

# 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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## ABSTRACT

Grinnell, M.H., Schweigert, J.F., Thompson, M., and Cleary, J.S. yyyy.  
Calculating the spawn index for Pacific Herring (*Clupea pallasii*) in British  
Columbia, Canada. Can. Tech. Rep. Fish. Aquat. Sci. nnnn: vii + 41 p.

The spawn index time series is one component of Pacific Herring (*Clupea pallasii*) stock assessments in British Columbia, Canada. This document describes 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: (1) observations of spawn taken from the surface usually at low tide; (2) underwater observations of spawn on giant kelp, *Macrocystis* (*Macrocystis* spp.); and (3) underwater observations of spawn on other types of algae and the substrate, which we refer to as ‘understory.’ We calculate the spawn index in four steps. First, we develop a sampling protocol to estimate the number of eggs in a given area. Second, we develop a conversion factor to convert Pacific Herring eggs to biomass, which is critical to calculating the spawn index. Third, 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 produce a relative index of combined sex spawning biomass. In addition, we identify uncertainties in spawn index calculations, and we describe how users can install the **R** package to calculate the spawn index using an example database. Although we transform the spawn survey data from egg density to biomass in tonnes, the annual time series of egg density and biomass are relative indices of spawning biomass.



## RÉSUMÉ

Grinnell, M.H., Schweigert, J.F., Thompson, M., and Cleary, J.S. yyyy.  
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La série chronologique de l'indice de frai est une composante des évaluations des stocks de hareng du Pacifique (*Clupea pallasii*) en Colombie-Britannique, Canada. Ce document décrit comment nous calculons l'indice de frai à partir des observations du relevé du frai (par ex., l'étendue du frai, le nombre de couches d'œufs, le type de substrat). Il existe trois types d'observations du relevé des frayères: (1) les observations des frayères prélevées à la surface habituellement à marée basse; (2) les observations sous-marines des frayères sur varech géant, *Macrocystis* (*Macrocystis* spp.); et (3) les observations sous-marines des frayères sur les autres algues et le substrat, que nous appelons «sous-étage». Nous calculons l'indice de frai en quatre étapes. Premièrement, nous élaborons un protocole d'échantillonnage pour estimer le nombre d'œufs dans une zone donnée. Deuxièmement, nous élaborons un facteur de conversion pour convertir les œufs de hareng du Pacifique en biomasse, ce qui est essentiel pour calculer l'indice de reproduction. Troisièmement, nous calculons l'indice de frai pour chacun des trois types de relevés de frai susmentionnés: surface, *Macrocystis*, et sous-étage. Enfin, nous combinons les trois indices de frai, et les regroupons par région d'évaluation du stock et par année pour produire un indice relatif de la biomasse reproductrice combinée des sexes. De plus, nous identifions les incertitudes dans le calcul de l'indice de frai, et nous décrivons comment les utilisateurs peuvent installer le packet **R** pour calculer l'indice de frai à l'aide d'une base de données exemple. Bien que nous transformions les données du relevé de la densité des œufs en biomasse en tonnes, les séries chronologiques annuelles de la densité et de la biomasse des œufs sont des indices relatifs de la biomasse des géniteurs.

# 1 INTRODUCTION

Statistical age-structured stock assessment models rely on an indicator of relative population abundance to reconstruct a time series of estimated abundance. For Pacific Herring (*Clupea pallasii*) in British Columbia (BC), Canada, an index of relative population abundance is provided by monitoring the extent and intensity of spawn (i.e., egg) deposition throughout coastal BC (DFO 2020). This document describes our calculations to convert spawn survey observations (e.g., spawn extent, number of egg layers, substrate type) to the spawn index for Pacific Herring in BC. These calculations have been described elsewhere, in either published or informal, internal documents. The objective of this document is to collate the various calculations in their order of application. Spawn index calculations have been updated over the years as more data and analyses justify improvements; we restrict this document to describing the current method.

Hart and Tester (1934) first demonstrated that an estimate of Pacific Herring abundance could be determined from a count of egg deposition in a small set of sampling quadrats. Based on their work, annual spawn surveys collect data used to calculate the spawn index. There are three types of spawn survey observations:

1. Observations of spawn taken from the surface usually at low tide,
2. Underwater observations of spawn on giant kelp, *Macrocystis* (*Macrocystis* spp.), and
3. 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 under water using SCUBA gear, and have been used for all major spawns since 1988. Thus, we 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.

The inclusion of dive surveys in 1988 makes it challenging to compare the

spawn index between these two periods. For example, surface surveys are less accurate than dive surveys (appendix A.1), and spawn surveys used subjective intensity categories instead of direct egg layer estimates until 1978 (subsubsection 3.1.1). In addition, Pacific Herring spawn survey effort has been inconsistent over the time series due to available resources and departmental priorities. For example, in the past, surveyors often dedicated several months each year to spawn surveys; they used small vessels to search for spawn, and surface surveys to estimate spawn biomass. Currently, surveyors use flights to search for spawn, and underwater SCUBA surveys to estimate spawn biomass. Thus, widespread effort (both spatially and temporally) in the past has been replaced with intense effort in the present. Pacific Herring spawn surveys began in 1928, but are considered incomplete for indexing purposes prior to 1937 because many potential areas were not surveyed (Hay and Kronlund 1987).

Pacific Herring spawn survey observations have a nested hierarchical structure: samples, *Macrocystis* plants, and quadrats are nested within transects, transects are nested within spawns, and spawns are nested within Locations. To develop spawn indices, Locations are nested within Sections (Figure 1a), Sections are nested within Statistical Areas (Figure 1b), and Statistical Areas are nested within stock assessment regions (SARs; Figure 1c). There are seven SARs in BC, which we categorize as either ‘major’ or ‘minor’ (Figure 2; Haist and Rosenfeld 1988). The terms ‘major’ and ‘minor’ describe relative differences in geographic and biomass scales. The major SARs are Haida Gwaii (formerly known as 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 do not develop spawn indices for minor SARs.

We calculate the spawn index in four steps. First, we develop a sampling protocol to estimate the number of eggs in a given area (section 2, section 3). Second, we develop a conversion factor to convert Pacific Herring eggs to biomass (section 4), which is critical to calculating the spawn index. Third, 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 use subsections to separate levels of spatial aggregation (e.g., calculations at the quadrat, or transect level; Figure 3). Finally, we combine the three spawn indices, and aggregate by stock assessment region and year to produce a relative index of combined sex spawning biomass

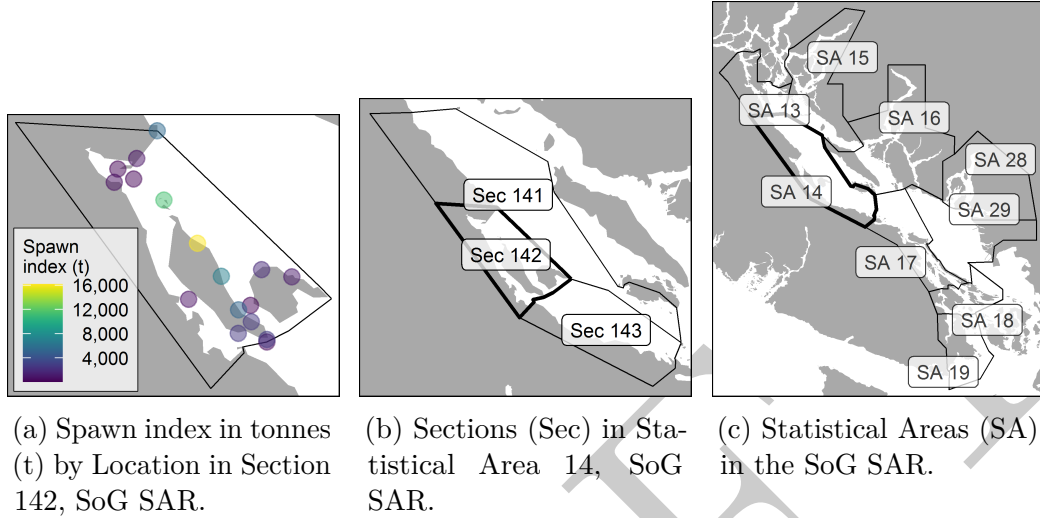


Figure 1. Pacific Herring spawn index by Location in 2019 (a), Sections (b), and Statistical Areas (c) in the Strait of Georgia (SoG) stock assessment region (SAR; Figure 2).

73 (section 8).

74 We developed this document while converting spawn index calculations  
 75 implemented in a **Microsoft Access** database to an **R** (RCT 2017) package,  
 76 **SpawnIndex**. We updated the calculations from a database to an **R** package  
 77 for several reasons. First, the database has been used for various purposes  
 78 over the last two decades and has incidental calculations that make it overly  
 79 complex. Second, the database is difficult to troubleshoot because it is hard  
 80 to differentiate between input (i.e., data) and derived values. Third, the **R**  
 81 package is open and transparent; researchers can view and download the  
 82 package and an example spawn survey database. For example, users can  
 83 run the **R** package functions to implement the calculations described in this  
 84 document using a small set of actual observations. Fourth, we consider it good  
 85 practice to separate data from analyses. Fifth, an **R** package will facilitate  
 86 future research to quantify spawn index uncertainty. Finally, an **R** package  
 87 will allow us to generate dynamic documents in the spirit of reproducible  
 88 research using **knitr** (Xie 2015; Marwick et al. 2018). Essentially, we have  
 89 attempted to follow ‘good enough’ practices in scientific computing (Wilson  
 90 et al. 2016).

