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 + 33 p.

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

RÉSUMÉ

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 + 33 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 (C-B), 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: les observations des frayères prélevées à la surface habituellement à marée basse, les observations sous-marines des frayères sur varech géant, Macrocystis (*Macrocystis* spp.), et 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 plusieurs étapes. Premièrement, nous quantifions la production d'œufs de hareng du Pacifique, ce qui est essentiel au calcul de l'indice du frai. Ensuite, 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 des stocks et par année afin de les harmoniser avec l'échelle spatiale et temporelle des avis scientifiques et de la gestion des pêches du hareng du Pacifique en C-B. De plus, nous identifions les incertitudes dans le calcul de l'indice de frai, et nous décrivons comment les utilisateurs peuvent télécharger le script pour calculer l'indice de frai à l'aide d'une base de données exemple. Il est à noter que « l'indice du frai » ne représente que les données brutes du relevé, et n'est pas mis à l'échelle par le paramètre d'échelle du relevé du frai; il s'agit donc d'un indice relatif de la biomasse reproductrice.

1 INTRODUCTION

Statistical age-structured stock assessment models rely on an indicator of relative population abundance to reconstruct a time series of absolute abundance. For Pacific Herring (*Clupea pallasii*), an index of relative population abundance is provided by monitoring the extent and intensity of the egg or spawn deposition throughout coastal British Columbia (BC), Canada (DFO 2019*b*). Model estimates of spawning biomass are derived from a statistical catch-at-age model fit to commercial catch, biological data, and the spawn index. Key results from the stock assessment model include stock reconstructions, estimated current stock status, and projected spawning biomass (DFO 2019*b*). Projected spawning biomass is used to inform fisheries management decisions. Note that the 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter q (DFO 2019*b*); therefore it is a relative index of spawning biomass.

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. Coast wide surveys of Pacific Herring spawn deposition in BC have subsequently provided a number of indices or proxies of the total spawning biomass for fisheries management for almost a century. This document describes the calculations used to convert spawn survey observations (e.g., spawn extent, number of egg layers, substrate type) to the spawn index for Pacific Herring in BC. The process and calculations described in this document have been described elsewhere, in either published or informal, internal documents. The objective of this document is to summarize and clarify the details necessary to understand spawn index calculations. 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.

We decided to document the spawn index calculations when we translated the process from a **Microsoft Access** database to an **R** (RCT 2017) script.

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

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

Pacific Herring spawn survey observations have a nested hierarchical structure: sampling quadrats and Macrocystis plants are nested within transects,

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

We calculate the spawn index in several steps. First, we quantify Pacific Herring egg production (section 2), which is critical to calculating the spawn index. Then we calculate the spawn index for each of the three aforementioned spawn survey types: surface (section 5), Macrocystis (section 6), and understory (section 7). Within each section, we separate each level of spatial aggregation (e.g., calculations at the quadrat, or transect level) into subsections. Finally, we combine the three spawn indices to get the total spawn index (section 8), and aggregate the total by stock assessment region and year (Figure 2).

2 EGG PRODUCTION

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

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

where *fecundity* is the number of eggs per kilogram of total female body weight in $\text{eggs} \cdot \text{kg}^{-1}$, *pFemale* is the proportion of spawners that are female, and ECF is in $\text{eggs} \cdot \text{t}^{-1}$. Thus, we convert eggs to the spawn index in tonnes by dividing the number of eggs by $ECF = \text{eggs} \cdot 10^8 \cdot \text{t}^{-1}$. Although Pacific

