PACIFIC SALMON
FOUNDATION

AN EXPLORATORY ANALYSIS INTO SPATIAL PATTERNS OF CORRELATION RELATIVE TO ENHANCEMENT: CAN AN ENHANCEMENT SIGNAL BE FOUND IN NEARBY WILD SYSTEMS?

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Prepared for BCSRIF
March, 2023

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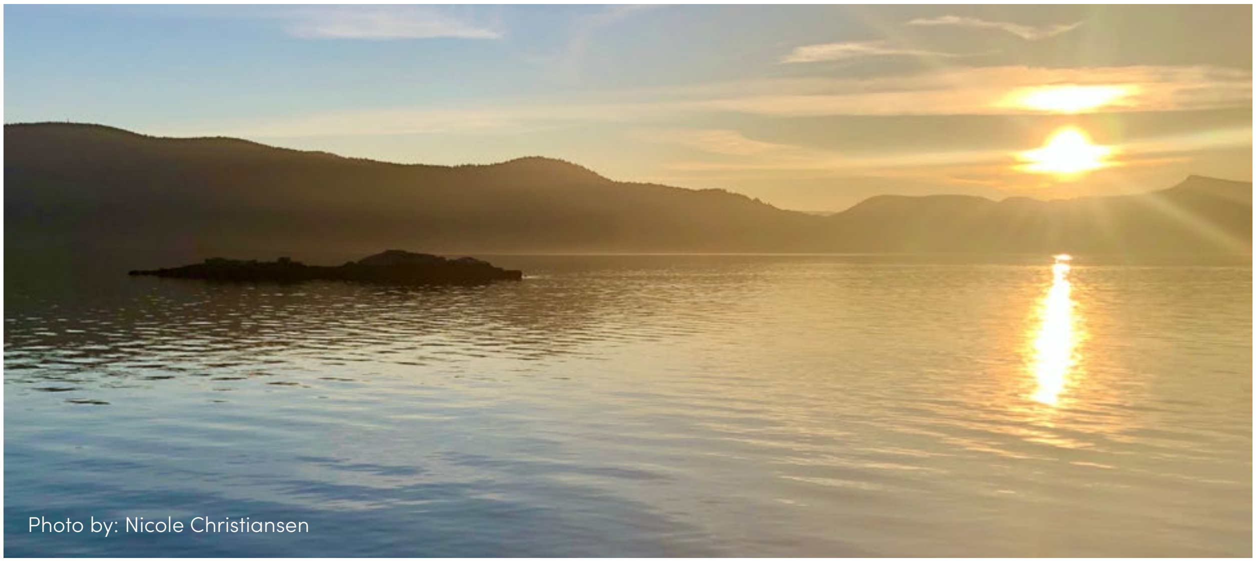

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1 INTRODUCTION

The causes and consequences of straying in Pacific salmon (*Oncorhynchus spp.*) populations have received increasing attention in the ecological literature over the past 40 years. Straying, or returning to streams of non-natal origin, occurs in all five Pacific salmon species, has been observed in both wild and hatchery-origin populations, and is known to be most prevalent in populations of chum (*O. keta*) and pink (*O. gorbuscha*) salmon (Keefer and Caudill 2014; Quinn 1984). Individuals which stray while homing to their natal streams function as an insurance population against (i) systems which show high interannual variability in juvenile survival, (ii) populations which have little variation in age at maturity, and (iii) populations spawning in unstable streams or in streams with a high density of analogous streams nearby (Quinn 1984). As a life history strategy in wild populations, straying can offer resilience to disturbances, though straying of hatchery-origin populations into wild systems can have unintended consequences to ecosystem integrity.

Investigations into the effects of salmon straying examine the issue within a source-sink framework; strays are classified as originating from 'donor' populations into 'recipient' populations and the study of the consequent ecological effects mimics this directionality. Historically, studies tended to focus on the sink component, studying straying from the perspective of lost productivity within donor populations. More recent work including an upcoming CSAS review of straying rates in Chinook salmon (*O. tshawytscha*) in British Columbia (Luedke, personal communication, 2021a) has focused on straying rates of hatchery Chinook into non-origin populations. While the effects of straying on donor populations are relatively straightforward and usually directly related to lost productivity, stray hatchery fish may have unintended consequences on recipient populations through many mechanisms.

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When the donor population is of hatchery-origin, determining the effects of straying on nearby wild systems becomes even more complex. While strays from enhanced systems bring with them the possibility of providing additional spawners and increased production to nearby systems, numerous studies have shown the negative effects of hatchery enhancement on salmon fitness and genetics. Indeed, the addition of hatchery-origin spawners into a wild system can lead to numerous types of effects including *(i)* effects on the reproductive success of wild spawners (particularly so if hatchery-origin spawners are less fit than their wild counterparts), *(ii)* competition for available spawning habitat and juvenile rearing resources, *(iii)* domestication and hybridization effects, and *(iv)* outbreeding depression (Keefer and Caudill 2014). Conversely, in small systems where local spawners are declining in abundance, hatchery-origin strays could provide a 'rescue' effect via additional, though unintentional, spawners (Bett *et al.* 2017).

To-date, most of the research investigating hatchery *x* wild interactions has been conducted in Alaska, where the regulatory landscape requires aquaculture associations to conduct mass otolith thermal marking on hatchery-reared fry and baseline escapement data are relatively widespread and relatively long-term. In British Columbia, the focus of the present study, enhancement of salmon systems through the Salmonid Enhancement Program (SEP) has been ongoing in varying degrees since the 1970s, albeit historically enhancement was present at smaller scales in many places in BC. While there has been considerable information on straying of hatchery Chinook and coho (*O. kisutch*) salmon from the DFO's Coded Wire Tagging (CWT) program (Quinn 1993, Tallman and Healey 1993, Candy 2000, Labelle 2011), the effects of straying rates in pink and chum salmon have been less studied. This limitation may be in part logistical; in Chinook and coho salmon, both population sizes and enhancement numbers are typically lower than in pink and chum systems, and relatively labour-intensive methods such as CWT are well-suited in these cases. Determining straying rates in larger populations of pink and chum salmon is more intensive as it requires both *(A)* investment in some form of mass marking technology (such as *(i)* automated adipose fin clip systems, which can be relatively cost-effective but are limited when differentiating recaptured adults from their hatchery of origin, *(ii)* upgraded hatchery infrastructure for otolith thermal marking, which can be cost-prohibitive; the effective use of this strategy also requires an entity to administer unique hatch codes for different hatcheries and brood years, or *(iii)* genetic methods which allow for identification of non-natal fish but is to-date limited by the resolution of stock identification methods, which for most species is still at scales larger than the local scale at which straying occurs) and *(B)* structured research, monitoring, and sampling programs of adult salmon returns that encompass the large estuarine systems in which pink and chum salmon occur. For example, to our knowledge, there is little sampling for enhanced contributions of 'wild' chum systems (e.g. Area 6 or Area 8).

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The impetus behind this study is to explore alternative and comparably cost-effective methods which use existing, though often limited, data to determine if it is possible to detect a signal from stray hatchery fish in nearby wild systems. Straying of salmon from non-natal systems within a Conservation Unit may not present a concern when amongst wild populations, however the same is not true for hatchery raised fish. To our knowledge, this type of analysis has not been done before, although multiple studies have investigated both spatial coherence and covariation across distance in juvenile and adult salmon, an aspect which shares elements with and inform the present study. Myers *et al.* (1997) explored how spatial scale related to variability in recruitment for several life stages of pink and sockeye (*O. nerka)* salmon and found little spatial correlation in interannual survival in the freshwater stage, but spatial correlation in survival from spawner to recruit was higher since it included larger scale shared marine environments. Meuter *et al.* (2002) examined spatial coherence in sockeye and chum survival indices and found a regional decorrelation at scales of 100s — 1,000s of km. Teo *et al.* (2009) investigated spatio-temporal variability in coho salmon from California to Alaska and found that in all but two groups, correlations between systems were smaller than for other species of Pacific salmon and predicted a 50% correlation distance between 150 – 217 km. Two studies examined spatial coherence in Chinook salmon over relatively large scales (>700 km and <400 km) using different methods (Sharma *et al.* 2014; Kilduff *et al.* 2014), and Dorner *et al.* (2018) found that there was synchrony of Chinook salmon productivity from Oregon to Alaska in relation to ocean factors such as the North Pacific Gyre Oscillation and the North Pacific Current.

These studies were conducted over large regional scales ranging from 100 km to over 700 km. We proposed to study spatial correlation in metrics of system productivity at the smaller, local scale (<50 – 100 km) by spatially grouping streams by inlet — a scale more appropriate for detecting potential straying signals as salmon home among various waterbodies of marine entry. Given the small spatial scale of the study, we would expect large-scale but consistent regional patterns such as sea surface temperatures and the Pacific Decadal Oscillation (PDO) to have minimal impacts on our analyses since correlations are done on an annual basis. However, changes in the regional processes over time may influence the before and after enhancement analyses. At this scale, we expect that there will be generally high correlation between streams at the inlet level, which will decrease with distance between inlets. As distance increases further, we would also expect that decorrelation would increase as marine entry locations become further apart and more subject to local influences such as weather patterns and freshwater inputs.


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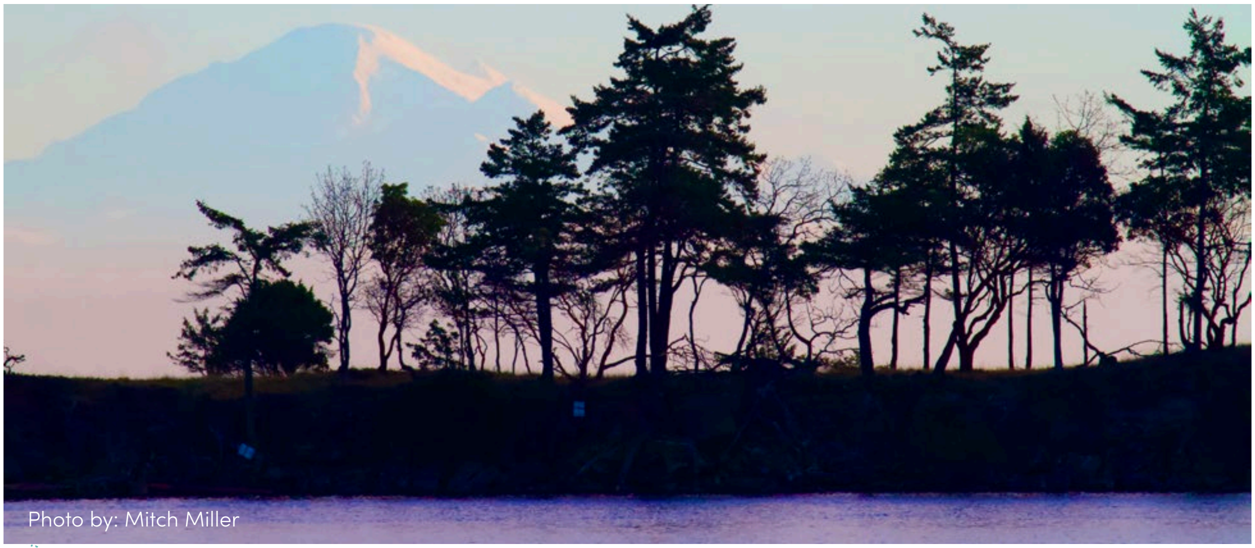
In the effort to detect hatchery signals in wild systems, the phenomenon of decorrelation increasing with distance may be a potential confounding factor, particularly when combined with localised environmental or habitat perturbations. Further, there could be changes to correlations over time that are related to factors beyond the scale of the study which could mask potential signals (e.g. Dorner *et al.* 2018). Another challenge to this endeavour is the enormous deficit of information available for use in statistical analyses. An idealized study would include data on spawner abundance, annual age class breakdowns of both outmigrating smolts and returning adults, stream and inlet specific exploitation rates, and enhanced contributions at the stream level. There is no area on the BC coast where this level of information exists in a long time series which covers both pre- and post-enhancement periods for multiple systems within a given area. Since enhancement began in many places prior to development of more rigorous spawner enumeration guidelines under DFO Science in the early 1990s, the inclusion of historical spawner estimates may also confound analyses. We do of course recognize that producing this suite of extensive data would be both expensive and onerous to collect over large scales and long periods of time.

The aim of this exploration was to relate stream-level metrics of population productivity against each wild system's distance away from nearby enhanced systems to test the hypothesis that an enhancement signal can be detected in more proximal streams. To do this we attempted to create a workflow in which an end user could define a focal species within a chosen Pacific Fishery Management Area (PFMA; hereafter 'Area') and receive a code-generated report outlining the outputs and predictions from a suite of statistical models and visualization tools which are described below. The workflow included code to extract and organize data from the New Salmon Escapement Database System (NuSEDs) and release information from DFO's Enhancement Planning and Assessment Database (EPADs) based on the user's filter criteria. In this way, we had aimed to create a scalable tool that could be used to systematically investigate stray rates in each Area by species. Unfortunately, we were hampered with a deficit of information that made scaling the workflow prohibitive as data gaps and temporal completeness were vastly different between management areas and species, making true standardized comparisons between areas unlikely to be pragmatic. Instead, we chose chum salmon in three Areas (Areas 6, 8, and 25) to use as exemplars for the study. In these areas, we lacked full stock-recruit information, so we undertook exploratory analyses using estimates of recruits-per-spawner as a metric of system productivity. We then produced three code-generated reports (Appendices 1-3) to demonstrate how cross-correlation matrices, dendrogram and tanglegram visualization tools, and generalised linear models were used to attempt to discern an enhancement signal in natural systems. A Github repository of all data and codes that produced these reports is available in this report's supplemental materials.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2 METHODS

2.1 DATA

2.1.1 HATCHERY RELEASES

Release data by site and by stock for relevant areas were extracted from the DFO EPADs which was provided by Cheryl Lynch at DFO (Lynch, personal communication, 2021). The release database contains information on release stock origin, release location, unmarked and marked numbers of releases, release stage (e.g., fed fry etc.), release year, and release Conservation Unit name, amongst other fields. All releases of the same life stage were summed for a total release by release year, stage, and release site. For visual presentation, they were also summarised by site-stock combinations, as some releases do not originate from the system that they were released into. Release information was used to determine the year of the start of enhancement which was then used to compare pre- and post-enhancement periods.

2.1.2 ESCAPEMENT RECORDS

Escapement data were extracted from the Pacific Salmon Explorer dataset[1], which is derived from DFO's NuSEDs database[2]. Filters were applied on a case study-by-case study basis to extract escapement systems with enough information to allow for quantitative statistical analyses. Filters are described in each case study area, although we tried to remain consistent between areas. Filters are primarily based on the number of enumerations within the pre- and during/post-enhancement periods. We did not consider the escapement quality rankings recorded in the NuSEDs, however an additional filter could be easily implemented. Our rationale for not adding this was that it would limit even further the number of streams in the already limited analysis.

Photo by: Mitch Miller

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[1] Available online at: https://www.salmonexplorer.ca/#!/2

[2] Available online at: https://open.canada.ca/data/en/dataset/c48669a3-045b-400d-b730-48aafe8c5ee6

2.1.3 STOCK RECRUIT INFORMATION (AGE AND EXPLOITATION)

True stream level stock-recruit (SR) information (e.g., stream specific age structure, accurate spawners estimates, and exploitation rates) is not readily available, and, as far as we understand, may only exist for a few places in BC (e.g., PSC Chinook Technical Committee exploitation rate indicator stocks, some heavily enhanced chum salmon systems, and possibly a few wild indicator stocks for other species). This makes analysis of SR relationships at the stream level problematic considering recruits per spawner (RPS) would be simply scaled to the same level across a set of streams with common age proportions and exploitation. However, each stream will have a unique pattern of escapements that may change SR relationships, either through natural environmental and biological variation, or through observer bias such as error in enumerations. It is quite likely that the age data for each area is derived from hatchery-origin chum taken from broodstock sampling. This has the potential to bias the hatchery streams and the wild streams since age is likely different in hatchery dominated and wild systems (and likely different between wild systems from year to year as well).