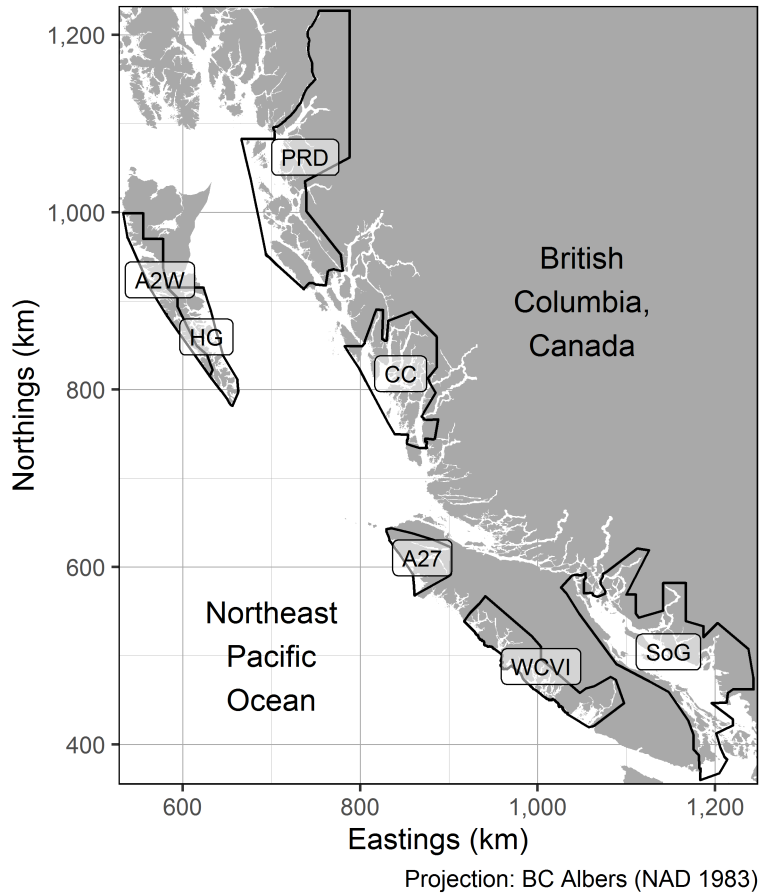


Figure 2. Spatial boundaries for Pacific Herring stock assessment regions (SARs) in British Columbia. There are five major SARs: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). There are two minor SARs: Area 27 (A27)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

## 2 STATISTICAL FRAMEWORK

Historical and recent surface spawn surveys use an ad hoc sampling regimen, where surveys are often opportunistic given the state of the tide, as well as available sampling tools such as boats, rakes, and viewers. The data are analysed assuming simple random sampling, which likely generates a biased

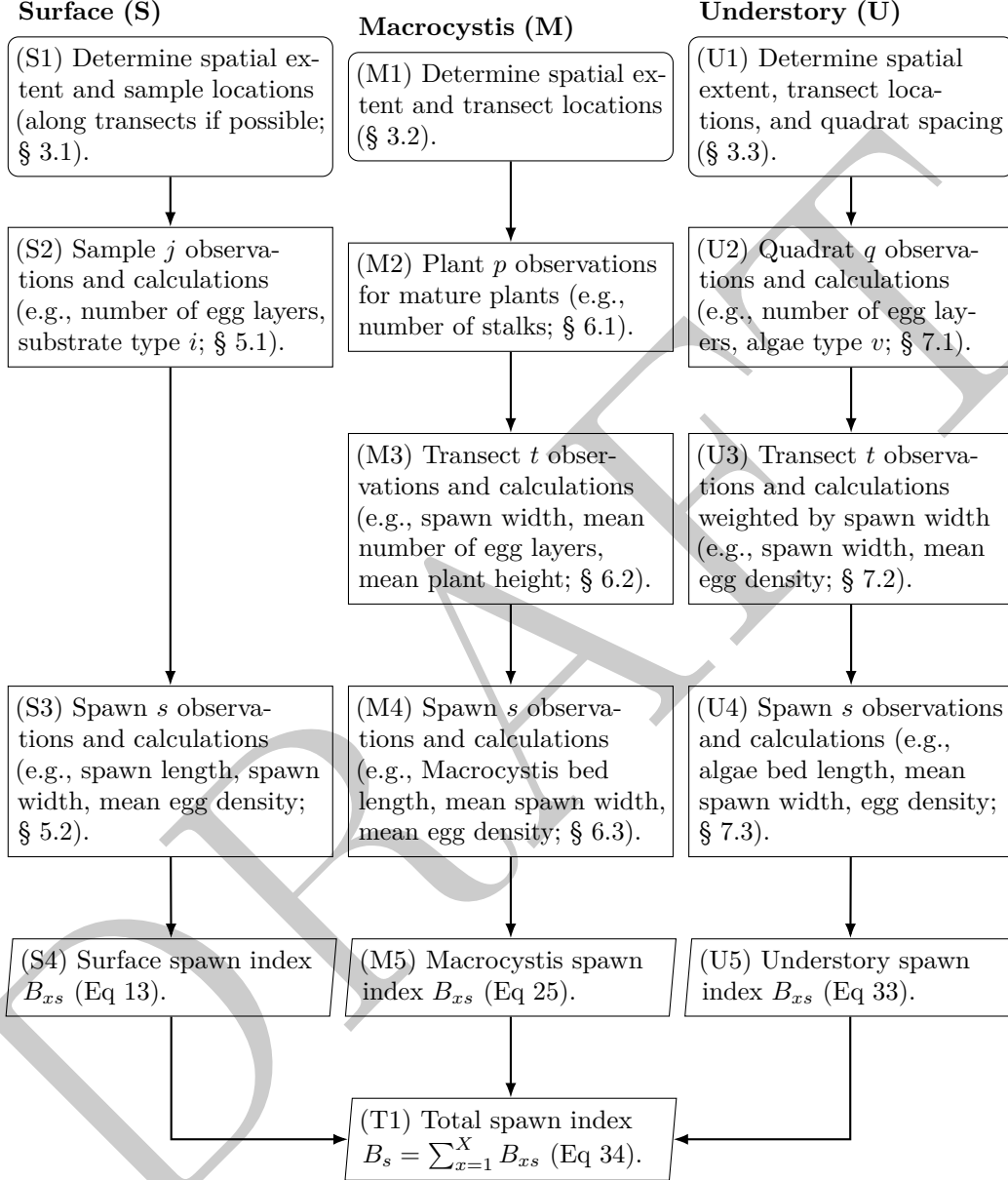


Figure 3. Sequence of steps (e.g., S1) for Pacific Herring spawn index calculations for the three spawn survey types  $x = \{\text{surface, Macrocystis, understory}\}$ . Legend: rounded rectangles indicate start, rectangles indicate observations and calculations, parallelograms indicate output, arrows show order of operation, ‘§’ indicates section, and ‘Eq’ indicates equation.

96 estimate of mean egg density.

97 In contrast, underwater dive surveys using SCUBA gear instituted in  
 98 1988 follow a two-stage systematic sampling design where transects are the  
 99 first sampling stage, and individual quadrats within transects are the second  
 100 sampling stage (Jessen 1978). Two steps are required to calculate mean  
 101 understory egg density in each surveyed spawn  $s$  (Table 1). Note that we  
 102 simplify index notation in this section by suppressing subscripts for spawn  
 103 survey type  $x$ , Location  $n$ , SAR  $r$ , and year  $y$ . First, mean egg density for  
 104 transect  $t$  in spawn  $s$  is

$$\bar{\rho}_{ts} = \frac{1}{Q} \sum_{q=1}^Q \rho_{qts} \quad (1)$$

105 where  $\rho_{qts}$  is egg density in thousands of eggs per square metre (m) for quadrat  
 106  $q$  (eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ ),  $Q$  is the number of quadrats in transect  $t$  (Table 2), and  
 107  $\bar{\rho}_{ts}$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ . Before we calculate the mean egg density for spawn  
 108  $s$ , we determine the mean number of potential quadrats in spawn  $s$

$$\bar{Q}'_s = \frac{1}{T} \sum_{t=1}^T Q' \quad (2)$$

109 where  $Q'$  is the number of potential quadrats in transect  $t$  (i.e., a function of  
 110 spawn width). Then, we calculate mean egg density in eggs per square metre  
 111 for spawn  $s$

$$\bar{\rho}_s = \frac{1}{T\bar{Q}'_s} \sum_{t=1}^T Q' \bar{\rho}_{ts} \quad (3)$$

112 where  $T$  is the number of transects in spawn  $s$ ,  $\bar{Q}'_s$  is the mean number of  
 113 potential quadrats in spawn  $s$  from Equation 2,  $Q'$  is the number of potential  
 114 quadrats in transect  $t$ ,  $\bar{\rho}_{ts}$  is the mean transect egg density from Equation 1,  
 115 and  $\bar{\rho}_s$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ . The egg density estimator from Equation 3 is  
 116 unbiased, and the variance is

$$\sigma_s^2 = \frac{T' - T}{TT'} \sum_{t=1}^T \frac{(Q' \bar{\rho}_{ts} - \bar{Q}'_s \bar{\rho}_s)^2}{\bar{Q}'_s^2 (T - 1)} + \frac{f^t}{T^2} \sum_{t=1}^T \left( \frac{Q'}{\bar{Q}'_s} \right)^2 \frac{(1 - f^q) \sigma_{ts}^2}{Q} \quad (4)$$

117 where  $T'$  is the number of potential transects in spawn  $s$  (i.e., a function of  
 118 spawn length),  $\bar{\rho}_{ts}$  is the mean transect egg density from Equation 1,  $\bar{\rho}_s$  is  
 119 the mean spawn egg density from Equation 3,  $f^t$  is the transect sampling

fraction for spawn  $s$

$$f^t = \frac{T}{T'}, \quad (5)$$

$f^q$  is the quadrat sampling fraction for transect  $t$

$$f^q = \frac{Q}{Q'}, \quad (6)$$

and  $\sigma_{ts}^2$  is the within transect egg density variance

$$\sigma_{ts}^2 = \frac{1}{Q-1} \sum_{q=1}^Q (\rho_{qts} - \bar{\rho}_{ts})^2 \quad (7)$$

where  $\rho_{qts}$  is egg density for quadrat  $q$ , and  $\bar{\rho}_{ts}$  is the mean transect egg density from Equation 1.

