

The estimated value provided by nitrate removal is \$3,103,831 ± 1,034,405. This assumes that only 5,824.13 hectares of bull kelp, the most current estimate given limited monitoring locations, exist in Puget Sound. This likely represents an underestimate of the total bull kelp coverage. Additional data collection would improve the accuracy of this valuation. In Puget Sound, carbon and phosphorous sequestration rates are unknown, and carbon sequestration may be limited, and for this reason are valued at zero in this analysis (Roethler, 2026). Furthermore, this valuation estimates the value of temporary nitrate removal, not long-term removal, which can occur through denitrification or anaerobic ammonium oxidation reactions (Bristow *et al.*, 2017). The rate of nutrient recycling in bull kelp is unknown, making it difficult to measure total nitrate removal.

This analysis suggests that habitat dependency indices can be used on a local scale to create estimates of the value of regional ecosystem services, although they may be limited by data deficiencies. The habitat dependency indices calculated in this analysis reveal that juvenile salmon are at a higher risk than Pacific Herring given a loss of bull kelp. However, the habitat dependency indices are also reflective of the quality of literature surrounding the given species. Studies examining juvenile salmon usage of bull kelp were limited and often, due to the challenges associated with conducting observational studies within a kelp forest, focused on the fringes of the kelp bed. Additionally, habitat dependency would realistically vary between different kelp beds due to location in relation to natal rivers and migratory corridors. Moreover, studies often focused on presence/absence, not on habitat usage, which resulted in assignment of lower HDIs to the respective study. Habitat dependency indices reflect both the ecological reality and the availability of published data, and therefore may be refined with the publication of additional relevant studies.

The HDI is based on juvenile salmon, whereas the commercial and recreational fisheries valuations are derived from adult biomass. This mismatch introduces uncertainty into the analysis and could be addressed with species-specific estimates of survivorship. Additionally, species-specific HDIs would be refined given data on the residency time of juveniles in kelp beds.

Slightly over half (54.6%) the contribution of bull kelp to fisheries comes from commercial fisheries, while slightly less than half (45.4%) comes from recreational fisheries. This recreational estimate assumes that all fish are of hatchery origin, and all fish are retained, not released. The recreational estimate does not include the value associated with fishing trips in which no fish are caught.

Because of this, it is likely that the recreational fishery value is an underestimate and would likely increase if unsuccessful fishing trips are included.

The fishery valuation also assumes that all Puget Sound salmon species are caught each year in commercial fisheries and three species (Chinook, Chum, and Pink) are caught each year in recreational fisheries. This valuation can easily be amended to consider only a subset of these species to simulate years in which certain species, e.g. Pink, are not caught.

This valuation represents the value lost given total bull kelp loss; it does not consider varying levels of decline. However, losses are likely to occur before a complete disappearance of kelp given the likelihood of a tipping point, or "a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system" (Lenton *et al.,* 2008). While bull kelp may continue to take up nitrate until a complete loss, the rate of uptake per hectare would decrease as kelp abundance declines. Additionally, the habitat will lose the ability to function as habitat for juvenile salmon and herring, as the loss of kelp is associated with the decline of fish abundance and the recruitment of early life history stages (Bodkin, 1988; Pérez-Matus *et al.,* 2025). It is possible that, given a decline in bull kelp, the species included in this analysis will find alternative species to fill their functional needs. For example, Pacific herring, when given choice of multiple spawning substrates, spawn on the invasive brown algae *Sargassum muticum* more than expected by chance (Shelton *et al*., 2014). This may mean that the impacts of the loss of bull kelp may be reduced by the presence of alternative species that fill similar functional roles. However, it is unlikely that alternative habitats fully replace all services provided by bull kelp.

This economic valuation only captures a subset of the benefits that bull kelp provides. For example, salmon contribute to ecosystem services beyond simply being foundational to Puget Sound commercial and recreational fisheries. They are culturally important to Coast Salish peoples in the region and serve as food for species such as the endangered Southern Resident Killer Whale (*Orcinus orca*). Similarly, bull kelp provides additional ecosystem services such as the contribution to marine and terrestrial food webs and habitat support to endangered and threatened species such as the bocaccio rockfish (*Sebastes paucispinis*), yelloweye rockfish (*Sebastes ruberrimus*), and canary rockfish (*Sebastes pinniger*), for which bull kelp has recently been designated critical habitat (National Marine Fisheries Service, 2014a).

