Calculate the spawn index for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada

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CALCULATE 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., Hawkshaw, S., and Cleary, J.S. 2021. Calculate the spawn index for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. Can. Tech. Rep. Fish. Aquat. Sci. nnnn: viii + 47 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., spatial 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 statistical framework and 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 spawn indices from the three types of survey observations, and aggregate by stock assessment region and year to produce a relative index of combined sex spawning biomass. We identify uncertainties in spawn index calculations, and describe how users can install the SpawnIndex **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.

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RÉSUMÉ

Grinnell, M.H., Schweigert, J.F., Thompson, M., Hawkshaw, S., and Cleary, J.S. 2021. Calculate the spawn index for Pacific Herring (*Clupea pallasii*) in British Columbia, Canada. Can. Tech. Rep. Fish. Aquat. Sci. nnnn: viii + 47 p.

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 spatiale, le nombre de couches d'oeufs, 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 cadre statistique et un protocole d'échantillonnage pour estimer le nombre d'oeufs dans une zone donnée. Deuxièmement, nous élaborons un facteur de conversion pour convertir les oeufs 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 indices de frai des trois types d'observations des relevés, et nous les agrégeons par région d'évaluation des stocks et par année pour produire un indice relatif de la biomasse reproductrice des sexes combinés. Nous identifions les incertitudes dans les calculs de l'indice de frai, et décrivons comment les utilisateurs peuvent installer le paquet **R** SpawnIndex pour calculer l'indice de frai en utilisant une base de données d'exemple. Bien que nous transformions les données du relevé de la densité des oeufs en biomasse en tonnes, les séries chronologiques annuelles de la densité et de la biomasse des oeufs sont des indices relatifs de la biomasse des géniteurs.

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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 2021). This document describes our calculations to convert spawn survey observations (e.g., spatial extent, number of egg layers, substrate type) to the Pacific Herring spawn index in BC. These calculations have been described elsewhere, in either published or informal, internal documents. The objective of this document is to collate the calculations in their order of application. Spawn index calculations have been updated over the years as more data and analyses justified 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 by counting 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), unusually early or late spawns, and during exceptional circumstances such as the COVID-19 pandemic. 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 survey periods based on the predominant survey type: the surface survey period from 1951 to 1987, and the dive survey period from 1988 to present.

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The introduction 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 (section A.1), and spawn surveyors used subjective intensity categories instead of direct egg layer estimates until 1978 (section 3.1.1). In addition, Pacific Herring spawn survey effort has been inconsistent over time due to variation in 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 egg deposition. Currently, surveyors use aircraft to search for spawn, and underwater SCUBA surveys to estimate egg deposition. It typically takes less time to search for spawn using aircraft, and more effort to measure egg deposition using SCUBA surveys, 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 (formerly known as North Coast), 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 four main steps. First, we develop a statistical framework (section 2) and sampling protocol (section 3) to estimate the number of eggs in each spawn. Second, we develop a conversion factor to convert Pacific Herring eggs to spawning biomass (section 4), which is critical to spawn index calculations. 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). Note that in this report, we use subsections within sections to separate levels of spatial aggregation

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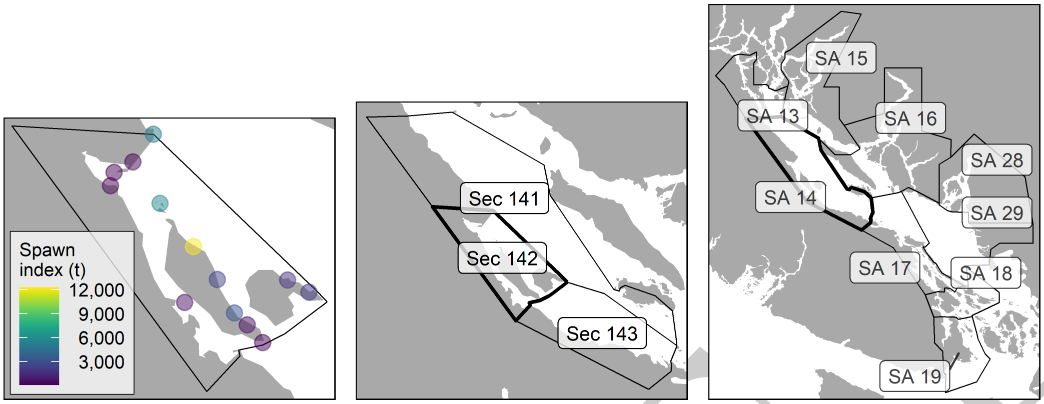

(a) Spawn index in tonnes (t) by Location in Section 142, SoG SAR.

(b) Sections (Sec) in Statistical Area 14, SoG SAR.

(c) Statistical Areas (SA) in the SoG SAR.

Figure 1. Pacific Herring spawn index by Location in 2020 (a), Sections (b), and Statistical Areas (c) in the Strait of Georgia (SoG) stock assessment region (SAR; Figure 2).

(e.g., calculations at the quadrat, or transect level; Figure 3). Finally, we combine the spawn indices from the three types of survey observations, and aggregate by SAR and year to produce a relative index of combined sex spawning biomass (section 8).

This document accompanies our SpawnIndex package (section 13). The SpawnIndex package has functions to calculate the spawn index, and is a step towards 'good enough' practices in scientific computing (Wilson et al. 2016). Previously, spawn index calculations were implemented in a **Microsoft Access** database. We updated the calculations from a database to an **R** (RCT 2021) package for several reasons. First, the database has been used for various purposes over the last two decades and has incidental calculations that make it overly complex. Second, the database is difficult to troubleshoot because it is hard to differentiate between input (i.e., data) and derived values. Third, the **R** package is open and transparent; researchers can view and download the package and an example spawn survey database. For example, users can run **R** package functions to implement calculations described in this document using a small set of actual observations. Fourth, we consider it good practice to separate data from analyses. Fifth, an **R** package will facilitate future research to quantify spawn index uncertainty. Finally, an **R** package

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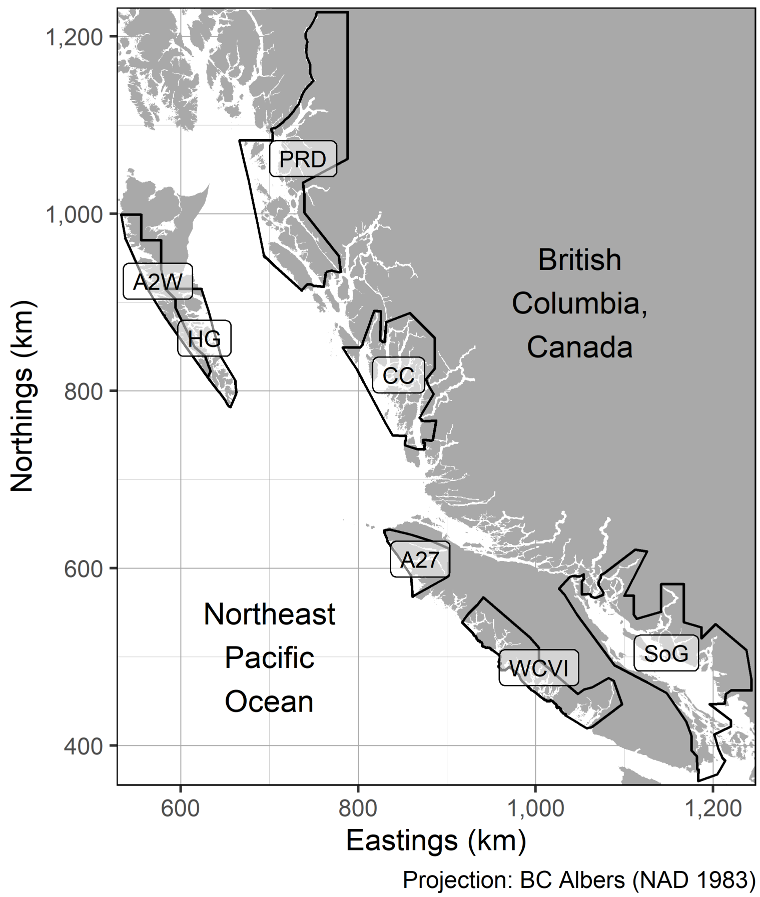

Figure 2. Spatial boundaries for Pacific Herring stock assessment regions (SARs) in British Columbia. There are five major SARs: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). There are two minor SARs: Area 27 (A27)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

will allow us to generate dynamic documents in the spirit of reproducible research using **knitr** (Xie 2015; Marwick et al. 2018).