To this end, we used aggregate level data to develop SR datasets. While each stream gets scaled by the same age and exploitation rates, variation in stream specific escapement leads to different RPS in each stream (unless of course the escapement is equal). For all areas, we used Conservation Unit-level age and exploitation data from the Pacific Salmon Explorer (Hertz, personal communication, 2022) (Table 1). Some details on the source of ages and exploitation rates are provided in PSF (2021).

Table 1: Data sources for age and exploitation rate data for case study areas.

Species/Area	Age Data (original source)	ER Data (original source)	Conservation Unit Source
Chum/WCVI/Area 25	PSE* (DFO stock assessment — Diana Dobson)	PSE (DFO stock assessment — Diana Dobson)	Used age and ER data from Southwest and West Vancouver Island CU
Chum/NC/Douglas Gardner	PSE (DFO age database)	PSE (English *et al.*, 2018)	Used age and ER data from the Douglas-Gardner CU
Chum/NC/Area 8	PSE (DFO age database)	PSE (English *et al.*, 2018)	Used age and ER data from Bella Coola-Dean Rivers / Bella Coola River Late CUs

* Pacific Salmon Foundation Pacific Salmon Explorer

2.1.4 SPATIAL INFORMATION

Because we expect to find greater correlation within inlet groups rather than between them, individual streams were assigned to their respective inlet groups based on qualitative examination of maps in QGIS. These were used to categorise streams to inlets and sub-inlets, which were then used in dendrograms and other analyses to compare inlet level metrics. We also calculated distance from stream mouth to stream mouth to explore correlations in spawners or RPS versus 'over water' distance between streams within each management area.

Distance between the enhanced stream(*s*) mouth(*s*) and non-enhanced streams was completed in QGIS using a node-based approach, as was the pairwise stream mouth to stream mouth distance. This approach used nodes placed proximate to the enhancement and then nodes at each inlet intersection point, and finally nodes at the mouth of each stream, which allows for consistent measurement. Between nodes, lines down the length of the inlet, and then distance to each stream was measured perpendicular from the inlet center line to the mouth of the stream. For inlets with multiple entries and/or connections, a subjective decision was made for the distance measurement, typically considering the shortest water only route. This allows for consistent measurement between systems. Initial setup of the nodes, stream assignments, and distance from enhancement were completed in QGIS using the NAD83 (CSRS)/BC Albers datum.

For the pairwise stream mouth to every other stream mouth distances, we used Feature Manipulation Engine (FME) software and the node based distance network created for the distance from enhancement estimates. The calculations were undertaken using four major steps: **1)** Isolate the point nodes associated with the line network which are closest to the stream mouths, and assign them the name of the closest stream, **2)** generate straight lines between all possible pairings of points identified during step one, a necessary input for the third step, **3)** run the ShortestPathFinder transformer with the lines from step two and the 'as the fish swims' line network as inputs, to calculate distances between all stream mouths while following the network, **4)** output the results as CSVs (non-spatial) and shapefiles (polylines) including attributes for distance between all possible pairings of stream mouths (branded using GEOGRAPHIC name column from BC Gazetteer dataset) calculated in metres and kilometers. All data inputs and outputs were assigned a NAD 1983 BC Environment Albers: 3005 projected coordinate system. All distances used in models and analysis were in kilometers.


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2.1.5 WORKFLOW

The following describes the steps we took for analysis in each case study area.

1. Examine release data for the defined enhancement time frame
2. Extract escapement data from the NuSEDs for the defined study Area
3. Filter out streams in the dataset with insufficient escapement data for analysis
4. Calculate escapement metrics for each analysis stream[3]
    - **a.** Log escapement: A metric of escapement which has been log-transformed to fit a linear model
    - **b.** Z-score: A statistical measurement that compares all values against the population mean
    - **c.** Pavg: A standardized metric of escapement estimated by dividing the logged escapement for each stream, in each year, by the average logged escapement recorded over all years — see equation (1.)
    - **d.** Mavg: The moving average of escapement over the duration of a salmon life cycle (e.g. 4 years for chum)
    - **e.** RPS: A metric of recruits per spawner, i.e. how many juveniles survive to spawning age from each brood year
    - **f.** Log(RPS): A log-transformation of recruits per spawner to fit linear models

4. Calculate the cross-correlation matrix for each of the six metrics
   - **a.** Visualize hierarchical groupings identified in the cross-correlation analysis using dendrograms
   - **b.** Visualize how stream correlation groupings differ between metrics using tanglegram plots tracing dendrogram differences

4. For selected metrics (z-score and log(RPS)), create and compare correlation matrices and dendrograms for pre- and post-1980 enhancement periods

5. Use generalised linear regression models (GLM) to explore the relationships between enhancement and log(escapement) and log(RPS)

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[3] note that after preliminary work identified the four escapement metrics to be very similar, the Pavg and Mavg metrics were dropped from further analysis.

2.2 ANALYSES

All statistical analyses and data manipulation were completed in R (R Core Team, 2022).

2.2.1 DATA TREATMENTS

Escapement information

Escapement information was extracted from the PSE dataset as described above. We applied a filter that selected analysis streams based on having spawner counts in at least 50% of years in both the before and after-enhancement periods. Not all systems had spawner estimates in all years, however the pairwise correlations used only years with enumerations in both systems being compared. This significantly reduced the number of streams included in analyses. While a target of 50% completeness was a subjective value, the backend code for these analyses allows for the data filtering criteria to be easily changed — provided that the user provides spatial stream data and a distance matrix for all streams which pass the filter.

It is well known that escapement information is log-normal distributed, so we converted raw escapement to logged escapements, computed average *P*-score (*Pavg*) and Z-score for each stream-year, and calculated a moving average over one generation length (four years for chum salmon). Gaps in escapement where not infilled, however we allowed the moving average to be calculated on four year periods with only partial information. This allowed for comparison of various metrics. The P average method is estimated by (Equation 1) dividing the logged escapement (E) for each stream (i) in each year (t) by the average logged escapement recorded over all years and was adapted from the P_{max} method in Holtby *et al.* (2000) in an unpublished draft report on Nass River chum.

$$P_{i,t} = \frac{log\,(E_{i,t})}{avg(log(E_i))} \quad \textbf{(1.)}$$

Stock Recruit Information

Age and exploitation rate information were used to construct stream-level brood tables for each area, for each of the filtered streams. Exploitation rate and age data were held constant between streams since long time-series of age data by stream does not exist, and exploitation rates are not available for specific streams.

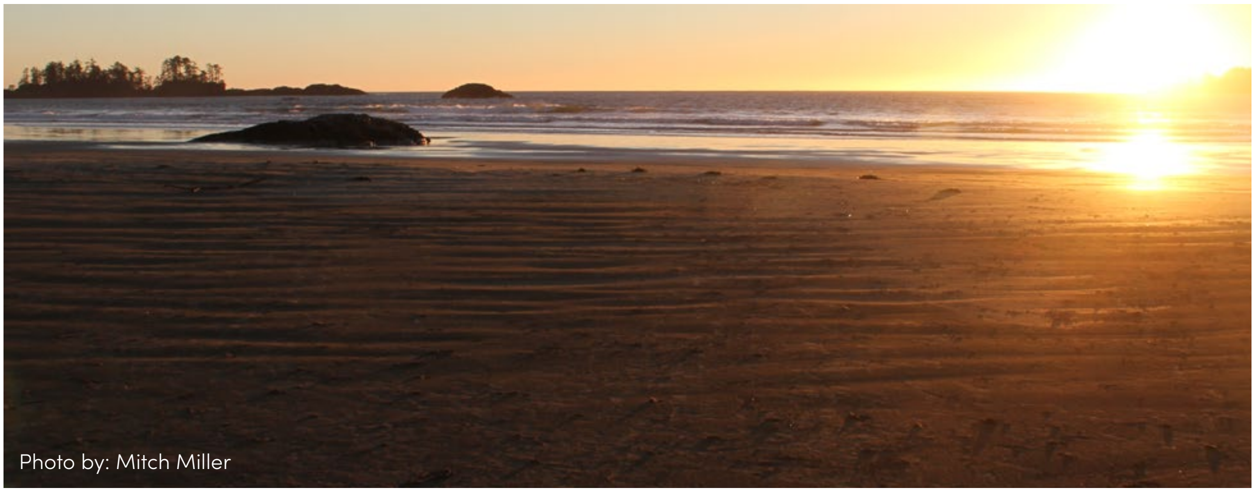

Photo by: Mitch Miller

2.2.2 CORRELATION AND CLUSTER ANALYSIS

We initially used the 4 spawner abundance metrics listed above to explore correlation between streams. However, preliminary analyses showed that all the spawner abundance metrics produced the same results (visually determined through dendrogram and tanglegram comparisons between metrics), so we only included Z-scores of log(escapement) for correlation analyses using dendrograms. We also compared RPS versus logged(RPS) in the same way, with identical results, so we included only the analysis based on log(RPS) to reduce redundancy. Locally estimated scatterplot smoothing (LOESS) was used to visually identify trends in metric summary plots.

Cross-correlation matrices were used to visually explore patterns in correlation between metrics or time periods. An example cross-correlation matrix is shown in Figure 1. Large blue squares indicate strong positive correlation, with large red squares showing strong negative correlation. Boxes represent an arbitrary number of hierarchical clusters to help visually illustrate changes in correlations either between metrics or different time periods.

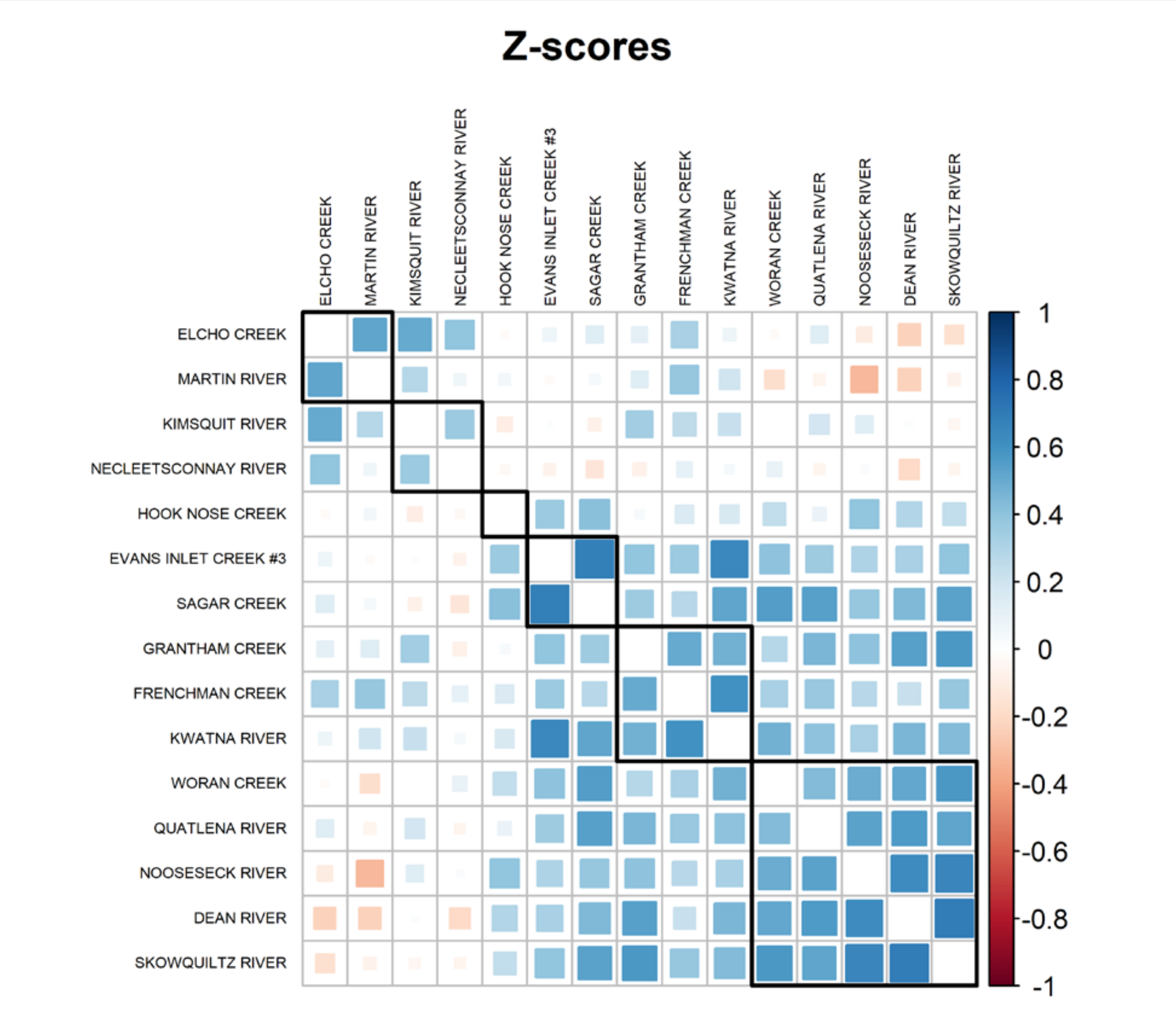

Figure 1: An example cross-correlation matrix for Area 8 chum, showing pairwise correlations between streams for Z-score of log (escapement).

Dendrograms were used to visualize how the use of different metrics influenced the structure of inter-system correlation clusters. An example dendrogram is shown in Figure 2 for Area 25. Stream names are coloured by inlet/sub-inlet assignment. Streams that are grouped together have higher correlation in the associated metric than streams that are not grouped together. Differences between metric dendrogram clusters were traced through the use of tanglegrams (Scornavacca *et al.* 2011). Tanglegrams were developed to compare differences between phylogenetic trees (dendrograms). An example tanglegram is shown in Figure 3 (next page). These allow comparisons between stream groups by metric or time period. The lines between stream names show the movement of streams between groupings. Coloured lines indicate that the grouping of streams indicated by the lines has remained constant, however the location of the group within the dendrogram has shifted. Additional tanglegrams were created to further compare each metric against its pre- and post-1980 enhancement structure. Dendrograms and tanglegrams were compiled and made using R package dendextend (Galili, 2015).

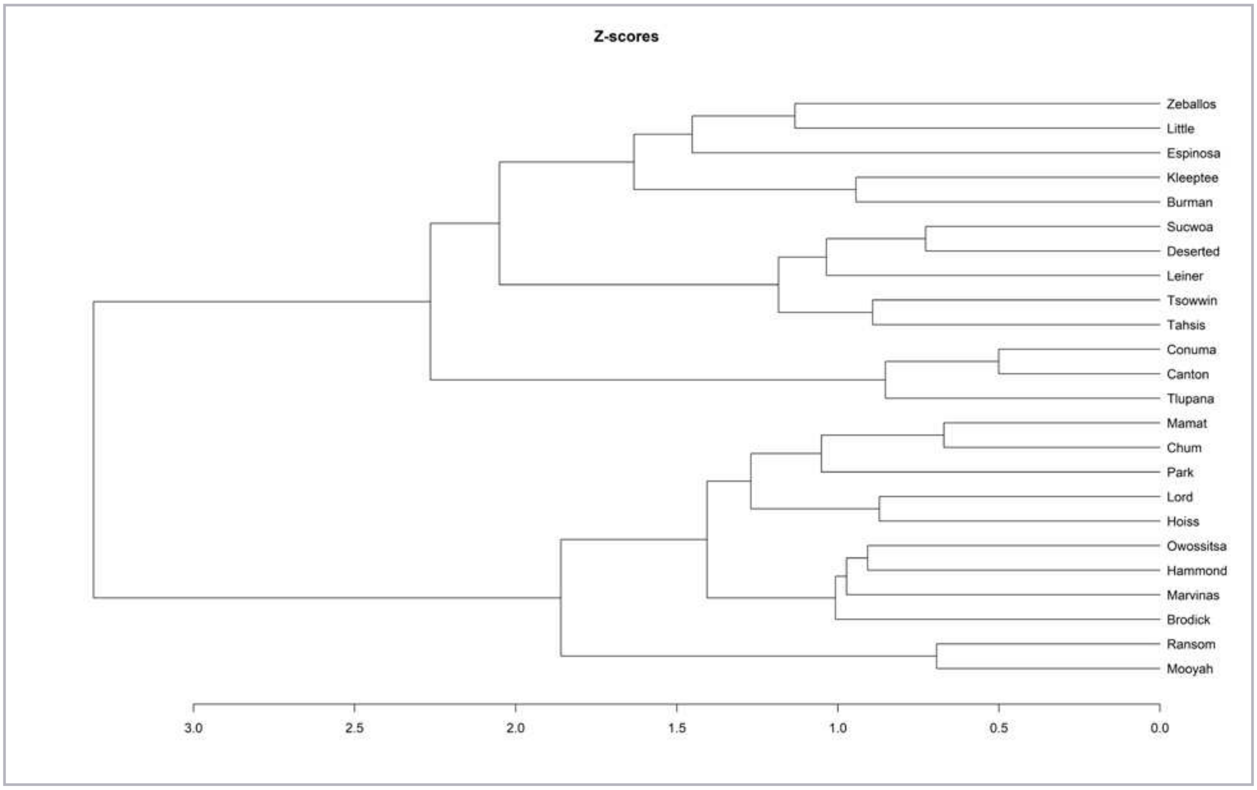

Figure 2: Example dendrogram for Z-score of log(escapement) for Area 8 chum.