It is also important to note that it is impossible to value the cultural and spiritual value of bull kelp to people in the Puget Sound region, specifically the Coast Salish peoples, who have cultivated a relationship with kelp-based ecosystems since time immemorial (Naar, 2020). Notably, the majority of valuations of cultural ecosystem services have been conducted in non-Indigenous contexts (Normyle *et al.,* 2023). There are multiple Indigenous-led initiatives aimed towards reshaping ecosystem valuation processes to better reflect Indigenous ways of thought, and any future attempts to include cultural services should center these reformed processes (Urzedo & Robinson, 2023).

Management Implications

This economic valuation is not intended to represent the total value of bull kelp in Puget Sound and should not be used alone to inform conservation spending decisions. Instead, it provides a local-scale framework for quantifying ecosystem services and encourages the integration of ecosystem-service values into bull kelp management, which is especially important as bull kelp continues to decline. This valuation extends the global valuation reported by Eger *et al.* (2023), which found that, worldwide, bull kelp contributes, on average, $61,971 per hectare per year to fisheries and $79,956 per Kg per hectare per year to nutrient cycling, in the form of nitrogen and phosphorus uptake and carbon sequestration. Eger *et al.* (2023) estimate that bull kelp is worth $4.5 billion across its entire range and worth $142,000 per m^2 per year in fisheries value and nitrogen, phosphorus, and carbon sequestration. This global per-hectare fisheries valuation ($61,971) is significantly larger than the value I estimated for Puget Sound ($807 ± 113) because there are services considered by Eger *et al.* (2023) that I did not consider for Puget Sound (e.g., carbon sequestration, commercial urchin and sea cucumber fisheries) because they are of low or no relevance in the region. The value of fisheries associated with bull kelp globally is primarily attributed to invertebrate species, specifically abalone (*Haliotis sp*.), which is a closed fishery in Washington State but makes up close to half (47%) of the total fisheries value associated with bull kelp across its range (ibid). Eger *et al.* (2023) found Nereocystis to have the highest mean economic fisheries value of all kelp genera considered, yet their estimate does not consider salmon or Pacific herring fisheries.

My valuation contributes to the estimated value of Nereocystis by incorporating the dependence of juvenile salmon and Pacific herring on bull kelp. Because the ranges of salmon and Pacific herring overlap with the majority of the distribution of bull kelp (Erlandson *et al.* 2015), I offer that my valuation of salmon and Pacific herring fisheries could augment the per-hectare valuation by Eger *et al.* (2023). However, the harvested biomass of both salmon and Pacific herring varies regionally (National Marine Fisheries Service, 2014b) and my per-hectare valuation likely underestimates the value of these fisheries in other regions and therefore should not be extrapolated beyond Puget Sound.

This research serves to encourage a complete economic valuation of the ecosystem services provided by bull kelp in Puget Sound. To do so, it is essential that the extent of bull kelp in the region be properly quantified. While per-hectare valuations can be estimated, an accurate overall value is impossible to compute if the total number of hectares of bull kelp in the region is unknown. Increased monitoring of bull kelp is essential to encourage conservation spending by producing an accurate value of the ecosystem, and this research aims to motivate further work in this area.

This research also contributes to the discussion regarding connections between kelp, salmon, and forage fish. Establishing a measure of the dependency of a species on a habitat requires substantial information on the relationship. Further research on the relationship between kelp, salmon, and forage fish would improve the estimate of the contribution of bull kelp to salmon and Pacific herring fisheries and thereby improve the estimate of the total economic value of ecosystem services provided by bull kelp to Puget Sound. Bull kelp conservation in Washington State is funded under the umbrella of marine vegetation conservation. However, this analysis shows that one species can provide substantial value in just two ecosystem services, suggesting we are likely undervaluing the benefit to conserving bull kelp.

