Calculating the Spawn Index for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada

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CALCULATING THE SPAWN INDEX FOR PACIFIC HERRING (*Clupea pallasii*) IN BRITISH COLUMBIA, CANADA

by

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The spawn index time series is one component of Pacific Herring (*Clupea pallasii*) stock assessments in British Columbia (BC), Canada. This report documents how we calculate the spawn index from spawn survey observations (e.g., spawn extent, number of egg layers, substrate type). There are three types of spawn survey observations: observations of spawn taken from the surface usually at low tide, underwater observations of spawn on giant kelp, Macrocystis (*Macrocystis* spp.), and underwater observations of spawn on other types of algae and the substrate, which we refer to as 'understory.' We calculate the spawn index in several steps. First, we quantify Pacific Herring egg production, which is critical to calculating the spawn index. Then we calculate the spawn index for each of the three aforementioned spawn survey types: surface, Macrocystis, and understory. Finally, we combine the three spawn indices, and aggregate by stock assessment region and year to align with the spatial and temporal scale for Pacific Herring science advice and fishery management in BC. In addition, we identify uncertainties in spawn index calculations, and we describe how users can download the script to calculate the spawn index using an example database. The 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q; therefore it is a relative index of spawning biomass.

RÉSUMÉ

Grinnell, M.H., Schweigert, J.F., Thompson, M., and Cleary, J.S. 2018. Calculating the spawn index for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. Can. Tech. Rep. Fish. Aquat. Sci. XXXX: vii + 24 p.

[Et en français...]

1 INTRODUCTION

Statistical age-structured stock assessment models rely on an indicator of relative population abundance to reconstruct a time series of absolute abundance. For Pacific Herring (*Clupea pallasii*), an index of relative population abundance is provided by monitoring the extent and intensity of the egg or spawn deposition throughout coastal British Columbia (BC), Canada (DFO 2015). Model estimates of spawning biomass are derived from a statistical catch-at-age model fit to commercial catch, biological data, and the spawn index. Key results from the stock assessment model include stock reconstructions, estimated current stock status, and projected spawning biomass. Projected spawning biomass is used to develop harvest decision tables, which inform fisheries management decisions. Note that the 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q (DFO 2015); therefore it is a relative index of spawning biomass.

This report documents the calculations used to convert spawn survey observations (e.g., spawn extent, number of egg layers, type of substrate) to the spawn index for Pacific Herring in BC. The process and calculations described in this report have been documented elsewhere, in either published or informal, internal documents. The objective of this report is to summarize and clarify the details necessary to understanding spawn index calculations. Spawn index calculations have been updated over the years as more data and analyses justify improvements; we restrict this report to describing the current method.

We decide to document the spawn index calculations when we translated the process from a **Microsoft Access** database to an **R** (RCT 2017) script. We updated from a database to an **R** script for several reasons. First, the database has been used for various purposes over two decades, and has incidental calculations that make it overly complex. Second, the database is difficult to troubleshoot, and to differentiate between input (i.e., data) and derived values. Third, the **R** script is open and transparent; users are welcome to view and download the script and an example spawn survey database. Fourth, we consider it good practice to separate data from analyses. Finally, a separate **R** script allows us to generate dynamic documents in the spirit of reproducible research using **knitr** (Xie 2015).

Annual monitoring surveys of egg deposition collect data used to calculate the spawn index. There are three types of spawn survey observations: observations of spawn taken from the surface usually at low tide, underwater observations of spawn on giant kelp, Macrocystis (*Macrocystis* spp.), and underwater observations of spawn on other types of algae and the substrate, which we refer to as 'understory.' Surface spawn surveys are believed to be the least accurate of the three survey types, but they have the greatest temporal and spatial extent (Schweigert 1993). For example, surface spawn surveys were the only survey type prior to 1988, and they are still used extensively for minor spawns, remote spawns (i.e., outside stock assessment region boundaries; see below), as well as unusually early or late spawns. Macrocystis and understory spawn surveys are conducted using SCUBA gear, and have been used for all major spawns since 1988. Pacific Herring spawn surveys began in 1928, but are considered incomplete prior to 1937 because many potential areas were not surveyed (Hay and Kronlund 1987).