The calculation of the mean egg density for each spawn requires estimates of total spawn length, mean spawn width, length of each transect sampled, and estimated egg density in each sampling quadrat. The protocol to optimize sampling was determined through a series of studies conducted in the Strait of Georgia in 1981 and 1983 (Schweigert et al. 1985, 1990), and on the West Coast of Vancouver Island in 1982 (Schweigert et al. 1990). In the 1981 study, the location of transects and sampling quadrats along transects was determined using random allocation (Schweigert et al. 1985). However, this proved to be logistically difficult because neither the spawn length or width is known a priori, and divers had difficulty making the necessary calculations underwater. Nevertheless, data from these studies were used to determine a sampling protocol to estimate mean egg density with a standard error of no more than 25%. The results indicated that the sampling required to achieve this level of precision included surveying three transects per kilometre of spawn length, and sampling at least five quadrats per transect (i.e., spawn width). The sampling design was tested during a 1983 survey in the Strait of Georgia that applied a systematic rather than a random sampling protocol to simplify the logistics; variance estimates were similar to those from the 1981 study. This sampling protocol was further re-evaluated after additional surveys occurred in all areas of the coast during 1984 and 1985; the protocol was found to be robust and has been in routine use since 1988 (Schweigert et al. 1990). Although samples are collected systematically within each spawn, we assume that transects and quadrats are located randomly with respect to



Table 1. Index notation for Pacific Herring spawn index calculations. Legend: stock assessment region (SAR), spawn on kelp (SOK).

Name	Description	Range
$i$	Substrate type	1, 2, 3, ..., $I$
$I$	Number of substrate types in sample $j$ , type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$j$	Sample	1, 2, 3, ..., $J$
$J$	Number of samples in type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$p$	Plant	1, 2, 3, ..., $P$
$P$	Number of plants in transect $t$ , type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$t$	Transect	1, 2, 3, ..., $T$
$T$	Number of transects in type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$T'$	Number of potential transects in type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$v$	Algae (aka vegetation) type	1, 2, 3, ..., $V$
$V$	Number of algae types in quadrat $q$ , transect $t$ , type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$q$	Quadrat	1, 2, 3, ..., $Q$
$Q$	Number of quadrats in transect $t$ , type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$Q'$	Number of potential quadrats in transect $t$ , type $x$ , spawn $s$ , Location $n$ , SAR $r$ , and year $y$	
$x$	Spawn survey type	1, 2, 3, ..., $X$
$X$	Number of spawn survey types in spawn $s$ , location $n$ , SAR $r$ , and year $y$	
$s$	Spawn	1, 2, 3, ..., $S$
$S$	Number of spawns in Location $n$ , SAR $r$ , and year $y$	
$n$	Location	1, 2, 3, ..., $N$
$N$	Number of locations in SAR $r$ and year $y$	
$f$	SOK fishery	1, 2, 3, ..., $F$
$F$	Number of SOK fisheries in SAR $r$ and year $y$	
$r$	SAR	1, 2, 3, ..., $R$
$R$	Number of SARs	
$y$	Year	$y_1, y_2, y_3, \dots, Y$
$Y$	Last year of time series	

Table 2. Notation for Pacific Herring spawn survey statistical framework. Legend: metres (m).

Name	Description	Value or unit
$\rho$	Egg density	eggs $\cdot 10^3 \cdot \text{m}^{-2}$
$\bar{\rho}$	Mean egg density	eggs $\cdot 10^3 \cdot \text{m}^{-2}$
$f^t$	Transect sampling fraction	(0, 1]
$f^q$	Quadrat sampling fraction	(0, 1]
$\sigma^2$	Egg density variance	$\rho^2$

the underlying spawn distribution, and so these estimators are applicable. An analogous approach had previously been adopted in the sampling of various commercial fisheries where vessels arrive in port at random but are sampled in a systematic fashion to obtain a random sample (Quinn et al. 1983; Sen 1984).

Giant kelp, *Macrocystis* sp., requires a different sampling protocol than the aforementioned understory spawn survey protocol. Giant kelp routinely reach heights of 15 m, but once weighed down with herring eggs the plants can sink to lay flat on the bottom. After sampling dozens of giant kelp plants covered with herring eggs, it was determined that plant height, number of fronds per plant, and number egg layers per plant were key counts required to estimate the number of eggs per plant (Haegele and Schweigert 1990). The survey design employed to capture these data for each spawning bed rely on determining the average plant height, number of fronds in each plant holdfast, and number of giant kelp plants occurring within a 1 m swath on each side of the transect line. These data are used to determine the total egg deposition on *Macrocystis* sp. for each spawning bed (subsection 6.3).

### 3 SAMPLING PROTOCOL

The following is a brief summary of the spawn survey sampling protocol in the [Pacific Herring spawn survey manual](#). Pacific Herring in BC 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 combi-

172 nation of year, Location, and ‘spawn number.’ Spawns are numbered  
 173  $s = 1, 2, 3, \dots, S_{xnry}$  where  $S_{xnry}$  is the number of spawns in spawn sur-  
 174 vey type  $x$  (i.e.,  $x = \{\text{surface, Macrocystis, understory}\}$ ), Location  $n$ , SAR  
 175  $r$ , and year  $y$ . A distinct spawn is a continuous stretch of shoreline with no  
 176 detectable break in egg deposition; this is the finest scale at which we calculate  
 177 the spawn index. A break in egg deposition is determined by the absence of  
 178 Pacific Herring spawn on two consecutive transects, or by a temporal gap in  
 179 spawning. Most spawns are also characterized by longitude and latitude, as  
 180 well as start and end dates of spawning. Surveyors usually collect longitude  
 181 and latitude at the start and end of each transect; for surface spawn surveys  
 182 that don’t use transects (subsection 3.1), surveyors collect longitude and  
 183 latitude at the start and ends of the spawn (i.e., overall length and width).

184 Pacific Herring spawns typically extend along the shore; from above,  
 185 spawns are identified by a milky or turquoise discolouration of the ocean  
 186 caused by the release of milt, and often appear as bands running parallel to  
 187 the shore (Figure 4). Thus, spawn ‘length’ refers to distance parallel to the  
 188 shore, and ‘width’ refers to distance perpendicular to the shore. Similarly,  
 189 Macrocystis bed length  $L^m$  and algae (aka vegetation) bed length  $L^v$  refer  
 190 to distances that Macrocystis and algae beds extend parallel to the shore,  
 191 respectively.

192 Most areas of the BC coast have ‘permanent transect’ locations recorded  
 193 on charts which enable surveyors to place transects in the same place each  
 194 year. When permanent transects are unavailable for a given spawn, surveyors  
 195 set new transects perpendicular to the shore, beginning 200 m in from one  
 196 end of the spawn, and spaced 350 m apart along the length of the spawn.  
 197 The end of the spawn is determined by the absence of eggs. We digitize  
 198 new transects to make them available as permanent transects in subsequent  
 199 surveys. Transects generally go from the deep edge of the spawn towards  
 200 shore until divers reach the near-shore edge of the spawn; the near-shore edge  
 201 can be out of the water depending on the tide height.

202 Pacific Herring spawn surveyors first determine the spatial extent of the  
 203 spawn in terms of length of shoreline to survey (Figure 3, steps S1, M1, &  
 204 U1); this is done by raking (subsection 3.1) or brief dives to determine the  
 205 presence or absence of spawn. Surveyors place the first transect in from one  
 206 end (i.e., at the first permanent transect, or 200 m if there are no permanent  
 207 transects) to avoid surveying areas with patchy and sparse egg layers. Within  
 208 the spawn area, surveyors use transects to determine spawn width, quadrat



Figure 4. Aerial view of Pacific Herring spawn taken during a spawn reconnaissance flight in the Strait of Georgia. The spawn is identified by the band of discoloured water parallel to the shore.

209 placement, and which *Macrocystis* plants to survey. In some cases, we adjust  
210 spawn width to improve the accuracy of spawn index estimates (appendix A).

211 After determining the spatial extent, surveyors determine the number of  
212 egg layers on substrate and algae according to sampling protocols described  
213 in subsection 3.1, subsection 3.2, & subsection 3.3. For eggs on substrate,  
214 one egg layer is a layer of eggs one egg thick over the entire spawned surface  
215 (Figure 5a). For eggs on algae, surveyors count egg layers one of two ways  
216 depending on whether the algae is flat or round in cross-section. Egg layers  
217 on flat algae are counted on both sides of the algae (Figure 5b); egg layers on  
218 round algae are counted across the diameter of the algae (Figure 5c).

### 219 3.1 SURFACE SPAWN PROTOCOL

220 Surface spawn surveyors use the aforementioned transect interval when pos-  
221 sible, but the sampling interval relies on surveyor judgement and available  
222 resources. If the spawn area is sufficiently large, surface surveyors usually  
223 sample along permanent transects. Small spawns can still be mapped as they  
224 were historically, with surveyors deciding how to sample the spawn. To sample,  
225 surveyors deploy specialized rakes throughout the spawn to determine algae

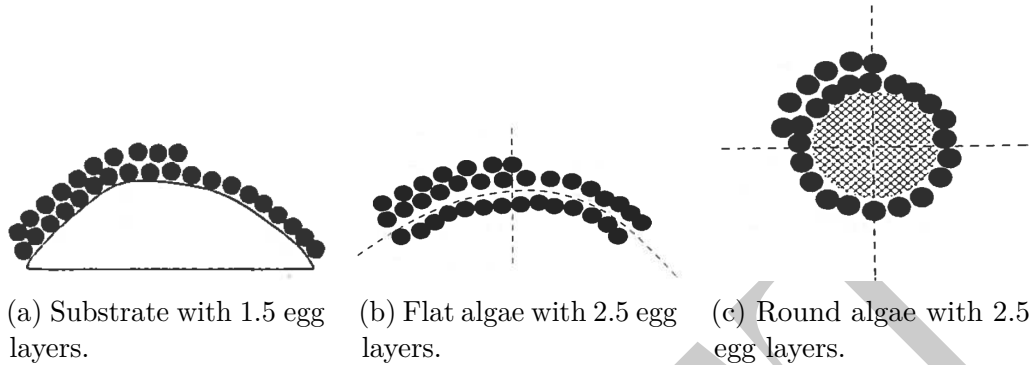


Figure 5. Cross-sections showing the number of Pacific Herring egg layers on substrate (a), flat algae (b), and round algae (c). Diagrams copied with permission from the [Pacific Herring spawn survey manual](#).

