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Precision biometrics data of Atlantic salmon (*Salmo salar* L.) in commercial grow-out sea-cages: Manual sampling and infrared diode frames compared to processing plant

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ABSTRACT

One of the critical challenges that the global salmon farming industry will confront when upscaling production is accurate biomass control. Commercial salmon farming requires a significant level of certainty regarding fish count, average weight measurement, live weight distribution, and other production indicators. A reliable control system for assessing the biomass of farmed Atlantic salmon is essential for sustainable and cost-effective precision aquaculture. A study was done in four production sea-cages in a Chilean Atlantic salmon marine grow-out farm to estimate the average weight and frequency distribution utilizing the Vaki Biomassdaily® diode frames as an alternate technology to manual weight measurement. From post-smolt reception to fish harvest, diode frames were put in each sea-cage in a secure position for 15 months. There were no significant changes in length or average weight between manual sampling and frame estimate. The mean degree of accuracy for the average weight estimation was 98.83 % for the frames utilized in the four sea cages. The diode frames also achieved a high degree of precision in predicting the frequency distribution of fish. There were no statistically significant variations between the distribution variances of the diode frame measurements and the distribution variances of the fish received at the fish processing facility (FPF). The maximum difference between the average weight calculated by the frames and the average weight of the fish received in the processing facility was 2.4 %, with 99.66 % being the highest accuracy with only 19 g of difference. We determined that diode frames might replace manual weight assessments with greater reliability for growth monitoring and production management. To assure the optimal performance of the diode frames in terms of accuracy and precision for future commercial-scale validations in the salmon farming business, the development of a standard best practice manual is necessary.

1. Introduction

Accurate biomass control is one of the critical challenges that the global salmon farming industry will confront when upscaling production (Haugholt et al., 2010; Føre et al., 2018; Li et al., 2020). Commercial salmon farming requires a significant level of certainty regarding fish count, average weight measurement, the live weight distribution of cultivated fish populations (Ruff et al., 1995), condition factor, and fish growth rate (Jones et al., 1999). The development of a reliable control system for assessing the biomass of farmed fish is essential for sustainable and cost-effective precision aquaculture (Little et al., 2015; Føre et al., 2018; Antonucci and Costa, 2020).

Notwithstanding the above, global salmon farming companies show differences in inventory and biomass control that persist today (Jensen et al., 2010; Misund, 2018; Sernapesca, 2019). Losing control of the fish count and biomass is attributable to several factors, such as: problems in hatcheries with fish counting equipment calibration (Fewings, 1994), inaccurate body weight estimation and grading (Gutreuter and Krzoska, 1994), low supervision during the counting of fish before transport, smolt reception recording errors, theft (White, 2016), escape of fish due to damaged nets (Thorstad et al., 2008; Føre and Thorvaldsen, 2021) and, lastly, mortality events that affect an accurate quantification of dead fish biomass (Solis, 2009; Aunsmo et al., 2013; Díaz et al., 2019).

To fully comprehend the progress and patterns of fish growth,

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biomass growth is one of the major production indicators for fish farmers, followed by the feed conversion factor (Aunsmo et al., 2014). Priority areas of improvement and management of fish growth include: identification of causal factors, quantifying effects that predict fish growth, as well as comparative evaluation of growing between genetic strains, breeding programs, photoperiod regimes, stocking densities, types of diets, sea-cages, and site locations (Björnsson et al., 1995; Rye and Mao, 1998; Fleming et al., 2002; Turnbull et al., 2005; Neely et al., 2008; Aunsmo et al., 2014).

Although difficult due to the thousands of salmonids farmed at sea-based commercial production sites, it may be feasible in the future to quantify the live weight biomass of each farmed fish (Nilsson et al., 2013; Difford et al., 2020). So farmers must operate sampling methods that allow them to estimate with high confidence the average biomass in live weight and fish growth in a productive unit through a representative sample of the population (Beddow et al., 1996; Zion, 2012; Vaki Aquaculture Systems, 2016; Difford et al., 2020).

Quantitative measurement methods used in salmon farms to estimate the mean weight and size distribution of individual fish in grow-out sea-cages are: 1) Manual netting for sampling or recording using mechanical or electronic scales (Gutreuter and Krzoska, 1994; Ross et al., 1998; Nilsson and Folkedal, 2019), 2) Size estimation image technology using stereoscopic cameras or diode frames (Lines et al., 2001; Costa et al., 2006; Difford et al., 2020), and 3) Estimators by acoustic systems (Juell and Westerberg, 1993; Soliveres, 2015; Terayama et al., 2019). Hydroacoustics and image measurement are known as noninvasive methods used for fish body measurement (Kundsen et al., 2004; Kim et al., 2018).

To present, published studies on salmon growth imply that the robustness of current production software models used in commercial aquaculture can be enhanced. So far, it has been considered nonlinear effects on growth and including abiotic factors like temperature, light, and latitude (Aunsmo et al., 2014). Recent scientific studies have shown that production planning software for Atlantic salmon (*Salmo salar* L.) tends to overestimate the average weight and growth based on the food consumed. Consequently, when a disease outbreak affects feed conversion and fish growth, corrective actions are not applied if a representative fish sample is absent (Føre et al., 2016). These issues may lead to a loss of control of the fish biomass precision with a subsequent loss of productivity (Føre et al., 2016). Based on the described background, to maintain effective control of the production results, it is necessary to continuously adjust the mathematical projection models with the current weights of the fish. This procedure will allow the farmer an early detection of productive deviations or losses during the cycle and not when it is too late to make decisions and take actions on the production strategy (Føre et al., 2016).

Capturing fish with dip nets or manual netting, an empirically verified handling procedure by salmon producers, is used to evaluate fish growth (Ross et al., 1998). Manual netting is a time-consuming technique and causes stress when handling fish, which generates some bias (Nilsson and Folkedal, 2019; Yogev et al., 2020). Usually, fishes swimming near the surface are easier to catch and are, as a consequence, often the only ones measured (Taksdal et al., 1998; Ramsay et al., 2009; Nilsson and Folkedal, 2019). In some cases dip net sampling method can have up to 10 % deviation between the average live weights recorded at sea-cages and biomass reported by the salmon processing facilities (Difford et al., 2020). Aware that accurate biomass control represents a relevant indicator to evaluate productivity levels (faster growth, reduction of the feed conversion factor), a commercial production scale study was carried out during 2014 and 2015 using diode frames for fish sampling (López-Riveros, 2016). These types of equipment are an alternative non-invasive method for estimating average live weights and live weight frequency distributions compared to traditional manual weight assessments. Therefore, the objective of the current study was to compare the growth measurement of Atlantic salmon reared in sea-cages by using a diode frame technology and the conventional method. This study will determine if it could be advantageous for sea-cage salmon farms to adopt diode frames for salmon biomass assessment.

2. Material and methods

The research was carried out in the Melinka district of Chile's Aysén Region on a commercial Atlantic salmon marine farm. This sea-cage farm was selected based on their experience with biomass estimators.

2.1. Fish and sea-cages

The steel-framed sea-cages were 30 × 30 m in size, with 20-meter-deep fishnets. This study used four sea-cages, numbered 101, 102, 103, and 104, that were part of a larger framework of twelve sea-cages (Fig. 1). Each sea-cage holds about 50,000 fish in 18,000 m^3 of water.

The sea-cages chosen for the study (Fig. 1), which are placed directly in front of the farm's barge, were selected from a total of twenty-four sea-cages holding 1,200,000 post-smolts of Atlantic salmon. The study covered a population of 202,897 fish, which is 16.9 % of the entire population of the commercial grow-out farm.

2.2. Biomassdaily® diode frames functioning

Four square metal sea-cages were used to house the biomass estimation diode frames and data transmission antenna system. The aquaculture equipment supplier, Vaki Chile, provided the Biomassdaily® diode frames system, which consisted of the following elements and equipment: Four units of standard size Vaki diode frames model FR550 (0.65 m height per 0.60 m width); Four 30 m cables for diode frame connections; Four 8 mm diameter with 40 m long holding lines; Four wireless transmission antennas or Vaki Remote Box; Four stainless steel pedestal supports of 1.5 m height to anchor the transmission antennas; Electrical network of 200 m of PVC pipe and cables connected to a 220v power distribution board; One Biomassdaily® base transmission antenna; One CPU with Bio-3000 software that commands the information generated by the frames; an Internet platform for viewing and downloading data at www.biomassdaily.com; and a brush and a bucket for cleaning and maintaining the diode frames.