Pacific Herring spawn survey observations have a nested hierarchical structure: sampling quadrats are nested within transects, transects are nested within spawns, and spawns are nested within locations. For stock assessment purposes, locations are nested within sections, sections are nested within statistical areas, and statistical areas are nested within five major and two minor stock assessment regions (SARs) in BC (Figure 1; Haist and Rosenfeld 1988). The major SARs are Haida Gwaii (formerly Queen Charlotte Islands), Prince Rupert District, Central Coast, Strait of Georgia, and West Coast of Vancouver Island; the minor SARs are Area 27, and Area 2 West.

We calculate the spawn index in several steps. First, we quantify Pacific Herring egg production (section 2), which is critical to calculating the spawn

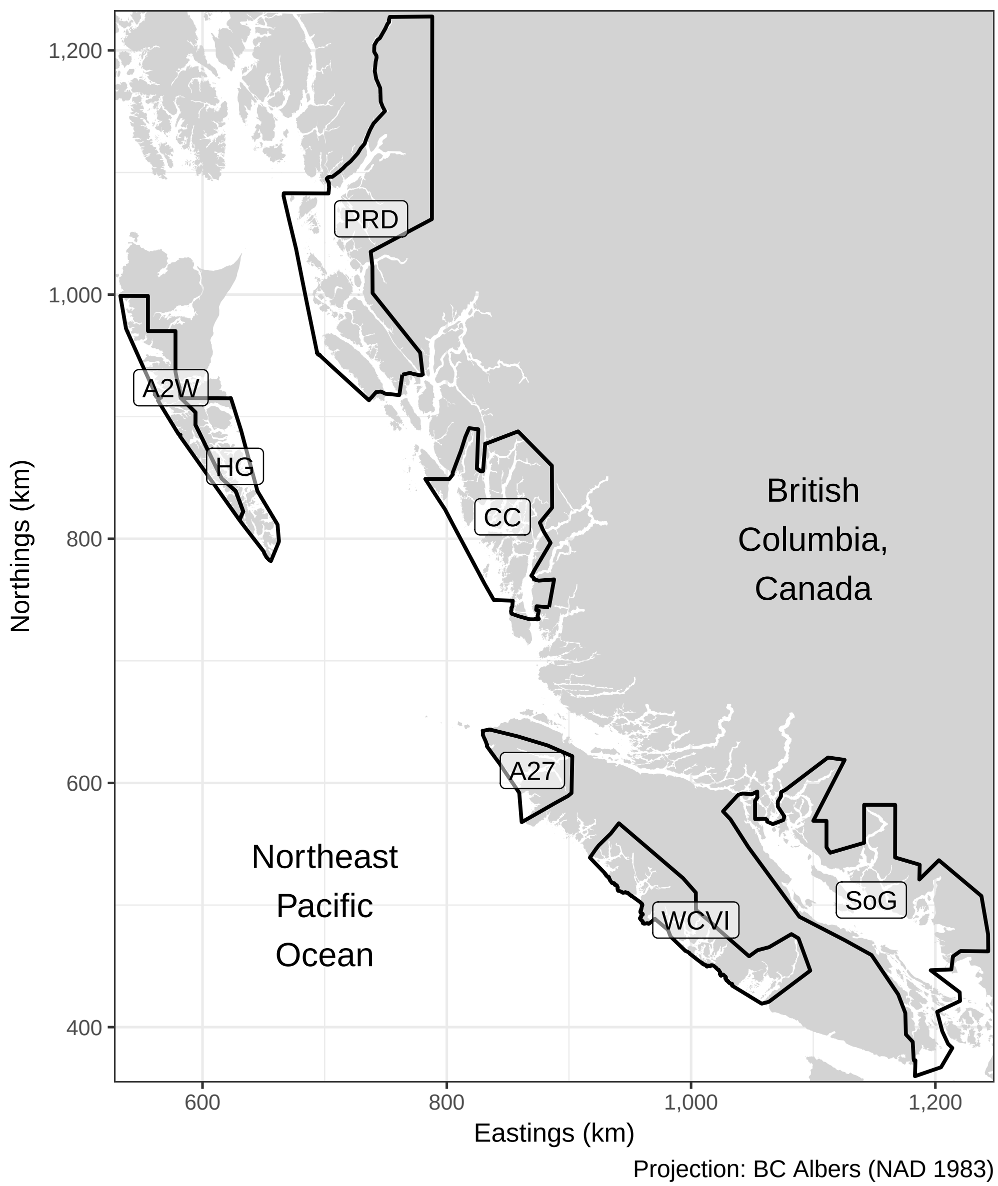

Figure 1. Spatial boundaries for British Columbia Pacific Herring stock assessment regions (SARs): there are five major SARs (Haida Gwaii, HG; Prince Rupert District, PRD; Central Coast, CC; Strait of Georgia, SoG; and West Coast of Vancouver Island, WCVI), and two minor SARs (Area 27, A27; and Area 2 West, A2W).