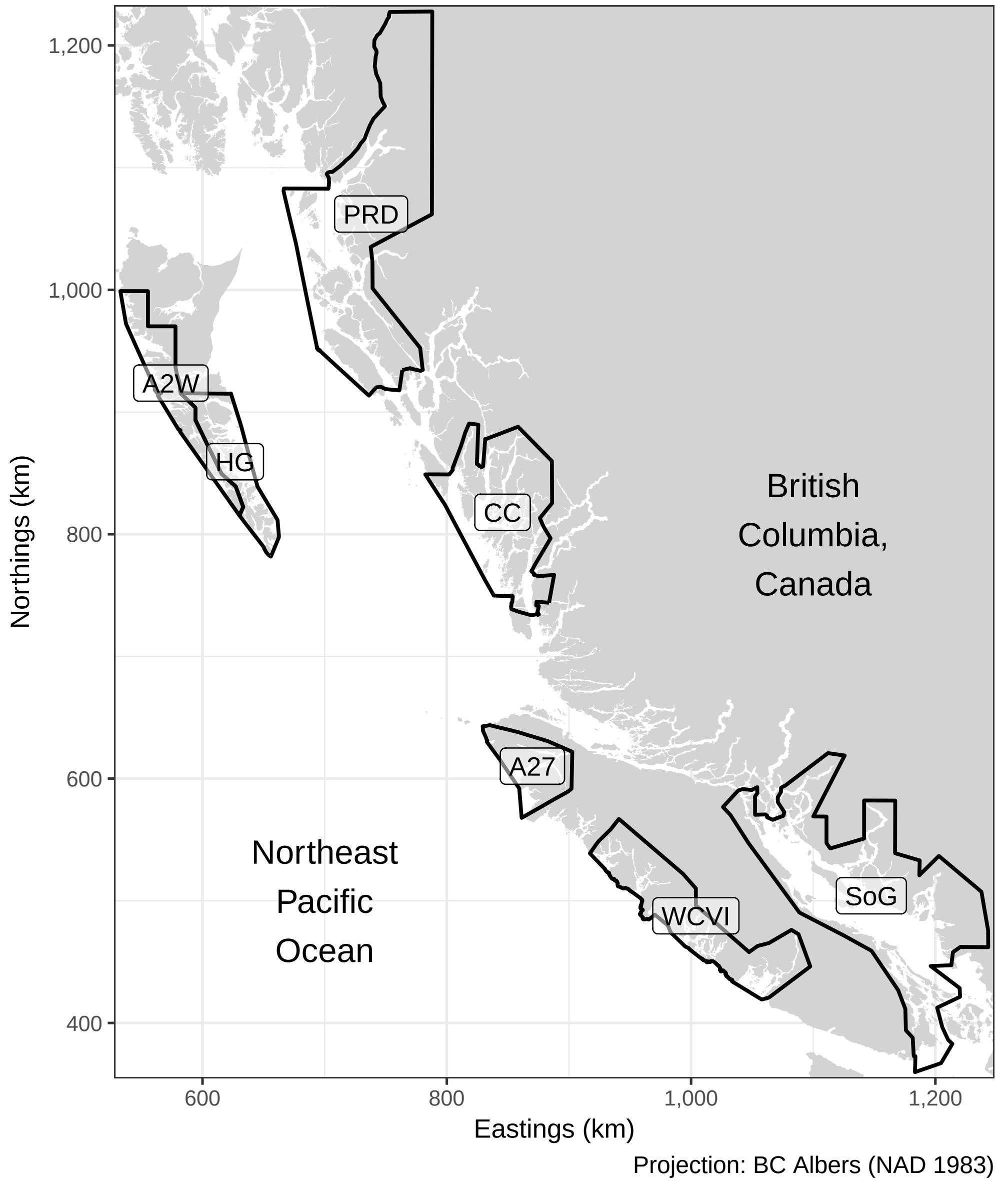


Figure 1. Spatial boundaries for British Columbia Pacific Herring stock assessment regions (SARs). There are five major SARs: Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). There are two minor SARs: Area 27 (A27),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