A more comprehensive valuation that includes estimates of other ecosystem services, such as cultural services, ecotourism, shoreline protection/storm surge reduction, and food web support, can be used to support management and conservation spending decisions. Valuing ecosystem services is a useful tool in encouraging conservation action surrounding vulnerable marine ecosystems. Economic valuations of ecosystem services provide quantitative justification for conservation spending and thus can encourage the protection of habitats that are not only economically valuable, but ecologically, culturally, and spiritually valuable as well.

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Appendix A

Table A1. Floating kelp extent in Puget Sound sub-basins (Claar et al, 2025).

Sub-Basin	**# of locations monitored**	**% of nearshore extent monitored**	**% of monitored nearshore extent with floating kelp**	**Hectares nearshore habitat**	**Estimated hectares monitored**
Admiralty Inlet	2	1%	22.6%	6,534	14.77
Central Puget Sound	9	3%	12.3%	9,599	35.42
North Puget Sound	10	6%	26.5%	19,521	310.38
San Juan Islands	48	100%	51.7%	10,452	5,403.68
South Puget Sound	6	1%	4.6%	12,219	5.62
Saratoga/Whidbey	5	3%	17%	10,638	54.25

Table A2. Mean and SD (μmol g^{-1} hr^{-1})) of Bull Kelp Nitrate Uptake under Low (1-3 μM), Medium (3-10 μM), and High (>10μM) ambient Nitrate concentrations (Fales et al., 2023).

	Mean (μmol g^{-1} hr^{-1})	**SD (μmol g^{-1} hr^{-1})**
Low Nitrate Uptake (1-3 μM)	0.214	0.121
Medium Nitrate Uptake (3-10 μM)	0.907	0.824
High Nitrate Uptake (>10 μM)	1.599	0.586

Table A3. Habitat Dependencies Indices generated for Chinook, Coho, Chum, Sockeye, and Pink Salmon and Pacific Herring.

Species	**HDI**
Pink Salmon	0.667
Coho Salmon	0.571
Chum Salmon	0.535

Chinook Salmon	0.500
Sockeye Salmon	0.250
Pacific Herring	0.219

Table A4. Commercial Salmon Species' average pounds per individual caught and average ex-vessel price per pound (Pacific Fishery Management Council, 2025).

Species	**Average lbs per individual caught**	**Average ex-vessel price per lb (USD)**
Chinook	11.4	3.72
Coho	5.8	2.07
Chum	7.5	0.85
Sockeye	3.9	2.65
Pink	3.8	0.87

Table A5. Commercial catch (in individuals caught) for Chinook, Coho, Chum, Sockeye, and Pink salmon for 2018-2023 (WDFW Puget Sound Commercial Salmon Team, 2024).

Years	**Chinook**	**Coho**	**Chum**	**Sockeye**	**Pink**
2018	13700	9647	388943	397671	NA
2019	9509	2980	135230	NA	92790
2020	9286	6652	103069	NA	NA
2021	7316	11964	85109	NA	155754
2022	17757	17189	471516	75537	NA
2023	15786	10076	65502	NA	229770

Table A6. Weight ranges and Willingness to Pay (adjusted for 2023 inflation) for each size class of Puget Sound salmon considered in recreational catch valuation (Anderson et al., 2013).

Size Range (lbs)	**Species**	**Willingness to Pay (2023 USD)**
0-10	Chinook	122.01
10-20	Chinook	202.13
20-30	Chinook	232.70
0-5	Coho	50.95
5-10	Coho	90.64
10-15	Coho	144.39
4	Pink	22.77

Table A7. Chinook, Coho, and Pink Salmon caught by recreational fishermen in years 2021-2025 (Washington Puget Sound Creel reports, 2021-2025).

Year	**Chinook**	**Coho**	**Pink**
2021	4,870	11,169	11,249
2022	5,537	15,676	7
2023	6,059	25,706	27,462
2024	7,343	35,683	9
2025	7,315	28,413	36,475