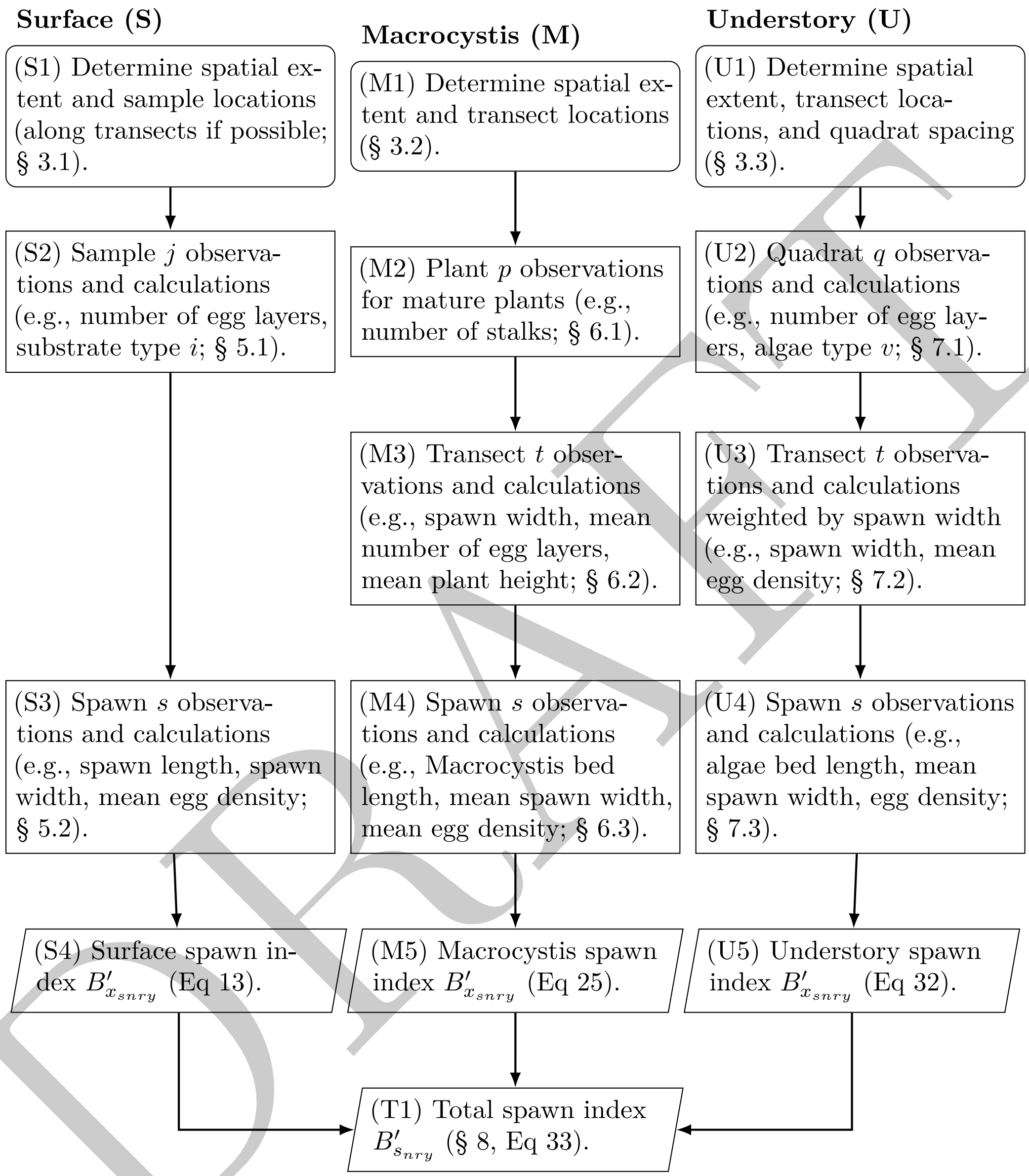

Figure 3. Sequence of steps (e.g., S1) for Pacific Herring spawn index calculations for the three spawn survey observation types x = {surface, Macrocystis, understory} (Table 1). Legend: rounded rectangles indicate start, rectangles indicate observations and calculations, parallelograms indicate output, arrows show order of operation, '§' indicates section, and 'Eq' indicates equation.

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2 STATISTICAL FRAMEWORK

Each spawn survey type has a different statistical framework and sampling protocol (section 3): surface observations, and two types of dive observations (Macrocystis and understory).

2.1 SURFACE SPAWN 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 estimate of mean egg density.

2.2 DIVE SPAWN FRAMEWORK

In contrast to surface surveys, underwater dive surveys using SCUBA gear instituted in 1988 follow a two-stage systematic sampling design where transects are the first sampling stage, and individual quadrats within transects are the second sampling stage (Jessen 1978). First we describe the understory spawn framework, then we describe the Macrocystis spawn framework which is related to understory, but simpler.

2.2.1 UNDERSTORY SPAWN FRAMEWORK

Two steps are required to calculate mean understory egg density in each surveyed spawn s (Table 1). First, mean egg density for transect t is

$$\overline{\rho_{t_{xsnry}}} = \frac{1}{Q_{txsnry}} \sum_{q_{txsnry}=1}^{Q_{txsnry}} \rho_{q_{txsnry}}, \tag{1}$$

where ρ_q is egg density in thousands of eggs per square metre (m) for quadrat q ($10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$), Q is the number of quadrats (Table 2), and $\overline{\rho_t}$ is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$. Before we calculate the mean egg density for spawn s, we determine the mean number of potential quadrats in spawn s

$$\overline{Q'_{xsnry}} = \frac{1}{T_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} Q'_{txsnry}, \tag{2}$$

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

Name	Description	Range
y	Year	$y_1, y_2, y_3, \ldots, Y$
Y	Last year of time series	
r	SAR	$1, 2, 3, \ldots, R$
R	Number of SARs	
n_{ry}	Location	$1, 2, 3, \ldots, N_{ry}$
N_{ry}	Number of locations	
s_{nry}	Spawn	$1, 2, 3, \ldots, S_{nry}$
S_{nry}	Number of spawns	
x_{snry}	Spawn survey type	$1, 2, 3, \ldots, X_{snry}$
X_{snry}	Number of spawn survey types	
j_{xsnry}	Sample	$1, 2, 3, \ldots, J_{xsnry}$
J_{xsnry}	Number of samples	
i_{jxsnry}	Substrate type (surface)	$1, 2, 3, \ldots, I_{jxsnry}$
I_{jxsnry}	Number of substrate types (surface)	
t_{xsnry}	Transect	$1, 2, 3, \ldots, T_{xsnry}$
T_{xsnry}	Number of transects	
T'_{xsnry}	Number of potential transects	
p_{txsnry}	Plant	$1, 2, 3, \ldots, P_{txsnry}$
P_{txsnry}	Number of plants	
$k_{ptxsnry}$	Stalk	$1, 2, 3, \ldots, K_{ptxsnry}$
$K_{ptxsnry}$	Number of stalks	
q_{txsnry}	Quadrat	$1, 2, 3, \ldots, Q_{txsnry}$
Q_{txsnry}	Number of quadrats	
Q'_{txsnry}	Number of potential quadrats	
$i'_{qtxsnry}$	Substrate type (understory)	$1, 2, 3, \ldots, I'_{qtxsnry}$
$I'_{qtxsnry}$	Number of substrate types (understory)	
$v_{qtxsnry}$	Algae (i.e., vegetation) type	$1, 2, 3, \ldots, V_{qtxsnry}$
$V_{qtxsnry}$	Number of algae types	
g_{ry}	SOK fishery	$1, 2, 3, \ldots, G_{ry}$
G_{ry}	Number of SOK fisheries	