index. Then we calculate the spawn index for each of the three aforementioned spawn survey types: surface (section 5), Macrocystis (section 6), and understory (section 7). Within each section, we separate each level of spatial aggregation (e.g., calculations at the quadrat, or transect level) into subsections. Finally, we combine the three spawn indices to get the total spawn index (section 8), and aggregate the total by stock assessment region and year. Note that we avoid subscript notation in the following equations to correspond with the **R** script which avoids subscripts (e.g., no '`for`' loops).

2 EGG PRODUCTION

Female Pacific Herring produce an average of approximately $200,000$ eggs per kilogram, kg of total body weight (Hay 1985; Hay and Brett 1988). We assume that females account for 50% of spawners, and we use the following egg conversion factor, *ECF* to convert eggs to tonnes, t of spawners

$$ECF = fecundity \cdot pFemale \cdot \frac{10^3 \text{ kg}}{\text{t}} \tag{1}$$

where *fecundity* is the number of eggs per kilogram of total female body weight in $\text{eggs} \cdot \text{kg}^{-1}$, *pFemale* is the proportion of spawners that are female, and *ECF* is in $\text{eggs} \cdot \text{t}^{-1}$. Thus, we convert eggs to the spawn index in tonnes by dividing the number of eggs by $ECF = \text{eggs} \cdot 10^8 \cdot \text{t}^{-1}$. Note that our unit of measurement for eggs is in thousands (i.e., $\text{eggs} \cdot 10^3$) in the **R** script, and correspondingly in this report. Although Pacific Herring egg production is affected by environmental variability and other factors (Tanasichuk and Ware 1987; Hay and Brett 1988), we assume that bias to the spawn index from Equation 1 is insignificant in most areas and years (Schweigert 1993).

3 STATISTICAL FRAMEWORK

Historical and recent surface surveys were conducted using an ad hoc sampling regimen based on the assumption of random sampling, where surveys were often opportunistic given the state of the tide, as well as available sampling tools such as boats, rakes, and viewers. In contrast, underwater diver surveys instituted in 1988 follow a two-stage sampling design with transects being the first stage of sampling, and individual quadrats along transects being the second stage of sampling. The specifics of the current sampling protocol were determined through a series of directed studies in 1981 and 1983 in the Strait of Georgia (Schweigert et al. 1985, 1990).

4 SAMPLING PROTOCOL

The following is a brief summary of the spawn survey sampling protocol in the Pacific Herring spawn survey manual. In BC, Pacific Herring primarily spawn in sheltered bays and inlets, depositing their eggs on rocks and algae between depths of 1.5 m above and 18 m below the 0-tide level (Humphreys and Hourston 1978; Haegele and Schweigert 1985). We identify distinct spawns (both spatially and temporally) by a unique 'spawn number.' A distinct spawn is typically a continuous stretch of shoreline with no detectable break in egg deposition. The spawn number is the finest scale at which we calculate the spawn index.

Pacific Herring spawns typically extend along the shore; from above, spawns are identified by a milky or turquoise discolouration of the ocean caused by the release of milt, and appear as bands running parallel to the shore. Thus, spawn 'length' refers to distances parallel to the shore, and 'width' refers to distances perpendicular to the shore. For example, Macrocystis bed length, *LengthMacroS* and algae bed length, *LengthAlgS* refer to distances that Macrocystis beds and algae beds extend parallel to the shore, respectively. One exception is transect width, $\mathit{TransectWidth} = 2\,\mathrm{m}$, which refers to the swath of substrate along Macrocystis transects.

When surveying spawn, surveyors first determine the spatial extent of the Pacific Herring spawn in terms of length of shoreline to be surveyed. Next, transects are set perpendicular to the shore, beginning 200 m in from one end, and spaced 350 m apart along the length. These transects are used to determine the spawn width, quadrat placement, and the location of Macrocystis plants. Transects generally go from 20 m depth or the edge of the spawn, whichever is shallower, to 0 m. Most areas have 'permanent transect' locations recorded on charts which enable surveyors to place transects in the same location each year. When permanent transect locations are unavailable, surveyors set new transects based on the aforementioned criteria. New transect locations are digitized to make them available as permanent transect locations for future spawn surveys.