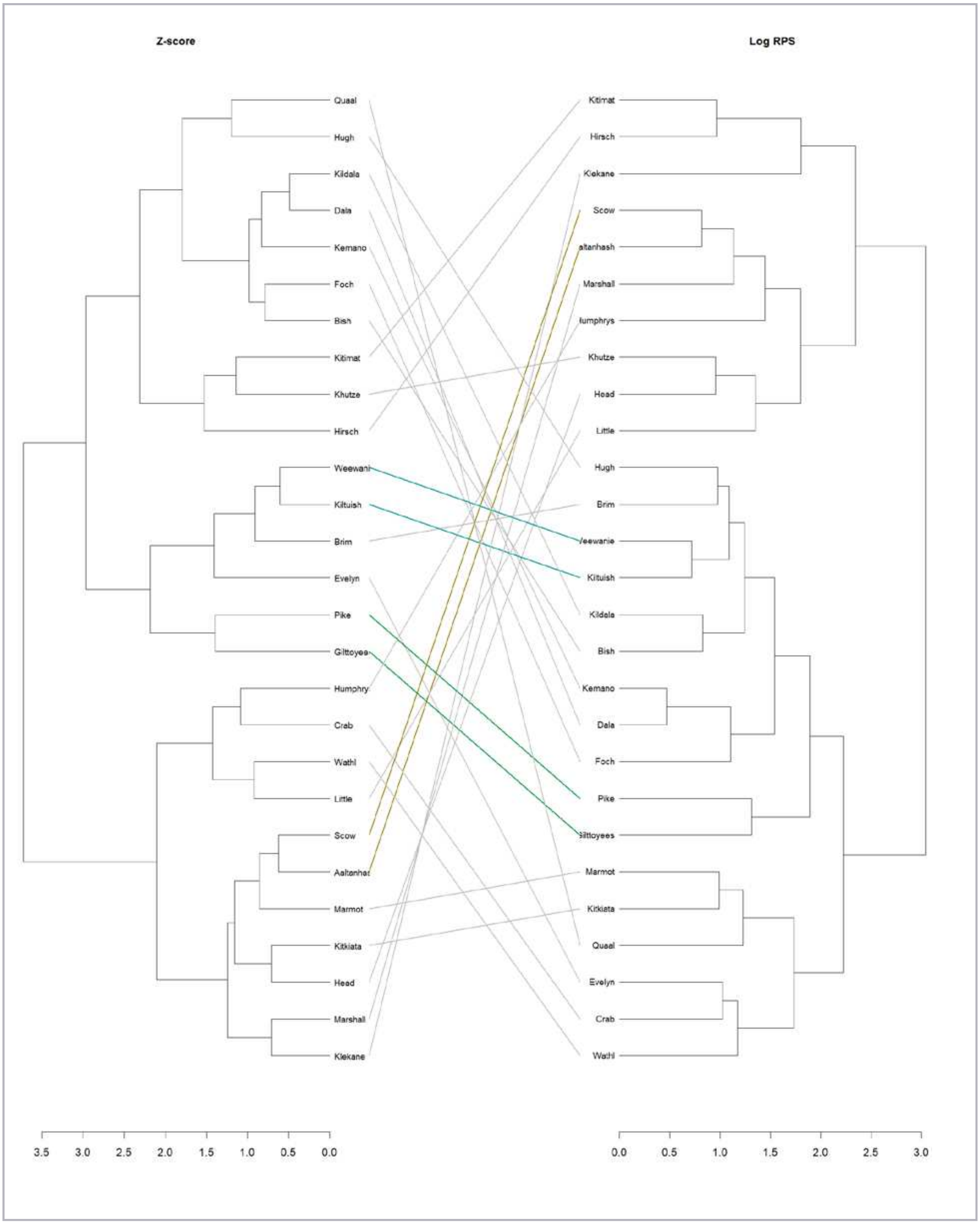

Figure 3: An example tanglegram for Douglas-Gardner chum to visually identify changes in stream groupings between metrics or time periods, in this case the comparison is between all years for Z-score of log(escapement) and log(RPS).

2.2.3 REGRESSION MODELS

Multiple regression generalised linear models were used to explore the effects of distance from enhancement, year, correlation coefficient, and total releases on logged RPS. The models took the form:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots \beta_n X_n + \varepsilon,$$

Where:

y_i = Logged recruits per spawner (Log RPS)

x_i = Explanatory variables (Distance from enhancement, year, correlation coefficient, total releases)

β_0 = y-intercept

β_i = The slope coefficients of the explanatory variables

ε = Error terms/residuals

Fitted models were ranked and compared using Akaike Information Criterion (AIC) to select the most parsimonious model. Residuals were tested against the assumptions of normality and heteroscedasticity, and models which violated these assumptions were log-transformed and refit.

Further models were fit to explore the relationship between Z-scores of spawner abundance and distance from enhancement, year, and correlation coefficient.

The hypotheses tested by these models are as follows:

H_{OA} — RPS [via log(RPS)] has no relationship with any variables over time

H_{OB} — Escapement (via Z-scores) has no relationship with any variables over time

H_1 — There is a change in RPS with proximity to enhanced systems over time

H_2 — There is a change in RPS with the total number of hatchery-origin releases over time

H_3 — There is a change in RPS in streams closely correlated to enhanced systems over time

H_4 — There is a change in escapement with proximity to enhanced systems over time

H_5 — There is a change in escapement with the total number of hatchery-origin releases over time

H_6 — There is a change in escapement in streams closely correlated to enhanced systems over time

Photo by: Mitch Miller

Many candidate models were explored, and then ranked using AIC. Examples of the candidate models are shown in Table 2 and Table 3. Not all models explored are shown here. There are many additional models that could be considered, however initial explorations suggested that the data did not support the use of more complex models such as mixed effects models.

Table 2: Example table for candidate model selection development using logRPS as the dependent variable.

Candidate model
log rps ~ distance from enhancement + year
log rps ~ distance from enhancement + total releases + year
log rps ~ total releases + year
logrps ~ total releases + factor(year)
logrps ~ total releases + factor(year) + year
logrps ~ total releases + year + system name
logrps ~ total releases + year + subinlet
logrps ~ correlation coefficient + year
logrps ~ correlation coefficient + year + system name
logrps ~ correlation coefficient + year + total releases

Table 3: Example table for candidate model selection development using log escapement as the dependent variable.

Candidate models
log escapement ~ distance from enhancement + year
log escapement ~ distance from enhancement + total releases + year
log escapement ~ correlation coefficient + total releases + year
log escapement ~ correlation coefficient + total releases + inlet + year
log escapement ~ correlation coefficient + total releases + subinlet + year
log escapement ~ correlation coefficient + distance from enhancement + total releases + year

3 CASE STUDY AREAS

The initial concept of this study was to apply it to all enhanced species and areas in BC. However, initial explorations into the methods, applications, and data suggested that it would be a massive endeavour and beyond the resources and capacity available within the project. Also, many areas in BC have enhancement in many systems that are proximate, confounding the exploratory analysis we were attempting. Therefore, we selected a number of case study areas (Table 4).

Table 4: Case study areas considered in this report with detailed analysis.

Species	Area/CU	Release description
Chum	Area 25, WCVI	Hatchery origin chum are released into a number of systems in this area, including Conuma River.
Chum	Area 8, Central Coast	Hatchery origin chum are released in significant numbers in 2 places in Area 8, in the Bella Coola River tributaries and in McLoughlin Bay in coastal Area 8.
Chum	Douglas Gardner CU, North Coast	Hatchery origin chum are released largely in the Kitimat River.

3.1 AREA 25 CHUM (ESPERENZA AND NOOTKA INLETS)

DFO Pacific Fisheries Management Area 25 is comprised of two main inlets, Esperenza Inlet to the north, and Nootka Sound in the south (Figure 4). We divided Nootka Sound further into the Conuma region and the Gold River/Burman region. We also divided the entire Area into a number of sub-inlets (Ransom, Gold/Burman, Tahsis, Eliza, Zeballos, Nootka, Conuma, and Espinosa) for the purposes of refining regression and spatial comparisons.

There is very significant enhancement of chum in Nootka Sound to Conuma River and nearby systems including the Sucwoa, Canton, and Tlupana systems (Figure 4). As these systems are very close to each other relative to distances to other streams, Conuma River was used as the central location for enhancement in all spatial analyses by estimating distance from Conuma to the other streams in Area 25. Enhancement started in 1979 and quickly increased to between 10 and 15 million fry. In more recent years (since 2000), total releases to the area range between about 2 and 5 million. Some fry are also released in Conuma estuary in seapens. There was historical enhancement in Deserted Creek as well (Appendix 1, Figure 4) which is in the Conuma terminal area. In Esperenza Inlet, the Zeballos River is also enhanced with chum, however it is in a different inlet from the Conuma region and is enhanced to a much lower level, and only recently. There is also a connection between Esperenza Inlet and Nootka Sound which we have called the Tahsis region. There is no other significant enhancement of chum in Area 25. For our purposes, we considered only the Conuma region as having significant enhancement effect. Releases by release site are shown in Appendix 1.

Area 25 has 53 systems listed in the PSE database. After filtering (as described above) only 24 streams were included, however all inlets and sub-inlets had at least one stream in the filtered dataset. Distance to the mouth of each stream was measured from the Conuma River (as discussed above) using the node approach detailed above and ranged from 3km (Deserted Creek) to over 92km (Ransom River). This provides adequate contrast in distance. Figure 4 shows the Area 25 analysis streams and distance measurements. For Area 25 we applied our analysis workflow as detailed in the methods. More details on the streams, escapements, releases by release site, and total releases in Area 25 can be found in Appendix 1.

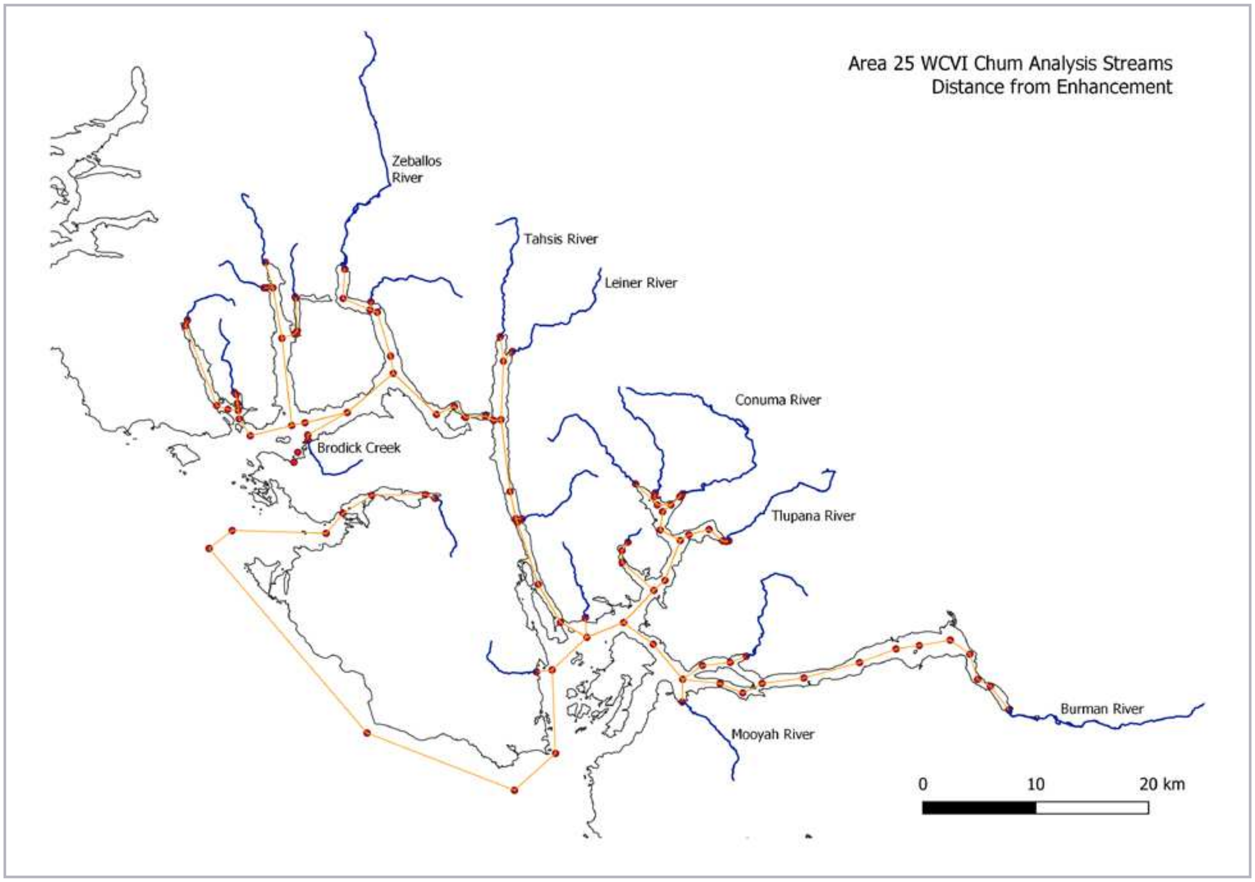

Figure 4: Map of Area 25 chum (WCVI, Nootka and Esperenza Inlets) showing node based approach for determining distance between enhanced and non-enhanced systems. Streams that pass input filters are shown in blue, with the points showing nodes at approximate midpoints of channels and at stream mouths. The red lines show the routes through nodes to each stream.

3.2 AREA 8 CHUM (BELLA COOLA/CENTRAL COAST)

Area 8 is located on BC's central coast with Bella Bella and McLoughlin Creek on the coast and Bella Coola and Dean River furthest inland. The Bella Coola River is at the terminal end of Bella Coola inlet and the Dean and Kimsquit Rivers are at the end of Dean Channel. There are two locations where enhancement has occurred in Area 8 in large numbers. These include the Bella Coola River and tributaries (where chum fry are released in Fish/Airport Creek, Snootli, Thorsen, and Saloompt systems), and in McLoughlin Bay near Bella Bella. Enhancement started in 1979 and quickly increased to around 7 million fry in the Bella Coola area and 500,000 to 3 million in McLoughin Bay. Details on enhancement are shown in Appendix 1 for Area 8. This makes for an interesting comparison as the number of releases are much higher in the Bella Coola River than in McLoughlin Creek, but we can include both systems in our total release and distance measurements (e.g. we measured distance from each enhanced area to each stream). If there is a signal from enhancement in the area, we should see similar effects versus distance from both release sites and perhaps a relationship to weighted distance.