A 12-volts electric supply powered the Biomassdaily® diode frame, which was put in each sea-cage at a depth of about 6 m. Each of the diode frames requires 1 amp of power to operate properly, which was supplied via a 220-volt electrical network. The transmission antennas or remote boxes were installed in each of the selected sea-cages and included an internal battery that allowed operation for up to 8 h in the

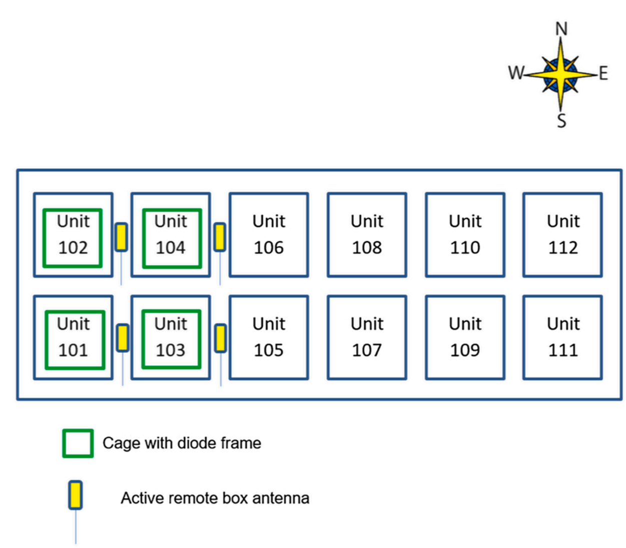

Fig. 1. Layout of the farm sea-cages where the diode frames were installed.

event of a power outage, as well as an internal current regulator that converted 220 V to 12 V, the voltage at which the equipment operates.

2.3. Weight and growth estimation by diode frames

There were three sets of infrared light gates or panels on the diode frame. Each gate has a 96-element LED array and a directly opposite receiver array (PHD) on the frame. The diode frame's upper face includes the frame's serial number on it, and it has an electronic control board for storing the frame data within it, in addition to the PHDs. When a salmon passes across the infrared scanner, and the frame is properly positioned, an instant image of the fish is obtained, and the automatic image processing software calculates the fish's size (Lekang, 2007; Haugholt et al., 2010; Folkedal et al., 2012; Zion, 2012). From the post-smolt phase until fish harvest, the diode frame is submerged in the sea-cage to collect daily weight samples (Folkedal et al., 2012; López-Riveros, 2016; Difford et al., 2020) and to build a historical growth trend of the cultured fish, and this biometric data is uploaded and stored in the www.biomassdaily.com cloud. Specific production data is provided by the diode frame measurements, like: individual fish total length, exact time of each fish measurement, individual and average fish weight, individual and average condition factor, coefficient of variation, tables, and graphs that allow data analysis of live or gutted fish biomass and growth comparison between fish in sea-cages (Vaki Aquaculture Systems, 2016).

Once all of the smolts had been stocked, sentinel or dummy frames were placed within each sea-cage to ensure that the salmon had adapted to the presence of the diode frames. Four working diode frames were set up when the fish at the site reached 0.3 kg average weight and kept in the same unit until an approximated harvest weight of 5.5 kg. The working diode frames were permanently submerged inside each sea-cage throughout the 15-month seawater production cycle. The diode frames were only taken out of the sea-cages once a week to clean the internal scanner panels and when sea lice bath treatments were applied to the fish in the sea-cages (López-Riveros, 2016).

The study consisted of sampling the total length of individual fish, estimating the weight of individual fish, and estimating the average fish population weight held in the first four production units of the grow-out sea site (Fig. 1). The diode frames required a minimum of 500 fish measurements to ensure reliable and accurate data for average weight and live weight estimation for each sea-cage. This fish quantity was equivalent to measuring 1 % of the total fish population in the sea-cage every day (Vaki Chile, 2020). The frame estimated the initial average weight from the first day of installation, and it was compared on a monthly basis with the average fish weight obtained from manual recordings performed by farm staff using scoop nets. In turn, the growth rates obtained by the diode frames and by manual weighing sampling were compared. The weight differences in grams and weight differences in % during the same sample date were used to compare the average weight of fish from each sea-cage. The diode frame data for weight comparison was the result of a linear regression of the growth trend graph final weight obtained during the last 30 days of fish measurements.

Frame data processing and analysis.

The diode frame consisted of infrared lights that form a grid of rays within the frame. Every time a fish swam through the frame, a digital image of the fish was recorded. The fish image was then used for the measurement of the length and width of the fish, and the weight (W) was as:

$$W = \frac{7.3xDxL^2}{1000} \tag{1}$$

where, 7.3 = constant for Atlantic salmon; D = fish width; L = fish total length.

Each diode frame recorded the daily measured information of all valid fish that swam throughout the infrared scanner. Both the fish's width and the total length were measured, and thereafter, the individual weight was calculated through an algorithm using the Vaki frame firmware version 1.21., specially designed for Atlantic salmon. Valid measurements were for individual fish that performed at a standard swimming speed (Johannesen et al., 2020) through the frame. The equipment was designed to collect data from fish swimming at one body length per second and perpendicular to the infrared diode frame (Vaki Chile, 2020). All measurements that did not meet the above standard were considered invalid samples and were not included in the measurement data source. The causes of the elimination of a given fish measurement are shown in Table 1. The elimination rate of invalid samples in the diode frames was between 50 % and 60 % (Vaki Chile, 2020).

All fish that individually swam through the frame's infrared rays, and were considered a valid measurement, were stored in the control panel on the top side of the frame, which transmitted the data to a remote antenna via a submarine cable. The remote antenna, anchored to a pedestal located in the corridor of each study sea-cage, wirelessly transmitted data to the Biomassdaily® base antenna installed in the feeding pontoon office of the site (Vaki Aquaculture Systems, 2016). The reception antenna received fish measurements from the frame and stored the data in the Vaki Bio-3000 software on a laptop PC. This software commands the system functions, downloads data from the diode frames, and uploads the fish measurements from the local site computer to a cloud server. The data gained by the diode frames was downloaded automatically every hour to the computer software (Vaki Aquaculture Systems, 2016). The general application and network requirements for the Vaki Biomassdaily® computer are shown in Table 2.

2.4. Weight and growth estimation by Manual assessment

The farm's manual fish weight assessment followed standard operating procedures for fish capture, holding, identification, and total length and weight measurement.

For the fish capture from the sea-cages, a 30 mt 7 mm fish dip net was employed to make the cut-off wall and catch the fish inside the sea-cage net. Once a group of approximately 10,000 fish was cornered, a smaller rectangle-shaped net was used to catch a smaller sample of around 2000 individuals. No feed was used to attract the fish to the net. The fish from each of the four sea-cages, on average, were manually weighed seven times during the 15-month production cycle. Approximately 200 fish were randomly assessed during each weight assessment per sea-cage.

2.4.1. Equipment and materials used for the manual assessment

Waterproof datasheets were employed for manually recording fish measurements. A measuring board with a ruler and calipers was used for fish sampling. A watch type mechanical Scale 12 kg per 50 g Pesamatic® Brand model DSM 12 K was used for fish weighing. A holding tank (e.g., a bucket, a Nally® bin, or another suitable container) for stocking the fish. A portable aerator (with spare batteries) with an air hose and air

Table 1
Causes for discarding fish measurements registered by the Vaki® diode frames.

N°	Fish measurements exclusion causes
1	The fish stay for too long inside de frame.
2	Frame not in use.
3	Two or more fish swim side by side.
4	The fish swims and returns inside the frame.
5	Distorsioned image of the fish.
6	Rejected because of condition factor: too high or too low, for instance two fish swim together or the fish does not swim straight through the diode frame.
7	Two fish together, seen from the top.
8	Two fish together, seen from the sides.
9	Fish swims too low or close to the bottom of the frame, a complete image of the fish cannot be obtained.
10	Uneven swimming speed.

Table 2
General application and network requirements for the Vaki Biomassdaily laptop PC.