4.1 SURFACE SPAWN

Surface spawn surveyors use the aforementioned transect interval when possible, but the sampling interval relies on surveyor judgement and available resources. If the spawn area is sufficiently large, surface surveyors usually use permanent transect locations. Small spawns can still be mapped as they were historically, with surveyors deciding how to sample the spawn. To sample, surveyors deploy specialized rakes throughout the spawn to determine vegetation type, number of egg layers, and vegetation coverage. In shallow waters a viewing box may be employed, and at low tide a portion of the spawn may be visible for direct observation.

4.2 MACROCYSTIS SPAWN

Macrocystis spawn surveyors take a census of Macrocystis plants within 1 m of the transect line, on both the left- and right-hand sides (i.e., $TransectWidth = 2\,\text{m}$). Divers categorize Macrocystis plants as either 'mature' or 'immature' based on stipe height; mature plants have stipes ≥ 1 m high, and are the only plants used for Macrocystis spawn index calculations. For each mature plant, divers record height, number of fronds, and number of egg layers. For each transect, divers record the average number of egg layers. Haegele and Schweigert (1985, 1990) provide a description of the sampling technique, and the basis for estimating the total number of eggs per plant.

4.3 UNDERSTORY SPAWN

Understory spawn surveyors place quadrats along transects, with a target frequency of ≥ 5 quadrats per transect, with a minimum spacing of 2 m, and a maximum spacing of 40 m. Quadrat size for understory spawn surveys is usually $0.5\,\mathrm{m}^2$; other sizes (e.g., $0.25\,\mathrm{m}^2$ and $1.0\,\mathrm{m}^2$) have been tested during research surveys (Schweigert 1993). Within each quadrat, divers record the dominant (i.e., most heavily spawned) substrate type, percentage of the quadrat covered by spawn, and number of egg layers. In addition, divers identify the three dominant algae types that have spawn. For each of these algae types, divers record the percentage of the quadrat covered by the algae, and number of egg layers.

4.4 SPAWN WIDTH ADJUSTMENTS

Spawn width is a critical component of spawn index calculations. There are two cases where we adjust spawn width estimates to improve spawn index estimates: surface spawn surveys, and certain understory spawn surveys between 2003 and 2013.

4.4.1 SURFACE SPAWN SURVEYS

As previously mentioned, surface surveys were the only survey type prior to 1988, while the majority of spawns since 1988 have been surveyed using SCUBA gear. Therefore, we typically describe the spawn index as having two periods based on the predominant survey type: the surface survey period from

1951 to 1987, and the dive survey period from 1988 to present. One issue with comparing these two partly overlapping protocols is that surface surveyors tend to underestimate spawn width (Hay and Kronlund 1987). To improve the consistency of spawn index estimates throughout the time period from 1951 to present, we adjust surface spawn width estimates using underwater estimates when available (Schweigert et al. 1993). Our preferred width is the median width from all dive surveys within the 'pool.' A pool is a group of locations within a section that are often adjacent, contain similar algae and bottom substrate, and can be treated as a group with likely similar widths. We summarise spawn width by the median instead of the mean because the data are not normally distributed (Schweigert et al. 1993). If there are no dive data that meet those criteria, we use the median width from all dive surveys within the section, or within the region if there are no dives within the section. If there are still no dive data that meet those criteria, we use the observed width from the surface survey. Note that we update the aforementioned median width values periodically, not annually.

4.4.2 UNDERSTORY SPAWN SURVEYS

In 2013, DFO staff realized that they were inadvertently underestimating spawn width for understory spawn surveys (Cleary et al. 2017). The issue was caused by the assumed behaviour of transect lines used by spawn surveyors to measure spawn width. As previously mentioned, Pacific Herring spawn surveyors determine spawn width by placing transects perpendicular to the shore. Surveyors use weighted lead lines to ensure that the line rests on the substrate; these lead lines are marked in 1 m increments, and were standardized to 20 m segments beginning in the early 1990s.