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where Q' is the number of potential quadrats (i.e., a function of spawn width). Then, we calculate mean egg density in eggs per square metre for spawn s

$$\overline{\rho_{s_{nry}}} = \frac{1}{T_{xsnry}\overline{Q'_{xsnry}}} \sum_{t_{xsnry}=1}^{T_{xsnry}} Q'_{txsnry}\overline{\rho_{t_{xsnry}}}, \tag{3}$$

where T is the number of transects in spawn s, $\overline{Q'}$ is the mean number of potential quadrats from Equation 2, Q' is the number of potential quadrats, $\overline{\rho_t}$ is the mean transect egg density from Equation 1, and $\overline{\rho_s}$ is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$. The egg density estimator from Equation 3 is unbiased, and the variance is

$$\begin{aligned}\sigma^2_{s_{nry}} = \frac{T'_{xsnry} - T_{xsnry}}{T_{xsnry}T'_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} \frac{\left(Q'_{txsnry}\overline{\rho_{t_{xsnry}}} - \overline{Q'_{s_{nry}}}\,\overline{\rho_{s_{nry}}}\right)^2}{\overline{Q'_{s_{nry}}}^2\left(T_{xsnry} - 1\right)} \\ + \frac{f_{t_{xsnry}}}{T^2_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} \left(\frac{Q'_{txsnry}}{\overline{Q'_{s_{nry}}}}\right)^2 \frac{\left(1 - f_{q_{txsnry}}\right)\sigma^2_{t_{xsnry}}}{Q_{txsnry}},\end{aligned} \tag{4}$$

where T' is the number of potential transects in spawn s (i.e., a function of spawn length), $\overline{\rho_t}$ is the mean transect egg density from Equation 1, $\overline{\rho_s}$ is the mean spawn egg density from Equation 3, f_t is the transect sampling fraction for spawn s

$$f_{t_{xsnry}} = \frac{T_{xsnry}}{T'_{xsnry}}, \tag{5}$$

f_q is the quadrat sampling fraction for transect t

$$f_{q_{txsnry}} = \frac{Q_{txsnry}}{Q'_{txsnry}}, \tag{6}$$

and σ^2_t is the within transect egg density variance

$$\sigma^2_{t_{xsnry}} = \frac{1}{Q_{txsnry} - 1} \sum_{q_{txsnry}=1}^{Q_{txsnry}} \left(\rho_{q_{txsnry}} - \overline{\rho_{t_{xsnry}}}\right)^2, \tag{7}$$

where ρ_q is egg density for quadrat q, and $\overline{\rho_t}$ 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,

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

Name	**Description**	**Value or unit**
ρ	Egg density	$10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$
$\bar{\rho}$	Mean egg density	$10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$
f_t	Transect sampling fraction	$0 < f_t \leq 1$
f_q	Quadrat sampling fraction	$0 < f_q \leq 1$
σ^2	Egg density variance	ρ^2

and estimated egg density in each sampling quadrat. The sampling protocol 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 standard error of 25% or less. 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 the underlying spawn distribution, and so these estimators are applicable (Schaeffer et al. 2012). Systematic sampling has advantages and disadvantages (Schaeffer et al. 2012): advantages include ease of implementation in the field, and more precision in certain situations; disadvantages include biased estimators when populations are periodic. An analogous approach has previously been adopted to sample commercial fisheries, where vessels arrive in port randomly but are sampled

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systematically to obtain a random sample (Quinn et al. 1983; Sen 1984).

2.2.2 MACROCYSTIS SPAWN FRAMEWORK

Giant kelp, Macrocystis (*Macrocystis* spp.), requires a different framework than the aforementioned understory spawn framework. Macrocystis plants routinely reach heights of 15 m, but once weighed down with Pacific Herring eggs the plants can sink to lay flat on the substrate. After sampling Pacific Herring eggs on Macrocystis plants, Haegele and Schweigert (1990) 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. The survey design employed to capture these data relies on determining the average plant height, number of fronds in each plant holdfast, and number of Macrocystis plants occurring within a 1 m swath on both sides of the transect line in a given spawn. These data are used to determine the total egg deposition on Macrocystis plants for each spawn (section 6.3).

3 SAMPLING PROTOCOL

The following is a brief summary of the spawn survey sampling protocol from the Pacific Herring spawn survey manual. Pacific Herring in BC primarily spawn in sheltered bays and inlets, depositing 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 combination of year, Location, and 'spawn number' $s_{nry} = 1, 2, 3, \ldots, S_{nry}$ (Table 1). Spawn numbers identify distinct spawns, which we define as a continuous stretch of shoreline with no detectable break in egg deposition; this is the finest scale at which we calculate the spawn index. A break in egg deposition is determined by the absence of Pacific Herring spawn on two consecutive transects, or by a temporal gap in spawning. Most spawns are also characterized by longitude and latitude, as well as start and end dates of spawning. Surveyors usually collect longitude and latitude at the start and end of each transect; for surface spawn surveys that are not along transects (section 3.1), surveyors collect longitude and latitude at the start and end of the spawn (i.e., overall length and width).

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 often appear as bands running parallel to the shore (Figure 4). Thus, spawn 'length' refers to distance parallel to the shore, and 'width' refers to distance perpendicular to the shore. Similarly, Macrocystis bed length L' and algae (i.e., vegetation) bed length L'' refer to distances that Macrocystis and algae beds extend parallel to the shore, respectively.

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

Pacific Herring spawn surveyors first determine the spatial extent of the

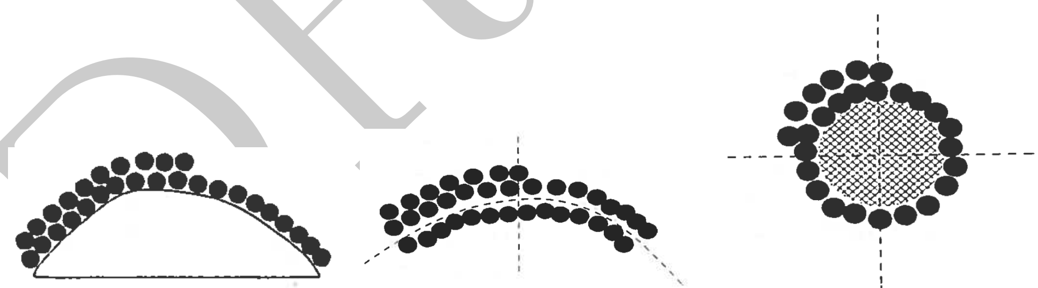
Figure 4. Aerial view of Pacific Herring spawn taken during a spawn reconnaissance flight in the Strait of Georgia. Spawn is identified by the band of discoloured water parallel to the shore.

spawn in terms of length of shoreline to survey (Figure 3, steps S1, M1, and U1); this is done by raking (section 3.1) or brief dives to determine the presence or absence of spawn. Surveyors place the first transect in from one end (i.e., at the first permanent transect, or 200 m if there are no permanent transects) to avoid surveying areas with patchy and sparse egg layers. Within the spawn area, surveyors use transects to determine spawn width, quadrat placement, and which Macrocystis plants to survey. In some cases, we adjust spawn width to improve the accuracy of spawn index estimates (Appendix A).

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

3.1 SURFACE SPAWN PROTOCOL

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



(a) Substrate with 1.5 egg layers. *(b) Flat algae with 2.5 egg layers.* *(c) Round algae with 2.5 egg layers.*

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.

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sample along permanent transects. 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 algae (i.e., 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 direct egg layer estimates (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 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, $\chi_t = 2\,\text{m}$ in transect t. Divers categorize Macrocystis plants as either 'mature' or

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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). Uncertainty in the number of egg layers is not available.

Intensity category			
1928–1968	**1969–1978**	**Description**	**Number of egg layers**
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

'immature' based on stipe height; mature plants have stipes ≥ 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 ≥ 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 quadrat position along permanent transects

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varies among years due to the location and extent (i.e., width) of spawn with respect to the shoreline: spawn location causes quadrats to shift seaward or shoreward, and spawn width causes transects to be shorter or longer. Understory spawn surveys use $0.5\,\mathrm{m}^2$ quadrats; other sizes (e.g., 0.25 and $1.0\,\mathrm{m}^2$) 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 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 by survey observation type, 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); we refer to this as fecundity. Average fecundity is derived from studies of BC Pacific Herring in 1974 and 1980 (Prince Rupert District, Strait of Georgia, and West Coast of Vancouver Island; Hay 1985), and California Pacific Herring in 1975 (Rabin and Barnhart 1975). We assume that females account for 50% of spawners, and we convert eggs to tonnes (t) of spawners using

$$\theta = \omega \female \frac{10^3\ \mathrm{kg}}{\mathrm{t}}, \tag{8}$$

where ω is female fecundity, $\female$ is the proportion of spawners that are female, and θ is the egg conversion factor in $10^8 \cdot \mathrm{eggs} \cdot \mathrm{t}^{-1}$ (Table 4). Thus, we convert eggs to biomass of both sexes combined in tonnes by dividing the number of eggs by θ. 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 (Ware 1985; Schweigert 1993).