(aka vegetation) type, number of egg layers, and percent cover. Surveyors may deploy a viewing box in shallow water, and at low tide a portion of the spawn may be visible for direct observation. We refer to these surface spawn observations as ‘samples.’

Recall that there are two cases of surface spawn surveys: all surveys prior to 1988, and surveys since 1988 when dive surveys are not possible. Data from surface surveys are combined with data from dive surveys (i.e., *Macrocystis*, understory) to produce the total spawn index (section 8).

### 3.1.1 SPAWN INTENSITY CATEGORIES

From 1928 to 1978, surface spawn surveyors categorized spawn by subjective ‘intensity’ categories instead of directly estimating the number of egg layers (Table 3). From 1928 to 1968 there were five intensity categories described as very light, light, medium, heavy, and very heavy (numbered 1 to 5, respectively). Starting in 1969 there were nine intensity categories; the change from five to nine 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 directly, and they continued to record intensity categories until 1981 to provide overlap between the two methods. In addition to recording the number of egg layers, surveyors sometimes recorded intensity after it was officially discontinued in 1981. We have converted spawn intensity observations in the Pacific Herring

spawn survey database from five to nine categories for spawns that used the five category scale between 1951 and 1968. Thus, spawn data used for stock assessments is represented either by a nine category intensity scale, or a direct estimate of the number of egg layers.

### 3.2 MACROCYSTIS SPAWN PROTOCOL

Macrocystis spawn surveyors take a census of Macrocystis plants within 1 m of the transect line, on both the left- and right-hand sides. We refer to the swath of substrate along Macrocystis transects as the transect swath,  $\chi_{ts} = 2$  m in transect  $t$  and spawn  $s$ . Divers categorize Macrocystis plants as either ‘mature’ or ‘immature’ based on stipe height; mature plants have stipes  $\geq 1$  m high, and are the only plants used for Macrocystis spawn index calculations. Immature plants are excluded because Pacific Herring spawn on Macrocystis fronds, not stipes; immature plants have limited fronds and slimy stipes that prevent egg adhesion. In addition, Pacific Herring typically deposit spawn higher up Macrocystis plants. For each mature plant, divers record the number of stalks. For each transect, divers record the average number of egg layers, and average plant height. Haegele and Schweigert (1990) provide a description of the sampling technique, and the basis for estimating the total number of eggs per plant.

### 3.3 UNDERSTORY SPAWN PROTOCOL

Understory spawn surveyors place quadrats along transects, with a target frequency of  $\geq 5$  quadrats per transect, given a minimum spacing of 2 m and a maximum spacing of 40 m. Similar to how the first transect is moved in from one end of the spawn, the first quadrat is moved in from the edge of the spawn to the first 5 m mark on the transect line to avoid surveying areas with patchy and sparse egg layers. Note that transect line position along permanent transects varies year to year: spawn location causes transects to shift seaward or shoreward, and spawn width causes transects to be shorter or longer. Understory spawn surveys use  $0.5 \text{ m}^2$  quadrats; other sizes (e.g.,  $0.25$  and  $1.0 \text{ m}^2$ ) have been used for research, but are not used to calculate the spawn index (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

Table 3. Spawn intensity categories, description, and number of egg layers for Pacific Herring surface spawn surveys for the periods 1928 to 1968, and 1969 to 1978 (Hay and Kronlund 1987; Schweigert and Stocker 1988).

Intensity category		Description	Number of egg layers
1928 to 1968	1969 to 1978		
1	1	Very light	0.5529
	2		0.9444
2	3	Light	1.3360
	4		2.1496
3	5	Medium	2.9633
	6		4.1318
4	7	Heavy	5.3002
	8		6.5647
5	9	Very heavy	7.8291

identify the three most abundant 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 CONVERTING EGGS TO BIOMASS

After estimating the number of eggs in a spawn, the next step is to estimate the biomass of Pacific Herring that spawned. 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 convert eggs to tonnes (t) of spawners using

$$\theta = \omega \phi^f \frac{10^3 \text{ kg}}{\text{t}} \quad (8)$$

where  $\omega$  is the number of eggs per kilogram of total female body weight,  $\phi^f$  is the proportion of spawners that are female, and  $\theta$  is the egg conversion factor (Table 4). Thus we convert eggs to biomass in tonnes of both sexes combined by dividing the number of eggs by  $\theta$ . 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 8 is insignificant in most areas and years (Schweigert 1993; Ware 1985).

## 5 SURFACE SPAWN CALCULATIONS

This section describes steps S2 to S4 in Figure 3. As in section 2, we simplify index notation in this section by suppressing subscripts for spawn survey type  $x$ , Location  $n$ , SAR  $r$ , and year  $y$ . Surface spawn surveyors sample along transects or using their judgement. Surveyors collect data for at the substrate type  $i$ , sample  $j$ , and spawn  $s$  levels; we calculate metrics at the substrate type  $i$ , sample  $j$ , and spawn  $s$  levels (Table 5). Recall that surface spawn ‘samples’ include observations collected using specialized rakes and viewing boxes (subsection 3.1). Occasionally, we use field data sheets to fill-in missing egg layer information for surface survey data (appendix B).

### 5.1 SAMPLE OBSERVATIONS AND CALCULATIONS

Each sample  $j$  (Figure 3, step S2) can have one or more substrate types  $i$ . The number of egg layers in substrate  $i$ , sample  $j$ , and spawn  $s$  is

$$E_{ijs} = E'_{ijs} \phi_{ijs}^b \quad (9)$$

where  $E'_{ijs}$  is the number of egg layers on substrate  $i$ , and  $\phi_{ijs}^b$  is the proportion of substrate  $i$  covered with spawn. The total number of egg layers in sample

Table 4. Notation for converting the number of Pacific Herring eggs to biomass. Legend: kilograms (kg), tonnes (t).

Name	Description	Value or unit	Reference
$\omega$	Female fecundity	200,000 eggs · kg <sup>-1</sup>	Hay (1985); Hay and Brett (1988)
$\phi^f$	Proportion female	0.5	Hay (1985); Hay and Brett (1988)
$\theta$	Egg conversion factor	eggs · 10 <sup>8</sup> · t <sup>-1</sup>	



Table 5. Notation for Pacific Herring surface spawn index calculations. Legend: metres (m), tonnes (t).

Name	Description	Value or unit	Reference
$E'$	Number of egg layers	$> 0$	
$\phi^b$	Proportion of substrate covered in eggs	$(0, 1]$	
$E$	Number of egg layers	$> 0$	
$\alpha$	Regression intercept	14.698 eggs $\cdot$ $10^3 \cdot \text{m}^{-2}$	Schweigert et al. (1997)
$\beta$	Regression slope	212.218 eggs $\cdot$ $10^3 \cdot \text{m}^{-2}$	Schweigert et al. (1997)
$\rho$	Egg density	eggs $\cdot 10^3 \cdot \text{m}^{-2}$	
$\bar{\rho}$	Mean egg density	eggs $\cdot 10^3 \cdot \text{m}^{-2}$	
$L$	Spawn length	m	
$W$	Spawn width	m	
$B$	Surface spawn index (i.e., biomass)	t	

312  $j$  and spawn  $s$  is

$$E_{js} = \sum_{i=1}^I E_{ijs} \quad (10)$$

313 where  $E_{ijs}$  is the number of egg layers in substrate  $i$  from Equation 9. For  
 314 the time period when surveyors recorded spawn ‘intensity’ categories instead  
 315 of direct egg layer estimates, we convert intensity to number of egg layers  $E_{js}$   
 316 (Table 3). Schweigert et al. (1997) developed a predictive model of surface  
 317 egg density as a function of number of egg layers using a linear regression  
 318 model<sup>1</sup>

$$\rho_{js} = \alpha + \beta E_{js} \quad (11)$$

319 where  $\alpha$  is the regression intercept,  $\beta$  is the regression slope,  $E_{js}$  is the total  
 320 number of egg layers in sample  $j$  from Equation 10, and  $\rho_{js}$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$   
 321 (Figure 6). Note that we only calculate  $\rho_{js}$  if  $E_{js} > 0$ .

<sup>1</sup>There is an error in Schweigert et al. (1997); surface egg density is in thousands per square metre (eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ ). Likewise, we report eggs in thousands (i.e., eggs  $\cdot 10^3$ ) in this document and in the **R** package script.

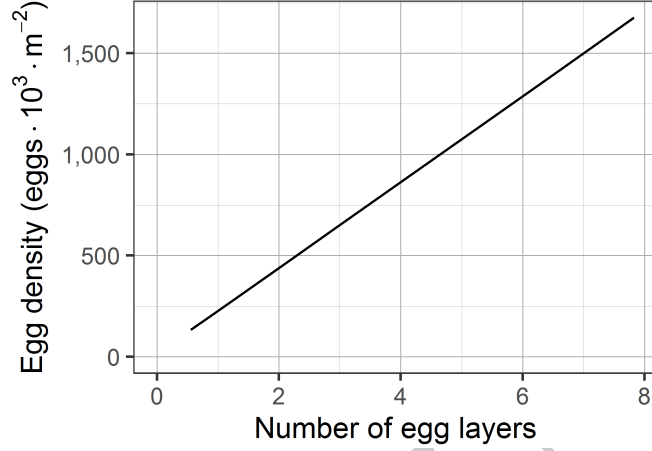


Figure 6. Egg density in thousands of eggs per square metre (m) as a function of number of egg layers for Pacific Herring surface spawn surveys (Equation 11; Schweigert et al. 1997). Note that number of egg layers can exceed those shown in this figure; values shown are for demonstration only.

## 5.2 SPAWN OBSERVATIONS AND CALCULATIONS

The mean egg density in spawn  $s$  (Figure 3, step S3) is

$$\bar{\rho}_s = \frac{1}{J} \sum_{j=1}^J \rho_{js} \quad (12)$$

where  $\rho_{js}$  is egg density in sample  $j$  from Equation 11,  $J$  is the number of samples, and  $\bar{\rho}_s$  is in eggs · 10³ · m⁻². Two other metrics are required at the spawn level: spawn length  $L_s$ , and spawn width  $W_s$ , both in metres. We set  $W_s$  to the first non-missing value of median pool width, median Section width, median SAR width, or observed width  $W'$  (in that order; subsection A.1). The surface spawn index in spawn  $s$  is

$$B_s = \frac{\bar{\rho}_s L_s W_s 10^3}{\theta} \quad (13)$$

where  $\bar{\rho}_s$  is mean egg density in spawn  $s$  from Equation 12,  $L_s$  is length of spawn  $s$ ,  $W_s$  is width of spawn  $s$ ,  $\theta$  is the egg conversion factor from Equation 8, and  $B_s$  is in tonnes (Figure 3, step S4).