Sometime in the mid- to late-1990s, surveyors observed that the 20 m segments shrank by approximately 1 m during the first season of use. DFO staff noticed that this issue was occurring coast wide, and began re-measuring lead lines each season. They also modified the lead line marking protocol to account for shrinkage by marking 1.15 m increments. DFO staff derived this 15% increase by measuring and re-marking lead lines each year. Lead lines are made of a mix of polypropylene and nylon. Nylon tightens up under repeated use, which is thought to explain the shrinkage. DFO staff re-measured lead line increments in the mid-2000s, and found that they still shrank from 1.15 m to 1.0 m, and continued to use the modified protocol.

In 2013, spawn surveyors observed that lead line increments were consistently 1.15 m. Following this observation, DFO staff re-measured additional lead lines and found that lead lines were made up of a combination of 1.0 m and 1.15 m increments. The combination of observed increment lengths is explained by the lifespan of lead lines: lead lines are replaced every 5 to 10 years, with some segments being replaced more frequently (i.e., inner segments are replaced more frequently than seaward segments). DFO staff suspect that a change in lead line manufacturing prevents newer lead lines from shrinking.

The oldest set of written instructions that describe the modified protocol of marking 1.15 m increments is from 2003, and this protocol was used until 2013. The practice of annually re-measuring lead line increments ceased in the early 2000s; thus we have been unable to determine when lead lines ceased shrinking. Given available written instructions from 2003, and the observations summarized above, we have adjusted spawn width estimates based on the written instructions for the marking protocol in 2003. Accordingly, our best estimate of years impacted by marking lead lines at 1.15 m increments (when shrinking was no longer occurring) is from 2003 to 2013. We have updated spawn widths in the database for the affected spawn surveys (Cleary et al. 2017).

5 SURFACE SPAWN

Surface spawn surveyors collect data along transects or using their judgement, and we calculate spawn metrics at the transect, and spawn level.

5.1 TRANSECT LEVEL CALCULATIONS

For each substrate type, egg layers is

$$EggLyrs = Layers \cdot Proportion \tag{2}$$

where *Layers* is the number of egg layers on a given substrate type, and *Proportion* is the proportion of the transect covered by the substrate type. At the transect level, the sum of *EggLyrs* is *EggLyrsTotT*. That is to say, *EggLyrsTotT* is the sum of *EggLyrs* for each substrate type within a given transect. For the time period when spawn 'intensity' categories were recorded instead of estimating the number of egg layers, intensity is converted to *EggLyrsTotT* (Table 1). Surface egg density in thousands per square metre is (Schweigert et al. 1997)[1]

$$EggDensT = EggLyrsTotT \cdot 212.218 + 14.698 \tag{3}$$

where *EggDensT* is in eggs $\cdot 10^3 \cdot \text{m}^{-2}$.

5.2 SPAWN LEVEL CALCULATIONS

At the spawn level, the mean of *EggDensT* is *EggDensMeanS*. Two other summary statistics are required at the spawn level: the spawn length *Length* and width *WidthS*, both in metres (m). We set *WidthS* to the first non-missing value of median pool width, median section width, median region width, or observed width (in that order; see subsubsection 4.4.1). The surface spawn index is

$$SurfSI = \frac{EggDensMeanS \cdot Length \cdot WidthS \cdot 10^3}{ECF} \tag{4}$$

where *SurfSI* is in tonnes.

[1] Notwithstanding the units provided in Schweigert et al. (1997), surface egg density is in thousands per square metre (eggs $\cdot 10^3 \cdot \text{m}^{-2}$).

Table 1. Spawn intensity categories and number of egg layers for Pacific Herring surface spawn surveys for the periods 1928 to 1950, and 1951 to 1978 (Schweigert and Stocker 1988). The change from 5 to 9 intensity categories was probably to accommodate the practice of reporting intermediate categories such as 3.5 (Hay and Kronlund 1987). Starting in 1979, spawn surveyors estimated the number of egg layers, and they continued to record intensity until 1981 to provide overlap between the two methods. In addition to the number of egg layers, intensity was sometimes recorded after being officially discontinued in 1981.

Intensity category		
1928 to 1950	1951 to 1978	Egg layers
0	0	0.0000
1	1	0.5529
	2	0.9444
2	3	1.3360
	4	2.1496
3	5	2.9633
	6	4.1318
4	7	5.3002
	8	6.5647
5	9	7.8291

5.3 MANUAL CORRECTIONS

One record in the surface spawn database since 1951 requires an update to fill-in missing egg layer information. Instead of updating the database permanently, we make this update in the **R** script to be transparent, and to prevent a mismatch between the original data sheets and the database. This affects the following record:

1. Update *EggLyrsTotT* from 0.0 to 0.5529 for the 1 record in the year 1962, statistical area 14, section 142, location code 820, and with *EggLyrsTotT* = 0.0. We update intensity from 0 to 1 because spawn was surveyed but not reported, and use Table 1 to fill in the missing

value.