Server description	
Download speed: min = 200 kBps (kilobytes) = 1.6Mb (megabit) recommended = 400 kBps (Kilobytes) = 3.2Mb (megabit)	
Upload speed: Min = 125 kBps (kilobytes) = 1Mb (megabit) recommended = 200 kBps (kilobytes) = 1.6Mb (megabit)	
For programs: Teamviewer (remote support); Upload of data by FTP, Automatic updates.	
Network requirements	
Bandwidth consumption (Upload / Download) Kbps.	200 kBps (kilobytes)/ 400 kBps (Kilobytes)
Ports and Protocols.	21, 50000, 50,001
Operating system.	Windows 7 pro sp1 / Windows 10 pro
Hours and frequency of communications between Client and Server.	Every 1 h
Size of the data package.	1Mb of data per day
Hardware and Software to Use.	
Hardware model. (Indicate MAC).	68-14-01-60-62-7D
Software Type.	BIO3000

stone provides oxygen to the stocked fish. Another container is for storing fish specimens for sedation with 20 % Benzocaine.

2.4.2. Comparison between frame estimation and manual assessment

Estimates of total length and weight of the frames fish measurements were contrasted with biometric data from manual fish sampling. The data comparisons were made monthly from the reception of the smolt until the moment of harvest, which included a production cycle of fifteen months. A data table was developed that shows the differences between the total number of fish sampled by each method per month; the total length and average weight, including standard deviation, for each method; and the estimates of partial specific growth rate (SGR) and accumulated specific growth rate. Fish measurements were performed with a daily frequency with the Biomassdaily® diode frames for the four sea-cages understudy. However, for comparative purposes, the diode frame's biometric measurements were reported at the same frequency and exact date as the manual weight assessments for each one of the sea-cages.

2.5. Production indicators analyzed

2.5.1. Fish allometric growth and condition factor used for manual weight assessment

The fish allometric growth was calculated with the power function:

$$W = aL^b \tag{2}$$

where, W was the dependent variable weight (morphometric measured character), and L was the independent variable (Total Length), a was the intercept, and b was the growth coefficient (Fuiman, 1983). If $b = 3$, the growth was isometric, if $b > 3$ means allometric growth was positive, and if $b < 3$ the allometric growth was negative (Fuiman, 1983).

The condition factor of each individual fish during the manual recording with the measuring board was calculated measuring total length in relation to individual weight. The widely equation used by the aquaculture industry is the Fulton Factor (K):

$$K = 100\frac{W}{L^3} \tag{3}$$

2.5.2. Diode frame fish growth trend, condition factor and average weight

The daily biometric fish measurements obtained by the diode frames were arranged into a growth trend graph on the cloud server. The daily number of validly transmitted biometric measurements of the fish, as well as the mean daily water temperature and depth of the frame in the sea-cage, were all quantified.

The formula used by the diode frame to calculate the fish condition factor (CF) is different to the Fulton (K) formula used in manual sampling. The fish condition factor was calculated measuring total length in relation to individual width:

$$CF = 0.515x\frac{D}{L} \tag{4}$$

Where: 0.515 = constant of condition factor; D = fish width; L = fish total length.

The diode frame software calculates the average weight of the fish population using all valid fish measurements. The software calculated the average daily weight of a fish population stocked in a sea-cage based on the average weight obtained during five days of sampling: the present day, two days back, and two days forward (Vaki Aquaculture Systems, 2016). If the daily weight is the last one before harvest, the software calculates valid fish measurements from the present day and two days back.

2.5.3. Diode frame live weight distribution

The live fish weight distribution, measured by the diode frame, was calculated similarly to the average weight. The live fish weight distribution was averaged for the samples collected during five days of measurements: the present day, two days back, and two days forward. The software allows the user to filter data based on minimum or maximum values for fish weight and condition factor (Vaki Chile, 2020).

2.5.4. Specific growth rate on diode frame and manual assessment

The following formula was used to calculate the specific growth rate:

$$SGR = \frac{(lnWf - lnWix100)}{t} \tag{5}$$

where: lnWf = the natural logarithm of the final weight; lnWi = the natural logarithm of the initial weight; t = time (d) between lnWf and lnWi.

2.5.5. Diode frame live average weight at harvest

With the historical linear regression, obtained from the Vaki Biomassdaily® online data cloud, was determined the final weight of each group of fish per sea-cage. The fish weight trend line for the last 30 days was analyzed before fish were harvested from each sea-cage to calculate the final fish average weight. The fish weight was accepted if there was a representative sample (see description at 2.5.6), and the trend was positive.

2.5.6. Diode frame representative sample (*)

A representative sample for the diode frame requires that at least 200 fish measurements were taken per day. And according to the weight graph versus time, at least for the last five days, the samplings were random and with a homogeneous distribution during the day (Vaki Chile, 2020).

2.6. Statistical analysis

The coefficient of determination (R^2) was calculated for the comparison of the variables of length and average weights of salmon by the two sampling methods and to partition explained and unexplained variance. Finally, a Chi-square test was used to determine whether or not there were significant statistical differences between the diode-generated distribution frequencies of the fish and the fish processing facility's measurements (FPF).

The weight frequency distribution estimated by the diode frames at the farm site and those recorded at the FPF were broken down into 0.5 kg weight intervals, yielding 12 sets of weight distributions. The Z-test for means of two samples was used to evaluate the degree of accuracy of the biomass estimators. And whether or not there were significant differences compared to the manual weight assessments as to the degree of accuracy of live average weight compared to the average fish weight in the FPF and the distribution frequency of the different fish sizes.

3. Results

3.1. Data from the fifteen-month seawater cycle period

3.1.1. Fish average weight by both fish sampling methods

Tables 3–6 show the general chronologies and comparative findings of manual weight assessments and diode frame measurements over the fifteen-month research period. The detailed results reported for each sea-cage include average weight, standard deviation, sample size (N), partial specific growth rate, and accumulated specific growth rate (Tables 3–6). Comparatively, recorded data for sea-cage 101 was similar between traditional assessment and diode frame (Table 3). It may also be seen in the recorded data for sea-cages 102 (Table 4), 103 (Table 5), and 104 (Table 6). Due to a technical issue, the infrared diode frame positioned in the sea-cage 104 had no weight records throughout the first 5-months of the investigation (Table 6).

3.1.2. Growth trend graphs by both fish sampling methods

Fig. 2 depicts the fish growth trend graphs obtained from both sampling procedures. The related graphs show the average weights and standard deviations recorded for the four surveyed populations stocked in sea-cages 101, 102, 103, and 104. In each of the graphs, the fish mean weights obtained from the diode frames for a particular sampling date were estimated from an output trend graph. The 15-month study period runs from the smolt reception date (month zero) through the fish harvest date, and both sampling methods were quite similar for the fish average weight estimation (Fig. 2).

3.1.3. Comparison of fish total length and average weight by both sampling methods

The four sea-cages understudies yielded a positive correlation between the variables of total length and the average weight. The average R^2 value of the variable total length in both sampling methods was 0.9953 for the four sea-cages under study (Fig. 3). This R^2 result indicates that, at 99.53 %, the variation of the variable total length of the sampling with a diode frame is related to the fluctuation of the variable total length of the manual sampling and vice versa (Fig. 3). Both sample strategies had an average R^2 value of 0.9967 for the variable average weight (Fig. 4). This R^2 demonstrates that the variation of the variable average weight of the diode frame was caused by the variation of the variable average weight of the manual sampling, and vice versa, at a proportion of 99.67 % (Fig. 4).

3.2. Data from the fish processing facility (FPF)

3.2.1. Net biomass received in the FPF

The final net biomass registered at the fish processing facility (FPF) for the four sea-cages in the study was 1,026,340 kg (Table 7). The fish

Table 3
Average weight, standard deviation, sample size (N), partial and accumulated specific growth rate (SGR) obtained from manual weight recording compared to Biomassdaily® diode frame measurements of the fish from sea-cage 101. (-) means no information reported.