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

Name	Description	Value or unit	References
ω	Female fecundity	200,000 eggs $\cdot$ kg^{-1}	Hay (1985); Hay and Brett (1988)
♀	Proportion female	0.5	
θ	Egg conversion factor	$10^8 \cdot$ eggs $\cdot$ t^{-1}	

5 SURFACE SPAWN CALCULATIONS

This section describes steps S2 to S4 (Figure 3). As previously mentioned, surface spawn surveyors sample along transects or using their judgement (section 3.1). Surveyors collect data 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 1 and Table 5). We use the term 'metric' to refer to a measure of quantitative assessment. Recall that surface spawn 'samples' include observations collected using specialized rakes and viewing boxes (section 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 is

$$E_{i_{jxsnry}} = E'_{i_{jxsnry}} \phi_{i_{jxsnry}}, \tag{9}$$

where E'_i is the number of egg layers on substrate i, ϕ_i is the proportion of substrate i covered with spawn, and E_i is in number of egg layers. The total number of egg layers in sample j is

$$E_{j_{xsnry}} = \sum_{i_{jxsnry}=1}^{I_{jxsnry}} E_{i_{jxsnry}}, \tag{10}$$

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

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

where E_i is the number of egg layers in substrate i from Equation 9, and E_j is in number of egg layers. For the time period when surveyors recorded spawn 'intensity' categories instead of direct egg layer estimates, we convert intensity to number of egg layers E_j (Table 3). Schweigert et al. (1997) developed a model of surface egg density as a function of number of egg layers using a linear regression model[1]

$$\rho_{jxsnry} = \alpha + \beta E_{jxsnry}, \tag{11}$$

where α is the regression intercept, β is the regression slope, E_j is the total number of egg layers in sample j from Equation 10, and ρ_j is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$ (Figure 6). Note that $E_j = 0 \Rightarrow \rho_j = 0$ to avoid having $\rho_j = \alpha$ when there are no egg layers (i.e., $E_j = 0$).

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

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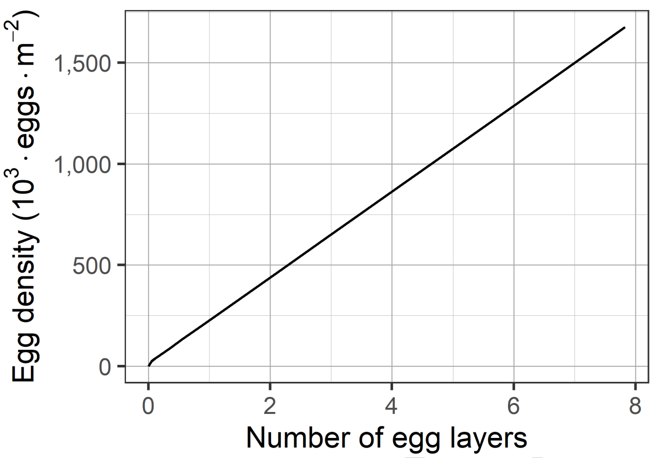

Figure 6. Relationship between egg density in thousands of eggs per square metre (m; line), and number of egg layers for Pacific Herring surface spawn surveys based on Equation 11 (Schweigert et al. 1997). Note that number of egg layers can exceed those shown in this figure.

5.2 SPAWN OBSERVATIONS AND CALCULATIONS

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

$$\overline{\rho_{s_{nry}}} = \frac{1}{J_{xsnry}} \sum_{j_{xsnry}=1}^{J_{xsnry}} \rho_{j_{xsnry}}, \tag{12}$$

where ρ_j is egg density in sample j from Equation 11, J is the number of samples, and $\overline{\rho_s}$ is in $10^3 \cdot \mathrm{eggs} \cdot \mathrm{m}^{-2}$. 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'_s (in that order; section A.1). 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.

The surface spawn index in spawn s is

$$B'_{s_{nry}} = \frac{\overline{\rho_{s_{nry}}} L_{s_{nry}} W_{s_{nry}} 10^3}{\theta}, \tag{13}$$

where $\overline{\rho_s}$ is mean egg density in spawn s from Equation 12, L_s is length

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of spawn s, W_s is width of spawn s, θ 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 (Figure 3). Macrocystis spawn surveyors use SCUBA gear to collect underwater data for individual plants p, transects t, and spawns s (section 3.2); we calculate metrics at the transect t, and spawn s levels (Table 1 and Table 6). Recall that divers enumerate every Macrocystis plant within the transect swath.

6.1 PLANT OBSERVATIONS

For each mature plant p (Figure 3, step M2), surveyors count the number of stalks K_p.

6.2 TRANSECT OBSERVATIONS AND CALCULATIONS

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

$$A_{t_{xsnry}} = W_{t_{xsnry}} \chi_{t_{xsnry}} \tag{14}$$

in square metres. In addition, divers estimate summary statistics for mature Macrocystis plants p along transect t: mean height $\overline{H_{t_{xsnry}}}$ in metres, and mean number of egg layers $\overline{E_{t_{xsnry}}}$. We calculate the total number of stalks K in transect t as

$$K_{t_{xsnry}} = \sum_{p_{txsnry}=1}^{P_{txsnry}} K_{p_{txsnry}}, \tag{15}$$

where K_p is the number of stalks on plant p, and K_t is in number of stalks.

6.3 SPAWN OBSERVATIONS AND CALCULATIONS

At the spawn s level (Figure 3, step M4), the Macrocystis bed length is L'_s in metres. If L'_s is inadvertently not recorded, we set L'_s to the spawn length L_s.

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

Name	**Description**	**Value or unit**	**References**
W	Spawn width	m	
χ	Transect swath	m	
A	Area	m^2	
$\overline{W}$	Mean spawn width	m	
$\overline{H}$	Mean plant height	m	
$\overline{E}$	Mean number of egg layers	$\overline{E} > 0$	
L'	Length of the Macrocystis bed	m	
L	Spawn length	m	
$\bar{\kappa}$	Mean number of stalks per plant	$\bar{\kappa} > 0$	
ξ	Regression slope	0.073 eggs $\cdot$ $10^3 \cdot$ plant^{-1}	Haegele and Schweigert (1990)
γ	Regression exponent on $\overline{E}$	0.673	Haegele and Schweigert (1990)
δ	Regression exponent on $\overline{H}$	0.932	Haegele and Schweigert (1990)
ϵ	Regression exponent on $\bar{\kappa}$	0.703	Haegele and Schweigert (1990)
$\bar{\psi}$	Mean number of eggs per plant	eggs $\cdot\ 10^3 \cdot$ plant^{-1}	
$\bar{\rho}$	Mean egg density	$10^3 \cdot$ eggs $\cdot$ m^{-2}	
B'	Macrocystis spawn index (i.e., biomass)	t	

370 The mean width of spawn s is

$$\overline{W_{snry}} = \frac{1}{T_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} W_{t_{xsnry}}, \tag{16}$$

where W_t is the spawn width at transect t, T is the number of transects in spawn s, and $\overline{W_s}$ is in metres. The total area of transects in spawn s is

$$A_{s_{nry}} = \sum_{t_{xsnry}=1}^{T_{xsnry}} A_{t_{xsnry}}, \tag{17}$$

where A_t is the transect area from Equation 14, and A_s is in square metres.