Spawn survey records prior to 1951 have additional missing or inaccurate egg layer information, and are unreliable.

While reviewing the spawn index calculations and translating them from the **Microsoft Access** database to **R**, we found several cases where good quality spawn index data were being over-written with no documented reason. These updates have been omitted, and affected the following records:

1. Update $EggLyrsTotT$ to 2.1496 for the 15 records in the year 1979, statistical area 2, and with intensity 4.
2. Update $EggLyrsTotT$ to 0.5529 for the 4 records in the year 1981, statistical area 24, and with $EggLyrsTotT = 0.0$.
3. Update $EggLyrsTotT$ to 1.3360 for the 7 records in the year 1982, statistical area 23, and with intensity 3.
4. Update $EggLyrsTotT$ to 2.33 for 41 records in the year 1984, statistical area 24, and with intensity 0, and
5. Update $EggLyrsTotT$ to to 2.98 for 14 records in the year 1982, statistical area 27, and with $EggLyrsTotT = 0.0$.

In the first three cases, $EggLyrsTotT$ was updated using Table 1; in the last two cases, $EggLyrsTotT$ was updated using historical averages.

6 MACROCYSTIS SPAWN

Macrocystis spawn surveyors collect data for individual plants, and we calculate spawn metrics at the transect, and spawn levels.

6.1 TRANSECT LEVEL CALCULATIONS

Several metrics are collected at the transect level: width $WidthT$, and transect width $TransectWidth = 2\,\text{m}$, both in metres, as well as transect area $AreaT$, in square metres. In addition, we calculate metrics for mature Macrocystis plants: mean height $HeightMeanT$ in metres, mean egg layers $EggLyrsMeanT$, total number of fronds $FrondsTotT$, and total number of plants $PlantsTotT$.

6.2 SPAWN LEVEL CALCULATIONS

At the spawn level, we determine the length of Macrocystis $LengthMacroS$, in metres. If $LengthMacroS$ is inadvertently not recorded, we set $LengthMacroS$ to the spawn length $Length$. We also calculate the mean of $WidthT$, $WidthMeanS$, in metres and the sum of $AreaT$ is $AreaTotS$, in square metres. In addition, the sum of $PlantsTotT$ is $PlantsTotS$, the sum of $FrondsTotT$ is $FrontsTotS$, the mean of $HeightMeanT$ is $HeightMeanS$, and the mean of $EggLyrsMeanT$ is $EggLyrsMeanS$. The number of fronds per plant is

$$FrondsPerPlantS = \frac{FrondsTotS}{PlantsTotS} \quad . \tag{5}$$

The number of eggs per plant in thousands is (Haegele and Schweigert 1990)

$$\begin{aligned} EggsPerPlantS = 0.073 \cdot EggLyrsMeanS^{0.673} \cdot \\ HeightMeanS^{0.932} \cdot FrondsPerPlantS^{0.703} \cdot 10^3 \end{aligned} \tag{6}$$

where $EggsPerPlantS$ is in eggs $\cdot\, 10^3 \cdot \text{plant}^{-1}$. Macrocystis egg density in thousands per square metre is

$$EggDensMeanS = \frac{EggsPerPlantS \cdot PlantsTotS}{AreaTotS} \tag{7}$$

where $EggDensMeanS$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$. The Macrocystis spawn index is

$$MacroSI = \frac{EggDensMeanS \cdot LengthMacroS \cdot WidthMeanS \cdot 10^3}{ECF} \quad (8)$$

where $MacroSI$ is in tonnes.

7 UNDERSTORY SPAWN

Understory spawn surveyors collect data in quadrats, and we calculate spawn metrics at the quadrat, transect, and spawn levels. We calculate two separate estimates of egg density at the quadrat level: spawn on substrate, and spawn on algae.