## 6 MACROCYSTIS SPAWN CALCULATIONS

This section describes steps M2 to M5 in Figure 3. As with the previous section, we simplify index notation in this section by suppressing subscripts for spawn survey type  $x$ , Location  $n$ , SAR  $r$ , and year  $y$ . Macrocystis spawn surveyors use SCUBA gear to collect underwater data for individual plants  $p$ , transects  $t$ , and spawns  $s$ ; we calculate metrics at the transect  $t$ , and spawn  $s$  levels (Table 6).

### 6.1 PLANT OBSERVATIONS

For each mature plant  $p$  in transect  $t$  and spawn  $s$  (Figure 3, step M2), surveyors count the number of stalks  $K_{pts}$ .

### 6.2 TRANSECT OBSERVATIONS AND CALCULATIONS

At the transect  $t$  level (Figure 3, step M3), spawn width is  $W_{ts}$ , and transect swath is  $\chi_{ts} = 2$  m, both in metres. We calculate the area in transect  $t$  and spawn  $s$  as

$$A_{ts} = W_{ts}\chi_{ts} \quad (14)$$

in square metres. In addition, divers estimate summary statistics for mature Macrocystis plants along transect  $t$  in spawn  $s$ : mean height  $\overline{H}_{ts}$  in metres, and mean number of egg layers  $\overline{E}_{ts}$ . The total number of plants in transect  $t$  and spawn  $s$  is  $P$ . We calculate the total number of stalks in transect  $t$  and spawn  $s$

$$K_{ts} = \sum_{p=1}^P K_{pts} \quad (15)$$

where  $K_{pts}$  is the number of stalks on plant  $p$ .

### 6.3 SPAWN OBSERVATIONS AND CALCULATIONS

At the spawn  $s$  level (Figure 3, step M4), we determine the length of the Macrocystis bed  $L_s^m$  in metres. If  $L_s^m$  is inadvertently not recorded, we set  $L_s^m$  to the spawn length  $L_s$ . The mean width of spawn  $s$  is

$$\overline{W}_s = \frac{1}{T} \sum_{t=1}^T W_{ts} \quad (16)$$

Table 6. Notation for Pacific Herring *Macrocystis* spawn index calculations.  
Legend: metres (m), tonnes (t).

Name	Description	Value or unit	Reference
$K$	Number of stalks	$> 0$	
$W$	Spawn width	m	
$\chi$	Transect swath	m	
$A$	Area	$\text{m}^2$	
$\bar{W}$	Mean spawn width	m	
$\bar{H}$	Mean plant height	m	
$\bar{E}$	Mean number of egg layers	$> 0$	
$L^m$	Length of the <i>Macrocystis</i> bed	m	
$L$	Spawn length	m	
$P$	Number of plants	$> 0$	
$\bar{\kappa}$	Mean number of stalks per plant	$> 0$	
$\beta$	Regression slope	$0.073 \text{ eggs} \cdot 10^3 \cdot \text{plant}^{-1}$	Haegle and Schweigert (1990)
$\gamma$	Regression exponent on $\bar{E}$	0.673	Haegle and Schweigert (1990)
$\delta$	Regression exponent on $\bar{H}$	0.932	Haegle and Schweigert (1990)
$\epsilon$	Regression exponent on $\bar{\kappa}$	0.703	Haegle and Schweigert (1990)
$\bar{\psi}$	Mean number of eggs per plant	$\text{eggs} \cdot 10^3 \cdot \text{plant}^{-1}$	
$\bar{\rho}$	Mean egg density	$\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$	
$B$	<i>Macrocystis</i> spawn index (i.e., biomass)	t	

where  $W_{ts}$  is the spawn width at transect  $t$ ,  $T$  is the number of transects in spawn  $s$ , and  $\bar{W}_s$  is in metres. The total area of transects in spawn  $s$  is

$$A_s = \sum_{t=1}^T A_{ts} \quad (17)$$

359 where  $A_{ts}$  is the transect area from Equation 14, and  $A_s$  is in square metres.  
 360 The total number of stalks in spawn  $s$  is

$$K_s = \sum_{t=1}^T K_{ts} \quad (18)$$

361 where  $K_{ts}$  is the number of stalks in transect  $t$  from Equation 15. The total  
 362 number of plants in spawn  $s$  is

$$P_s = \sum_{t=1}^T P_t \quad (19)$$

363 where  $P_t$  is the number of plants in transect  $t$ . The mean plant height in  
 364 spawn  $s$  is

$$\overline{H}_s = \frac{1}{T} \sum_{t=1}^T \overline{H}_{ts} \quad (20)$$

365 where  $\overline{H}_{ts}$  is the mean plant height in transect  $t$ ,  $T$  is the number of transects  
 366 in spawn  $s$ , and  $\overline{H}_s$  is in metres. The mean number of egg layers in spawn  $s$  is

$$\overline{E}_s = \frac{1}{T} \sum_{t=1}^T \overline{E}_{ts} \quad (21)$$

367 where  $\overline{E}_{ts}$  is the mean number of egg layers in transect  $t$ , and  $T$  is the number  
 368 of transects in spawn  $s$ . The mean number of stalks per plant in spawn  $s$  is

$$\overline{\kappa}_s = \frac{K_s}{P_s} \quad (22)$$

369 where  $K_s$  is the number of stalks in spawn  $s$  from Equation 18, and  $P_s$  is the  
 370 number of plants in spawn  $s$  from Equation 19.

371 Haeghele and Schweigert (1990) developed a predictive model of number of  
 372 eggs per plant as a function of number of egg layers on plants, plant height,  
 373 and number of stalks per plant using a nonlinear multiple regression model

$$\overline{\psi}_s = \beta \overline{E}_s^\gamma \overline{H}_s^\delta \overline{\kappa}_s^\epsilon 10^3 \quad (23)$$

374 where  $\beta$  is the regression slope,  $\overline{E}_s$  is the mean number of egg layers in spawn  
 375  $s$  from Equation 21,  $\gamma$  is the regression exponent on  $\overline{E}_s$ ,  $\overline{H}_s$  is the mean plant  
 376 height in spawn  $s$  from Equation 20,  $\delta$  is the regression exponent on  $\overline{H}_s$ ,  $\overline{\kappa}_s$  is

the mean number of stalks per plant in spawn  $s$  from Equation 22,  $\epsilon$  is the regression exponent on  $\bar{\kappa}_s$ , and  $\bar{\psi}_s$  is in eggs  $\cdot 10^3 \cdot \text{plant}^{-1}$  (Figure 7). Mean macrocystis egg density in spawn  $s$  is

$$\bar{\rho}_s = \frac{\bar{\psi}_s P_s}{A_s} \quad (24)$$

where  $\bar{\psi}_s$  is the mean number of eggs per plant in spawn  $s$  from Equation 23,  $P_s$  is the number of plants in spawn  $s$  from Equation 19,  $A_s$  is the total area of transects in spawn  $s$  from Equation 17, and  $\bar{\rho}_s$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ . The Macrocystis spawn index in spawn  $s$  is

$$B_s = \frac{\bar{\rho}_s L_s^m \bar{W}_s 10^3}{\theta} \quad (25)$$

where  $\bar{\rho}_s$  is the mean egg density in spawn  $s$  from Equation 24,  $L_s^m$  is the length of the Macrocystis bed in spawn  $s$ ,  $\bar{W}_s$  is the mean width of spawn  $s$  from Equation 16,  $\theta$  is the egg conversion factor from Equation 8, and  $B_s$  is in tonnes (Figure 3, step M5).

## 7 UNDERSTORY SPAWN CALCULATIONS

This section describes steps U2 to U5 in Figure 3. As with the previous two sections, we simplify index notation in this section by suppressing subscripts for spawn survey type  $x$ , Location  $n$ , SAR  $r$ , and year  $y$ . Understory spawn surveyors use SCUBA gear to collect underwater data for algae (aka vegetation) types  $v$ , quadrats  $q$ , transects  $t$ , and spawns  $s$ ; we calculate metrics at the algae type  $v$ , quadrat  $q$ , transect  $t$ , and spawn  $s$  levels (Table 7).

### 7.1 QUADRAT OBSERVATIONS AND CALCULATIONS

We calculate two separate estimates of egg density at the quadrat level (Figure 3, step U2): spawn on substrate, and spawn on algae  $v$ . Haegele et al. (1979) developed a predictive model of substrate egg density in quadrat  $q$ , transect  $t$ , and spawn  $s$  from egg layers using a linear regression model

$$\rho_{qts}^b = \alpha E_{qts}^b \phi_{qts}^b \quad (26)$$

where  $\alpha$  is the regression slope,  $E_{qts}^b$  is the number of egg layers on substrate in quadrat  $q$ ,  $\phi_{qts}^b$  is the proportion of substrate in quadrat  $q$  covered by spawn, and  $\rho_{qts}^b$  is substrate egg density in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$  (Figure 8).