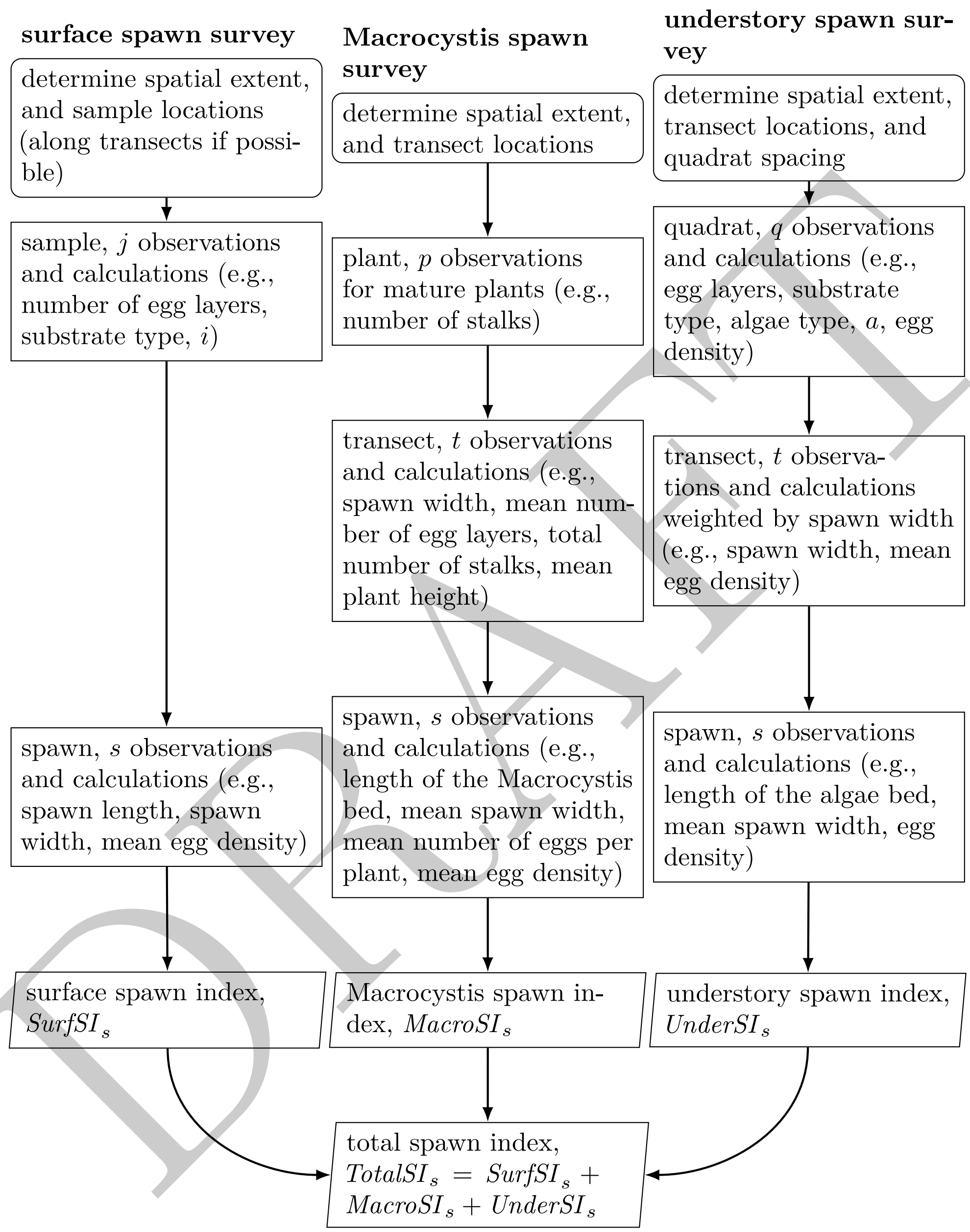


Figure 2. Sequence of Pacific Herring spawn index calculations for the three spawn survey types: surface, Macrocystis, and understory. Legend: rounded rectangles indicate the start, rectangles indicate observations and calculations, parallelograms indicate output, and arrows show the order of operation.

Herring egg production is affected by environmental variability and other factors (Tanasichuk and Ware 1987; Hay and Brett 1988), we assume that bias to the spawn index from Equation 1 is insignificant in most areas and years (Schweigert 1993; Ware 1985).

3 STATISTICAL FRAMEWORK

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

4 SAMPLING PROTOCOL

The following is a brief summary of the spawn survey sampling protocol in the Pacific Herring spawn survey manual. In BC, Pacific Herring primarily spawn in sheltered bays and inlets, depositing their eggs on rocks and algae between depths of 1.5 metres (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 the unique combination of year, location, and 'spawn number.' Spawns are numbered $s = 1, 2, 3, ..., S$ where S is the number of spawns at a given location in a given year. A distinct spawn is a continuous stretch of shoreline with no detectable break in egg deposition; this is the finest scale at which we calculate the spawn index. Most spawns are also characterized by longitude and latitude, as well as the start and end dates of spawning.

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 3). Thus, spawn 'length' refers to distances parallel to the shore, and 'width' refers to distances perpendicular to the shore. For example, Macrocystis bed length, *LengthMacro* and algae bed length, *LengthAlgae* refer to distances that Macrocystis beds and algae beds extend parallel to the shore, respectively.

When surveying Pacific Herring spawn, surveyors first determine the spatial extent of the spawn in terms of length of shoreline to be surveyed.