7.1 QUADRAT LEVEL CALCULATIONS

Substrate egg density in thousands per square metre is (Haegele et al. 1979)

$$EggsDSub = 340 \cdot SubLyrs \cdot SubProp \quad (9)$$

where $SubLyrs$ is the number of egg layers on substrate, $SubProp$ is the proportion of substrate covered by spawn, and $EggsDSub$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$. Algae egg density in thousands per square metre is (Schweigert 2005)

$$EggsDAlg = 600.567 \cdot AlgLyrs^{0.6355} \cdot AlgProp^{1.4130} \cdot A \cdot Q \quad (10)$$

where $AlgLyrs$ is the number of egg layers on a given algae type, $AlgProp$ is the proportion of the quadrat covered by the algae, A is the algae coefficient (Table 2), Q is the quadrat size coefficient (Table 3), and $EggsDAlg$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$. The total linear weighted understory egg density in thousands per metre is

$$EggDensWtQ = (EggsDSub + EggsDAlg) \cdot Width \quad (11)$$

where *Width* is spawn width in metres, and *EggDensWtQ* is in eggs $\cdot 10^3 \cdot \text{m}^{-1}$. We calculate the weighted mean egg density because spawn widths can vary greatly along their length; a weighted mean ensures that transects contribute proportionally to their area.

7.2 TRANSECT LEVEL CALCULATIONS

At the transect level, the mean *EggDensWtQ* is *EggDensWtMeanT*.

7.3 SPAWN LEVEL CALCULATIONS

At the spawn level, the sum of transect width *Width* is *WidthTotS*, the mean of *Width* is *WidthMeanS*, and the algae length is *LengthAlgS*, all in metres. If *LengthAlgS* is inadvertently not recorded, we set *LengthAlgS* to

Table 2. Algae types and coefficients, A for Pacific Herring understory spawn surveys (Schweigert 2005).

Algae type	Coefficient, A
Grasses	0.9715
Grunge	1.0000
Kelp, flat	0.9119
Kelp, standing	1.1766
Leafy algae	0.6553
Rockweed	0.7793
Sargassum	1.1766
Stringy algae	1.0000

Table 3. Quadrat sizes in square metres (m^2) and coefficients, Q for Pacific Herring understory spawn surveys (Schweigert 2005).

Quadrat size (m^2)	Coefficient, Q
1.00	0.4271
0.50	1.0512
0.25	1.0000

the spawn length *Length*. The sum of *EggDensWtMeanT* is *EggDensWtTotS*. Understory egg density in thousands per square metre is

$$EggDensWtS = \frac{EggDensWtTotS}{WidthTotS} \tag{12}$$

where *EggDensWtS* is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$. The understory spawn index is

$$UnderSI = \frac{EggDensWtS \cdot LengthAlgS \cdot WidthMeanS \cdot 10^3}{ECF} \tag{13}$$

where *UnderSI* is in tonnes.

8 TOTAL SPAWN

The total spawn index for each spawn is

$$TotalSI = SurfSI + MacroSI + UnderSI \tag{14}$$

where *TotalSI* is in tonnes. Although we track the location (i.e., eastings, northings) and date for each spawn event, we aggregate the total spawn index by SAR and year to align with the spatial and temporal scale for Pacific Herring science advice and fishery management in BC (DFO 2015). Recall that the 'spawn index' is a relative index of spawning biomass.

9 SPAWN ON KELP

Spawn on kelp (SOK) fisheries collect Pacific Herring roe that adhere to algae such as Macrocystis after spawning. There are two types of SOK fisheries in BC: 'open-pond' in which harvesters provide algae to spawning Pacific Herring, and 'closed-pond' in which harvests impound spawning Pacific Herring in floating nets that contain algae (Shields et al. 1985). Although SOK fisheries do not directly remove Pacific Herring, substantial quantities of eggs are removed that must be accounted for to manage populations for long term sustainability. Note that closed-pond operations also cause incidental mortality to spawning Pacific Herring (Shields et al. 1985), but we do not address this issue here. Thus, SOK fisheries present an issue in terms of their impact to the population, and accounting in stock assessment and monitoring. Although Pacific Herring stock assessments do not account for eggs removed by SOK fisheries at this time, there are a few options to account for the impact of SOK harvest. The most direct is to estimate the quantity of eggs removed from the population, and treat them as though they would have spawned and contributed to total spawning biomass.