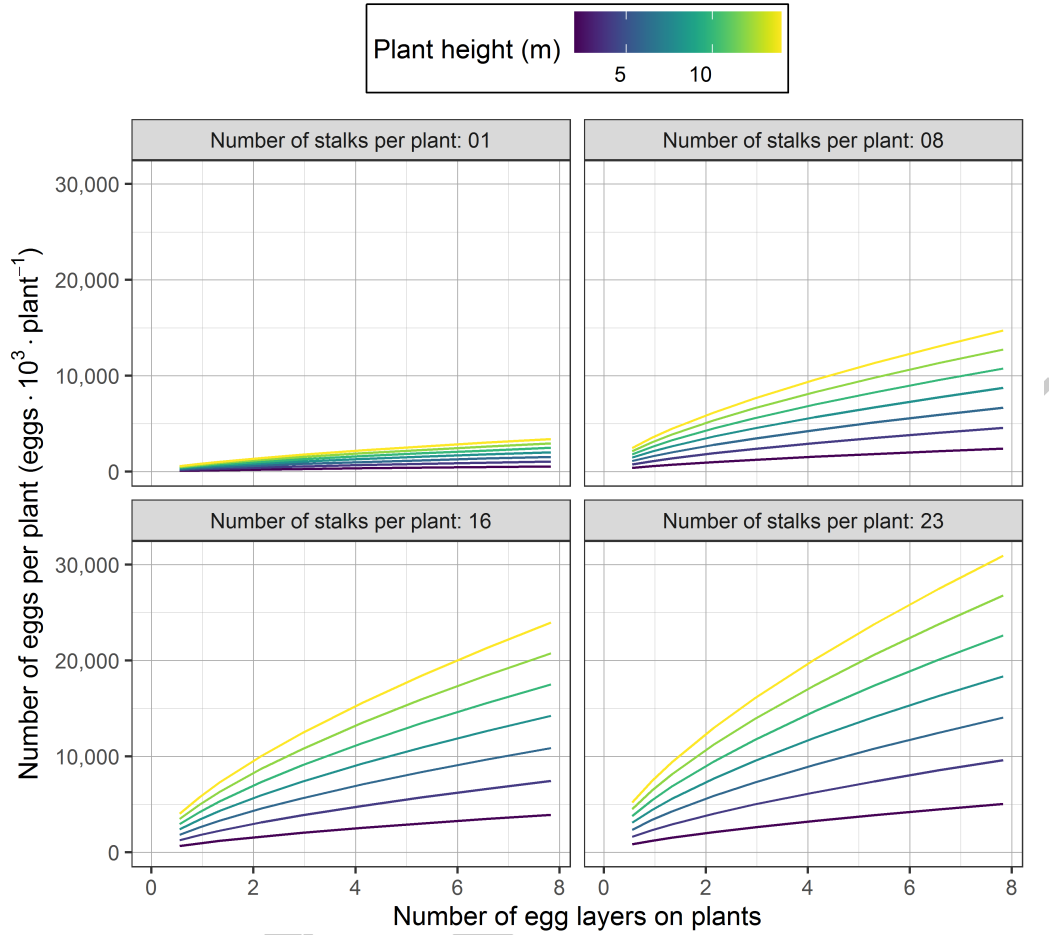


Figure 7. Number of eggs in thousands per *Macrocystis* plant as a function of number of egg layers on plants, plant height in metres (m), and number of stalks per plant for Pacific Herring *Macrocystis* spawn surveys (Equation 23; Haegele and Schweigert 1990). Note that number of egg layers, plant height, and number of stalks per plant can exceed those shown in this figure; values shown are for demonstration only.

403 Although quadrats have only one substrate type, they can have up to  
 404 three algae types  $v$  (subsection 3.3). Schweigert (2005) developed a predictive  
 405 model of algae egg density from egg layers, proportion of the quadrat covered  
 406 by algae, and an algae coefficient using a generalized linear model. Algae  
 407 coefficients account for the effect of algae morphology on Pacific Herring egg

Table 7. Notation for Pacific Herring understory spawn index calculations. Legend: metres (m), tonnes (t).

Name	Description	Value or unit	Reference
$E^b$	Number of substrate egg layers	$> 0$	
$\phi^b$	Proportion of substrate covered in eggs	$(0, 1]$	
$\alpha$	Regression slope for substrate	$340 \text{ eggs} \cdot 10^3 \cdot \text{m}^{-2}$	Haegeler et al. (1979)
$\rho^b$	Substrate egg density	$\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$	
$\beta$	Regression slope for algae	$600.567 \text{ eggs} \cdot 10^3 \cdot \text{m}^{-2}$	Schweigert (2005)
$E^v$	Number of algae egg layers	$> 0$	
$\gamma$	Regression exponent on $E^v$	0.6355	Schweigert (2005)
$\phi^v$	Proportion of algae covered in eggs	$(0, 1]$	
$\delta$	Regression exponent on $\phi^v$	1.413	Schweigert (2005)
$C$	Algae coefficient	see Table 8	
$\rho^v$	Algae egg density	$\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$	
$\rho$	Egg density	$\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$	
$W$	Spawn width	m	
$\bar{\rho}$	Mean egg density	$\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$	
$\bar{W}$	Mean spawn width	m	
$L^v$	Length of the algae bed	m	
$L$	Spawn length	m	
$B$	Understory spawn index (i.e., biomass)	t	

408 density (Table 8). Egg density on algae  $v$  in quadrat  $q$ , transect  $t$ , and spawn  
409  $s$  (Schweigert 2005) is

$$\rho_{vqts}^v = \beta E_{vqts}^{v\gamma} \phi_{vqts}^{v\delta} C_v \quad (27)$$

410 where  $\beta$  is the regression slope,  $E_{vqts}^v$  is the number of egg layers on algae  
411  $v$ ,  $\gamma$  is the regression exponent on  $E_{vqts}^v$ ,  $\phi_{vqts}^v$  is the proportion of quadrat  $q$



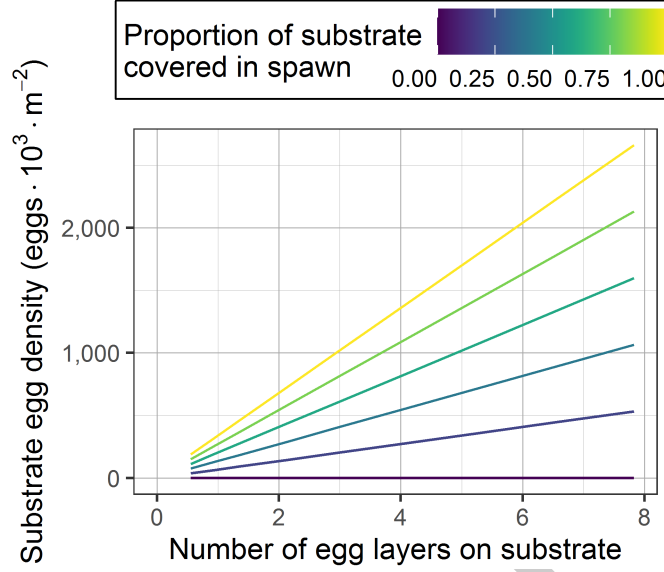


Figure 8. Substrate egg density in thousands of eggs per square metre (m) as a function of number of egg layers on substrate and proportion of substrate covered in spawn for Pacific Herring underwater spawn surveys (Equation 26; Haegele et al. 1979). Note that number of egg layers can exceed those shown in this figure; values shown are for demonstration only.

covered by algae  $v$ ,  $\delta$  is the regression exponent on  $\phi_{vqts}^v$ ,  $C_v$  is the coefficient for algae  $v$ , and  $\rho_{vqts}^v$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$  (Figure 9). The total algae egg density for quadrat  $q$  in transect  $t$  and spawn  $s$  is

$$\rho_{qts}^v = \sum_{v=1}^V \rho_{vqts}^v \quad (28)$$

where  $\rho_{vqts}^v$  is egg density on algae  $v$  from Equation 27, and  $\rho_{qts}^v$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ .

The total understory egg density for quadrat  $q$  in transect  $t$  and spawn  $s$  is

$$\rho_{qts} = \rho_{qts}^b + \rho_{qts}^v \quad (29)$$

where  $\rho_{qts}^b$  is substrate egg density from Equation 26,  $\rho_{qts}^v$  is algae egg density from Equation 28, and  $\rho_{qts}$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ . Thus, we assume that eggs on substrate and algae are independent, and can be added without bias.

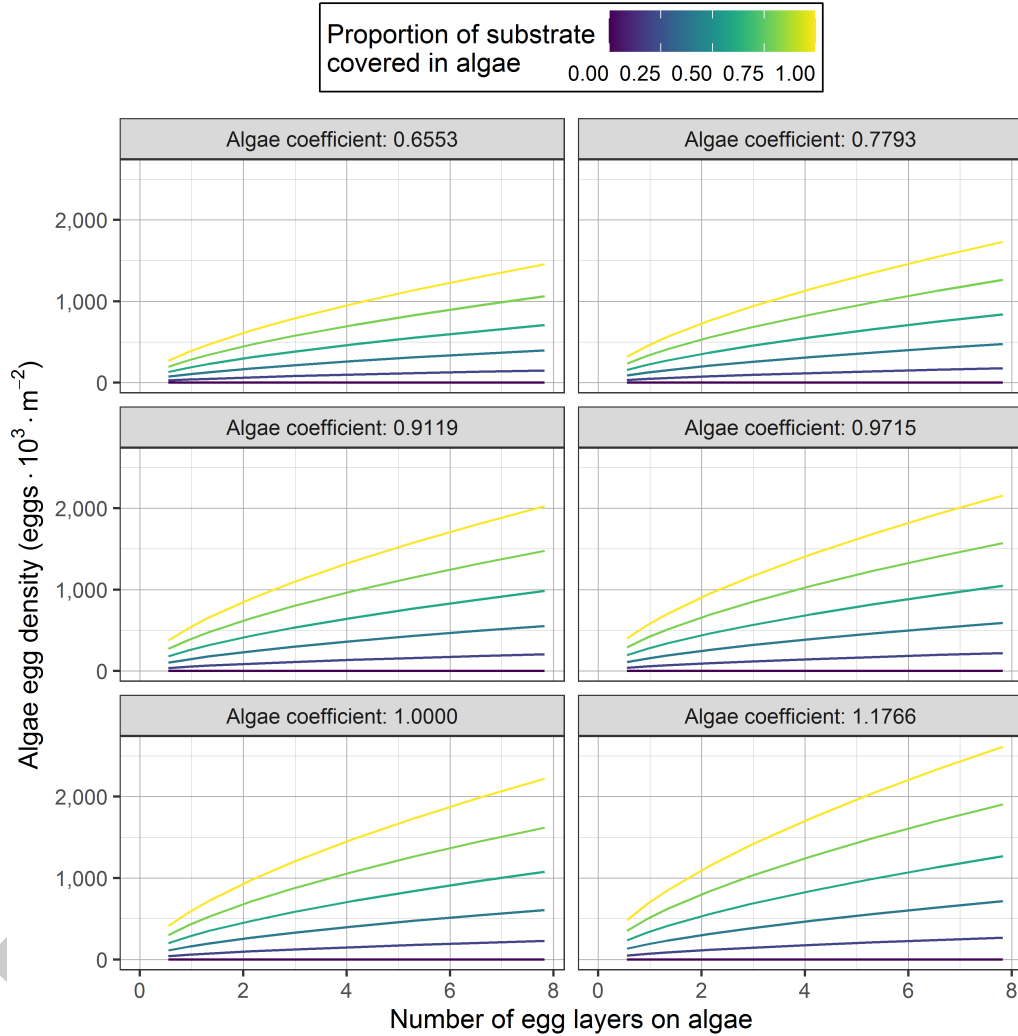


Figure 9. Algae egg density in thousands of eggs per square metre (m) as a function of number of egg layers on algae, proportion of substrate covered in algae, and algae coefficient (Table 8) for Pacific Herring underwater spawn surveys (Equation 27; Schweigert 2005). Note that number of egg layers can exceed those shown in this figure; values shown are for demonstration only.