	Sea-cage 101 Traditional assessment					Sea-cage 101 Diode frame estimation				
Month – Sample date	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)
1 -May 5th 2014	–	–	–	–	–	–	–	–	–	–
1 -May 21 st 2014	–	–	–	–	–	–	–	–	–	–
1 - May 24th 2014	–	–	–	–	–	–	–	–	–	–
2 - June 7th 2014	297	44	283	1.67	1.67	273	48	2950	1.53	1.53
3 - July 7th 2014	–	–	–	–	–	–	–	–	–	–
4 - August 26th 2014	747	111	286	1.15	1.38	758	143	6587	1.28	1.39
5 – no sampling	–	–	–	–	–	–	–	–	–	–
6 - October 11th 2014	–	–	–	–	–	–	–	–	–	–
6 – October 18th 2014						–	–	–	–	–
7 - November 14th 2014	1570	251	268	0.93	1.22	1542	294	13,183	0.89	1.21
8 - December 22nd 2014	–	–	–	–	–	–	–	–	–	–
9 - January 19th 2015	2408	500	303	0.65	1.09	2241	547	3707	0.57	1.06
10 - February 17th 2015	–	–	–	–	–	–	–	–	–	–
11 - March 27th 2015	3758	661	229	0.66	1.01	3542	850	1129	0.68	0.99
12 – no sampling	–	–	–	–	–	–	–	–	–	–
13 - May 5th 2015	–	–	–	–	–	–	–	–	–	–
13 - May 31 st 2015	4875	1125	251	0.4	0.91	5075	1136	6185	0.55	0.92
14 - June 29th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 1 st 2015	–	–	–	–	–	5259	1270	2351	0.11	0.87

Table 4
Average weight, standard deviation, sample size (N), partial and accumulated specific growth rate (SGR) obtained from manual weight recording compared to Biomassdaily® diode frame measurements of the fish from sea-cage 102. (-) means no information reported.

	Sea-cage 102 Traditional assessment					Sea-cage 102 Diode frame estimation				
Month – Sample date	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)
1 -May 5th 2014	–	–	–	–	–	–	–	–	–	–
1 -May 21 st 2014	–	–	–	–	–	–	–	–	–	–
1 - May 24th 2014	230	22	268	3.13	3.13	169	29	1276	1.03	1.03
2 - June 7th 2014	–	–	–	–	–	–	–	–	–	–
3 - July 7th 2014	466	66	303	1.05	1.63	374	42	1222	1.81	1.4
4 - August 26th 2014	763	122	270	0.99	1.41	712	143	546	1.29	1.36
5 – no sampling	–	–	–	–	–	–	–	–	–	–
6 - October 11th 2014	–	–	–	–	–	–	–	–	–	–
6 – October 18th 2014	1538	285	251	0.88	1.22	–	–	–	–	–
7 - November 14th 2014	–	–	–	–	–	1508	314	25,471	0.94	1.21
8 - December 22nd 2014	–	–	–	–	–	–	–	–	–	–
9 - January 19th 2015	2921	638	290	0.68	1.05	–	–	–	–	–
10 - February 17th 2015	3707	761	247	0.61	1.01	2813	598	27,535	0.66	1.04
11 - March 27th 2015	–	–	–	–	–	3571	794	3862	0.61	1.0
12 – no sampling	–	–	–	–	–	–	–	–	–	–
13 - May 5th 2015	–	–	–	–	–	–	–	–	–	–
13 - May 31 st 2015	–	–	–	–	–	–	–	–	–	–
14 - June 29th 2015	5807	1053	271	0.41	0.87	–	–	–	–	–
15 - July 1 st 2015	–	–	–	–	–	–	–	–	–	–
15 - July 13th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 15th 2015	–	–	–	–	–	5524	1484	494	0.4	0.86
15 - July 19th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 20th 2015	–	–	–	–	–	5605	1425	470	0.29	0.85

biomass was obtained by multiplying the average weight resulting from the individual weighing of the bled fish in the FPF times the total number of fish counted for each sea-cage (Table 7). The harvested fish were transferred by wellboat from the sea farm to the FPF and entered for humane slaughter the day after their harvest day (Table 7). The fish fastening period before the harvest was of only one day for the four sea-cages.

3.2.2. Gross biomass received in the FPF

The final gross biomass received in the FPF for the four sea-cages in the study was 1,103,591 kg (Table 8). This biomass was obtained by dividing by 0.93 the FPF average net weight resulting from each sea-cage (Tables 7 and 8), which represents a 7 % loss in live fish weight because of bleeding (Smith, 1966), scaling, and fasting of the fish (Table 8).

3.2.3. Comparison of live average weight between both sampling methods and the FPF

When compared to the true gross biomass processed in the FPF, the manual weight sample projected with FishTalk® software yielded a −0.63 % difference (6.96 kilos less) and the diode frame estimation yielded a −0.18 % difference (1.94 kg less). The underestimating of fish biomass in the diode frames was mostly explained by the extra fish count recorded in the FPF for all four sea-cages compared to the farm inventory (Table 9).

The variance of the mean weight of the fish estimated by the diode frames in the sea-cages was less than 3 % of the mean real weight obtained in the FPF (Table 10). The highest accuracy of diode frame average weight estimation was 99.66 % in sea-cage 102, with only −19 g of difference with the real mean weight, equivalent to a difference of −0.34 % (Table 10). The lowest accuracy of diode frame weight estimation was in sea-cage 101, which had an average weight difference of −128 g with the mean weight given by the FPF, with an absolute error of −2.38 % (Table 10).

3.2.4. Live weight distribution estimated by diode frames compared to FPF

The distribution interval is presented in pounds (lb) because this is the unit of measurement used by salmon farming companies to classify the sizes of fish that will be marketed (Fig. 5). The maximum deviation or error per frequency interval between the frequency distribution of

Table 5
Average weight, standard deviation, sample size (N), partial and accumulated specific growth rate (SGR) obtained from manual weight recording compared to Biomassdaily® diode frame measurements of the fish from sea-cage 103. (-) means no information reported.

	Sea-cage 103 Traditional assessment					Sea-cage 103 Diode frame estimation				
Month – Sample date	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)
1 -May 5th 2014	183	27	102	1.49	1.49	–	–	–	–	–
1 -May 21 st 2014	–	–	–	–	–	–	–	–	–	–
1 - May 24th 2014	–	–	–	–	–	–	–	–	–	–
2 - June 7th 2014	322	62	275	1.71	1.61	297	72	744	1.48	1.48
3 - July 7th 2014	–	–	–	–	–	–	–	–	–	–
4 - August 26th 2014	795	127	301	1.13	1.34	755	160	2283	1.17	1.3
5 – no sampling	–	–	–	–	–	–	–	–	–	–
6 - October 11th 2014	1201	202	239	0.9	1.23	1172	251	35,082	0.96	1.22
6 – October 18th 2014	–	–	–	–	–	–	–	–	–	–
7 - November 14th 2014	1857	419	254	0.61	1.06	–	–	–	–	–
8 - December 22nd 2014	–	–	–	–	–	1853	365	28,715	0.64	1.06
9 - January 19th 2015	2832	570	173	0.74	1.0	–	–	–	–	–
10 - February 17th 2015	3634	862	257	0.66	0.97	2746	644	12,899	0.69	0.99
11 - March 27th 2015	–	–	–	–	–	3591	919	1697	0.71	0.96
12 – no sampling	4384	NI	NI	0.48	0.92	–	–	–	–	–
13 - May 5th 2015	–	–	–	–	–	4482	1033	2656	0.57	0.92
13 - May 31 st 2015	5490	NI	NI	0.41	0.86	–	–	–	–	–
14 - June 29th 2015	–	–	–	–	–	5637	1441	3178	0.42	0.86
15 - July 1 st 2015	–	–	–	–	–	–	–	–	–	–
15 - July 13th 2015	–	–	–	–	–	5636	1385	1348	0	0.84
15 - July 15th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 19th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 20th 2015	–	–	–	–	–	–	–	–	–	–
15 - July 22nd 2015	–	–	–	–	–	–	–	–	–	–

fish by the diode frames and the real fish distribution received in the FPF was 3 % for the average of four sea-cages (Fig. 5).

3.2.5. Statistical comparison of live weight distribution between diode frames and FPF

3.2.5.1. Chi Square Test. The Chi-square test gave a value of 0.127, meaning that there were no significant differences between the Vaki® diode frames estimated live weight distribution frequency and the weight distribution of fish reported at the FPF (Fig. 6).