The PSE dataset includes a total of 52 systems in Area 8. Of these, only 15 included greater than 50% enumerations in both the pre- and post-enhancement periods. Unfortunately, the enhanced tributaries of the Bella Coola only have escapement estimates since the early 2000s, and this did not meet the analysis stream criteria. Figure 5 shows the analysis streams and distance route measurements in Area 8. Only major systems are labelled for orientation.

More details on the streams, escapements, releases by release site, and total releases in Area 8 can be found in Appendix 2. For Area 8 we used the same set of analyses as in Area 25, with the addition of models which included both the distance from Bella Coola and the distance from McLoughlin (interacting effects).

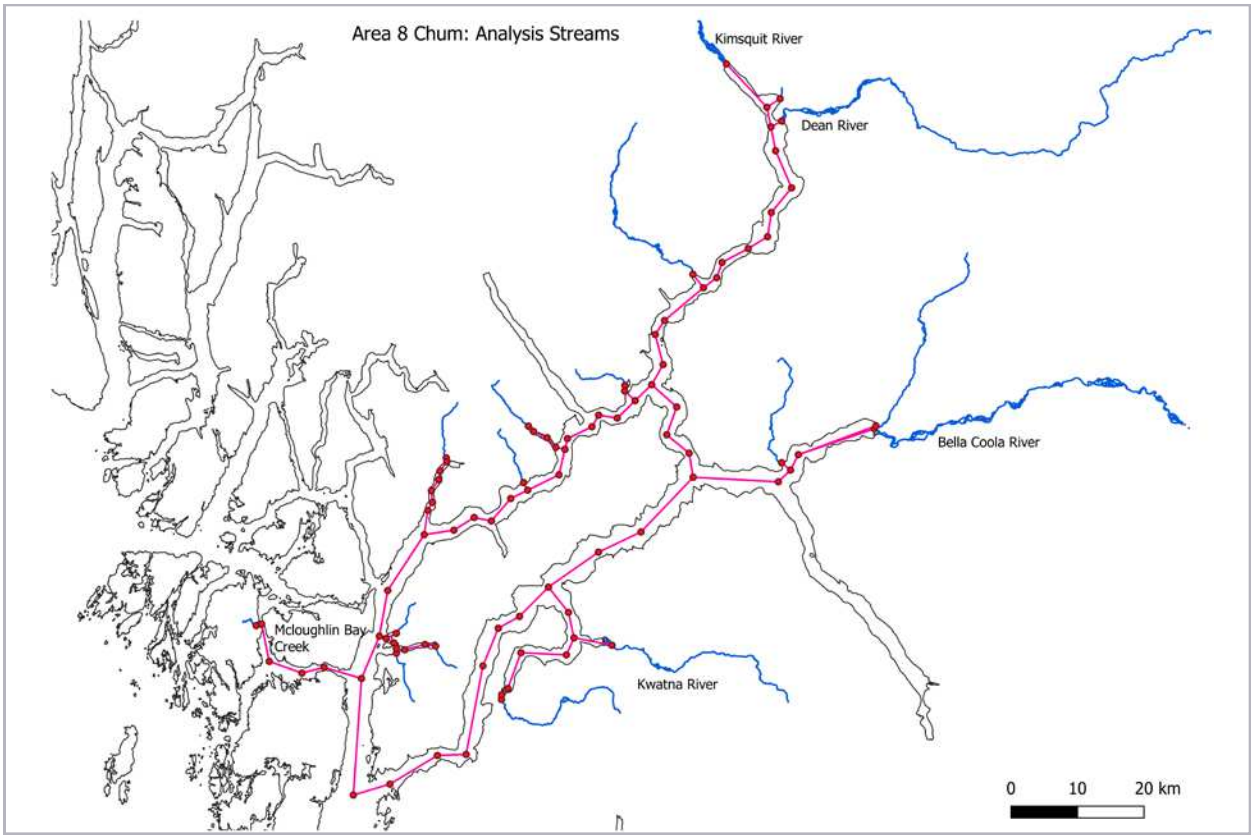

Figure 5: Map of Area 8 chum (BC Central Coast, Bella Coola/Bella Bella) showing node based approach for determining distance between enhanced and non-enhanced systems. Streams that pass input filters are shown in blue, with the points showing nodes at approximate midpoints of channels and at stream mouths. The red lines show the routes through nodes to each stream.

3.3 DOUGLAS-GARDNER CHUM (AREA 6/KITIMAT)

The Douglas-Gardner Conservation Unit is located on BC's North Coast surrounding the Kitimat/Hartley Bay area. We chose to look at the Conservation Unit level here due to the large size of chum management Areas on the north coast, which would confound our analysis. There are a number of major inlets in the Douglas Gardner Conservation Unit including Kitimat Arm (where most of the enhancement occurs in the Kitimat River), Douglas Channel, Kemano Inlet and the Khutze area off of Princess Royal Channel. Major enhancement of chum has occurred in the Kitimat area since around 1988, with 4-5 million fry released annually between 1990 and 2007, and around 2 million fry released annually since. There was minor enhancement in Bish Creek and the Dala/Kildala Rivers in the late 90s and early 2000s, however releases in stream were less than 1 million fry and are numerically dwarfed by the releases into the Kitimat River. As such, we did not include these as enhancement sites and only included the Kitimat River and its tributaries. Details on enhancement and by release site are shown in Appendix 3.

The PSE dataset includes over 100 systems in the Douglas-Gardner Conservation Unit. Of these, only 27 included greater than 50% enumerations in both the pre- and post-enhancement periods. Figure 6 shows the analysis streams and distance route measurements for Douglas Gardner chum. Only major systems are labelled for orientation.

More details on the streams, escapements, releases by release site, and total releases in the Douglas-Gardner CU can be found in Appendix 3. For Gardner-Douglas we used the same analyses as in Area 25 and Area 8.

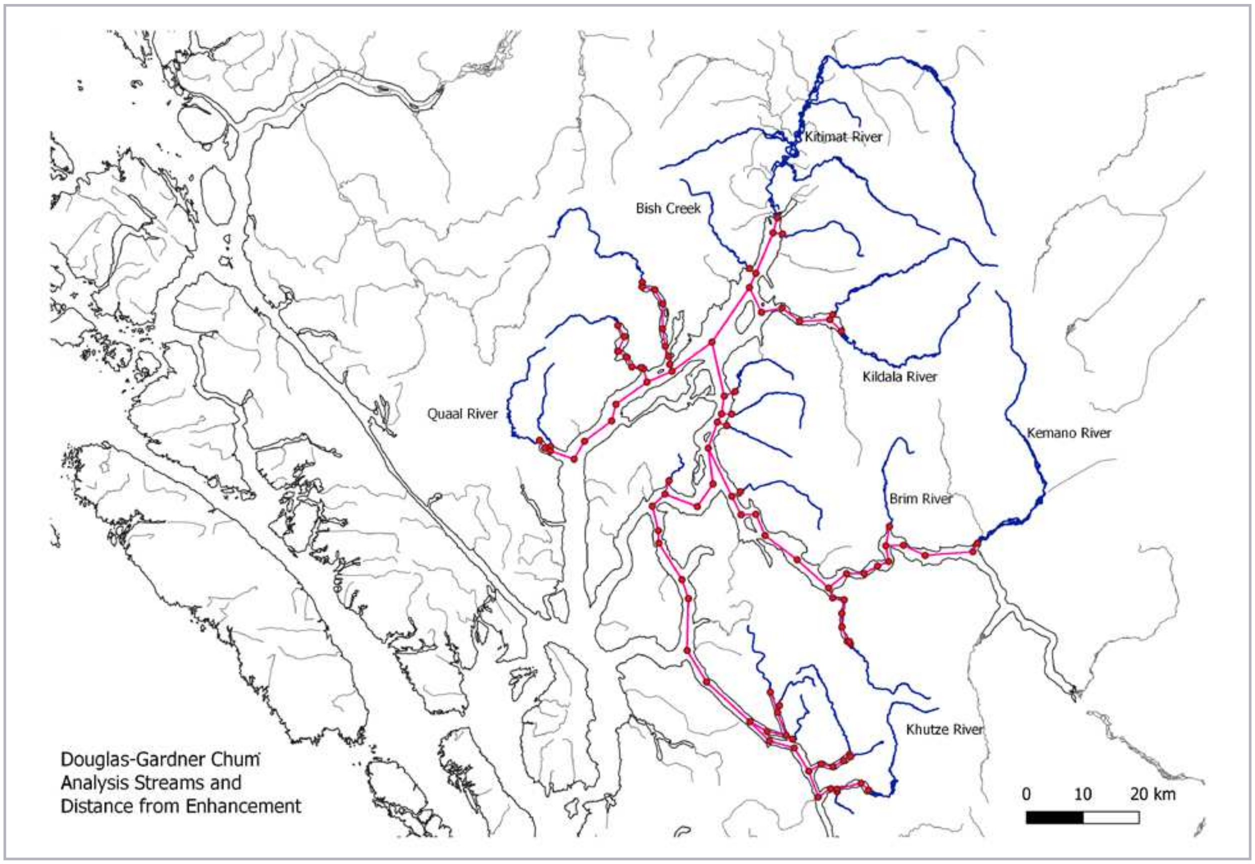

Figure 6: Map of Douglas Gardner chum (BC North Coast, Area 6) showing node based approach for determining distance between enhanced and non-enhanced systems. Streams that pass input filters are shown in blue, with the points showing nodes at approximate midpoints of channels and at stream mouths. The red lines show the routes through nodes to each stream. The thin grey lines show additional, not included DFO escapement systems.

4 RESULTS AND DISCUSSION

4.1 AREA 25 CHUM

Many escapement systems in Area 25 were excluded from the analysis due to inconsistent enumeration times series. At least 11 systems had relatively consistent enumerations until the last 10 years. Some of these systems were included as they passed the pre/post enhancement filters.

Escapement for all Area 25 streams, escapements for filtered streams, distance from enhancement, total releases, releases by stock:system combination, and escapement, logged escapement, *Pavg* escapement, Z-scores, and moving averages for analysis streams are all detailed in Appendix 1 (Figures 1-6). System specific escapements show some patterns, with significant ($p < 0.05$) increases in escapement post-enhancement in Canton, Conuma, and Tlupana Rivers (Appendix 1, Figure 2). Ransom and Mooyah Rivers were the only systems with a significant decrease post-enhancement. Other systems showed some differences between periods but none were significant. Generally, logged escapement, *Pavg*, and Z-scores showed similar patterns. Enhancement rank (with Conuma, Canton, Sucwoa, and Tlupana Rivers) influenced patterns over time, with all 3 metrics showing divergence after approximately 1980 between highly enhanced systems and low enhanced systems (Appendix 1, Figure 5). The moving averages also show this pattern (Appendix 1, Figure 6).

Mean Z-scores of log escapement were used to compare trends in systems with different enhancement categories over pre- and post-enhancement periods (Appendix 1, Figure 7). Highly enhanced sites showed increases in Z-score post-enhancement, while the mean Z-score across systems with no enhancement show a decline.

Visual examination of plots of log(RPS) showed some interesting patterns using pre- and post-enhancement regression analysis with log(RPS) declining in enhanced systems (Conuma, Canton, Sucwoa, and Tlupana, Deserted River) post-enhancement. We did not use piecewise regression or t-tests to detect changes in trends or mean values of RPS before and after enhancement, however these could be easily implemented. Trends in RPS over time are influenced by many factors, and comparing means pre- and post-enhancement may be inappropriate since we expect changes over time, and not stable RPS before and after the breakpoint. Autocorrelation was also not considered, partially since using the underlying age and exploitation data from the aggregate level do not produce stream specific RPS data in a robust way. In wild systems ($n = 19$), nine showed an initial decrease in log RPS after enhancement began, two showed a slight increase, and eight showed little to no initial change (Appendix 1, Figures 9 and 10).

Correlation analyses

Simple categorised bubbleplots of Z-score of log(escapement) and log(RPS) grouped by inlet show some patterns of similar trends in escapement and RPS with visual examination (Appendix 1, Figures 11-12).

Correlation plots in Area 25 over all years showed that there is generally high correlation between systems irrespective of distance (Appendix 1, Figure 13). There was very high correlation between systems using log(RPS), but this is likely due to the constant scaling of escapement using the same age structure and exploitation rates. In order to further explore patterns in correlation we transformed the correlation matrices into dendrograms to see if the resulting clusters were related to inlet location (Appendix 1, Figure 14). We also used tanglegrams to compare changes in the dendrograms between metrics (Appendix 1, Figure 15). When dendrograms were examined for all years with streams identified by inlet, streams did not cleanly separate into inlets grouping, indicating that even at small spatial scales (inlets) and generally high correlation within Area 25, there was correlation between streams in different inlets that was higher than within inlet correlation.

The differences in dendrograms between Z-score and log(RPS)indicate that the metric choice influences grouping of streams, with many changes between clades (Appendix 1, Figure 15). Interestingly, the four enhanced systems group closely together (with one additional system) using log(RPS). For both Z-score and log(RPS), the enhanced systems tended to be grouped relatively closely together, although their placement in the dendrogram structure changes.

Photo by: Mitch Miller

Z-scores and log(RPS) were further compared against themselves both before and after enhancement began in 1980 using correlations and dendrograms. Z-scores comparisons pre- and post-enhancement show some changes in groupings, however surprisingly the four enhanced systems did not form their own clade either before or after enhancement started (Appendix 1, Figures 16 and 17). Comparisons of log(RPS) pre- and post-enhancement shows significant shifts in correlation groupings between periods (Appendix 1, Figures 18 and 19). Pre-enhancement, log(RPS) had very high correlations between systems as indicated by the dark blue squares through out the correlation matrix. Post-enhancement, this has changed and there are many more systems that are much less strongly correlated. This may be an effect of enhancement on log(RPS), or it may be an artifact of assessment information such as cohesion in stream counts. For example, fisheries officer's counts before the early 1990s when the program switched to DFO Science are known to be much less accurate in many cases, and potentially very inaccurate on the WCVI (Luedke, personal communication, 2021b). Post-enhancement, the 4 enhanced systems show high correlation in log(RPS).

Overall pairwise correlation between all systems are similar between log(RPS) and Z-score, with the exception of log(RPS) in the pre-enhancement period (Appendix 1, Figure 20). Overall correlation was close to or greater than 0.50 (median) for log(RPS) and between 0.30-0.35 for Z-scores, with some outliers as low as -0.25, indicating that in general there was significant positive correlation in Area 25.

When pairwise correlations in Z-scores and log(RPS) are compared to distance using a declining power equation where y = a * distance ^ b, the 0.50 correlation threshold occurs are around 8km for Z-scores and at about 90km for log(RPS), and we see the expected decline in correlation with increasing distance (Appendix 1, Figure 21). Dendrograms based on distance show the expected inlet grouping structure (Appendix 1, Figure 22). Notably, when we extend the pre- and post-enhancement period analysis to the pairwise correlations in Z-scores and log(RPS) by distance, we see the much higher correlation pre-enhancement for log(RPS) using the model fit above, supporting changes to correlation between systems on a wide scale post-enhancement, although the mechanism is unknown (Appendix 1, Figure 23).

Statistical modeling and selection by Akaike's Information Criterion

Ten candidate models were fitted by multiple regression generalised linear models using log(RPS) as a response. While many of the non-log transformed models violated the assumptions of heteroscedasticity and normality, models were successfully fitted when using the log-transformed response variable. Model selection by AIC (Table 5) selected log(RPS) ~ totalreleases + year as the most parsimonious model, with significant effects indicating that both total hatchery releases and year have weakly negative significant correlations with log(RPS) (Appendix 1, Figures 24 and 25).

Table 5: AIC information for models using log RPS as a response variable for Area 25 chum.