Three metrics are required to calculate the number of eggs on Macrocystis plants (Haegele and Schweigert 1990): number of egg layers, plant height, and number of stalks per plant. First, the mean number of egg layers in spawn s is

$$\overline{E_{s_{nry}}} = \frac{1}{T_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} \overline{E_{t_{xsnry}}}, \tag{18}$$

where $\overline{E_t}$ is the mean number of egg layers in transect t, T is the number of transects in spawn s, and $\overline{E_s}$ is in number of egg layers. Second, the mean plant height in spawn s is

$$\overline{H_{s_{nry}}} = \frac{1}{T_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} \overline{H_{t_{xsnry}}}, \tag{19}$$

where $\overline{H_t}$ is the mean plant height in transect t, T is the number of transects in spawn s, and $\overline{H_s}$ is in metres. The third metric is the number of stalks per plant, which we calculate in three steps. The total number of observed stalks in spawn s is

$$K_{s_{nry}} = \sum_{t_{xsnry}=1}^{T_{xsnry}} K_{t_{xsnry}}, \tag{20}$$

where K_t is the number of stalks in transect t from Equation 15, T is the number of transects in spawn s, and K_s is in number of stalks. The total number of observed plants in spawn s is

$$P_{s_{nry}} = \sum_{t_{xsnry}=1}^{T_{xsnry}} P_{t_{xsnry}}, \tag{21}$$

where P_t is the number of plants in transect t, T is the number of transects in spawn s, and P_s is in number of plants. Thus, the mean number of stalks per plant in spawn s is

$$\overline{\kappa_{s_{nry}}} = \frac{K_{s_{nry}}}{P_{s_{nry}}}, \tag{22}$$

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where K_s is the number of stalks in spawn s from Equation 20, P_s is the number of plants in spawn s from Equation 21, and $\overline{\kappa_s}$ is in number of stalks per plant.

Haegele and Schweigert (1990) developed a model of the number of eggs per plant as a function of the three aforementioned metrics (number of egg layers, plant height, and number of stalks per plant) using a nonlinear multiple regression model

$$\overline{\psi_{snry}} = \xi \overline{E_{snry}}^{\gamma} \overline{H_{snry}}^{\delta} \overline{\kappa_{snry}}^{\epsilon} 10^3, \tag{23}$$

where ξ is the regression slope, $\overline{E_s}$ is the mean number of egg layers in spawn s from Equation 18, γ is the regression exponent on $\overline{E_s}$, $\overline{H_s}$ is the mean plant height in spawn s from Equation 19, δ 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, ϵ is the regression exponent on $\overline{\kappa_s}$, and $\overline{\psi_s}$ is in eggs $\cdot\, 10^3 \cdot$ plant^{-1} (Figure 7). Mean Macrocystis egg density in spawn s is

$$\overline{\rho_{snry}} = \frac{\overline{\psi_{snry}} P_{snry}}{A_{snry}}, \tag{24}$$

where $\overline{\psi_s}$ 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 21, A_s is the total area of transects in spawn s from Equation 17, and $\overline{\rho_s}$ is in $10^3 \cdot$ eggs $\cdot$ m^{-2}.

The Macrocystis spawn index in spawn s is

$$B'_{snry} = \frac{\overline{\rho_{snry}} L'_{snry} \overline{W_{snry}} 10^3}{\theta}, \tag{25}$$

where $\overline{\rho_s}$ is the mean egg density in spawn s from Equation 24, L'_s is the length of the Macrocystis bed in spawn s, $\overline{W_s}$ is the mean width of spawn s from Equation 16, θ 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 (Figure 3). Understory spawn surveyors use SCUBA gear to collect underwater data for substrate i', algae (i.e., vegetation) types v, quadrats q, transects t, and spawns s (section 3.3); we calculate metrics at the substrate i', algae type v, quadrat q, transect t, and spawn s levels (Table 1 and Table 7). Recall that divers collect understory observations in quadrats, which are distributed along transects.

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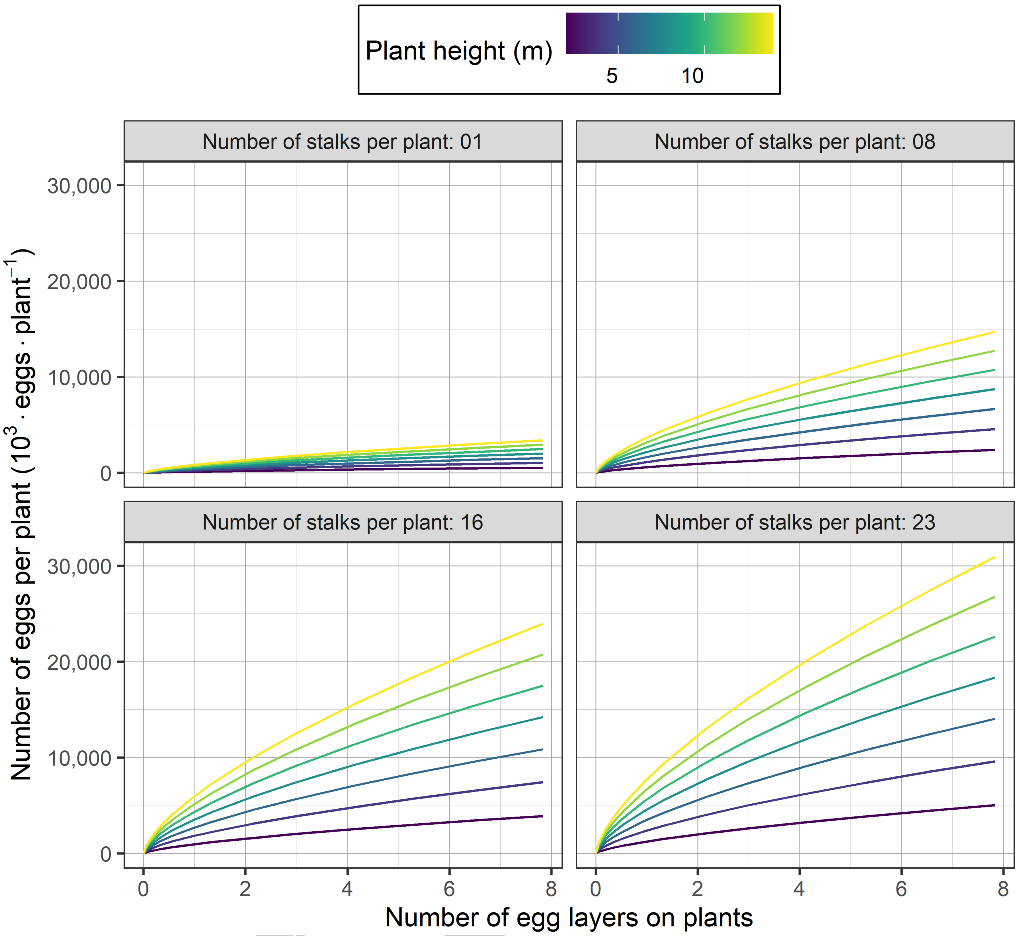

Figure 7. Relationship between number of eggs in thousands per Macrocystis plant (lines), and number of egg layers on plants, plant height in metres (m), and number of stalks per plant for Pacific Herring Macrocystis spawn surveys based on Equation 23 (Haegele and Schweigert 1990). Note that number of egg layers, plant height, and number of stalks per plant can exceed those shown in this figure.

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 i', and spawn on algae v. Haegele et al. (1979) developed a model of substrate egg density in quadrat q, transect

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

Name	Description	Value or unit	References
φ	Regression slope for substrate	340 $10^3 \cdot$eggs$\cdot$m^{-2}	Haegele et al. (1979)
E	Number of egg layers	$E > 0$	
ϕ	Proportion covered in eggs	$0 < \phi \leq 1$	
ρ	Egg density	$10^3 \cdot$ eggs $\cdot$ m^{-2}	
ϑ	Regression slope for algae	600.567 $10^3 \cdot$ eggs $\cdot$ m^{-2}	Schweigert (2005)
ϱ	Regression exponent on E	0.6355	Schweigert (2005)
ς	Regression exponent on ϕ	1.413	Schweigert (2005)
C	Algae coefficient	see Table 8	
W	Spawn width	m	
$\bar{\rho}$	Mean egg density	$10^3 \cdot$ eggs $\cdot$ m^{-2}	
$\overline{W}$	Mean spawn width	m	
L''	Length of the algae bed	m	
L	Spawn length	m	
B'	Understory spawn index (i.e., biomass)	t	

t, and spawn s from egg layers using a linear model

$$\rho_{i'_{qtxsnry}} = \varphi E_{i'_{qtxsnry}} \phi_{i'_{qtxsnry}}, \tag{26}$$

where φ is the slope, $E_{i'}$ is the number of egg layers on substrate i', $\phi_{i'}$ is the proportion of substrate i' covered by spawn, and $\rho_{i'}$ is substrate egg density in $10^3 \cdot$ eggs $\cdot$ m^{-2} (Figure 8).