Figure 3. 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.

Next, transects are set perpendicular to the shore, beginning 200 m in from one end (or at the first permanent transect; see below), and spaced 350 m apart along the length. The end of the spawn is determined by the absence of eggs; the first transect is located 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. These transects are used to determine the spawn width, quadrat placement, and which Macrocystis plants to survey. In some cases, we adjust spawn width to improve spawn index estimates (appendix A). 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 stage of the tide.

Spawn surveys have a systematic sampling design. Most areas have 'permanent transect' locations recorded on charts which enable surveyors to place transects in the same location each year. When permanent transect locations are unavailable, surveyors set new transects based on the aforementioned criteria. New transect locations are digitized to make them available as permanent transect locations for future spawn surveys.

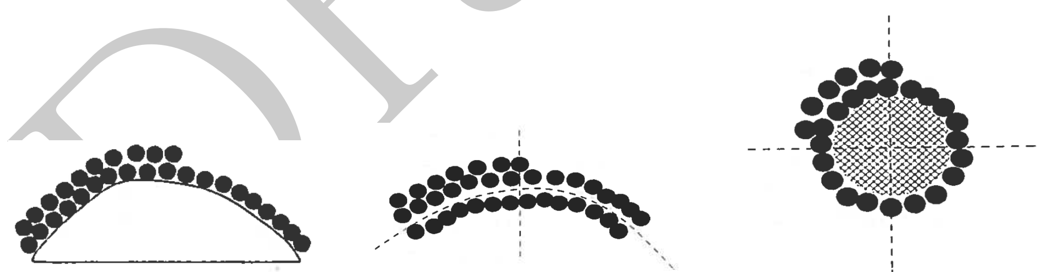
4.1 SURFACE SPAWN

Surface spawn surveyors use the aforementioned transect interval when possible, but the sampling interval relies on surveyor judgement and available resources. If the spawn area is sufficiently large, surface surveyors usually 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 type, number of egg layers (see below), and percent coverage. Surveyors may deploy a viewing box in shallow water, and at low tide a portion of the spawn may be visible for direct observation.

For eggs on substrate, one egg layer is a layer of eggs one egg thick over the entire spawned surface (Figure 4a). 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 4b); egg layers on round algae are counted across the diameter of the algae (Figure 4c).

4.1.1 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 1). 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 the number of egg layers, intensity was sometimes recorded after being officially discontinued in 1981. We have converted spawn intensity observations in the Pacific Herring spawn survey



(a) Substrate with 1.5 egg layers.

(b) Flat algae with 2.5 egg layers.

(c) Round algae with 2.5 egg layers.

Figure 4. Cross-sections showing the number of Pacific Herring egg layers on substrate, flat algae, and round algae. Diagrams copied with permission from the Pacific Herring spawn survey manual.

database from five to nine categories for spawns that used the five category scale between 1951 and 1969. 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.

4.2 MACROCYSTIS SPAWN

Macrocystis spawn surveyors take a census of Macrocystis plants within 1 m of the transect line, on both the left- and right-hand sides. We refer to the swath of substrate along Macrocystis transects as the transect swath, $Swath = 2\,\text{m}$. Divers categorize Macrocystis plants as either ‘mature’ or ‘immature’ based on stipe height; mature plants have stipes $\geq 1\,\text{m}$ 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 in Macrocystis plants. For each mature plant, divers record the number of stalks. For each

Table 1. Spawn intensity categories 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		
1928 to 1968	1969 to 1978	Egg layers
1	1	0.5529
	2	0.9444
2	3	1.3360
	4	2.1496
3	5	2.9633
	6	4.1318
4	7	5.3002
	8	6.5647
5	9	7.8291

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.

4.3 UNDERSTORY SPAWN

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. 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 surveys, 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.

5 SURFACE SPAWN

Surface spawn surveyors sample along transects or using their judgement, and we calculate spawn metrics at the sample j, and the spawn s levels (Table 2). Occasionally, we update surface survey data to fill-in missing egg layer information (appendix B).

5.1 SAMPLE OBSERVATIONS AND CALCULATIONS

Each sample j can have one or more substrate types. For each substrate type i, egg layers is

$$EggLyrs_i = Layers_i \cdot Proportion_i \tag{2}$$

Table 2. Notation for Pacific Herring spawn index calculations: surface spawn.