Table 8. Algae (aka vegetation) types  $v$  and coefficients  $C$  for Pacific Herring understory spawn surveys (Schweigert 2005).

Algae type $v$	Coefficient $C$
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

## 7.2 TRANSECT OBSERVATIONS AND CALCULATIONS

At the transect level (Figure 3, step U3), the mean understory egg density in transect  $t$  and spawn  $s$  is

$$\bar{\rho}_{ts} = \frac{1}{Q} \sum_{q=1}^Q \rho_{qts} \quad (30)$$

where  $Q$  is the number of quadrats in transect  $t$ ,  $\rho_{qts}$  is total understory egg density in quadrat  $q$  from Equation 29, and  $\bar{\rho}_{ts}$  is in  $\text{eggs} \cdot 10^3 \cdot \text{m}^{-2}$ . Note that we update spawn width to correct for errors regarding the assumed accuracy of transect lines used to measure spawn width for understory surveys between 2003 and 2014 (subsection A.2).

## 7.3 SPAWN OBSERVATIONS AND CALCULATIONS

At the spawn level (Figure 3, step U4), the mean width of spawn  $s$  is

$$\bar{W}_s = \frac{1}{T} \sum_{t=1}^T W_{ts} \quad (31)$$

where  $W_{ts}$  is the spawn width at transect  $t$ ,  $T$  is the number of transects in spawn  $s$ , and  $\bar{W}_s$  is in metres. The length of the algae bed in spawn  $s$  is  $L_s^v$ , also in metres. As with *Macrocystis* spawn calculations, if  $L_s^v$  is inadvertently not recorded, we set  $L_s^v$  to the spawn length  $L_s$ . Thus, we assume that eggs on

436 substrate and eggs on algae are represented by the same length measurement.  
 437 Next, we calculate the weighted mean egg density in spawn  $s$ , where transect  
 438 egg density is weighted by spawn width at transect  $t$ ,  $W_{ts}$ . We calculate a  
 439 weighted mean because spawn width varies along the spawn length; a weighted  
 440 mean ensures that transects contribute proportionally to their area. The  
 441 mean egg density in spawn  $s$  is

$$\bar{\rho}_s = \frac{\sum_{t=1}^T \bar{\rho}_{ts} W_{ts}}{\sum_{t=1}^T W_{ts}} \quad (32)$$

442 where  $\bar{\rho}_{ts}$  is the mean understory egg density in transect  $t$  from Equation 30,  
 443  $W_{ts}$  is the spawn width for transect  $t$  in metres, and  $\bar{\rho}_s$  is in eggs  $\cdot 10^3 \cdot \text{m}^{-2}$ .  
 444 The understory spawn index in spawn  $s$  is

$$B_s = \frac{\bar{\rho}_s L_s^v \bar{W}_s 10^3}{\theta} \quad (33)$$

445 where  $\bar{\rho}_s$  is the mean understory egg density from Equation 32,  $L_s^v$  is the  
 446 length of the algae bed,  $\bar{W}_s$  is the mean spawn width from Equation 31,  $\theta$   
 447 is the egg conversion factor from Equation 8, and  $B_s$  is in tonnes (Figure 3,  
 448 step U5).

## 8 TOTAL SPAWN CALCULATIONS

449  
 450 This section describes step T1 in Figure 3. Unlike the previous three sections,  
 451 we include subscripts for spawn survey type  $x$ , Location  $n$ , SAR  $r$ , and year  
 452  $y$  in the equations in this section (Table 9). The total spawn index in spawn  
 453  $s$ , Location  $n$ , region  $r$ , and year  $y$  is

$$B_{snry} = \sum_{x=1}^X B_{xsnry} \quad (34)$$

454 where  $B_{xsnry}$  is spawn index for surface, Macrocystis, and understory spawn  
 455 surveys from Equation 13, Equation 25, and Equation 33, respectively, and  
 456  $B_{snry}$  is in tonnes (Figure 3, step T1). Finally, we aggregate the total spawn  
 457 index by SAR  $r$  and year  $y$

$$B_{ry} = \sum_{n=1}^N \sum_{s=1}^S B_{snry} \quad (35)$$

where  $B_{snry}$  is the total spawn index from Equation 34, and  $B_{ry}$  is a relative index of combined sex spawning biomass for SAR  $r$  and year  $y$  in tonnes. We use  $B_{ry}$  as an indicator of Pacific Herring relative population abundance (i.e., biomass) in stock assessment models.

## 9 SPAWN ON KELP CALCULATIONS

Spawn on kelp (SOK) fisheries collect Pacific Herring roe that adhere to algae such as *Macrocystis* after spawning. Other similar fisheries include spawn on bough, in which operators collect roe that adhere to tree boughs; we refer to these fisheries collectively as SOK in this document. There are two types of SOK fisheries in BC: ‘open-pond’ in which operators provide algae to spawning Pacific Herring, and ‘closed-pond’ in which operators impound spawning Pacific Herring in floating nets that contain algae (Shields et al. 1985). Although SOK fisheries do not directly remove spawning Pacific Herring, they do remove eggs that could otherwise have contributed to recruitment. 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 (Schweigert et al. 2018). 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 spawning biomass.

Shields et al. (1985) collected information on the relationship between the number of egg layers in SOK product, and proportion of product weight that consists of eggs and kelp. They determined that kelp represents 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

Table 9. Notation for Pacific Herring total spawn index calculations. Legend: tonnes (t).

Name	Description	Value or unit
$B$	Spawn index (i.e., biomass)	t

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, wet product weight increases by about 13% due to salt uptake. By osmosis, 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) to be  $2.38 \cdot 10^{-6}$  kg.

We estimate spawning biomass removed from the population by SOK fishery  $f$  in SAR  $r$  and year  $y$  as

$$B_{fry} = \frac{H_{fry}\nu v}{M\theta} \quad (36)$$

where  $H_{fry}$  is the weight in kilograms of Pacific Herring SOK harvest in fishery  $f$ , SAR  $r$ , and year  $y$ ,  $\nu$  is the proportion of SOK product that is eggs, not kelp,  $v$  is the proportion of SOK product that is eggs after brining,  $M$  is the average mass in kilograms of a fertilized egg, and  $B_{fry}$  is spawning biomass in tonnes for SOK fishery  $f$  (Table 10). Then we aggregate spawning biomass by stock assessment region (SAR)  $r$  and year  $y$

$$B_{ry} = \sum_{f=1}^F B_{fry} \quad (37)$$

where  $B_{fry}$  is spawning biomass by fishery  $f$  from Equation 36, and  $B_{ry}$  is estimated spawning biomass removed by SOK fisheries in SAR  $r$  and year  $y$  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, precision), measurement error, and model structural complexity (Link et al. 2012). Some examples illustrate these sources of uncertainty:

1. Natural variability could affect Pacific Herring fecundity, and the sex ratio of spawning Pacific Herring (Equation 8). Fecundity could be influenced by biological processes such as the observed non-stationarity of weight-at-age, or a truncated age distribution caused by selective fishing or high natural mortality.

Table 10. Notation for Pacific Herring spawn on kelp (SOK) calculations. Legend: kilograms (kg), tonnes (t).

Name	Description	Value or unit	Reference
$H$	Weight of SOK harvest	kg	
$\nu$	Proportion of SOK product that is eggs, not kelp	0.88	Shields et al. (1985)
$v$	Proportion of SOK product that is eggs after brining	0.885	Whyte and Englar (1977)
$M$	Average mass of a fertilized egg	$2.38 \times 10^{-6}$ kg	Hay and Miller (1982)
$B$	Spawning biomass	t	

2. Measurement 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 11). In addition, spawn index prediction models are dated, and our understanding of these processes could have changed in the intervening years.

3. Uncertainty in fixed parameters that are used as data without error (e.g., Equation 11); uncertainty in spawn index parameters is currently unknown.

4. Uncertainty in the number of egg layers for spawn intensity categories (Table 3), and algae coefficients (Table 8). Again, uncertainty in these values is currently unknown.

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 perpetuate the misconception 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. Investigate factors that influence fecundity and sex ratios (Equation 8);

- 536 2. Quantify and report variability in estimated prediction model parameters and equations (e.g., Equation 11);
- 537
- 538 3. Bootstrap observed input data (see Schweigert 1993); and
- 539 4. Conduct sensitivity analyses.

540 Second, acknowledging uncertainty can 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, 542 acknowledging uncertainty will increase transparency, and enable users to 543 assess potential impacts to Pacific Herring stock assessments in a management strategy evaluation (MSE) approach (e.g., DFO 2019). Addressing data and 544 model uncertainty is a required component of MSE approaches (Punt et al. 545 2016).