Although quadrats have only one substrate type, they can have up to three algae types v (section 3.3). Schweigert (2005) developed a model of algae egg density from egg layers, proportion of the quadrat covered by algae, and algae coefficients using a generalized linear model. Algae coefficients account for the effect of algae morphology on Pacific Herring egg density (Table 8). Egg

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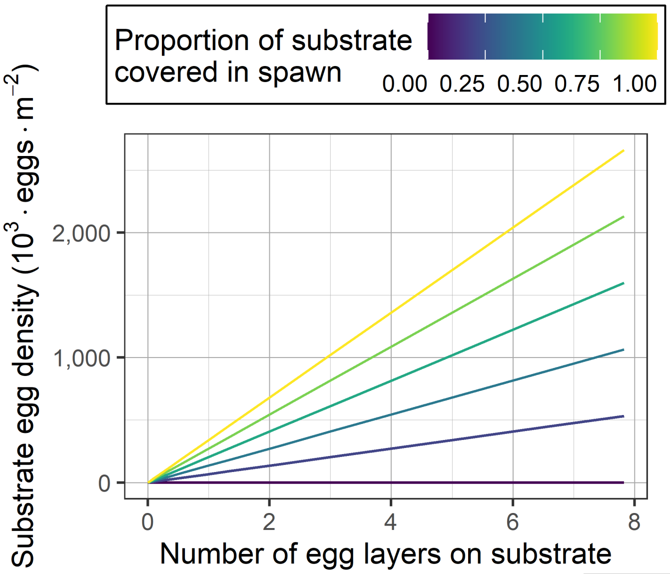

Figure 8. Relationship between substrate egg density in thousands of eggs per square metre (m; lines), and number of egg layers on substrate and proportion of substrate covered in spawn for Pacific Herring underwater spawn surveys based on Equation 26 (Haegele et al. 1979). Note that number of egg layers can exceed those shown in this figure.

density on algae v in quadrat q, transect t, and spawn s (Schweigert 2005) is

$$\rho_{v_{qtxsnry}} = \vartheta E^{\varrho}_{v_{qtxsnry}} \phi^{\varsigma}_{v_{qtxsnry}} C_v, \tag{27}$$

where ϑ is the regression slope, E_v is the number of egg layers on algae v, ϱ is the regression exponent on E_v, ϕ_v is the proportion of quadrat q covered by algae v, ς is the regression exponent on ϕ_v, C_v is the coefficient for algae v, and ρ_v is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$ (Figure 9).

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

$$\rho_{q_{txsnry}} = \rho_{i'_{qtxsnry}} + \sum_{v_{qtxsnry}=1}^{V_{qtxsnry}} \rho_{v_{qtxsnry}}, \tag{28}$$

where $\rho_{i'}$ is substrate egg density from Equation 26, ρ_v is egg density on algae v from Equation 27, and ρ_q is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$. Thus, we assume that eggs on substrate and algae are independent, and can be added without bias.

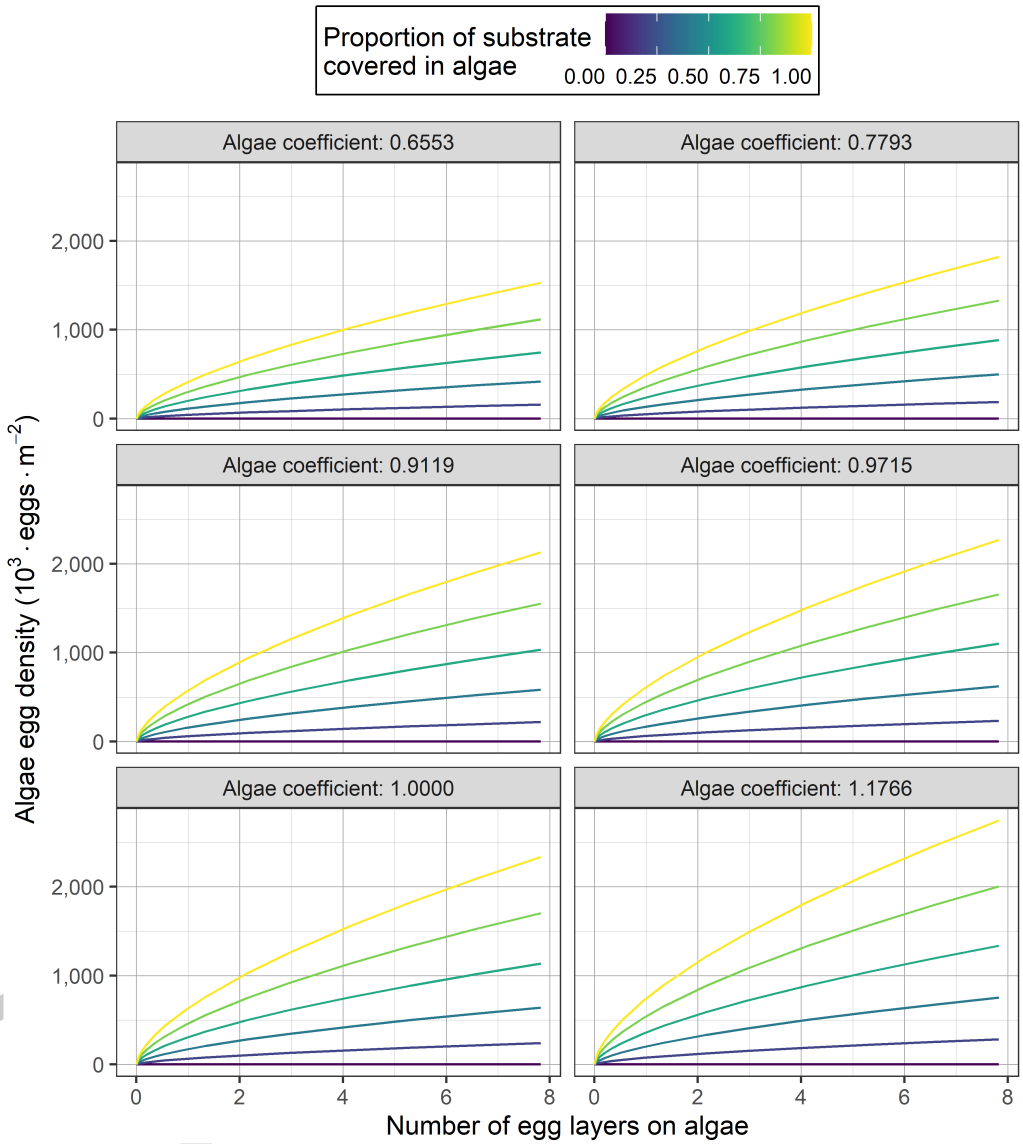

Figure 9. Relationship between algae egg density in thousands of eggs per square metre (m; lines), and number of egg layers on algae, proportion of substrate covered in algae, and algae coefficient (Table 8) for Pacific Herring underwater spawn surveys based on Equation 27 (Schweigert 2005). Note that number of egg layers can exceed those shown in this figure.

Table 8. Algae (i.e., vegetation) types v and coefficients C for Pacific Herring understory spawn surveys (Schweigert 2005). Uncertainty in algae coefficients is not available. Algae types are described in the Pacific Herring spawn survey manual.

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 is

$$\overline{\rho_{txsnry}} = \frac{1}{Q_{txsnry}} \sum_{q_{txsnry}=1}^{Q_{txsnry}} \rho_{q_{txsnry}}, \tag{29}$$

where Q is the number of quadrats in transect t, ρ_q is total understory egg density in quadrat q from Equation 28, and $\overline{\rho_t}$ is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$. 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 (section A.2).

7.3 SPAWN OBSERVATIONS AND CALCULATIONS

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

$$\overline{W_{snry}} = \frac{1}{T_{xsnry}} \sum_{t_{xsnry}=1}^{T_{xsnry}} W_{t_{xsnry}}, \tag{30}$$

where W_t is the spawn width at transect t, T is the number of transects in spawn s, and $\overline{W_s}$ is in metres. The algae bed length is L''_s, also in metres. As with Macrocystis spawn calculations, if L''_s is inadvertently not recorded, we set L''_s to the spawn length L_s. Thus, we assume that eggs on substrate and eggs on algae are represented by the same length measurement.