Description	Variable
Substrate type	i
Number of substrate types	I
Sample	j
Number of samples	J
Spawn	s

where $Layers_i$ is the number of egg layers on substrate i, and $Proportion_i$ is the proportion of substrate i covered with spawn. The total number of egg layers for each sample j is

$$EggLyrs_j = \sum_{i=1}^{I} EggLyrs_i \quad . \tag{3}$$

For the time period when spawn 'intensity' categories were recorded instead of estimating the number of egg layers, we convert intensity to the number of egg layers $EggLyrs_j$ (Table 1). Schweigert et al. (1997) developed a predictive model of surface egg density in thousands of eggs per square metre from egg layers using a linear regression model[1]

$$EggDens_j = EggLyrs_j \cdot 212.218 + 14.698 \tag{4}$$

where $EggDens_j$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$. Note that we only calculate $EggDens_j$ if $EggLyrs_j > 0$.

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

5.2 SPAWN OBSERVATIONS AND CALCULATIONS

For each spawn s, the mean egg density is

$$\overline{EggDens}_s = \frac{\sum_{j=1}^{J} EggDens_j}{J} \quad . \tag{5}$$

Two other metrics are required at the spawn level: the spawn length $Length_s$, and estimated width $\widehat{Width}_s$, both in metres. We set $\widehat{Width}_s$ to the first non-missing value of median pool width, median section width, median region width, or observed width (in that order; see subsection A.1). The surface spawn index is

$$SurfSI_s = \frac{\overline{EggDens}_s \cdot Length_s \cdot \widehat{Width}_s \cdot 10^3}{ECF} \tag{6}$$

where $SurfSI_s$ is in tonnes.

6 MACROCYSTIS SPAWN

Macrocystis spawn surveyors collect data for individual plants p, and we calculate spawn metrics at the transect t, and spawn s levels (Table 3).

Table 3. Notation for Pacific Herring spawn index calculations: Macrocystis spawn.

Description	Variable
Plant	p
Number of plants	P
Transect	t
Number of transects	T
Spawn	s

6.1 PLANT OBSERVATIONS

For each mature plant p, surveyors determine the number of stalks $Stalks_p$.

6.2 TRANSECT OBSERVATIONS AND CALCULATIONS

Several metrics are collected at the transect level: width $Width_t$, and transect swath $Swath = 2\,\mathrm{m}$, both in metres. We calculate transect area

$$Area_t = Width_t \cdot Swath \tag{7}$$

in square metres. In addition, divers collect summary metrics for mature Macrocystis plants: mean height $\overline{Height}_t$ in metres, and mean number of egg layers $\overline{EggLyrs}_t$. We also calculate the total number of stalks

$$Stalks_t = \sum_{p=1}^{P} Stalks_p \ , \tag{8}$$

and the total number of plants P_t.

6.3 SPAWN OBSERVATIONS AND CALCULATIONS

At the spawn level, we determine the length of the Macrocystis bed $LengthMacro_s$ in metres. If $LengthMacro_s$ is inadvertently not recorded, we set $LengthMacro_s$ to the spawn length $Length_s$. We calculate the mean width

$$\overline{Width}_s = \frac{\sum_{t=1}^{T} Width_t}{T} \tag{9}$$

in metres, and the total area

$$Area_s = \sum_{t=1}^{T} Area_t \tag{10}$$

in square metres. We also calculate the total number of plants

$$P_s = \sum_{t=1}^{T} P_t \quad , \tag{11}$$

the total number of stalks

$$Stalks_s = \sum_{t=1}^{T} Stalks_t \quad , \tag{12}$$

the mean height

$$\overline{Height}_s = \frac{\sum_{t=1}^{T} Height_t}{T} \quad , \tag{13}$$

and the mean number of egg layers

$$\overline{EggLyrs}_s = \frac{\sum_{t=1}^{T} EggLyrs_t}{T} \quad . \tag{14}$$

The mean number of stalks per plant is

$$\overline{StalksPerPlant}_s = \frac{Stalks_s}{P_s} \quad . \tag{15}$$

Haegele and Schweigert (1990) developed a predictive model of the number of eggs per plant in thousands from egg layers, plant height, and number of stalks per plant using a nonlinear multiple regression model

$$\overline{EggsPerPlant}_s = 0.073 \cdot \overline{EggLyrs}_s^{0.673} \cdot \overline{Height}_s^{0.932} \cdot \overline{StalksPerPlant}_s^{0.703} \cdot 10^3 \tag{16}$$

where $\overline{EggsPerPlant}_s$ is in eggs $\cdot\, 10^3 \cdot$ plant^{-1}. Mean macrocystis egg density in thousands per square metre is

$$\overline{EggDens}_s = \frac{\overline{EggsPerPlant}_s \cdot P_s}{Area_s} \tag{17}$$

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

$$MacroSI_s = \frac{\overline{EggDens}_s \cdot LengthMacro_s \cdot \overline{Width}_s \cdot 10^3}{ECF} \tag{18}$$

where $MacroSI_s$ is in tonnes.