3.2.5.2. Z test for two-sample means with normal distribution. The z test was applied to the variance of the frequency distribution estimated by the diode frames, which were obtained through the means of the two samples that corresponded to a catch fraction of 21,075 fish received at the FPF from the sea-cage fish 103. The z-value of the normal distribution in a two-tailed test had a result of 0.9738 (Table 11). The recorded gross average weight from the FPF was utilized to compare the fish live weight distribution estimated with the two sampling approaches. The linear regression of the trend graph for the previous 30 days before the harvest yielded the live fish average weight of the frame fish measurements, known as "end weight" also known as "official Vaki weight". The z test for each of these two sampling techniques was performed on their calculated mean, standard deviation, variance, and fish sample number (N) (Table 11, and Fig. 7). The critical z value resulting from the comparison of the end weight of the diode frames with the gross average weight in the FPF for sea-cage 103 was 1.96 (Table 11). According to the z test for the means of two samples, there are no significant differences, and there is a 0.97 probability that the mean is the same for the two samples (Table 12).

Table 6
Average weight, standard deviation, sample size (N), partial and accumulated specific growth rate (SGR) obtained from manual weight recording compared to Biomassdaily® diode frame measurements of the fish from sea-cage 104. (-) means no information reported.

	Sea-cage 104 Traditional assessment					Sea-cage 104 Diode frame estimation				
Month – Sample date	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)	Average weight (g)	Standard deviation (g)	Sample size (N)	Partial SGR (%)	Accumulated SGR (%)
1 -May 5th 2014	–	–	–	–	–	–	–	–	–	–
1 -May 21 st 2014	229	27	331	1.78	1.78	–	–	–	–	–
1 - May 24th 2014	–	–	–	–	–	–	–	–	–	–
2 - June 7th 2014	–	–	–	–	–	–	–	–	–	–
3 - July 7th 2014	452	65	303	1.45	1.61	–	–	–	–	–
4 - August 26th 2014	724	123	355	1.1	1.45	–	–	–	–	–
5 – no sampling	–	–	–	–	–	–	–	–	–	–
6 - October 11th 2014	1227	199	273	0.88	1.27	–	–	–	–	–
6 – October 18th 2014	–	–	–	–	–	1238	350	4999	1.28	1.28
7 - November 14th 2014	1812	444	250	0.6	1.11	–	–	–	–	–
8 - December 22nd 2014	–	–	–	–	–	1951	415	5406	0.7	1.13
9 - January 19th 2015	2840	634	238	0.79	1.05	–	–	–	–	–
10 - February 17th 2015	3620	744	224	0.62	1.0	2912	560	15,782	0.7	1.06
11 - March 27th 2015	–	–	–	–	–	3556	757	1377	0.51	1.0
12 – no sampling	–	–	–	–	–	–	–	–	–	–
13 - May 5th 2015	–	–	–	–	–	–	–	–	–	–
13 - May 31 st 2015	–	–	–	–	–	–	–	–	–	–
14 - June 29th 2015	5656	1206	245	0.39	0.86	–	–	–	–	–
15 - July 1 st 2015						–	–	–	–	–
15 - July 13th 2015						–	–	–	–	–
15 - July 15th 2015						–	–	–	–	–
15 - July 19th 2015						5547	1424	1176	0.39	0.85
15 - July 20th 2015						–	–	–	–	–
15 - July 22nd 2015						5579	1363	533	0.19	0.85

4. Discussion

4.1. Features of size and weight estimation through manual weight assessment

During the grow-out in the seawater sea-cages, salmon farmers periodically need to sample fish from the production sea-cages (Fig. 1) to determine the total or fork fish length and mean fish weight, which allows adjusting the growth projection of the farming software (Føre et al., 2018). This established practice, from a statistical point of view and degree of data confidence, does not consistently offer a high level of accuracy, resulting in biased estimations and sampling errors ranging between 1 % and 12 % for the hand net manual weight assessments (Ross et al., 1998; Nilsson and Folkedal, 2019; Yogev et al., 2020). Manual weight assessments are bimonthly performed, as part of salmon farming company standards, and sometimes even with less frequency because of weather conditions, closed harbor that suspends on-farm activities, fish stress conditions, and lack of sufficient staff to perform the job (López-Riveros, 2017). This lack of consistency in the manual netting regime is clearly shown in our study results. Manual sampling was only achieved for two of the four sea-cages (102 and 104) during the harvest month (Tables 4 and 6). For reporting the other two sea-cages (101 and 103), the fish farmers used the commercial production software projection (FishTalk®) from the last manual assessment during the cycle performed in May 2015 for sea-cage 101 and in June 2015 for sea-cage 103 (Tables 3 and 5).

This widely used fish sampling method consists of the manual recording of the weight and length of individual fish on a mechanical or electronic scale from a net sample of 200–500 fish extracted from each sea-cage (Ross et al., 1998; Nilsson and Folkedal, 2019). Although manual recording has been a sampling method used since the early days of aquaculture, it is not devoid of errors and can be biased (Gutreuter and Krzoska, 1994; Nilsson and Folkedal, 2019). One good example is when comparing manual weight recording against biomass estimation devices, the fish weight assessments obtained from dip nets during the fish harvest (5.5 kg of average weight). The sample obtained by manual

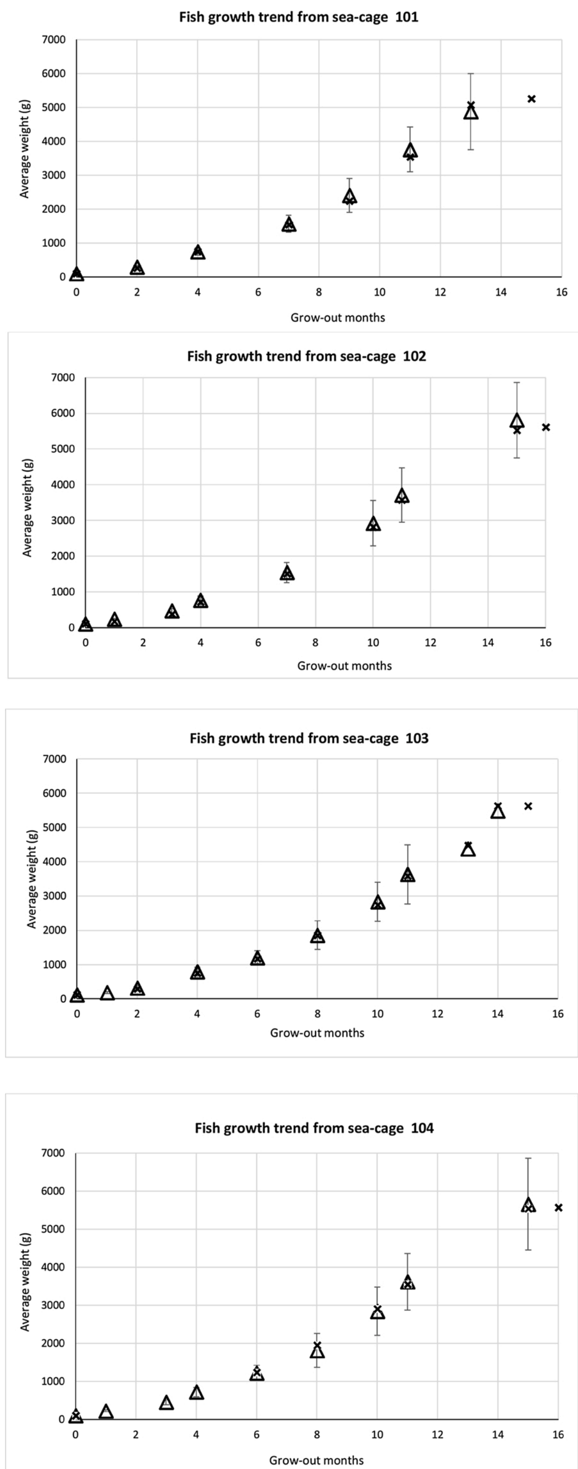

Fig. 2. Atlantic salmon growth trend during the seawater production phase of the four sea-cages studied. Each graph depicts the fish population's growth trend as determined by manual weight assessments (**x**) and diode frame measurements (Δ). Note the comparison between the average weight and standard deviation of both sampling methods during the grow-out months.

netting resulted in a lower coefficient of variation in the sample and a higher condition factor. Even experienced salmon farmers have noticed that the size of the fish caught using the scoop net is not always representative of the overall population size. Lower-sized fish (less than 2 kg in weight) and larger-sized fish (over 10 kg in weight) do not usually appear in the sample. The main advantage of this commonly used

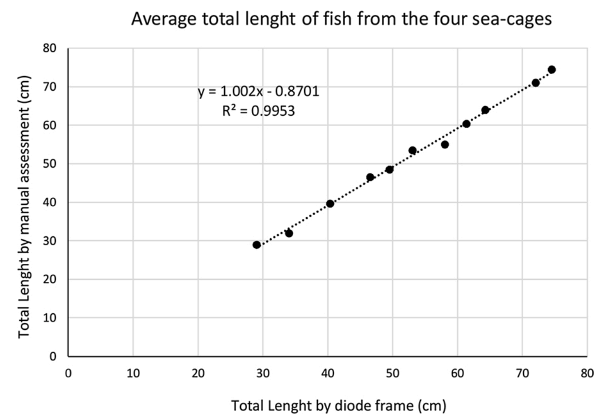

Fig. 3. Proportion in which the variation of the variable total length of the sampling with diode frame from the four sea-cages under study, is due to the variation of the variable total length of the manual sampling and vice versa.