Next, we calculate the weighted mean egg density in spawn s, where transect egg density is weighted by spawn width at transect t, W_{ts}. We calculate a weighted mean because spawn width varies along the spawn length; a weighted mean ensures that transects contribute proportionally to their area. The mean egg density in spawn s is

$$\overline{\rho_{s_{nry}}} = \frac{\sum_{t_{xsnry}=1}^{T_{xsnry}} \overline{\rho_{t_{xsnry}}} W_{t_{xsnry}}}{\sum_{t_{xsnry}=1}^{T_{xsnry}} W_{t_{xsnry}}}, \tag{31}$$

where $\overline{\rho_t}$ is the mean understory egg density in transect t from Equation 29, W_t is the spawn width for transect t in metres, and $\overline{\rho_s}$ is in $10^3 \cdot \text{eggs} \cdot \text{m}^{-2}$.

The understory spawn index in spawn s is

$$B'_{s_{nry}} = \frac{\overline{\rho_{s_{nry}}} L''_{s_{nry}} \overline{W_{s_{nry}}} 10^3}{\theta}, \tag{32}$$

where $\overline{\rho_s}$ is the mean understory egg density from Equation 31, L''_s is the length of the algae bed, $\overline{W_s}$ is the mean spawn width from Equation 30, θ is the egg conversion factor from Equation 8, and B'_s is in tonnes (Figure 3, step U5).

8 TOTAL SPAWN CALCULATIONS

This section describes step T1 (Figure 3). The total spawn index in spawn s (Table 1) is

$$B'_{s_{nry}} = \sum_{x_{snry}=1}^{X_{snry}} B'_{x_{snry}}, \tag{33}$$

where B'_x is the spawn index for surface, Macrocystis, and understory spawn surveys from Equation 13, Equation 25, and Equation 32, respectively, and B'_s is in tonnes (Figure 3, step T1).

Finally, we aggregate the total spawn index by SAR r and year y

$$B'_{ry} = \sum_{n_{ry}=1}^{N_{ry}} \sum_{s_{nry}=1}^{S_{nry}} B'_{s_{nry}}, \tag{34}$$

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Table 9. Notation for Pacific Herring total spawn index calculations. Note that in this table q represents the spawn index scaling parameter, not quadrat number as in other sections of this report. Legend: tonnes (t).

Name	Description	Value or unit	References
B'	Spawn index (i.e., biomass)	t	
q	Spawn index scaling parameter	$0.0 < q \leq 1.0$	DFO (2021)
B	Scaled abundance (i.e., biomass)	t	

where B'_s is the total spawn index from Equation 33, and B'_{ry} is a relative index of combined sex spawning biomass for SAR r and year y in tonnes.

8.1 SCALED ABUNDANCE

We use B'_{ry} as an indicator of relative population abundance (i.e., biomass) in Pacific Herring stock assessment models (DFO 2021). We scale B'_{ry} to abundance

$$B_{ry} = \frac{B'_{ry}}{q_{ry}}, \tag{35}$$

where B'_{ry} is the total spawn index in tonnes from Equation 34, q_{ry} is the spawn index scaling parameter (DFO 2016), and B_{ry} is scaled abundance (i.e., biomass) for SAR r and year y in tonnes. To be consistent with stock assessments, in this section q represents the spawn index scaling parameter, not quadrat number as in other sections of this report. In Pacific Herring stock assessment models, q describes the proportion of spawn observed in spawn surveys, accounting for egg loss (e.g., due to predation) and unobserved spawns (DFO 2016). Although q is uncertain and a number of assumptions are made within the assessment model, there are differences between the proportion of spawn observed in the two spawn survey periods (DFO 2021). Therefore, for each SAR we estimate one spawn index scaling parameter for the surface survey period q_1 (1951 to 1987), and a second one for the dive survey period q_2 (1988 to present).

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9 SPAWN-ON-KELP CALCULATIONS

Spawn-on-kelp (SOK) fisheries collect Pacific Herring roe that adheres to algae such as Macrocystis after spawning. Other similar fisheries include spawn-on-bough, in which operators collect roe that adhere to submerged 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). For example, failing to account for SOK spawn in assessments is analogous to treating it as missed spawn via the q parameter (section 8.1); conversely, accounting for SOK spawn directly in assessments may reduce the uncertainty in q. 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 determine the biomass of Pacific Herring that produced those eggs.

Shields et al. (1985) collected information on the relationship between the number of egg layers in SOK product, and the 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 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 wet product weight increases by approximately 13% due to salt uptake during a 24-hour brining period. By osmosis, brining would also draw some water from the eggs (Alderice et al. 1979); unfortunately we are unable to account for osmosis at this time. The last factor to consider is the mean fertilized egg weight, $2.38 \cdot 10^{-6}$ kg (Hay and Miller 1982).

We estimate the spawn index for Pacific Herring that spawned and produced eggs which were removed from the population by SOK fishery g (Table 1) as

$$B'_{g_{ry}} = \frac{H_{g_{ry}} \left(1 - \nu\right) \frac{1}{1+\upsilon}}{w\theta}, \tag{36}$$

where H_g is the weight in kilograms of Pacific Herring SOK harvest in fishery g, ν is the proportion of SOK product weight that is kelp, υ is the SOK product weight increase due to brining as a proportion, w is the average weight in kilograms of a fertilized egg, θ is the egg conversion factor from Equation 8, and B'_g is in tonnes (Table 10). Then we aggregate the spawn index by SAR r and year y

$$B'_{ry} = \sum_{g_{ry}=1}^{G_{ry}} B'_{g_{ry}}, \tag{37}$$

where B'_g is the spawn index for fishery g from Equation 36, and B'_{ry} is in tonnes. Thus, B'_{ry} is the estimated Pacific Herring biomass that produced eggs which were 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

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

Name	**Description**	**Value or unit**	**References**
H	Weight of SOK harvest	kg	
ν	Proportion of SOK product that is kelp	0.12	Shields et al. (1985)
υ	SOK product weight increase due to brining (proportion)	0.132	Whyte and Englar (1977)
w	Average weight of a fertilized egg	2.38×10^{-6} kg	Hay and Miller (1982)
B'	SOK spawn index (i.e., biomass)	t	

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(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 (DFO 2021), or a truncated age distribution caused by selective fishing (Brunel and Piet 2013).

2. Measurement error could affect input data (e.g., number of egg layers, spawn length and width), 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 the processes could have changed in the intervening years (e.g., Equation 11, Equation 23).

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) who derived a variance estimator). 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. An additional issue for stock assessments is that the model formulation could interpret the spawn index as being more precise than it actually is, and estimates of stock status and future prognosis could be artificially precise.

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. Quantify and report variability in estimated prediction model parameters and equations (e.g., Equation 11),

2. Propagate uncertainty in parameters and prediction models through spawn index calculations,

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3. Incorporate the underlying data that informs prediction model equations into spawn index calculations,
4. Bootstrap observed input data (see Schweigert 1993), and
5. Conduct sensitivity analyses.

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

Quantifying uncertainty may also identify options to increase survey program efficiency by targeting data that have the greatest impact on spawn index accuracy. In addition, there is a trade-off between 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 reduced survey effort. Potential strategies to improve spawn survey efficiency include:

1. Conduct underwater surveys for major spawns in core areas, and surface surveys for other spawns,
2. Review transect and quadrat spacing (section 2; see Schweigert 1993), and
3. Conduct periodic versus annual surveys.

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.

11 FUTURE RESEARCH

Many of the studies to quantify parameters and prediction models used in spawn index calculations are dated (Table 11); these analyses could be reviewed with new information, and updated if required. In addition, some of these studies had limited number of samples, limited spatial or temporal range, or both. In addition to work mentioned here and in section 10, potential research includes:

Table 11. Details for studies to quantify parameters and prediction models used in Pacific Herring spawn index calculations. Study details include where, when, and how many samples, when available. The major stock assessment regions are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI) (Figure 2). Legend: equation (Eq), sample size (n), standard error (SE), standard deviation (SD), spawn-on-kelp (SOK), and not available (NA).