Candidate model	Degrees of freedom	AIC
logrps ~ total releases + factor(year)	33	1360.448
logrps ~ total releases + factor(year) + year	33	1360.448
log rps ~ total releases + year	4	1720.592
logrps ~ correlation coefficient + year + total releases	5	1720.627
log rps ~ distance from enhancement + total releases + year	5	1722.590
logrps ~ correlation coefficient + year	4	1722.756
log rps ~ distance from enhancement + year	4	1724.998
logrps ~ total releases + year + subinlet	12	1730.376
logrps ~ total releases + year + system name	27	1756.327
logrps ~ correlation coefficient + year + system name	26	1758.053

Six additional models were fitted by multiple regression using log(escapement) as a response. Model selection by AIC (Table 6) selected log escapement ~ correlation coefficient + distance from enhancement + total releases + year as the most parsimonious model, with significant effects suggesting that log(escapement) decreases with distance from the enhanced system and over time, and increases with total releases and in streams that are correlated with the enhanced systems) (Appendix 1, Figures 24 and 25).

Table 6: AIC information for models using log escapement as a response variable for Area 25 chum.

Candidate models	Degrees of freedom	AIC
log escapement ~ correlation coefficient + distance from enhancement + total releases + year	14	2645.411
log escapement ~ correlation coefficient + total releases + subinlet + year	13	2651.303
log escapement ~ correlation coefficient + total releases + inlet + year	7	2896.195
log escapement ~ correlation coefficient + total releases + year	5	2934.982
log escapement ~ distance from enhancement + total releases + year	5	2982.832
log escapement ~ distance from enhancement + year	4	2991.802

The results of this modeling study have led us to reject the null hypotheses that either RPS or escapement have no relationship with the candidate explanatory variables. We instead accept hypotheses H2 — Recruits per spawner decrease with the total number of hatchery-origin releases over time; H4 — Escapement decreases with distance from the enhanced systems (Conuma area) over time; H5 — Escapement increases with the total number of hatchery-origin releases over time; and H6 — Escapement is increased in streams closely correlated to enhanced systems over time.

4.2 AREA 8 CHUM

Many escapement systems in Area 8 were excluded from the analysis due to inconsistent enumeration times series. Unfortunately, the 4 enhanced tributaries of the Bella Coola River have only been enumerated since 2003 and were excluded due to filtering criteria and no pre-enhancement spawner data. However, there was adequate data from nearby wild tributaries to merit including Area 8 in this analysis.

Escapement for all Area 8 streams, and escapement for filtered streams, distance from enhancement, total releases by system, releases by stock:site combination, and escapement, logged escapement, *Pavg* escapement, Z-scores, and moving averages for analysis streams are all detailed in Appendix 2 (Figures 1-6). Escapement for all systems in area 8 and only the included filtered systems are shown in Appendix 2, Figures 1 and 2. Releases to the area are predominantly from enhancement to the Bella Coola system and tributaries (Appendix 2, Figure 3). Generally, logged escapement, *Pavg*, Z-scores, and moving averages show similar patterns in low and non-enhanced systems (Appendix 2, Figures 5 and 6), with stable escapements prior to 1980, a decline through the mid-90s followed by an increase. Unfortunately, the systems with high enhancement rank (e.g. the Bella Coola tributaries) are not included in the analysis systems and therefore are not shown here.

Mean Z-scores of logged escapement were used to compare trends in systems with different enhancement categories over pre- and post-enhancement periods (Appendix 2, Figure 7). Non-enhanced sites show a trend of decreasing Z-score over time, with low enhancement sites showing an increasing trend over time.

Visual examination of plots of log (RPS) show declines in most systems post-enhancement (10 of 15) and increases in 3 of 15 systems (Appendix 2, Figures 9 and 10). In general, log(RPS) were highly variable in most systems. Indeed, boxplots of log(RPS) pre- and post-enhancement indicate very few if any statistically differences between periods which is expected given the observed variability in log(RPS) (Appendix 2, Figure 11).

Photo by: Mitch Miller

Correlation analyses

Simple categorised bubble-plots of Z-score of log(escapement) and log(RPS) grouped by inlet in Area 8 do not show any clear patterns of similar trends in escapement and log(RPS) with visual examination (Appendix 2, Figures 11-12).

As in Area 25, cross-correlation plots for Area 8 show that there is generally high correlation between many systems (Appendix 2, Figure 13), albeit less than in Area 25, with more systems showing no or negative correlation. In order to explore patterns in correlation we transformed the correlation matrices into dendrograms to see if the resulting clusters were related to inlet location (Appendix 2, Figure 14). We also used tanglegrams to compare changes in the dendrograms between log(RPS) and Z-scores of log(escapement (Appendix 2, Figures 15). When dendrograms were examined for all years with streams identified by inlet, there was limited separation of systems into specific inlets except for the Sagar, Evans, and Hook Nose systems with Z-scores. This separation was not evident in log(RPS) dendrogram.

As in Area 25, the differences in dendrograms between Z-score and log(RPS) indicate that the metric choice influences grouping of streams, with many changes between clades (Appendix 1, Figure 15). Some systems remained proximate, however there were no discernable patterns otherwise.

Z-scores of escapement and log(RPS) were further compared against themselves both before and after enhancement began in 1980 using correlations and dendrograms (Appendix 2, Figures 16-19). Correlation matrices and dendrograms show significant changes in inter-stream correlations and groupings before and after enhancement. For Z-scores, a few clades remained the same pre- and post-enhancement (the Sagar, Evans Inlet and Hook Nose group, the Kwatna and Frenchman group, and the Skowquiltz and Dean River group). Most of these groups contain systems that are close together (km). Log(RPS) correlations and dendrograms showed similar changes but with different groups of systems; Nooseseck and Hook Nose, Sagar and Evans, and Kimsquit and Elcho remained closely related post-enhancement.

Pairwise correlation for all pairwise comparisons of systems are similar between log(RPS) and Z-score (Appendix 2, Figure 20). Overall correlation in Area 8 was less than in Area 25 for all combinations of metrics, and medians of correlations were all near 0.25, with some outliers nearly as low as -0.5.

When pairwise correlations in Z-scores and log(RPS) are compared to distance, there appears to be almost no relationship between distance and correlation, at least at this scale (< 150km) (Appendix 2, Figure 21). Dendrograms based on distance show the expected inlet grouping structure, although it is not as clear as in Area 25 due to the over water distance estimation procedures and inlet groupings (Appendix 2, Figure 22). When we compare the pairwise correlation of Z-scores of log(escapement) and log(RPS) pre- and post-enhancement, we again see very little relationship between correlation and distance for either metric or time-period (Appendix 2, Figure 23), indicating that there is no large scale shift in stream-stream correlation versus distance in this Area post-enhancement.

Statistical modeling and selection by Akaike's Information Criterion

Seven candidate models were fitted by multiple regression using log RPS as a response. For Area 8, we tested the effect of distance from both Bella Coola and McLoughlin Bay. We also tested weighting the distances by releases from each area to account for the numerical difference in releases between systems. Model selection by AIC selected log(RPS) ~ weighted distance Bella Coola + weighted distance McLoughlin + releases McLoughlin + releases Bella Coola + Year as the most parsimonious model, suggesting that releases, distance, and year had effects on log RPS (Table 7). However, effects of year and distance were insignificant (zero overlap) and log(RPS) increases with increased releases from Bella Coola and decreases with increasing releases from McLoughlin Bay (Appendix 2, Figures 24 and 25).

Table 7: AIC information for models using log RPS as a response variable for Area 8 chum.

Candidate model	Degrees of freedom	AIC
Log RPS ~ Wt. dist. Bella Coola + Wt. dist. McLoughlin + Rel.McLoughlin + Rel.Bella Coola + Year	7	2776.004
Log RPS ~ dist. from Bella Coola + dist. from McLoughlin	4	2783.424
Log RPS ~ Wt. dist. from Bella Coola + Wt. dist. from McLoughlin	4	2783.424
Log RPS ~ dist. from Bella Coola + dist. from McLoughlin + Year	5	2785.416
Log RPS ~ Wt. dist. from Bella Coola + Wt. dist. from McLoughlin + Year	5	2785.416
Log RPS ~ dist. from Bella Coola + dist. from McLoughlin + Year + Subinlet	9	2790.437
Log RPS ~ Wt. dist. from Bella Coola + Wt. dist. from McLoughlin + Year + Subinlet	9	2790.437

Seven additional models were fitted by multiple regression using log escapement as a response. Model selection by AIC selected logesc ~ distance from Bella Coola + distance from McLoughlin + Year + Subinlet as the most parsimonious model (Table 8). For this model, there were significant relationships between distance from Bella Coola (increased log(escapement) with increasing distance), distance from McLoughlin Bay (decreased log(escapement) with increasing distance) and significant large sub-inlet effects (with positive effect of Kimsquit inlet, and negative effects in other inlets) (Appendix 2, Figures 26 and 27). Year did not have a significant effect. The effects of sub-inlet were much larger than those of distance, but this is explained by sub-inlet abundance with Kimsquit being by far the largest system in the included analysis (since the Bella Coola River was excluded from analysis). Models including releases (not shown) showed that there were small effects of total releases from Bella Coola on log(escapement).

Table 8: AIC information for models using log escapement as a response variable for Area 8 chum.

Candidate model	Degrees of freedom	AIC
log escapement ~ dist. from Bella Coola + dist. from McLoughlin + Year + Subinlet	9	3019.123
log escapement ~ Wt. dist. Bella Coola + Wt. dist. McLoughlin + Year + Subinlet	9	3019.123
log escapement ~ Wt. dist. Bella Coola + Wt. dist. McLoughlin + Rel.Bella Coola + Rel.McLoughlin + Year	7	3045.062
log escapement ~ Wt. dist. from Bella Coola + Wt. dist. from McLoughlin	4	3059.479
log escapement ~ dist. from Bella Coola + dist. from McLoughlin	4	3059.479
log escapement ~ dist. from Bella Coola + dist. from McLoughlin + Year	5	3060.954
log escapement ~ Wt. dist. from Bella Coola + Wt. dist. from McLoughlin + Year	5	3060.954

The results of this modeling study have led us to reject the null hypotheses that either RPS or escapement have no relationship to the candidate explanatory variables. We instead accept hypothesis H2: *There is a change in RPS with the total number of hatchery-origin releases over time*, and H4: *There is a change in escapement with proximity to enhanced systems over time.*

4.3 DOUGLAS-GARDNER (AREA 6) CHUM

Escapement for all Douglas-Gardner chum streams, escapements for filtered streams, distance from enhancement for each stream, total releases, releases by stock:system combination, and escapement, logged escapement, *Pavg* escapement, Z-scores, and moving averages for analysis streams are all detailed in Appendix 3 (Figures 1-6). Generally, log (escapement), *Pavg*, and Z-scores showed similar patterns, with significant interannual variability and some covariation between non-enhanced systems, especially in historical years (before ~1970). There are few discernable patterns in metrics for Douglas-Gardner chum (Appendix 3, Figures 5 and 6), other than the increase in log(escapement), Z-score, and moving average in the highly enhanced system (Kitimat River) following enhancement.

Appendix 2, Figure 7 shows the mean Z-scores by enhancement rank which shows stable or increased escapement in the enhanced systems (high: Kitimat, mod:Hirsch, low:Dala, Kildala, Bish and Humphreys), versus declining Z-score in the non-enhanced systems over time. The pattern follows the temporal trend in releases with releases occurring in the moderate and low enhanced systems 1985 to around 2000 and releases in Hirsch from 1985 to 2010. Releases in the Kitimat River have declined since 2008 from around 3.5M to just under 2M, however the Kitimat River does not have consistent escapement estimates over that time period. There is also a long term decline evident in the mean Z-score for streams with no enhancement.

Visual examination of plots of log(RPS) show increasing log(RPS) post-enhancement in 7 systems and declining in 15 systems (Appendix 2, Figures 9 and 10). Other systems show either no trend or very weak trends. Before enhancement, annual log(RPS) were highly variable. Interestingly, log(RPS) increased immediately following enhancement in the Kitimat River, but then decline substantially until around 2000 where the gap in escapement starts. The most recent estimates of log(RPS) are extremely low. Comparison of log RPS using boxplots before and after enhancement started in 1980 show some differences, but there is overlap between periods in all cases, no doubt due to the high interannual variability in RPS (Appendix 3, Figure 11).

Photo by: Mitch Miller

Correlation analyses

Simple categorised bubble plots of Z-score for log(escapement) and log(RPS) grouped by inlet show qualitatively similar patterns or trends in escapement and RPS within inlets.(Appendix 3, Figures 12-13).

Correlation plots for Douglas-Gardner show that there is generally high correlation between systems irrespective of distance, however, similar to Area 8, there are more streams that are negatively correlated than in Area 25 (Appendix 3, Figure 14). As in Area 8, the high level of correlation in the log(RPS) in Area 25 was not observed in Area 6; even though escapements were similarly expanded using consistent age structure and exploitation rate across all systems. In order to explore patterns in correlation we transformed the correlation matrices into dendrograms to see if the resulting clusters were related to inlet location (Appendix 3, Figure 15). We also used tanglegrams to compare changes in the dendrograms between metrics (Appendix 3, Figure 16). When dendrograms were examined for all years with streams identified by inlet, there were interesting patterns. While there was not complete separation into inlets, the Z-score of log(escapement) showed a group of systems in the Khutze area (with the exception of the Khutze River itself), and a group containing the Kildala and Dala Rivers (proximate to each other). The Khutze Inlet group (without the Khutze River) was maintained using log(RPS), however the Dala and Kildala group was not. The Kitimat, Douglas, Dala, and Kemano areas, which are all relatively close to each other, were intermixed. In general, there is not a high degree of separation between inlets as shown by the dendrogram analysis. When comparing log(escapement) to log(RPS) metrics using a tanglegram (Appendix 3, Figure 16), some relationships were maintained, however there were many shifts in groupings in correlation, indicating the two metrics used are not necessarily linked.

Z-scores of escapement and log RPS were further compared against themselves both before and after enhancement began in 1980 using correlations and dendrograms (Appendix 3, Figures 17-20). Correlation matrices and dendrograms show significant changes in inter-stream correlations and groupings before and after enhancement, with more positive correlation between streams post-enhancement. As in the other areas and analyses, there were substantial shifts pre- and post-enhancement in clades for both Z-scores and log(RPS) using tanglegrams, but no clear pattern evident in regards to spatial distance.

Overall pairwise correlation between all systems are generally similar between log(RPS) and Z-score for the Douglas-Gardner CU, with slightly lower median correlation in the pre-enhancement period (Appendix 1, Figure 21). Overall median correlation was around 0.30 and 0.25 for the pre-enhancement period, with slightly higher median correlation (0.45 and 0.30) in the post enhancement period for log(RPS) and Z-scores respectively. Even more so than in other areas, there were extreme outliers (e.g. -0.80) indicating that there were some streams with strong opposite trends in escapement.

When pairwise correlations in Z-scores and log(RPS) are compared to distance using a liner regression (no other model better supported), there are significant declines in correlation with increasing distance ($p < 0.05$), with a stronger negative relationship for log(RPS) (Appendix 3, Figure 22). The model fit does not go above 0.50 correlation even at very low distances. Dendrograms based on distance show the expected inlet grouping structure (Appendix 1, Figure 23). When we extend the pre- and post-enhancement period analysis to the pairwise correlations in Z-scores and log(RPS) by distance (Appendix 3, Figure 24), there are only slight differences in linear regression model fits and small significant negative slopes are maintained in both periods, indicating that there is no large scale shift in stream-stream correlation versus distance post-enhancement.

Statistical modeling and selection by Akaike's Information Criterion

Seven candidate models were fitted by multiple regression using log RPS as a response. For the Douglas-Gardner CU, we tested the effect of distance, total releases, and year in various combinations. Model selection by AIC selected logRPS ~ Distance + Total Releases + Year as the most parsimonious model (Table 9). Summary effects plots show the effects of all the factors incorporated into the model, with significant effects plots shown for total releases and year (Appendix 3, Figures 25 and 26). The effect of distance on log(RPS) was not significant, however both total releases and year had significant effects ($p < 0.005$). Total releases had a negative effect on log(RPS) per million releases and year had a slight positive effect on log(RPS), indicating that log(RPS) declines with increasing total releases, and increases over time.

Table 9: AIC information for models using log RPS as a response variable for the Douglas-Gardner CU chum.