Shields et al. (1985) collected information on the relationship between the number of egg layers in SOK product, and the proportion of the product weight that consisted of eggs and kelp. They determined that kelp represented an average of 12% of the total product weight. Since SOK product is universally brined at the time of harvest, it is necessary to also consider the uptake of salt by the eggs, which increases the overall product weight. However, there is uncertainty in the degree of brining that occurs prior to weighing the product. Nevertheless, Whyte and Englar (1977) determined that following a 24 hour brining period, the wet product weight increased by about 13% due to salt uptake. By osmosis, the brining would also draw some water from the eggs; unfortunately we are unable to account for osmosis at this time. The last factor to consider is the mean fertilized egg weight, which was determined by Hay and Miller (1982) as $2.38 \cdot 10^{-6}$ kg.

We estimate spawning biomass removed from the population by SOK fisheries as

$$SB = \frac{SOK \cdot eggKelpProp \cdot eggBrineProp}{eggWt \cdot ECF} \tag{15}$$

where *SOK* is the weight in kilograms of Pacific Herring SOK harvest, *eggKelpProp* is the proportion of SOK product that is eggs, not kelp (0.88), *eggBrineProp* is the proportion of SOK product that is eggs after brining (0.87), *eggWt* is the average weight in kilograms of a fertilized egg ($\text{kg} \cdot \text{egg}^{-1}$), and *SB* is the estimated spawning biomass in tonnes.

10 SOURCES OF UNCERTAINTY

Like all biological models, spawn index calculations are affected by various potential sources of uncertainty including natural variability, observation error (e.g., bias, imprecision), and model structural complexity (Link et al. 2012). Two examples illustrate these sources of uncertainty. First, natural variability could affect Pacific Herring fecundity, and the sex ratio of spawning Pacific Herring (Equation 1). Fecundity could be influenced by time-varying biological processes such as the observed non-stationarity of weight-at-age, or a truncated age distribution. Second, observation error could affect input data such as the number of egg layers, while model structural complexity could affect estimated prediction model parameters, or the form of their relationship, or both (e.g., Equation 3). Despite these assumptions and potential sources of uncertainty, the spawn index has typically been reported without quantifying uncertainty (but see Schweigert et al. 1993). Reporting the spawn index without uncertainty may create the wrong impression that the spawn index is observed data, whereas it is derived data with assumptions and uncertainties.

There are several potential benefits to addressing spawn index uncertainty. First, quantifying uncertainty could identify parameters to target with future research. Potential analyses to quantify spawn index uncertainty include:

1. Investigating factors that influence fecundity and sex ratios;
2. Quantifying and reporting variability in estimated prediction model parameters (e.g., Equation 3);
3. Bootstrapping observed input data (see Schweigert 1993); and
4. Conducting sensitivity analyses.

Second, acknowledging uncertainty will reduce another source of uncertainty: inadequate communication among scientists, managers, and stakeholders, which can lead to misapplication of scientific advice (Link et al. 2012). Finally, acknowledging uncertainty will increase transparency, and enable users to assess potential impacts to, for example, Pacific Herring stock assessments in a management strategy evaluation (MSE) approach. Addressing data and model uncertainty is a required component of an MSE approach (Punt et al. 2016).

Quantifying uncertainty may also identify options to increase survey program efficiency, in terms of data precision and accuracy. Sampling surveys trade off precision of estimated quantities versus survey effort or cost. Ideally, reducing survey effort does not result in biased target variable estimates. Therefore, understanding this trade-off is important if, for example, budget reductions cause a reduction in survey effort. Strategies to improve spawn survey efficiency could include:

1. Conducting underwater surveys for major spawns in core areas, and surface surveys for other spawns;
2. Quantifying the precision and accuracy of spawn width estimates, and reviewing transect and quadrat spacing (see Schweigert 1993);
3. Reviewing the accuracy of egg prediction models and temporal stability of egg layer estimates; and
4. Conducting periodic versus annual surveys.

Even with a fixed budget, there is a trade-off between higher precision in some areas, versus lower precision or no information in other areas.

11 DOWNLOAD

As previously mentioned, the **R** script to calculate the Pacific Herring spawn index, `SpawnIndex.R` is publicly accessible on the Pacific Herring spawn index repository. The repository includes instructions, and an example database of Pacific Herring spawn survey observations to use with the script.

Essentially, the **R** script imports tables from the database, and follows the calculations described in this report. This report is meant to accompany the **R** script, which has complete details regarding how we calculate the spawn index. Sections in this report correspond to functions in the **R** script. For example, section 5, 'Surface spawn' follows the **R** function `CalcSurfSpawn`. In addition, variable names in this report correspond to variable names in the script. Finally, we have commented the **R** script to promote accessibility and transparency.

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