7 UNDERSTORY SPAWN

Understory spawn surveyors collect data in quadrats, and we calculate spawn metrics at the quadrat q, transect t, and spawn s levels (Table 4). We calculate two separate estimates of egg density at the quadrat level: spawn on substrate, and spawn on algae a.

7.1 QUADRAT OBSERVATIONS AND CALCULATIONS

Haegele et al. (1979) developed a predictive model of substrate egg density in thousands of eggs per square metre from egg layers using a linear regression model

$$EggDensSub_q = 340 \cdot SubLyrs_q \cdot SubProp_q \tag{19}$$

Table 4. Notation for Pacific Herring spawn index calculations: understory spawn.

Description	Variable
Algae type	a
Number of algae types	A
Quadrat	q
Number of quadrats	Q
Transect	t
Number of transects	T
Spawn	s

where $SubLyrs_q$ is the number of egg layers on substrate in quadrat q, $SubProp_q$ is the proportion of substrate in quadrat q covered by spawn, and $EggDensSub_q$ is in eggs $\cdot\, 10^3 \cdot \mathrm{m}^{-2}$.

Each quadrat q can have one or more algae types. Schweigert (2005) developed a predictive model of algae egg density in thousands of eggs per square metre from egg layers, proportion of the quadrat covered by algae, and an algae coefficient using a generalized linear model. Algae coefficients account for the effect of algae morphology on Pacific Herring egg density (Table 5). The model takes the form (Schweigert 2005)

$$EggDensAlg_a = 631.316 \cdot AlgLyrs_a^{0.6355} \cdot AlgProp_a^{1.4130} \cdot Coef_a \tag{20}$$

where $AlgLyrs_a$ is the number of egg layers on algae a, $AlgProp_a$ is the proportion of the quadrat covered by algae a, $Coef_a$ is the coefficient for algae a, and $EggDensAlg_a$ is in eggs $\cdot\, 10^3 \cdot \mathrm{m}^{-2}$. The total algae egg density for quadrat q is

$$EggDensAlg_q = \sum_{a=1}^{A} EggDensAlg_a \ . \tag{21}$$

Table 5. Algae types, a and coefficients, $Coef$ for Pacific Herring understory spawn surveys (Schweigert 2005).

Algae type, a	Coefficient, $Coef$
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

The total understory egg density is

$$EggDens_q = EggDensSub_q + EggDensAlg_q \tag{22}$$

where $EggDens_q$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-2}$.

7.2 TRANSECT OBSERVATIONS AND CALCULATIONS

At the transect level, the mean linear weighted understory egg density is

$$\overline{EggDensL_t} = \frac{\sum_{q=1}^{Q} EggDens_q}{Q} \cdot Width_t \ \ . \tag{23}$$

where $Width_t$ is the spawn width in metres, and $EggDensL_t$ is in eggs $\cdot 10^3 \cdot \mathrm{m}^{-1}$. We calculate a weighted mean egg density because spawn width can vary greatly along the spawn length; a weighted mean ensures that transects contribute proportionally to their area. Note that we update spawn width to correct for an error regarding the assumed accuracy of transect lines used to measure spawn width for understory surveys between 2003 and 2013 (subsection A.2).

7.3 SPAWN OBSERVATIONS AND CALCULATIONS

At the spawn level, the sum of transect widths is

$$Width_s = \sum_{t=1}^{T} Width_t \ \ , \tag{24}$$

the mean width is

$$\overline{Width}_s = \frac{Width_s}{T} \ \ , \tag{25}$$

and the length of the algae bed is $LengthAlgae_s$, all in metres. If $LengthAlgae_s$ is inadvertently not recorded, we set $LengthAlgae_s$ to the spawn length $Length_s$. Thus, we assume that eggs on the substrate and eggs on algae are represented by the same length measurement. The sum of transect egg densities is

$$EggDensL_s = \sum_{t=1}^{T} EggDensL_t \ . \tag{26}$$

Understory egg density in thousands per square metre is

$$EggDens_s = \frac{EggDensL_s}{Width_s} \ . \tag{27}$$

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

$$UnderSI_s = \frac{EggDens_s \cdot LengthAlgae_s \cdot \overline{Width}_s \cdot 10^3}{ECF} \tag{28}$$

where $UnderSI_s$ is in tonnes.