Response	Candidate model	Degrees of freedom	AIC
Log RPS	Log RPS ~ dist. + totrel + year	5	4640.250
Log RPS	Log RPS ~ dist. + totrel	4	4649.087
Log RPS	Log RPS ~ dist.	3	4674.840
Log RPS	Log RPS ~ dist. + year	4	4675.224
Log RPS	Log RPS ~ totrel + year	4	5207.687
Log RPS	Log RPS ~ releases	3	5213.524
Log RPS	Log RPS ~ year	3	5237.491

Seven additional models were fitted by multiple regression using log escapement as a response. Model selection by AIC selected log escapement ~ Distance from enhancement + Year as the most parsimonious model (Table 10). For this model, there were small but significant relationships between distance from Kitimat and over time ($p < 0.01$). Log escapement decreased with both distance from Kitimat and over time.

Table 10: AIC information for models using log escapement as a response variable for Area 8 chum.

Response	Candidate model	Degrees of freedom	AIC
log escapement	Log esc ~ dist. + year	4	5455.093
log escapement	Log esc ~ dist. + totrel + year	5	5457.085
log escapement	Log esc ~ dist. + totrel	3	5468.276
log escapement	Log esc ~ dist.	3	5478.798
log escapement	Log esc ~ year	3	6220.673
log escapement	Log esc ~ totrel + year	4	6222.325
log escapement	Log esc ~ releases	3	6236.895

Taken together, we can reject the null hypotheses of no effects on RPS or escapement and accept hypotheses H2: *there is a decrease in log RPS as total hatchery releases increase and over time*; and H6: *there is a decrease in escapement with distance from enhancement.*

5 DISCUSSION

The intent of this study was to explore patterns in escapement and recruits-per-spawner as they may relate to enhancement in a spatial context. We were particularly interested in determining if we could identify a signal of increased production in systems closer to enhancement, and if there were changes in RPS for systems close to enhancement and those further away. While we originally intended on applying standardised methodology across the BC coast for enhanced Chinook, chum, and coho systems, this was not possible for a number of reasons. Escapement data for pre- and post-enhancement periods are inconsistent in many streams, with over half of streams in each area not meeting filter criteria for inclusion. There is also very little, if any, stream specific data required for stock recruit analyses except for some enhanced systems and perhaps a few wild indicator[4] stocks. There are also many locations in BC where multiple enhancement projects occur very close to each other, or where there is historical enhancement that has started and stopped, perhaps confounding analyses. Our rationale for using chum salmon in this study, rather than Chinook or coho salmon, included the following reasons:

- Chum salmon are known to stray at relatively high rates, which may increase our ability to identify effects over distance
- Monitoring for enhanced chum in proximate and non-enhanced systems is limited making chum a good candidate for signal detection in lieu of traditional monitoring strategies
- There is much more information on straying of hatchery Chinook salmon through CWT and thermal mark sampling programs
- Coho salmon spawner counts are likely even more uncertain than chum counts.

Therefore, we selected three slightly different case study areas and used chum salmon to explore analyses which may elucidate patterns in production within a spatial context. These included Area 25 chum on WCVI — an area with very little enhancement, historical or recent (outside the Conuma River area), Area 8 chum on BC's central coast, an area with very little enhancement outside of two places (Bella Coola and McLoughlin Bay) which are at opposite ends of the Area, and the Douglas-Gardner chum Conservation Unit on BC's North Coast, which has had some historical enhancement in a few systems spread through the CU, and major consistent enhancement in the Kitimat River. The intent in choosing these three areas in our exploratory analysis was to have different areas in BC which had 1) numerically large long-term releases, 2) terminal inlet enhancement locations, 3) relatively consistent monitoring in a number of nearby systems on the scale of ~ 100km or less.

Analysis metrics, correlations, and spatial structure

In terms of our initial analysis metrics, we selected a number of standard approaches using log(escapement), Z-scores of log(escapement), and a ratio of annual escapement to the average stream escapement over the whole time-series. Mathematically, these are similar and we did not expect to see any differences, which was indeed the case in all 3 Areas. A such we did not include the preliminary explorations of these metrics in our dendrogram and tanglegram analysis, choosing to focus on Z-scores of log(escapement), log(escapement), and log(RPS). We feel that these are most closely related to the response variable for modeling. An example of the patterns of Z-scores for Douglas-Gardner chum is shown in Figure 7. This shows that while there are some consistent patterns in inlets (e.g. Dala and Kildala), there is also a substantial range of Z-scores for any give year across the entire area. Other interesting patterns occur, such as Wathl Creek in Kitimat Arm. Z-scores do not increase in Wathl when Bish Creek, and the Kitimat River are beginning to be enhanced in the 1980s.

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[4] 'Indicator' is a term commonly used to identify streams which have either consistent high-quality enumerations over time (escapement indicators), and/or have information based on tagging or other sampling that allows estimation of exploitation rates (exploitation rate indicators). Indicator streams are often used as proxies for nearby non-indicator systems.

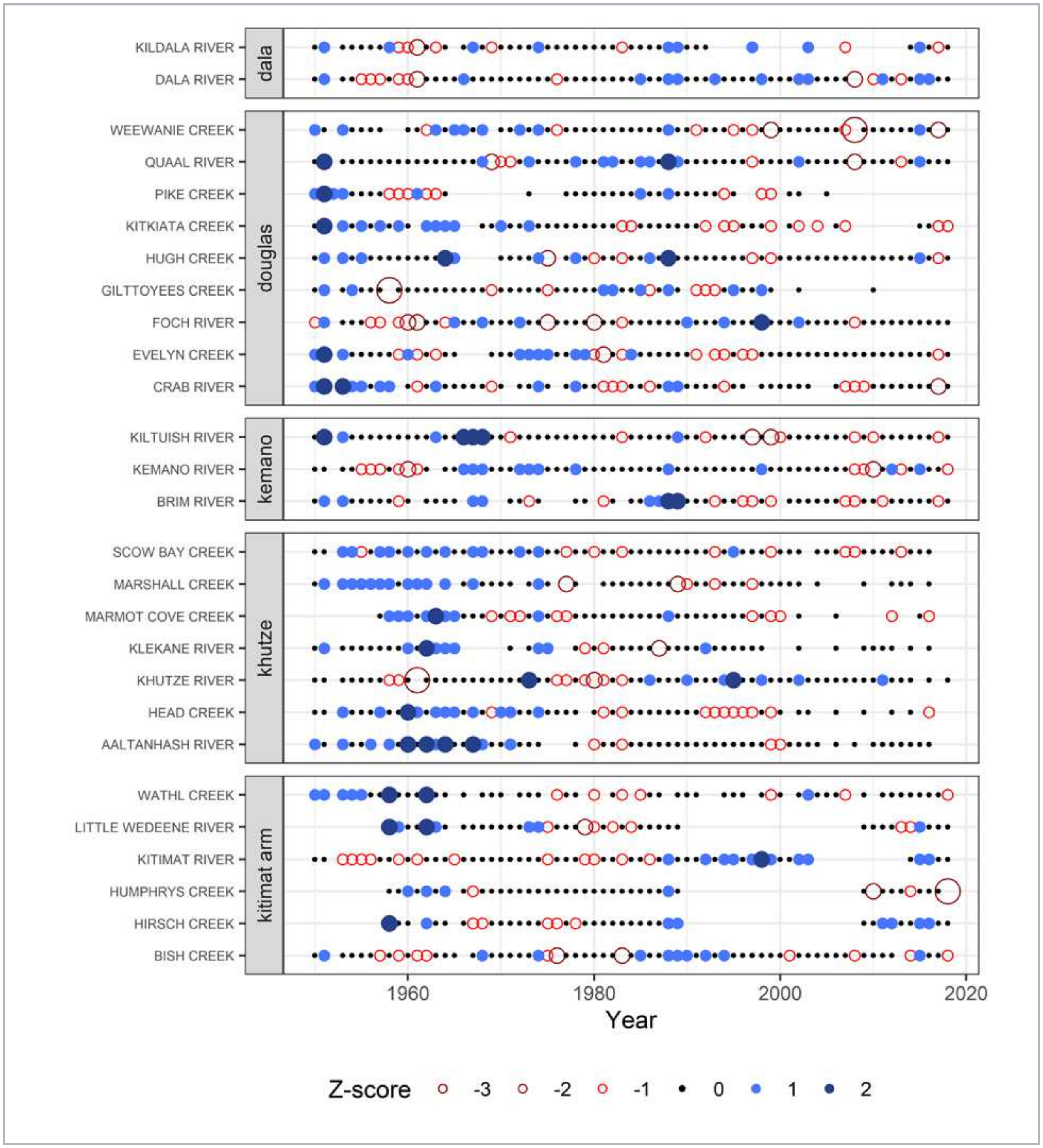

Figure 7: Z-scores by system grouped by inlet. The size and the colour of the points indicates the value of the Z-score. Blue indicates positive Z-score (SDs above average), and red indicates negative Z-score (SDs below average).

Moving averages (by average generation length, four years for chum), did change the correlations between streams, and sometimes quite substantially. We suspect that this is due to the smoothing effect of a moving average which will reduce the inter-annual variation and perhaps do a better job of identifying underlying trends. A Dynamic Factor Analysis (DFA) following Malick and Cox (2016) might be useful to examine underlying trends as well, along with factors such as inlet structure, regional environmental indices, and other local factors. However, Malick and Cox (2016) examined these trends in productivity on a much larger scale. A DFA is out of the scope of this particular analysis but could be considered in the future since the analysis may identify a number of underlying trends in time-series data.

During our exploratory analyses we expected to see groupings by inlet which would indicate a distance relationship among points of marine entry, as shown by the simple pairwise stream to stream distance dendrograms. However, this was not the case when using Z-scores of log(escapement) or log(RPS). Douglas-Gardner chum had one group of streams (the Khutze group) that separated out in the log(escapement) metrics, (with the exception of the Khutze River itself), but this was not evident in the log(RPS) or other metrics. There was little evidence to support our expectation that there would be correlation within inlets/sub-inlets based on these analyses.

We also explored the pairwise correlations within inlets (and sub-inlets in Area 25), following an analysis in Olmos *et al.* (2018) based on spatial coherence of time trends of marine life histories in Atlantic Salmon. In their case, the correlations were done at very large scales (continental), and were generally much lower than ours on average. Figure 8, Figure 9, and Figure 10 show boxplots of pairwise stream correlations within inlets and sub-inlets for Douglas Gardner, Area 25, and Area 8. Overall, these show few differences in correlations between streams within inlets or sub-inlets — indicating that correlation is relatively consistent across different areas. In Area 25, the Nootka sub-inlet has slightly higher within sub-inlet correlation than other sub-inlets, however it is not the sub-inlet with enhancement (which is Conuma sub-inlet). Figure 11 extends this comparison at the sub-inlet level in Area 25 to pre- and post-enhancement. Boxplots of pairwise stream correlations within sub-inlets show few differences for Z-scores of log(escapement), however show major declines in correlation post-enhancement for log(RPS) in most of the sub-inlets. If this was a direct effect of enhancement, then we would expect to see these shifts taking place in the enhanced areas (Conuma) and perhaps declining with increasing distance, however this is not the case and there are broad scale shifts.

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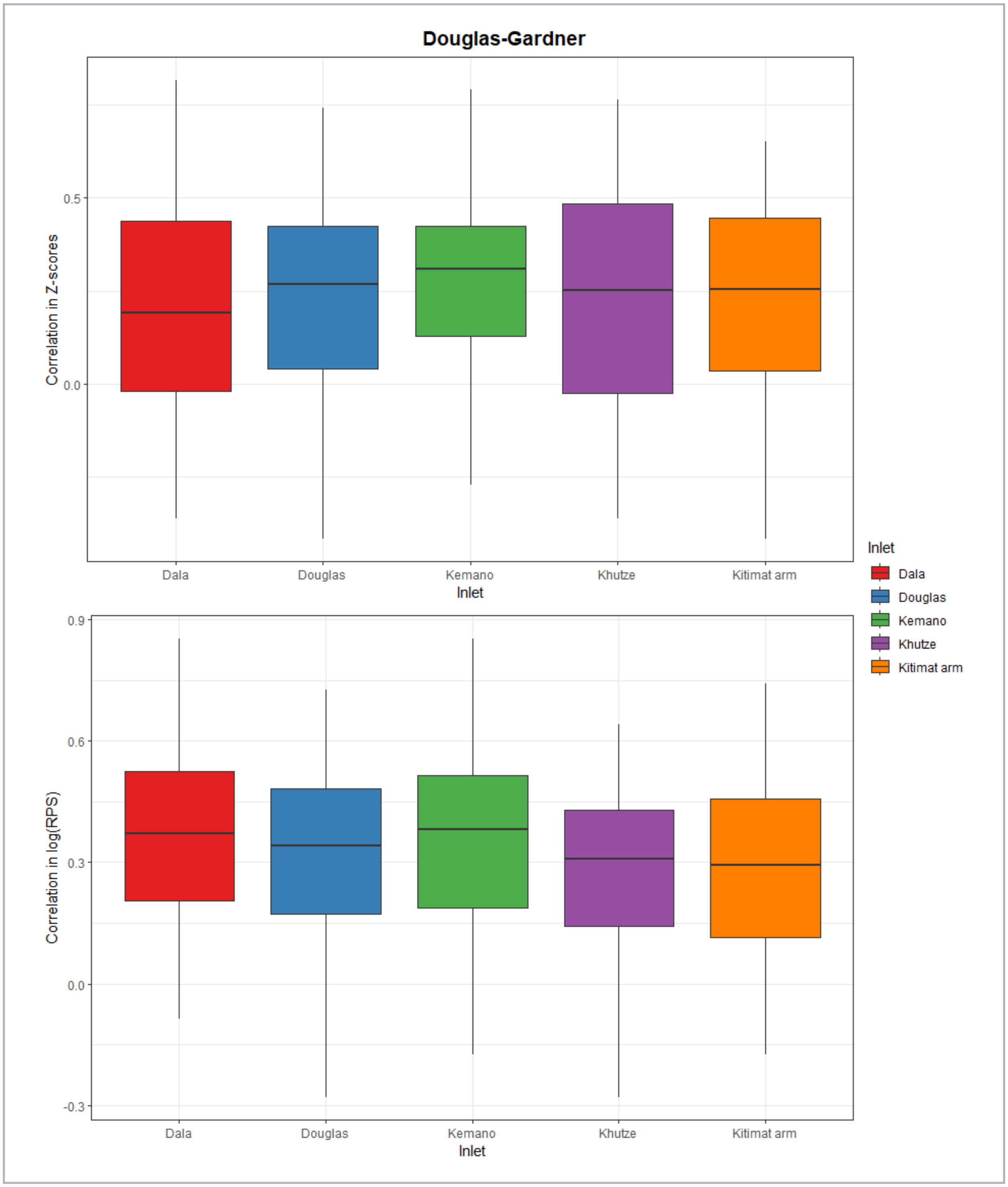

Figure 8: Boxplots of pairwise correlations by inlet for Douglas-Gardner chum for Z-scores of log(escapement) and log(RPS).