Parameters	**Description**	**Study details**	**Uncertainty**	**References**
f_t, f_q	Parameters for statistical framework (Eq 4).	SoG in 1981 and 1983; WCVI in 1982.	Objective is mean egg density SE $\leq$ 25%.	Schweigert et al. (1985, 1990)
Intensity	Spawn intensity categories and number of egg layers (Table 3).	NA	NA	Hay and Kronlund (1987); Schweigert and Stocker (1988)
ω	Female fecundity (Eq 8); values in eggs $\cdot$ kg^{-1}.	PRD, WCVI, and SoG in 1974 ($n = 3{,}293$ fish) and 1980 ($n = 1{,}642$); California in 1975 ($n = 37$).	$186{,}800 \leq \omega \leq 224{,}500$; $16{,}900 \leq \text{SD} \leq 53{,}500$.	Hay (1985); Hay and Brett (1988)
♀	Proportion female (Eq 8).	NA	NA	NA
α, β	Parameters for surface survey egg density model (Eq 11).	Coastwide from 1976 to 1987 ($n = 5{,}111$ samples).	NA	Schweigert et al. (1997)

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Table 11 continued

Parameters	Description	Study details	Uncertainty	References
ξ, γ, δ, ϵ	Parameters for number of eggs per Macrocystis plant model (Eq 23).	HG in 1981 and 1987 ($n =$ 112 plants); PRD in 1986 ($n = 15$); CC in 1986 ($n =$ 5); WCVI in 1985 and 1986 ($n = 35$).	Model accounts for 78% of variation in eggs per plant.	Haegele and Schweigert (1990)
φ	Parameter for substrate egg density model (Eq 26).	SoG in 1976, 1977, and 1978; PRD, CC, and WCVI in 1977.	NA	Haegele and Humphreys (1976, 1978*a*,*b*); Haegele et al. (1979)
ϑ, ϱ, ς, C_v	Parameters for algae egg density model (Eq 27, Table 8).	Coastwide from 1976 to 1987 ($n =$ 5,111 samples).	Model accounts for 40% of variation in egg density.	Schweigert (2005)
ν	Proportion of SOK product that is kelp (Eq 36).	HG in 1982 and 1983; PRD in 1982.	SD = 4.2.	Shields et al. (1985)
υ	SOK product weight increase due to brining (proportion; Eq 36).	SoG ca. 1977.	NA	Whyte and Englar (1977)
w	Average weight of a fertilized egg (Eq 36).	SoG in 1980 ($n = 7$ samples).	SE = 3.4×10^{-7}.	Hay and Miller (1982)

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1. Check the assumed statistical framework for spawn index calculations,
2. Check accuracy and temporal stability of fecundity and sex ratios (Equation 8),
3. Compare two methods to calculate the mean number of stalks per plant (Equation 22): ratio of means (i.e., current method) versus mean of ratios,
4. Review the assumptions that eggs on substrate and algae are:
   (a) Independent (Equation 28), and
   (b) Represented by the same length measurement (section 7.3),
5. Review surface spawn width adjustments (section A.1):
   (a) Mean versus median width,
   (b) Annual versus periodic updates, and
   (c) Occurrence of relationship between spawn width and spawning biomass,
6. Periodically review the accuracy of egg density models using egg layer and vegetation cover estimates collected underwater, compared to egg counts in a subset of sampled quadrats,
7. Quantify incidental mortality in SOK operations, and
8. Account for osmosis in SOK calculations (Equation 36).

12 CAVEATS

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

1. The spawn index is a relative index of spawning biomass,
2. The spawn survey is a presence only survey; thus the spawn index is a minimum spawning biomass,
3. There are two different spawn survey periods with substantial differences in survey effort and method (section 3.1):
   (a) Surface period from 1951 to 1987, and
   (b) Dive period from 1988 to present,

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4. Surface spawn surveys use two different methods to estimate the number of egg layers (section 3.1.1):
   (a) Spawn intensity categories:
      i. Five categories from 1951 to 1968, and
      ii. Nine categories from 1969 to 1978, and
   (b) Direct estimates from 1979 to present,
5. The spawn index is derived from surface and dive observations of egg deposition, and includes uncertainty and assumptions (section 10), and
6. Spawn index calculations rely on dated parameters and models (section 11).

13 R PACKAGE

We created an **R** (RCT 2021) package to implement the calculations described in this document. The SpawnIndex **R** package is publicly accessible on the Pacific Herring spawn index repository. The SpawnIndex package contains an example database of Pacific Herring spawn survey observations, as well as functions to import tables from the database, and calculate the spawn index. The SpawnIndex package is documented, and has examples to promote accessibility and transparency. There is also a vignette with an example workflow.

To facilitate pairing this document with the SpawnIndex **R** package, we cross-reference equations in this document with functions in the **R** package (Table 12). In addition, parameters names in this document have corresponding function argument names in the **R** package. For example, theta θ in Equation 8 corresponds to `theta` in the function `eggs_to_sb`. Similarly, egg layers E_j in Equation 11 corresponds to `egg_layers` in the function `dens_surf`.

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*Table 12. Crosswalk table for equations in this document (i.e., technical report) and functions in the SpawnIndex **R** package (Pacific Herring spawn index repository).*

	Technical report		R package
Description	**Section**	**Equation(s)**	**Function**
Egg conversion factor	4	8	`eggs_to_sb`
Surface spawn calculations	5	9 to 13	`calc_surf_index`
Surface egg density	5.1	11	`dens_surf`
Macrocystis spawn calculations	6	14 to 25	`calc_macro_index`
Number of eggs per Macrocystis plant	6.3	23	`eggs_macro`
Understory spawn calculations	7	26 to 32	`calc_under_index`
Understory egg density on substrate	7.1	26	`dens_under_sub`
Understory egg density on algae	7.1	27	`dens_under_alg`
Spawn-on-kelp calculations	9	36	`calc_sok_index`

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APPENDIX A SPAWN WIDTH ADJUSTMENTS

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

A.1 SURFACE SPAWN WIDTH

Surface surveys were the only survey type prior to 1988, while the majority of spawns since 1988 have been surveyed using SCUBA gear. Recall that we describe the spawn index as having two periods based on the predominant survey type: surface survey period from 1951 to 1987, and 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 from dive surveys when dive data are available (Schweigert et al. 1993). Our 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 skewed (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.

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In the rare instances where no dive data meet these criteria (e.g., outside SAR boundaries), we use the observed width W' from the surface survey. We update the aforementioned median width values periodically, not annually. Note that we use this process to update widths for spawns in previous years using current observations.

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 (i.e., a 'chain'). Segments refer to individual sections of line, which can be linked together to make complete transects.

During the late 1990s it became apparent 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 we think explains 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. For example, inner segments are replaced more frequently than seaward segments, and segments in some SARs are replaced more frequently than in other SARs. We 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 remote 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; $\tau_{ry} = 1.000$), others had all 1.15 m increment lengths ($\tau_{ry} = 1.150$), 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 width by multiplying the observed width by the correction factor

$$W_{t_{xsnry}} = W'_{t_{xsnry}} \tau_{ry}, \tag{A.1}$$

where W'_t is the observed spawn width for transect t, τ_{ry} is the spawn width correction factor for SAR r and year y (Table A.1), and W_t 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 to be transparent, and to prevent mismatches between the original data sheets and databases. It is now standard practice to re-measure transect segments annually to ensure that this issue does not reoccur due to another change in lead line manufacturing.

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:

1. Update 'intensity' from 0 to 1 for the records (there is 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.

Table A.1. Spawn width correction factors τ_{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).

	SAR						
Year	**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
τ	Spawn width correction factor	See Table A.1
W	Corrected spawn width	m

Spawn survey records prior to 1951 have additional missing or inaccurate egg layer information, and are unreliable for indexing purposes. Therefore, we exclude spawn data prior to 1951 from stock assessments.

While reviewing spawn index calculations and translating them from a **Microsoft Access** database to **R**, we found several cases where index data were being over-written with no documented reason. These updates have

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been omitted, and affected the following records:

1. Update E_j (i.e., number of egg layers; Table 5) to 2.1496 for the records (there are 15 records) in the year 1979, Statistical Area 2, and with intensity 4,
2. Update E_j to 0.5529 for the records (4) in the year 1981, Statistical Area 24, and with $E_j = 0.0$,
3. Update E_j to 1.3360 for the records (7) in the year 1982, Statistical Area 23, and with intensity 3,
4. Update E_j to 2.3300 for the records (41) in the year 1984, Statistical Area 24, and with intensity 0, and
5. Update E_j to 2.9800 for the records (14) in the year 1982, Statistical Area 27, and with $E_j = 0.0$.

In the first three cases, E_j was updated using intensity categories (Table 3); in the last two cases, E_j was updated using historical averages. These changes have negligible effects on spawn index values.

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