546 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, 548 reducing survey effort does not result in biased target variable estimates. Therefore, understanding this trade-off is important if, for example, budget 549 reductions cause reduced survey effort. Potential strategies to improve spawn survey efficiency include:

- 550 1. Conduct underwater surveys for major spawns in core areas, and surface surveys for other spawns;
- 551
- 552 2. Quantify the precision and accuracy of spawn width estimates (e.g., appendix A.1);
- 553
- 554 3. Review transect and quadrat spacing (section 2; see Schweigert 1993);
- 555
- 556 4. Review egg prediction model accuracy (Equation 8);
- 557
- 558 5. Review temporal stability of egg layer estimates; and
- 559
- 560 6. Conduct periodic versus annual surveys.
- 561

562 Even with a stable budget, there is a trade-off between high survey effort in some areas, versus low survey effort or no information in other areas.

## 565 11 FUTURE RESEARCH

566 Many of the parameters and prediction models used to calculate the spawn index are dated; these analyses could be checked with new information, and 567



568 updated if required. Parameters include  $\omega$ ,  $\phi^f$ ,  $\nu$ ,  $v$ , and  $M$ . Prediction  
 569 models include Equation 11, Equation 23, Equation 26, and Equation 27. In  
 570 addition, parameter and prediction model uncertainty should be propagated  
 571 through the calculations to quantify spawn index uncertainty (section 10).  
 572 One approach to account for prediction model uncertainty is to incorporate the  
 573 underlying data that informs these equations into spawn index calculations.  
 574 In addition, future work could review the assumed statistical framework.

## 575 12 CAVEATS

576 There are a few caveats to consider when interpreting the Pacific Herring  
 577 spawn index, and using spawn index data in analyses. These caveats include:

- 578 1. The spawn index is a relative index of spawning biomass,
- 579 2. The spawn survey is a presence only survey; thus the spawn index is a  
 580 minimum spawning biomass,
- 581 3. There are two different spawn survey periods with substantial differences  
 582 in survey effort and method (subsection 3.1):
  - 583 (a) Surface period from 1951 to 1987, and
  - 584 (b) Dive period from 1988 to present,
- 585 4. Surface surveys use two different methods to estimate the number of  
 586 egg layers (subsubsection 3.1.1):
  - 587 (a) Spawn intensity categories:
    - 588 i. Five categories from 1951 to 1968, and
    - 589 ii. Nine categories from 1969 to 1978, and
  - 590 (b) Direct estimates from 1979 to present,
- 591 5. The spawn index is derived from surface and dive observations, and  
 592 includes uncertainty and assumptions (section 10), and
- 593 6. Spawn index calculations rely on dated parameters and models (sec-  
 594 tion 11).

595 For example, in stock assessments, we scale the Pacific Herring spawn  
 596 index to abundance by dividing the index by  $q$ , which we refer to as the  
 597 ‘spawn index scaling parameter’, and we calculate a separate scalar for each  
 598 period (DFO 2020). That is to say, we estimate one spawn index scaling

599 parameter for the surface survey period  $q_1$ , and a second spawn index scaling  
600 parameter for the dive survey period  $q_2$ .

### 601 13 DOWNLOAD

602 The **R** package to calculate the Pacific Herring spawn index **SpawnIndex**, is  
603 publicly accessible on the [Pacific Herring spawn index repository](#). The package  
604 includes an example database of Pacific Herring spawn survey observations,  
605 and a vignette with examples. The **R** package contains functions to import  
606 tables from the database, and calculate the spawn index. This document  
607 is meant to accompany the **R** package, which implements the calculations  
608 described here. The **R** package is documented and has examples to promote  
609 accessibility and transparency.

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## 751 APPENDIX A SPAWN WIDTH ADJUSTMENTS

752 Spawn width is a critical component in spawn index calculations. There are  
753 two cases where we adjust spawn width estimates to improve spawn index  
754 accuracy: surface surveys in all years from 1951 to present, and understory  
755 dive surveys from 2003 to 2014.

### 756 A.1 SURFACE SPAWN WIDTH

757 Surface surveys were the only survey type prior to 1988, while the majority  
758 of spawns since 1988 have been surveyed using SCUBA gear. Recall that we  
759 describe the spawn index as having two periods based on the predominant  
760 survey type: the surface survey period from 1951 to 1987, and the dive survey  
761 period from 1988 to present.

762 One issue with comparing these two partly overlapping protocols is that  
763 surface surveyors tend to underestimate spawn width (Hay and Kronlund  
764 1987). To improve the consistency of spawn index estimates throughout the  
765 time period from 1951 to present, we adjust surface spawn width estimates  
766 using underwater estimates when available (Schweigert et al. 1993). Our  
767 preferred width is the median width from all dive surveys within a ‘pool.’ A

pool is a group of Locations within a Section that are often adjacent, contain similar algae and substrate, and can be treated as a group with likely similar widths. We summarise spawn width by the median because widths are not normally distributed (Schweigert et al. 1993). If there are no dive data that meet these criteria, we use the median width from all dives within the Section, or within the SAR if there are no dives within the Section. If there are still no dive data that meet these criteria, we use the observed width  $W'$  from the surface survey. We update the aforementioned median width values periodically, not annually.

## A.2 UNDERSTORY SPAWN WIDTH

In 2013, Fisheries and Oceans Canada (DFO) staff realized that they were inadvertently underestimating spawn width for Pacific Herring understory dive surveys (Cleary et al. 2017). The issue was caused by the assumed accuracy of transect lines used by spawn surveyors to measure spawn width. Spawn surveyors determine spawn width by placing transects perpendicular to the shore. Surveyors use weighted lead lines to ensure that lines rest on the substrate; these lines are marked in 1 m increments, and are standardized to 20 m segments. Segments refer to individual sections of line, which may be linked together to make complete transects.

Sometime in the mid- to late-1990s, spawn surveyors observed that the 20 m segments shrank by approximately 1 m during the first season of use, and continued to shrink over time. 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; thus, segments were extended to 23 m. 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 about 2005, 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, and no longer appeared to be shrinking. 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, and segments in some SARs are replaced more frequently than in other SARs). DFO staff believe that a change in lead line manufacturing prevents new lead lines from shrinking.

The earliest written instructions that describe the modified protocol of marking 1.15 m increments is from 2003, and this protocol was used until 2013. Note that some SARs continued to use old lead lines in 2014. The practice of annually re-measuring lead line increments ceased around 2005; thus we are unable to determine when lead lines ceased shrinking. Given the observations summarized above, we adjust spawn width estimates based on 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 no longer occurred) is from 2003 to 2014. However, not all SARs  $r$  and years  $y$  are impacted equally by this issue (Table A.1): some SARs and years had all 1.0 m increment lengths (no correction factor needed;  $\tau_{ry} = 1.0$ ), others had all 1.15 m increment lengths ( $\tau_{ry} = 1.15$ ), and others had a combination of 1.0 m and 1.15 m increment lengths which we assume to be in equal proportion ( $\tau_{ry} = 1.075$ ). We correct understory spawn widths by multiplying the observed width by the correction factor

$$W_{txsnry} = W'_{txsnry} \tau_{ry} \quad (\text{A.1})$$

where  $W'_{txsnry}$  is the observed spawn width for transect  $t$  in spawn survey type  $x$  (i.e., understory), spawn  $s$ , Location  $n$ , SAR  $r$ , and year  $y$ ,  $\tau_{ry}$  is the spawn width correction factor for SAR  $r$  and year  $y$  (Table A.1), and  $W_{txsnry}$  is the corrected understory spawn width in metres (Table A.2). Instead of updating the database permanently, we adjust spawn width in the **R** package script to be transparent, and to prevent mismatches between the original data sheets and databases.

## APPENDIX B SURFACE SPAWN UPDATES

One record in the surface spawn database since 1951 requires an update to fill-in missing egg layer information. As with understory spawn width updates, we make this update in the **R** package script. This affects the following record:



Table A.1. Spawn width correction factors  $\tau_{ry}$  for Pacific Herring understory spawn surveys by stock assessment region (SAR,  $r$ ) and year  $y$ . Legend: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), West Coast of Vancouver Island (WCVI), Area 27 (A27), and Area 2 West (A2W).

Year	SAR						
	HG	PRD	CC	SoG	WCVI	A27	A2W
2003	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2004	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2005	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2006	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2007	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2008	1.000	1.075	1.075	1.075	1.075	1.075	1.000
2009	1.150	1.075	1.075	1.075	1.075	1.075	1.150
2010	1.150	1.075	1.075	1.075	1.075	1.075	1.150
2011	1.150	1.075	1.075	1.075	1.075	1.075	1.150
2012	1.150	1.075	1.075	1.075	1.075	1.075	1.150
2013	1.150	1.150	1.075	1.075	1.075	1.000	1.150
2014	1.150	1.150	1.000	1.000	1.000	1.000	1.150

Table A.2. Notation for Pacific Herring understory spawn width adjustments. Legend: metres (m).

Name	Description	Value or unit
$W'$	Observed spawn width	m
$\tau$	Spawn width correction factor	see Table A.1
$W$	Corrected spawn width	m

1. Update 'intensity' from 0 to 1 for the 1 record in the year 1962, Statistical Area 14, Section 142, Location code 820, and with intensity = 0. We update intensity from 0 to 1 because spawn was surveyed but not reported.

Spawn survey records prior to 1951 have additional missing or inaccurate egg layer information, and are unreliable for indexing purposes. Therefore, we do

841 not include spawn data prior to 1951 in stock assessments.

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

- 846 1. Update  $E_{js}$  (i.e., the total number of egg layers) to 2.1496 for the 15  
847 records in the year 1979, Statistical Area 2, and with intensity 4;
- 848 2. Update  $E_{js}$  to 0.5529 for the 4 records in the year 1981, Statistical Area  
849 24, and with  $E_{js} = 0.0$ ;
- 850 3. Update  $E_{js}$  to 1.3360 for the 7 records in the year 1982, Statistical Area  
851 23, and with intensity 3;
- 852 4. Update  $E_{js}$  to 2.3300 for 41 records in the year 1984, Statistical Area  
853 24, and with intensity 0; and
- 854 5. Update  $E_{js}$  to 2.9800 for 14 records in the year 1982, Statistical Area  
855 27, and with  $E_{js} = 0.0$ .

856 In the first three cases,  $E_{js}$  was updated using intensity categories (Table 3);  
857 in the last two cases,  $E_{js}$  was updated using historical averages. These changes  
858 had negligible effects on spawn index values.