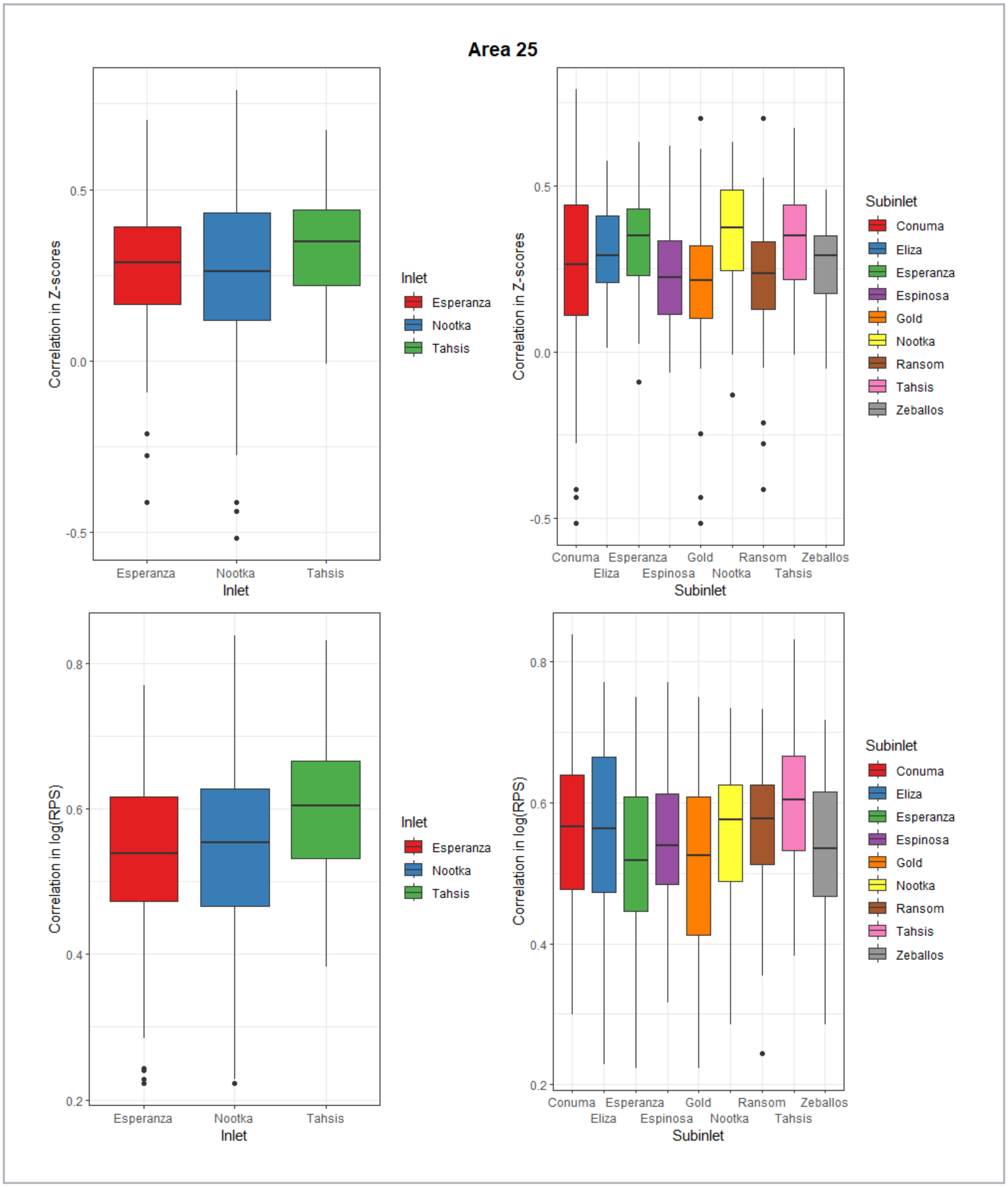

Figure 9: Boxplots of pairwise correlations by inlet and sub-inlet for Area 25 chum for Z-scores of log(escapement) and log(RPS).

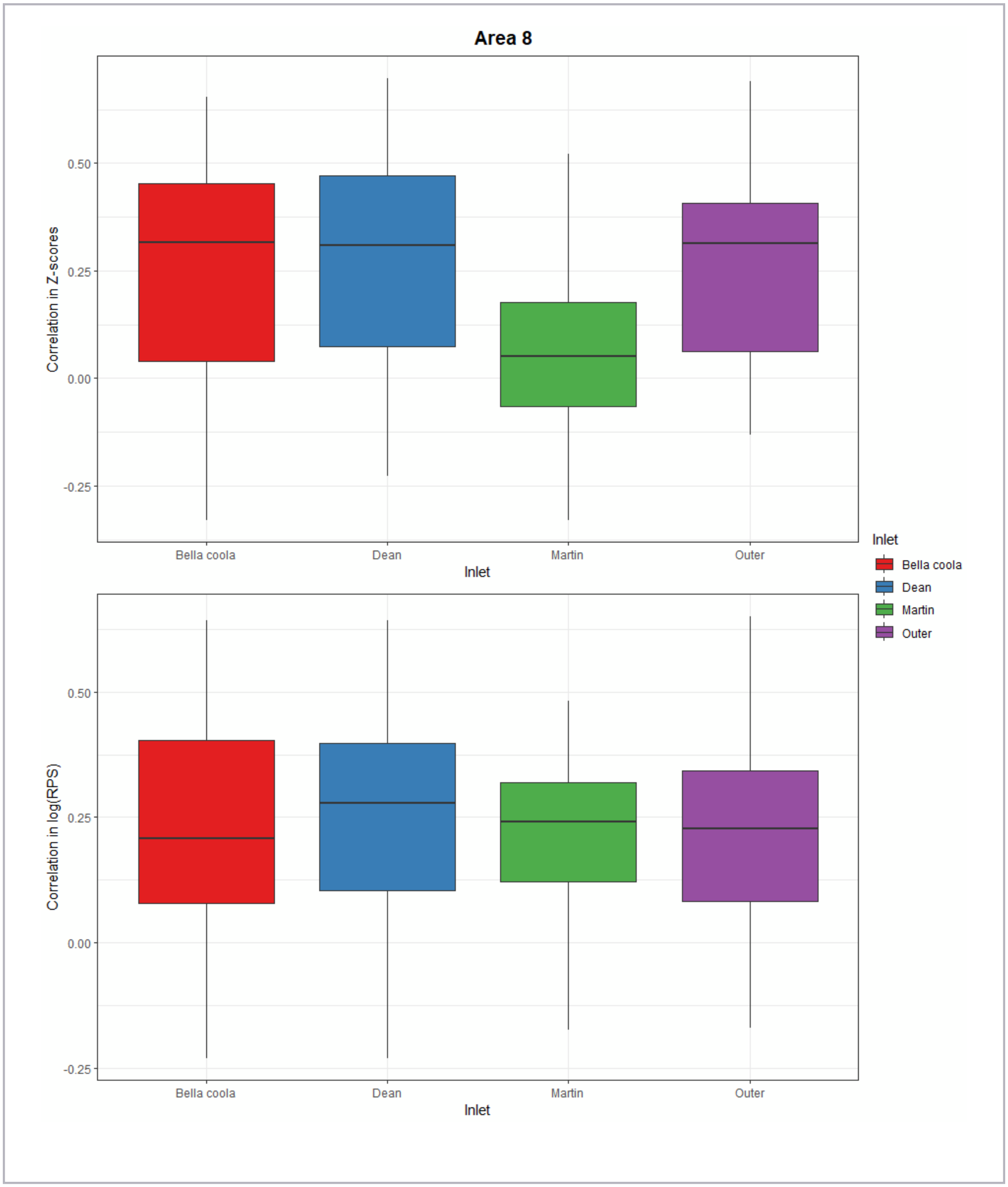

Figure 10: Boxplots of pairwise correlations by inlet for Area 8 chum for Z-scores of log(escapement) and log(RPS).

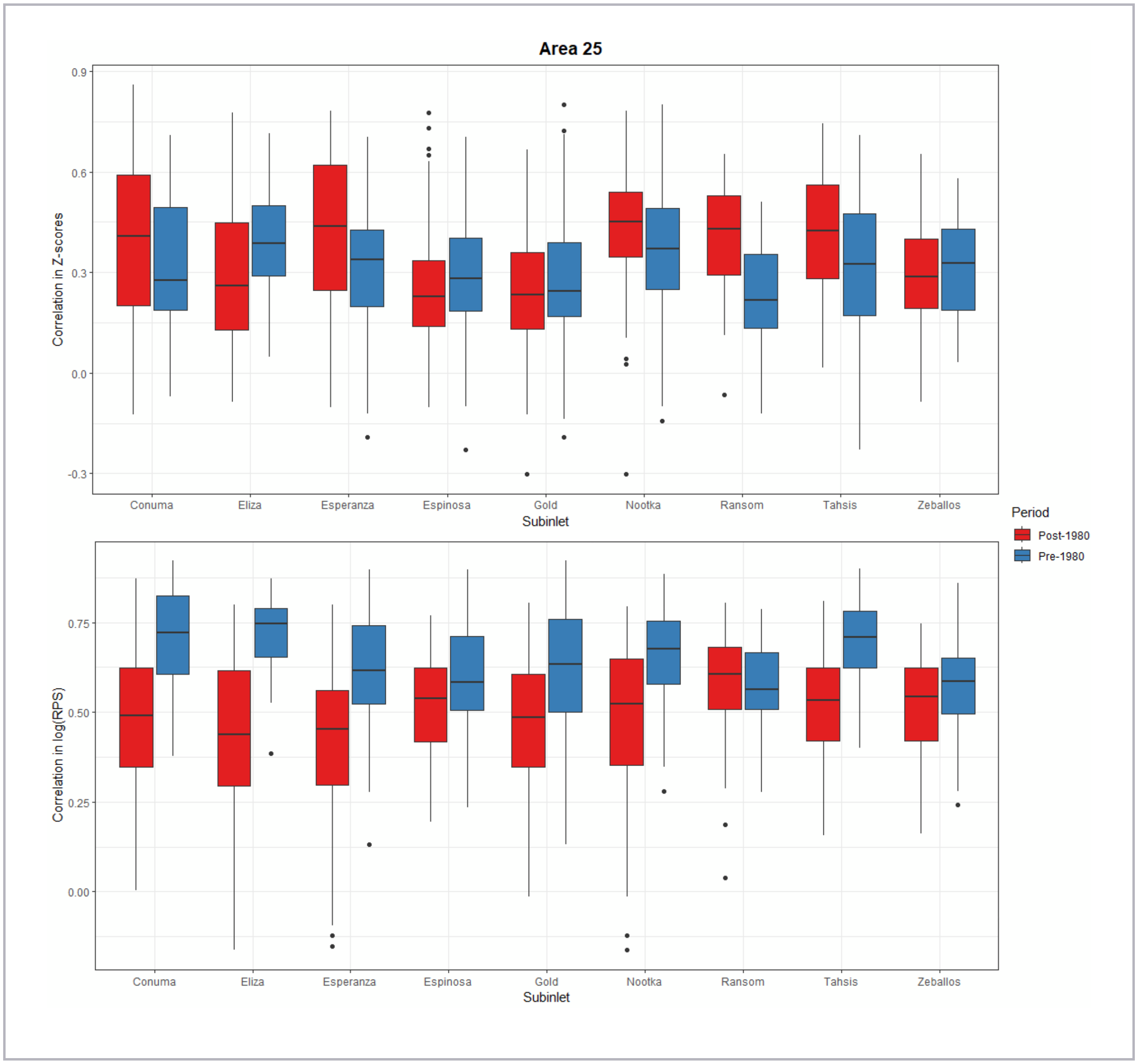

Figure 11: Boxplots of pairwise correlations by sub-inlet for Area 25 chum for Z-scores of log(escapement) and log(RPS), pre (blue) and post/during (red) enhancement.

This is probably not surprising as there was a generally high level of correlation within each case study area at the area level, and previous studies have determined correlation on the 100s of km scale (e.g. Pyper *et al.* 2001, Pyper *et al.* 2002, Meuter *et al.* 2002, Kilduff *et al.* 2014, Malick and Cox 2016). In comparison, the furthest distance from enhancement in our areas was around 130km. Interestingly, Pyper *et al.* (2002) found correlation between chum survival rates at a large scale (e.g. Fraser River versus mainland BC, Central BC, Northern BC) generally around 0.3, which is similar to our average correlation over all pairwise streams (Figure 12).

There were not significant differences between periods for any Areas and metrics except for Area 25 which shows decreased correlation in Z-score of escapement during enhancement (~ 1980-present). Area 25 also showed the highest mean correlation in log(RPS) during the pre-enhancement period, with a median of about 0.62. It should be noted that there were some extreme outliers with very low pairwise correlation coefficients which would be expected given the potential for local conditions to influence patterns in escapement and log(RPS) over time.

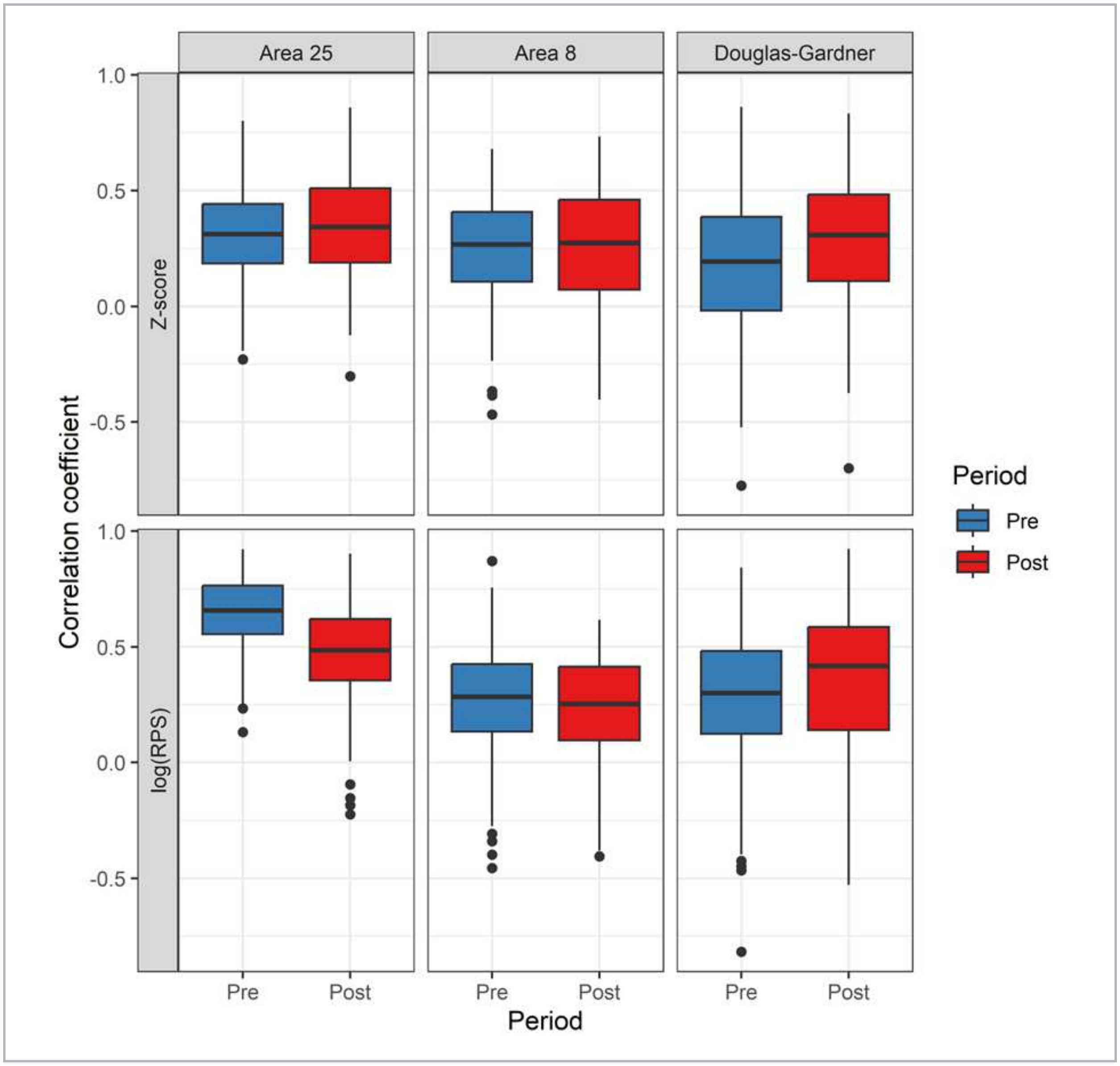

Figure 12: Mean correlation coefficients by area for the pre- and during-enhancement periods for Z-scores (left panel) and for logRPS (right panel).