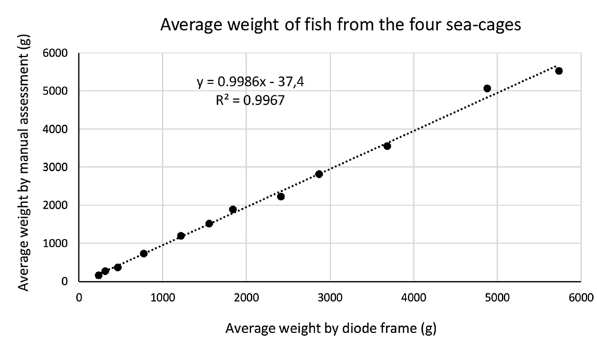

Fig. 4. Proportion in which the variation of the variable average weight of the diode frame from the four sea-cages under study, is due to the variation of the variable average weight of the manual sampling and vice versa.

Table 7
Fish processing facility (FPF) net biomass from the harvested fish of the four sea-cages (average weight after fish were fasted, stunned and bled).

Sea-Cage	Harvest date	FPF date	Av. weight (g)	Fish count	Net Biomass (kg)
101	01-07-2015	02-07-2015	5010	48,491	242,940
102	20-07-2015	21-07-2015	5230	46,271	241,997
103	13-07-2015	14-07-2015	5210	50,414	262,757
104	22-07-2015	23-07-2015	5130	54,337	278,749
Total (kg)	**1,026,343**				

sampling method is that it allows a thorough inspection of the fish body condition, skin health, and the general welfare of the farmed fish (Forsberg, 1995; Pennel and Barton, 1996; Jones et al., 1999). However, currently, there is available technology with stereoscopic cameras utilizing digital software that processes captured fish images and allows the farmer to assess the welfare condition in real-time (Li et al., 2020).

4.2. Size and weight estimation using diode frames

The methods for estimating biomass are based on different approaches for determining the volume of individual fish (Nilsson et al., 2013) and calculating biomass by averaging over a large population (>50.000). The statistical size distribution is also estimated. The total fish biomass was approximated from the distribution after accounting

Table 8
Fish processing facility (FPF) gross biomass from the harvested fish of the four sea-cages (average live weight before fish were fasted, stunned and bled).

Sea-Cage	Harvest date	FPF date	Av. weight (g)	Fish count	Gross Biomass (kg)
101	01-07-2015	02-07-2015	5387	48,491	261,221
102	20-07-2015	21-07-2015	5624	46,271	260,228
103	13-07-2015	14-07-2015	5602	50,414	282,419
104	22-07-2015	23-07-2015	5516	54,337	299,723
Total (kg)	**1,103,591**				

for the number of individuals in the sea-cage (Haugholt et al., 2010). These estimations make two conditions very important for the accuracy of the biomass estimate, namely the number of fish in the sea-cage and how representative the sized subpopulation is for the total population in the sea-cage. A third factor is that the statistical estimate of the fish volume is unbiased, which will ensure that one gets an increasingly better estimate of the number of fish sized (Haugholt et al., 2010). These three factors apply to nearly all methods of biomass estimation.

Size measurements of fish in aquaculture sea-cages can be gathered using an optical measurement of fish dimensions (Ruff et al., 1995; Lines et al., 2001; Gümüş and Balaban, 2010). The mass of individual measured fish was inferred from external measures such as length, height, and sometimes width (Vaki Aquaculture Systems, 2016; Vaki Chile, 2020). Empirical coefficients based on the species and condition of the fish were used to convert the external size to weight (Haugholt et al., 2010).

Diode frames, also known as biomass estimation frames, are specialized measurement tools used in aquaculture for many years (Løvik, 1987; Vaki Aquaculture Systems, 1992). There are two major European manufacturers of diode frames for aquaculture precision farming technology (Haugholt et al., 2010). Both manufacturers are applying similar electronic operating principles. However, Icelandic technology already offers a larger frame (0.91 m height × 0.84 m width) as well as a wireless data transmission system for the frames, allowing rapid access to daily size estimation data on a website accessible to anybody with an Internet connection (López-Riveros, 2016).

The fish farmer may capture reliable and real-time productive data by permanently installing the diode frame inside the same sea-cage during the whole seawater cycle, as proven in the current work. According to the current research, it may take a month or more for Atlantic salmon post-smolts to develop a schooling behavior and adapt to the presence of the diode frames following seawater transfer. This could explain why fish measurements for sea-cages 101 and 103 were delayed in June 2014, as seen in Tables 3 and 5.

According to our results of variance comparison of length and average weight, using diode frame technology is similar to performing a traditional manual assessment (Figs. 3 and 4). The diode frame

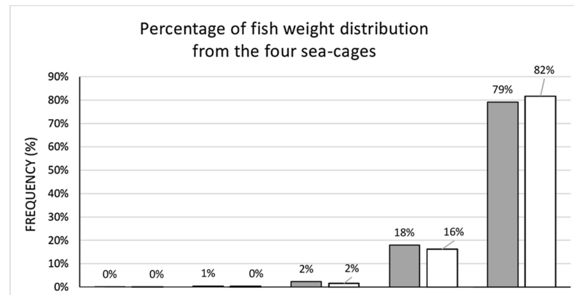

Fig. 5. Percentage of weight distribution in pounds of the fish from the four sea-cages received in the FPF (white bars) compared to distribution of frequencies of fish sampled by the diode frames prior to fish harvest (gray bars).

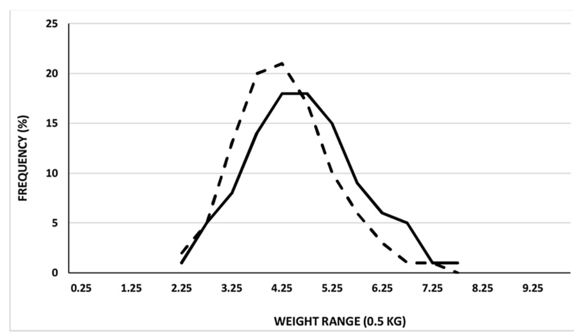

Fig. 6. Frequency distribution of individual weights of 20,918 fish received in the fish processing facility (FPF) from sea-cage 103 (dashed line) compared to Frequency distribution of 1040 individual fish measurements delivered by the diode frames (solid line) prior to fish harvest in the same sea-cage. Based on the Chi square Test result of 0.127, there is no significant difference in the weight distribution between the FPF and the diode frame estimation.

Table 9
Final harvest biomass estimated by the diode frames from the four sea-cages (diode frame live average weight multiplied by fish inventory number reported by the grow-out farm). Data from diode frames was compared to the real biomass processed in the FPF.

Sea-Cage	Harvest date	Live average weight (g)	Stocked Fish number (farm)	Estimated harvest biomass (kg)	Fish count at FPF	Gross Biomass at FPF(kg)
101	01-07-2015	5259	47,116	247,783	48,491	255,014
102	20-07-2015	5605	42,781	239,788	46,271	259,349
103	13-07-2015	5636	48,256	271,971	50,414	284,133
104	22-07-2015	5579	51,504	287,341	54,337	303,146
Total (kg)				**1,046,883**		**1,101,642**

Table 10
Accuracy of the live average weight estimation of the diode frames compared to the average weights of total fish harvested and weighted in the FPF. Note the differences in grams, percentage and degree of accuracy between each of the four sea-cages.