8 TOTAL SPAWN

The total spawn index for each spawn s is

$$TotalSI_s = SurfSI_s + MacroSI_s + UnderSI_s \tag{29}$$

where $TotalSI_s$ is in tonnes (Table 6). Although we track the location (i.e., eastings, northings) and date for each spawn event, we aggregate the total spawn index by SAR r and year y

$$TotalSI_{ry} = \sum_{s=1}^{S} TotalSI_s \tag{30}$$

to align with the spatial and temporal scale for Pacific Herring science advice and fishery management in BC (DFO 2019*b*). Recall that the 'spawn index' represents the raw survey data only, and is not scaled by the spawn survey scaling parameter, q (DFO 2019*b*); therefore it is a relative index of spawning biomass. The spawn survey scaling parameter accounts for unobserved spawns, observed yet unquantified spawns, and wrongly quantified spawns.

9 SPAWN ON KELP

Spawn on kelp (SOK) fisheries collect Pacific Herring roe that adhere to algae such as Macrocystis after spawning. There are two types of SOK fisheries in BC: 'open-pond' in which 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 Pacific Herring, substantial quantities of eggs are removed that must be accounted for to manage populations for long term sustainability (Schweigert et al. 2018). Note that closed-pond operations also cause incidental mortality to spawning Pacific Herring (Shields et al. 1985), but we do not address this issue here. Thus, SOK fisheries present an issue in terms of their impact to the population, and accounting in stock assessment and monitoring. Although Pacific Herring stock assessments do not account for eggs removed by SOK fisheries at this time, there are a few options to account for the impact of SOK harvest. The most direct is to estimate the quantity of eggs removed from the population, and treat them as though they would have spawned and contributed to total spawning biomass.

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

Table 6. Notation for Pacific Herring spawn index calculations: total spawn. Legend: Region is the stock assessment region (SAR).

Description	Variable
Spawn	s
Number of spawns	S
Region	r
Year	y

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

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

$$SB_x = \frac{SOK_x \cdot eggKelpProp \cdot eggBrineProp}{eggWt \cdot ECF} \tag{31}$$

where SOK_x is the weight in kilograms of Pacific Herring SOK harvest for fishery x, *eggKelpProp* is the proportion of SOK product that is eggs, not kelp (0.88), *eggBrineProp* is the proportion of SOK product that is eggs after brining ($\frac{1}{1.13}$), *eggWt* is the average weight in kilograms of a fertilized egg $(\text{kg} \cdot \text{egg}^{-1})$, and SB_x is spawning biomass in tonnes.

10 SOURCES OF UNCERTAINTY

Like all biological models, spawn index calculations are affected by various potential sources of uncertainty including natural variability, observation error (e.g., bias, imprecision), and model structural complexity (Link et al. 2012). Three examples illustrate these sources of uncertainty. First, natural variability could affect Pacific Herring fecundity, and the sex ratio of spawning Pacific Herring (Equation 1). Fecundity could be influenced by time-varying biological processes such as the observed non-stationarity of weight-at-age, or a truncated age distribution. Second, observation error could affect input data such as the number of egg layers, while model structural complexity could affect estimated prediction model parameters, or the form of their relationship, or both (e.g., Equation 4). In addition, these prediction models are dated, and our understanding of these processes could have changed in the intervening years. Third, fixed parameters are used as data without error (e.g., Equation 4). Despite these assumptions and potential sources of uncertainty, the spawn index has typically been reported without quantifying uncertainty (but see Schweigert et al. 1993). Reporting the spawn index without uncertainty may create the wrong impression that the spawn index is observed data, whereas it is derived data with assumptions and uncertainties.