To inform our correlation analyses, we looked at the correlation in Z-scores of log(escapement) and log(RPS) versus distance from enhancement. For this analysis we included only Area 25 and Douglas-Gardner since Area 8 does not have long escapement time series for the Bella Coola River or its tributaries. Figure 13 shows the correlation coefficient between each analysis system and the main enhanced system for Douglas-Gardner and Area 25 chum, for both Z-scores in escapement and log(RPS). There is a clear pattern of reduced correlation in Area 25 with increasing distance for escapement, less so with log(RPS), however, this pattern is not apparent in the Douglas-Gardner CU. In Area 25 this is expected because the 3 other enhanced systems are very close to Conuma River (Sucwoa, Canton, and Tlupana).

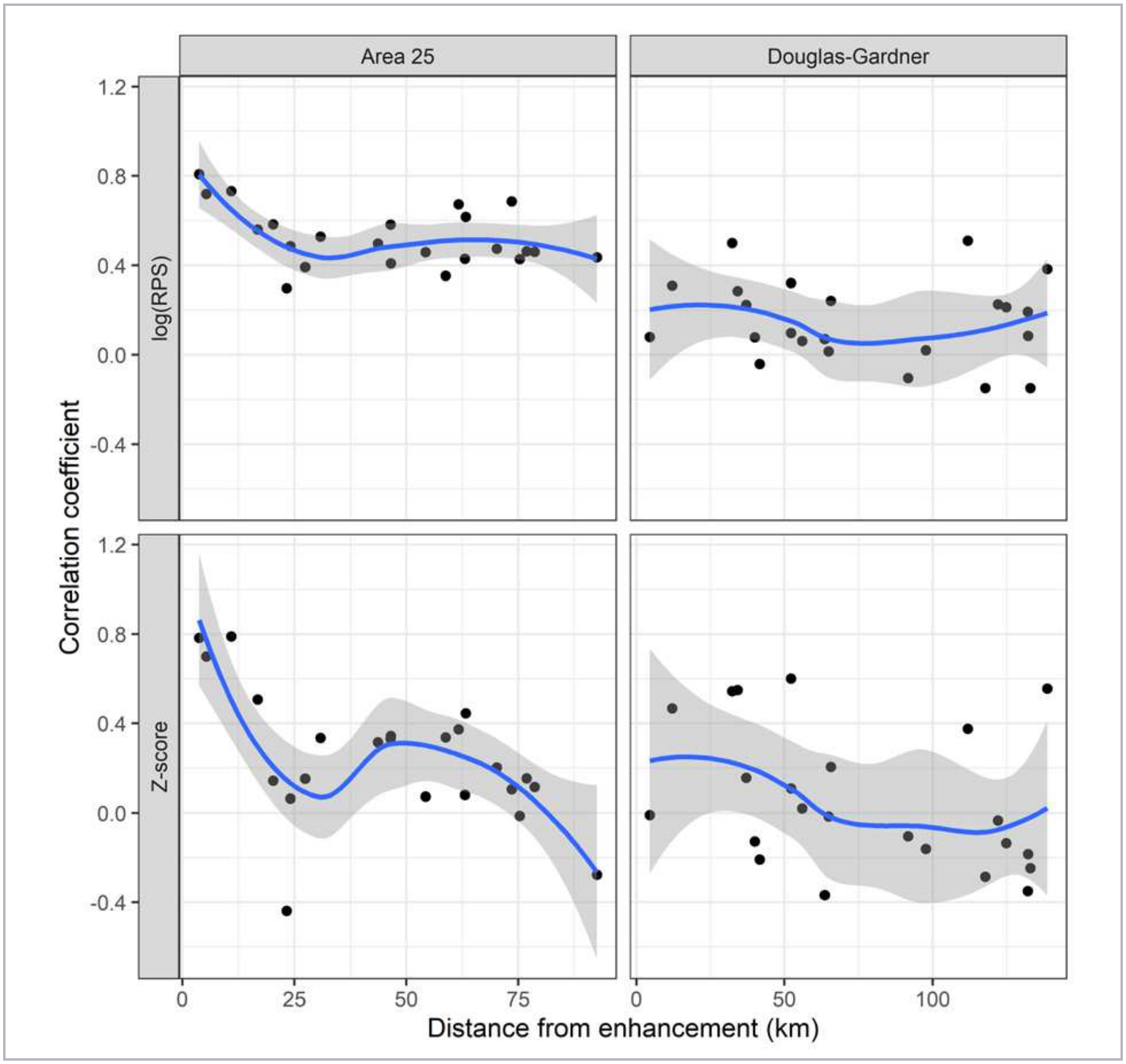

Figure 13: Correlation coefficients for comparisons between each analysis system and the enhanced stream plotted by distance from the enhanced system.

We also explored correlation in systems by computing stream mouth to stream mouth distances using the node-based approach for all pairwise comparisons of systems. While this produced the expected dendrograms showing inlet/sub-inlet groupings, the pattern of correlation between systems and distance from each other was not consistent between Areas, or between pre- and post-enhancement periods (Figure 14). Area 25 showed a declining power model fit that indicated correlation decreased with increasing distance, and that it changes between periods for log(RPS). Area 8 and Douglas-Gardner chum did not show the same type of relationship, although both areas had similar small but significant declines in correlation with increasing distance.

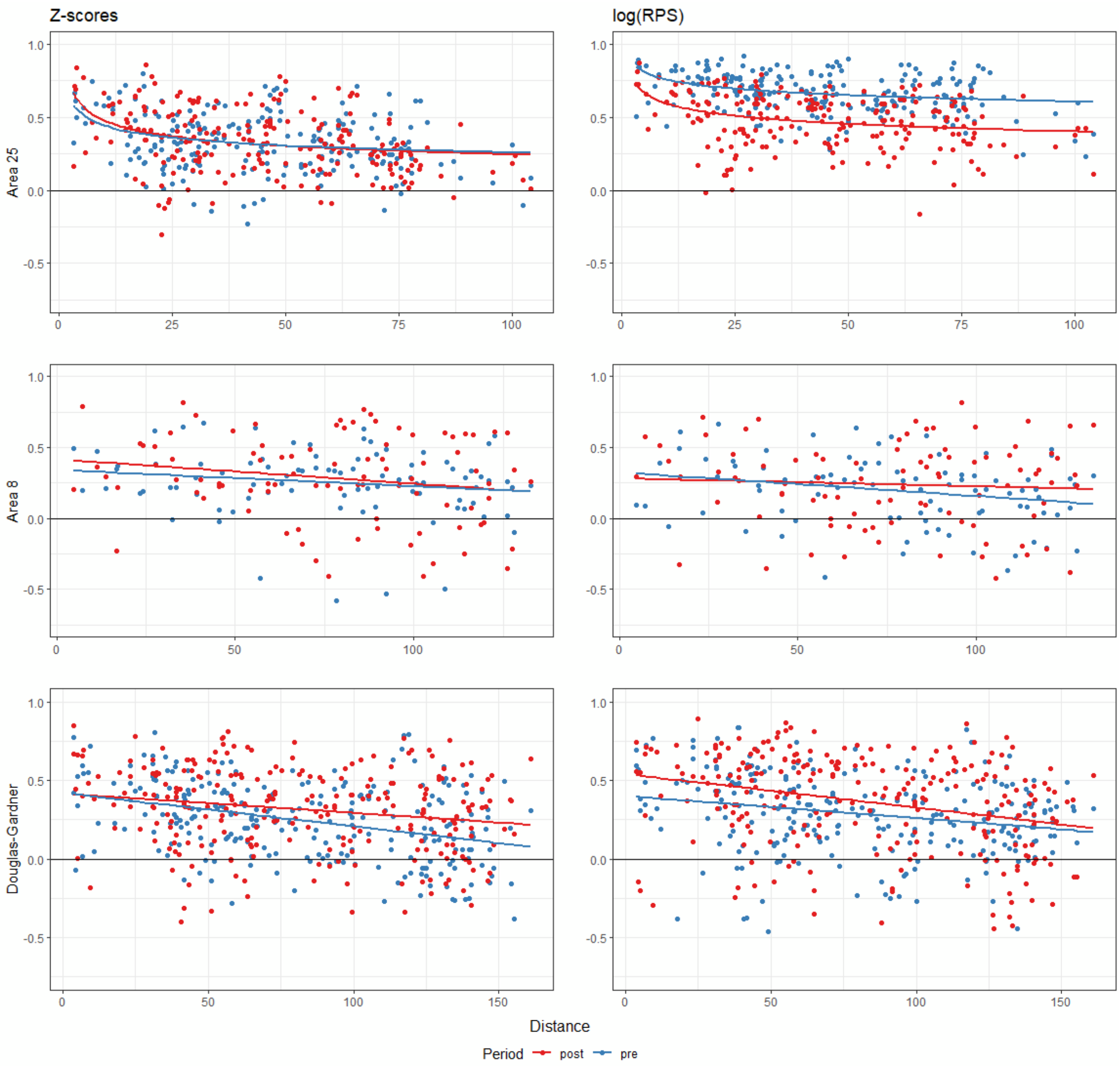

Figure 14: Pairwise stream to stream correlations versus pairwise stream to stream distance for Z-score of log(escapement) and log(RPS) for Area 25, Area 8 and Douglas-Gardner chum.

Linear Models

In our exploratory analysis, we compared the effects of enhancement on the number of spawners (escapement metrics), but also the productivity of surrounding systems (in our case, we used RPS and log(RPS)). While enhancement in one system might increase the escapement in nearby systems through straying, it may also have an affect on RPS. RPS could be decreased if hatchery origin adults that return to nearby streams reduce spawning success or reduce fitness of hybrid cross juveniles (wild *x* hatchery matings), or negatively compete in some other way (e.g., through displacement of wild fish, etc.). Alternatively, RPS could be increased if hatchery adults boost wild spawning populations out of depensation abundances, are more fit than wild spawners, or improve habitat productivity through additional marine derived nutrients. Results from modeling are summarised in Table 11.

Table 11: Table of effects from best fitting models with log escapement and log(RPS) as response variable. All factors are listed however the top performing model may not have included all factors in each area. A plus sign indicates a positive effect on the response variable, with a minus sign indicating a negative effect on the response variable. NS indicates included in top model but not significant, NI indicates tested but not included in top model, and NT indicates not tested.

Response Variable	Factor	Area 25	Area 8	Douglas-Gardner
log escapement	Total releases	+	NI	NI
	Distance from enhancement	-	+ from Bella Coola - from McLoughlin	-
	Year	-	NS	+
	Correlation coefficient	+	NT	NT
	Subinlet	Yes-various	Yes-various	NT
log(RPS)	Total releases	-	+ from Bella Coola - from McLoughlin	-
	Distance	NI	NS	NS
	Year	-	NS	+
	Subinlet	NI	NI	NT

Results from modeling were mixed for all variables across the areas, including some unintuitive results such as escapement increasing further from enhancement. However, these could be explained by other variables such as absolute spawner abundance being high in systems further from the enhanced system, not due to any interacting effects, but simply because of larger capacity and populations. Indeed, in Area 25, where we see this effect, there is a relatively high escapement in some of the most distal systems from Conuma enhancement (Ransom, Espinosa, and Hammond). The mixed results either show that there are differences in responses to enhancement between areas, or that our analysis was not able to detect consistent signals in escapement or RPS response variables. Possibly, other variables may simply be confounding the analysis.

The relationship between total releases and log(RPS) were not the same in all areas, with decreases in log(RPS) with increasing total releases in Area 25 and Douglas-Gardner, and the reverse in Area 8. Douglas-Gardner and Area 25 also had opposite temporal trends with log(RPS) increasing over time in Douglas-Gardner and decreasing over time in Area 25. In Area 25, escapement increased with total releases, but total releases were not included in the top models for Area 8 or Douglas-Gardner in relation to log(escapement). There were also opposite effects of distance from enhancement between the areas. These trends may be due to local factors such as network topology or emergent effects of the conspecific interactions among wild *x* stray fish. For example, sub-inlets in Area 25 are centrally grouped within two main inlets along the coast; Area 8 has two very proximate main inlets leading into long corridors of fjords with sub-inlets interspersed; and Area 6 (Douglas-Gardner) is a braided estuary of many cross-channels and lots of opportunities for straying. Among the three network topologies, it is very possible that there are varying degrees of straying as a simple function of the water:coastline ratio, which would be an interesting aspect to explore in future analyses. As detailed above, the log(RPS) metric is an indication of productivity (we did not explore Ricker stock-recruit models given the constant exploitation rate and age composition applied across all streams). Our results provide evidence that log(RPS) is influenced by the total number of releases, but this is not dependent on distance from enhancement. Decreased log(RPS) may indicate reduced productivity in systems within the same area as enhancement, but there is no indication of a clear mechanism. There may also be co-linearity between total releases and underlying trends in productivity due to other factors such as large-scale regional processes. These would confound our analyses.

Trends in RPS

We observed some trends in log(RPS) in both Douglas-Gardner and Area 25 in enhanced systems. We were not able to explore this in Area 8 since the enhanced systems were not included in the analysis streams. In Douglas-Gardner, enhancement in the Kitimat River and other streams (there was some historical low enhancement in Bish, the Kildala and Dala, and Hirsch) was followed by an increase in log(RPS) which then declined over time. In Area 25, enhancement to the 4 systems (Canton, Conuma, Sucwoa, and Tlupana), was immediately followed by a decline in log(RPS). We do not know the cause of these changes, but it does provide evidence of differential effects of addition of hatchery juveniles to systems in different areas.


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Conclusions and Recommendations

In conclusion, while we did find interesting and pertinent relationships between hatchery production and metrics of wild population productivity, we did not observe a clear signal from enhancement that was consistent and repeatable between Areas using our approach. We found that:

- In some areas there was increased escapement in streams closer to enhancement, significant shifts in correlative relationships over distance, and significant shifts in correlation in metrics of escapement and productivity between pre- and post-enhancement periods;
- Our analyses provide average correlations among productivity metrics across distances that were close to results for chum in previous work (± 100 km, e.g. Pyper *et al.* 2002), and there is evidence that these correlations decline with increasing distance;
- Our analyses provide information consistent with other research showing generally positive correlation of these metrics across regional scales;
- We also found evidence that different metrics (e.g., log(escapement) versus log(RPS)) show different patterns, consistent with different mechanisms of effects;
- There are likely confounding variables even within the factors we selected, such as sub-inlet abundance and distance from enhancement, that may detecting signals from enhancement difficult to detect;
- Data limitations prevent more robust analysis using, for example, Ricker stock-recruit relationships due to missing stream specific age and exploitation rate data; and
- The lack of escapement information in some Areas for the major enhanced systems hindered our analysis since there was little information in some areas to compare the non-enhanced systems with.

In future work, we would encourage the use of more complex statistical approaches, though we acknowledge that there simply may not be enough data and too much interannual variation to identify clear patterns across spatial areas. Some specific investigations that we think would be useful include:

- Conducting a Dynamic Factor Analysis (e.g., Zuur *et al.* 2003, Malick and Cox 2016) to detect common patterns in a time series of explanatory spatial variables;
- Conducting additional analyses on reference areas with very little enhancement as a benchmark;
- Conducting additional analyses in different areas for chum salmon, ideally within each broad region (e.g. Fraser, ECVI, WCVI, Inner South Coast, Central Coast, North Coast, Haida Gwaii); and
- Conducting additional analyses for different species, particularly Chinook salmon to enable comparison of our workflow results to known straying rates from the CWT program.

As our analysis was data limited in some aspects, we also recommend the following to enable more robust investigations on the influence of enhancement on nearby non-enhanced systems:

- Collecting empirical field information on chum in wilds systems surrounding enhanced systems, especially in areas with thermally marked releases (this may be in development in some areas already);
- Collecting stream specific age information in more non-enhanced systems to inform a more robust approach to explore changes in productivity;
- For Areas such as Area 8, which have terminal fisheries in a number of areas in close proximity to enhanced systems and non-enhanced systems, development of more nuanced exploitation rates would also aid in stock-recruit analysis.

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Funding for the project is provided by the BC Salmon Restoration and Innovation Fund, a contribution program funded jointly between Fisheries and Oceans Canada and the Province of BC.

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