Sea-Cage	Final live weight diode Frame (g)	Final live weight in FPF (g)	Difference in grams frame – FPF	Difference in percentage frame – FPF	Percentage of accuracy of diode frame
101	5259	5387	−128 g	−2.38 %	97.62 %
102	5605	5624	−19 g	−0.34 %	99.66 %
103	5636	5602	+34 g	+0.66 %	99.34 %
104	5579	5516	+63 g	+1.32 %	98.68 %
W. Avg.			**±61 g**	**±1.18 %**	**98.83 %**

Table 11
Z-test for means of the diode frame end live weight and the average weight of total fish harvested and weighted in the FPF from sea-cage 103.

	FPF-gross weight	Frame-End weight
Mean	4603	4567
Variance (known)	1,125,015	1,221,512
Observations (*N*)	21,075	1040
Hypothetical difference of means	0	
z	0.0328	
P(Z<=z) one tail	0.4869	
Critical value of z (one tail)	1.6449	
P(Z<=z) two tails	**0.9738**	
Critical value of z (two tails)	**1.9600**	

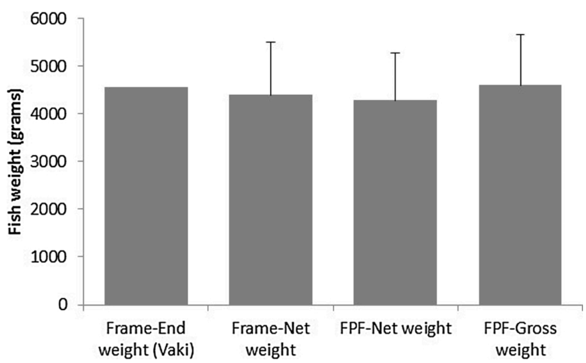

Fig. 7. Average weights and standard deviation of the fish samples from sea-cage 103 obtained using the diode frames and the real fish received in the FPF.

Table 12
Two-tailed z-test for the four average weight combinations from fish harvest of sea-cage 103: two frame average values (end and net weight) and two average weight values in the FPF (gross and net weight).

	Diode frame	
Two-tailed z-test	Net weight	End weight
FPF-Net weight	0.9199	0.7958
FPF-Gross weight	0.8486	**0.9738**

technology can monitor the fish population growth trend, fish condition factor, mean weight, and live weight distribution with a high level of certainty (average deviation below 2 %). When compared to traditional manual weight sampling, the diode frame fish mean weight and fish live weight distribution estimations are highly accurate.

To achieve high estimation accuracy and representativeness, as demonstrated by the findings obtained in this study in commercial grow-out sea cages, the fish farmer must reposition the depth of the frames during the day to minimize population stratification errors (Folkedal et al., 2012; Nilsson et al., 2013). Reposition of the diode frames also allows us to achieve the highest fish sample size (N) or several valid samples (López-Riveros, 2016). According to the findings of this study with these devices in Atlantic salmon marine grow-out sea-cages in Chile, the minimum number of fish measurements required to ensure an estimate with an accuracy ≥ 98 % should be at least 1 % of the total fish population in the sea-cage (López-Riveros, 2016).

The average fish sample size obtained by the diode frames from the four sea-cages during the last measurement before the harvest was 1176 fish (Tables 3–6), representing roughly 2,6 % of a total population of approximately 45,000 fish per sea-cage. As a result, a sea-cage stocked with 45,000 salmon will require a minimum of 500 fish per day to pass through the scanner frame (López-Riveros, 2016). This number increased to 1300 fish sampled in larger open sea-cages of 40 × 40 m, and in our case, there were up to 2351 fish sampled for sea-cage 101 (Table 3).

To achieve the optimal location of the diode frame and ensure a high number of fish measurements, the grow-out farmer must take into account the environmental drivers or key variables (Oppedal et al., 2011) that affect the salmon's swimming pattern and behavior in the sea-cages (Dempster et al., 2009; Bui et al., 2013). The following are the main variables associated with the farming sites that have been reported to affect salmon swimming behavior and, thus, the number of measurements obtained with the diode frames: Atlantic salmon vertical distribution and size-dependent swimming depth in the sea-cages (Folkedal et al., 2012; Nilsson et al., 2013), feeding regime (Smith et al., 1993; Fernö et al., 1995), tidal current speed (Fig. 8), tidal direction (Johansson et al., 2014), presence of artificial photoperiod (Juell and Fosseidengen, 2004; Oppedal et al., 2007; Davidsen et al., 2008; Føre et al., 2013), and density of fish in the sea-cage (Juell et al., 2003).

4.3. Non-invasive diode frame biomass estimation to replace manual weight assessment

The development of a reliable system to monitor the biomass of farmed fish is essential for a sustainable industry in the long term, and more transparent with the consumer and stakeholders towards controlling maximum levels of fish farmed biomass at each site in the promotion of fish welfare and the protection of the marine environment (Little et al., 2015). On a global scale, commercial aquaculture companies need to seek new technologies and other alternatives beyond traditional weight sampling to estimate the weight and biomass of the fish in their sea-cages (Føre et al., 2016; Hersoug et al., 2021). The main reasons for gradually replacing fish management operations with non-invasive technologies such as biomass estimators in routine activities are: the need to prevent diseases and avoid additional stress on the fish that may compromise their health status and immune defenses (Barton and Iwama, 1991), the need to reduce the expenditure of time and resources in sampling tasks (Lines and Frost, 1999), maintain permanent monitoring and reliability of the productive parameters of weight and growth (Difford et al., 2020), the rapid implementation of corrective actions in the face of early detected productivity deviations, and to have a high accuracy estimate of the biomass of fish available in each sea-cage and farm (Haugholt et al., 2010).

Manual weight sampling has been the most reliable method of weight measurement since the early days of salmon aquaculture (Jones et al., 1999). However, current global aquaculture trends are toward fish production in ever-larger sea-cages (circumferences of 157 m, square sea-cages of 60 × 60 m in area, and depths of up to 50 m), and with larger fish stocks (between 200,000 and 400,000 per sea-cage), making this management more difficult on farming sites (Jensen et al., 2010; Føre et al., 2016). The development of new technologies, such as infrared diode frames (Haugholt et al., 2010; Folkedal et al., 2012; Difford et al., 2020), has been stimulated as a result of the aforementioned reasons for the current shift toward the use of new methods and technologies for fish biomass estimation (Soliveres, 2015).

Each variable in the four sea-cages understudies yielded a very strong positive correlation between the variables of total length and the average weight of both weight estimation methods, biomass estimators, and manual scale sampling, according to the coefficient of determination test (R^2) applied to our results. For the four sea-cages studied, the average R^2 value of the variable total length in both sampling methods was 0.995325. This R^2 result indicates that the fluctuation of the variable total length of the sampling with the biomass estimator is related to the variation of the variable total length of the manual sampling, and vice versa, at a proportion of 99.53 % (Fig. 3). On the other hand, related to the result, the average R^2 value of the variable average weight in both sampling methods was 0.996725 for the four sea-cages under study. This R^2 result indicates that, at a proportion of 99.67 %, the variation of the variable average weight of the biomass estimator is due to the variation of the variable average weight of the manual sampling and vice versa

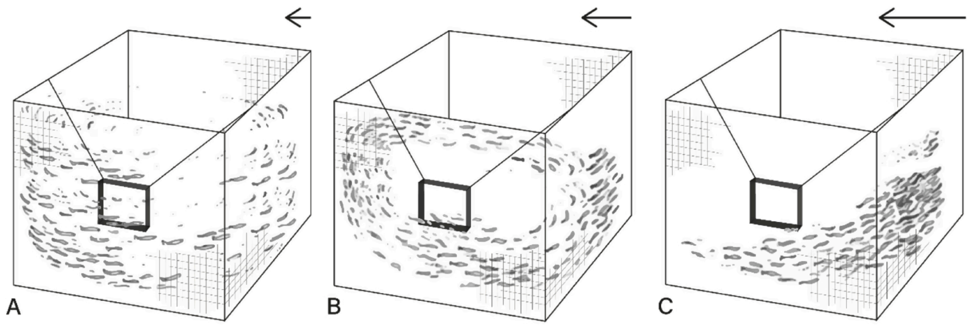

Fig. 8. It shows how tidal current speeds affect the swimming patterns of farmed Atlantic salmon, favoring or hindering fish swimming through the diode frames. Circle swimming (A, circular movement) at water current velocities less than 20 cm/s; Mixed swimming (B, Circle and On Current) at currents between 20 and 35 cm/s; or On Current swimming (C, standing on the current) at current greater than 47 cm/s. The arrows at the top indicate the water currents direction and velocity level (longer arrow represents a higher velocity). Priscilla López-Riveros created the drawings.