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

1. Investigating factors that influence fecundity and sex ratios;
2. Quantifying and reporting variability in estimated prediction model parameters and equations (e.g., Equation 4);
3. Bootstrapping observed input data (see Schweigert 1993); and
4. Conducting 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*a*). 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, in terms of data precision and accuracy. Sampling surveys trade off precision of estimated quantities versus survey effort or cost. Ideally, reducing survey effort does not result in biased target variable estimates. Therefore, understanding this trade-off is important if, for example, budget reductions cause a reduction in survey effort. Strategies to improve spawn survey efficiency could include:

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

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

11 FUTURE RESEARCH

Many of the parameters and prediction models used to calculate the spawn index are dated; these analyses could be checked with new information, and updated if required. Parameters include *fecundity*, *pFemale*, *eggKelpProp*, *eggBrineProp*, and *eggWt*. Prediction models include Equation 4, Equation 16, Equation 19, and Equation 20. In addition, the uncertainty in these parameters and prediction models should be propagated through the calculations to quantify uncertainty in the spawn index (see section 10). One approach to account for prediction model uncertainty is incorporating the underlying data that informs these equations into the spawn index calculations. Future work could review the assumed statistical framework, as well as investigate the assumption that eggs on the substrate and algae are independent, and can be safely added without bias.

12 DOWNLOAD

The **R** script to calculate the Pacific Herring spawn index, `SpawnIndex.R` is publicly accessible on the Pacific Herring spawn index repository. The repository includes instructions, and an example database of Pacific Herring spawn survey observations to use with the script. Essentially, the **R** script imports tables from the database, and follows the calculations described in this document. This document is meant to accompany the **R** script, which has complete details regarding how we calculate the spawn index. Sections in this document correspond to functions in the **R** script. For example, 'Surface spawn' (section 5) follows the **R** function `CalcSurfSpawn`. In addition, variable names in this document correspond to variable names in the script. Finally, we have commented the **R** script to promote accessibility and transparency.

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APPENDIX A SPAWN WIDTH ADJUSTMENTS

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

A.1 SURFACE SURVEYS

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

One issue with comparing these two partly overlapping protocols is that surface surveyors tend to underestimate spawn width (Hay and Kronlund 1987). To improve the consistency of spawn index estimates throughout the time period from 1951 to present, we adjust surface spawn width estimates using underwater estimates when available (Schweigert et al. 1993). Our preferred width is the median width from all dive surveys within 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 instead of the mean because the data are not normally distributed (Schweigert et al. 1993). If there are no dive data that meet those criteria, we use the median width from all dive surveys within the section, or within the region if there are no dives within the section. If there are still no dive data that meet those criteria, we use the observed width from the surface survey. We update the aforementioned median width values periodically, not annually.

A.2 UNDERSTORY SURVEYS

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 are replaced more frequently in some SARs that others). 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 and years are impacted equally by this issue (Table 7): some SARs and years had all 1.0 m increment lengths (no correction factor needed; $WidthFac = 1.0$), others had all 1.15 m increment lengths ($WidthFac = 1.15$), and others had a combination of 1.0 m and 1.15 m increment lengths which we assume to be in equal proportion ($WidthFac = 1.075$). We correct understory spawn widths by multiplying the observed transect width $WidthObs_t$ by the correction factor

$$Width_t = WidthObs_t * WidthFac \ . \tag{32}$$

Instead of updating the database permanently, we adjust spawn widths in the **R** script to be transparent, and to prevent a mismatch between the original data sheets and the database.

APPENDIX B SURFACE SPAWN MANUAL 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** script. This affects the following record:

Table 7. Spawn width correction factors *WidthFac* for Pacific Herring understory spawn surveys by stock assessment region (SAR) from 2003 to 2014. 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

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

Spawn survey records prior to 1951 have additional missing or inaccurate egg layer information, and are unreliable. Therefore, we do not include spawn data prior to 1951 in stock assessments.

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

1. Update *EggLyrs* to 2.1496 for the 15 records in the year 1979, statistical

area 2, and with intensity 4;

2. Update *EggLyrs* to 0.5529 for the 4 records in the year 1981, statistical area 24, and with *EggLyrs* = 0.0;

3. Update *EggLyrs* to 1.336 for the 7 records in the year 1982, statistical area 23, and with intensity 3;

4. Update *EggLyrs* to 2.33 for 41 records in the year 1984, statistical area 24, and with intensity 0; and

5. Update *EggLyrs* to 2.98 for 14 records in the year 1982, statistical area 27, and with *EggLyrs* = 0.0.

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