(Fig. 4).

In other words, the correlation results obtained (Figs. 3 and 4) demonstrated that replacing traditional manual weight assessment with non-invasive diode frame technology to estimate average weight and size in farmed salmon populations is practical and reliable. The findings of this study also allow salmon producers to use the fish measurements provided by the diode frames with high confidence to update the production software in terms of monthly weight and distribution adjustments. This advancement in fish farming population data upload simplifies the farmer's work by eliminating the need for labor hours and staff to perform manual weight assessments (López-Riveros, 2017) and providing accurate real-time data even when weather conditions are not ideal for a traditional scoop net fish assessment.

4.4. Accuracy and precision of diode frame for average weight and size estimation

The genuine fish biomass from the four sea-cages received in the FPF was slightly overestimated by both methods: manual weight evaluation and diode frame measurements, based on the fish average weight (Table 11). According to the results, a −0.63 % difference was obtained for the final biomass by the manual weight sample projected with FishTalk® software (6958 kg less), and a −0.18 % difference was obtained for the final biomass by diode frame estimation (1949 kg less) compared to the real gross biomass processed in the FPF (Fig. 7; Table 11). These findings show that diode frame estimation was more accurate in estimating live average weight than FishTalk® adjusted to each sea-latest cage's hand weight sampling.

The mean weight variance of the fish estimated by the diode frames in the sea-cages was less than 3 % of the mean real weight obtained in the FPF (Table 10), results that show similarities with a small scale trial of 5000 individually PIT-tagged Atlantic salmon post-smolts that were stocked in a sea-cage and monitored growth using a diode frame and PIT tag reader (Difford et al., 2020). At the end of the growth period, all fish were measured for body length and weight using a manual recording. At the population level, diode frames were highly accurate with a mean difference of 0.002 % for length and 4 % for weight, in both cases not statistically significant. Individual-level length and weight records were repeatable at 0.34 and 0.35, respectively (Difford et al., 2020).

We could not find previously published studies that compared diode frame average weight estimation and distribution of commercially farmed Atlantic salmon with harvested fish received in an FPF. As the first study of its kind, we recorded and validated a high level of accuracy of diode frames for Atlantic salmon size estimation. From our results compared to the FPF, the highest accuracy of diode frame average weight estimation was in sea-cage 102, with only −19 g of difference with the real mean weight, equivalent to a difference of −0.34 % (Table 10). The lowest accuracy obtained from the diode frame weight estimation was in sea-cage 101, which had an average weight difference of -128 g with the mean weight given by the FPF and an absolute error of −2.38 % (Table 10).

Concerning the live weight distribution of the fish received from the four sea-cages in the FPF, a Chi-square test was performed on one of the harvested sea-cages (103), yielding a value of 0.127, indicating that there were no significant differences between the live weight distribution frequency of the Vaki® diode frames and the weight distribution of fish recorded at the FPF. Because the FPF did not share individual weights for all of the fish from the four collected sea-cages understudies from the farm, we only had access to individual fish data from this production unit.

4.4.1. Z test for two-sample means with normal distribution

The weight used for the comparison of the fish weight distribution was the FPF recorded gross average weight, which was compared to the live average fish weight derived from the diode frame fish measurements "end weight," also known as "official Vaki weight." The live average fish weight was estimated using linear regression on a trend graph of the last 30 days preceding harvest, identical to the one shown in Fig. 2. We proceeded this way because the accuracy and precision of the diode frames must be at the farm level, which requires that the final net weight recorded in the FPF must be transformed into a live fish weight (gross weight) by dividing the net fish weight by 0.93. That is equivalent to adding a 7 % weight of blood and fastening weight loss (Smith, 1966).

When the end weight of the biomass estimators was compared to the gross average weight in the FPF, the critical z value was 1.96. (Table 11). There were no significant differences in the means of the two samples, according to the z test, and there was a 0.97 probability that the mean was the same for the two fish samples (Tables 11 and 12). These findings may allow us to validate for the first time an applied engineering study that demonstrates that infrared diode frames are an effective technique for estimating fish biomass in commercial grow-out Atlantic salmon sea cages. In this work, we show that the diode frame accurately and precisely predicts the real average weight.

4.5. Future global perspectives for biomass estimation in salmon aquaculture

Despite being supplied in global commercial aquaculture, fish biomass estimation technologies have not been consolidated as a method of high accuracy in mean weight estimation compared to traditional sampling (Haugholt et al., 2010). The main reasons can be attributed to: dubious reputation due to previous adverse experiences (Difford et al., 2020), lack of formal studies with results database (López-Riveros, 2016, 2017), and due to an overestimated confidence in manual weight recording as a gold standard (Gutreuter and Krzoska, 1994). Other reasons could be related to the lack of understanding of the proper use of the equipment and its biometric data (López-Riveros, 2016) and possibly untrustworthy weighing methods in fish processing facilities post-harvest (Aunsmo et al., 2013; López-Riveros, 2016; Difford et al., 2020).

A reliable control system of the biomass of fish in sea-cages, like the one presented in this study, shows that it is possible to save costs for companies in terms of potential flaws in production planning due to errors in estimating the actual existing fish biomass. From the results presented, a more considerable difference was demonstrated between the final biomass declared by the farm and the final biomass estimated by the diode frames compared to the real final biomass that was registered at the fish processing facilities. The biomass deficit projected by manual weight sampling was 6.96 tons less in the four sea-cages studied versus 1.95 tons by diode frame measurements. Establishing this observed difference in the final months of salmon grow-out at sea, if the company had diode frames as a production planning support tool, this underestimation of the weight and biomass of the manual weight sampling could be detected in advance. The beneficial consequences would be, for instance, harvesting the fish from these sea-cages at the precise moment of their harvest target weight. This management decision will avoid unnecessary fixed and variable costs (food being the highest variable cost) by intentionally keeping the fish for longer in the water with certain risks of sexual maturation, potential loss of fish quality, and possible exposure to an infectious disease outbreak.

On the other hand, if this difference could be hypothetically repeated for the twenty-four sea-cages at the grow-out site, then a negative biomass difference of 41.76 tons could be achieved for the manual weight record and 11.7 tons for the diode frames. This difference brought to a market price of US$ 4.8 / pound of salmon, with the accuracy achieved by the diode frames, only for one marine farm, the ability to know with greater certainty what the real fish biomass would reach savings of US$ 317,462. Greater precision in estimating biomass at the company level allows greater control of deviations in biomass (hundreds of tons), which can represent millions of dollars in savings by ensuring compliance with trade commitments.

The Biomassdaily® diode framework system allows integration with software that is already available on the market and applies it to the planning of the salmon industry using biological, productive, and financial aspects. To aspire to the development of precision aquaculture with high productivity, competitiveness, and sustainability (Haugholt et al., 2010; Little et al., 2015; Føre et al., 2018; Antonucci and Costa, 2020), it will be necessary to provide to the industry with tools that accurately and in real-time measure the biomass of fish in marine cages (Zion, 2012; Li et al., 2020). In this context, both in the northern and southern hemispheres, salmon companies are validating non-invasive biomass estimation technologies to incorporate them as a production control standard (López-Riveros, 2016; Difford et al., 2020). It is to be expected that biomass estimation systems based on artificial intelligence and machine learning will soon become the measuring instrument that replaces the old school of manual weight sampling. In precision aquaculture operations, traditional handling methods will also be required to confirm certain milestones during the cycle and/or to confirm the accuracy and precision of non-invasive automatic measurement systems such as the one analyzed in this research.

5. Conclusion

In comparison to the fish processing facility, the diode frame average weight estimation was 98.83 % $\pm$ 1.18 % accurate for the four sea-cages studied. Based on our findings, we believe that using diode frames for monitoring salmon biomass instead of manual evaluations may be advantageous for sea-cage salmon farms. Future biometric research to supplement this study would concentrate on estimating the live weight distribution of at least 50 % of a commercial grow-out salmon farm.

CRediT authorship contribution statement

César A. López-Riveros: Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Germán E. Merino:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Héctor Flores-Gatica:** Conceptualization, Resources, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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