Targets and Measures: Challenges associated with reporting low sea lice levels on Atlantic salmon farms

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Abstract

A popular framing of Goodhart's Law states, "When a measure become a target, it ceases to be a good measure". The extent to which this may be the case in the reporting of sea louse infestation on salmon farms is explored here. Due to the importance of controlling sea louse infestation on salmon farms, monitoring programmes are active in most salmon producing regions and, in many, a maximum allowable sea louse level is specified. Using publicly accessible data from Norway and BC, Canada, this study investigated the extent to which the framing of these programmes, in particular the specification of low threshold levels, may be affecting the veracity of the reported sea louse infestation data. In BC, where the threshold level is set to 3 mobile *Lepeophtheirus salmonis* little evidence of anomalous patterns in the data and the overall proportion of females within the adult sea lice population is around 0.43. By contrast, in Norway where lower sea louse limits are in place (at either 0.5 or 0.2 adult female *L. salmonis*), there is evidence of unexpected and sharp reductions in the abundance of adult females reported around these threshold values. In addition, the average proportion of females is estimated to be only around 0.20 of the total adult *L. salmonis* population. The unexpected observations in the data were much more evident for farms in the southern areas of Norway and over the most recent years. These findings appear to support the case that the measurement of sea lice on salmon farms can be significantly influenced by targets (particularly those which are highly demanding), and that as such, researchers and fish health professionals should be aware of potential biases within these data. In addition, regulators should carefully consider the unintended consequences of setting certain sea louse thresholds and the ways in which the potential to effectively review data quality and accuracy may be impacted by the choice of sea louse stage(s) that are reported.

Keywords: *Lepeophtheirus salmonis*; louse limit; parasite monitoring; salmon aquaculture; sea lice; treatment thresholds

1. Introduction

The sea louse (*Lepeophtheirus salmonis*) is an ectoparasite of substantial concern for Atlantic salmon (*Salmo salar*) aquaculture across most salmon producing regions, both in terms of reduced farm productivity and also the potential to negatively affect wild salmonid populations (Costello et al., 2006). The parasitic stages, during which *L. salmonis* attach to fish, are divided into copepodid, chalimus, pre-adult, and adult stages (Hamre et al., 2013). As the pre-adults and adults can move around their host, these stages are referred to as "mobile" stages.

Monitoring the abundance of *L. salmonis* is a fundamental step in the effective management of sea lice. Such monitoring relies on farms reporting the mean abundance of various sea louse stages on a regular basis. Authorities in salmon producing countries have enacted laws or guidelines stipulating monitoring protocols to be used on farms (Revie et al., 2009). For example, Norwegian authorities require salmon farmers to count and report sea louse infestations weekly when water temperatures are above 4°C (Guarracino et al., 2018). A sample of ten salmon per pen is required in the winter and spring, while 20 salmon per pen should be sampled in the summer (van Walraven et al., 2021). Moreover, most authorities set an allowable maximum number of sea lice per salmon, which if exceeded will result in requiring the farm to take some action, such as carrying out a sea lice treatment or even the early harvest of fish. In Norway, since 2009 farms have been required to keep their *L. salmonis* levels below 0.5 adult females (AF) per fish at all times during the year. Since 2017, this louse limit was reduced to 0.2 AF *L. salmonis* between weeks 16–21 in southern Norway, and between weeks 21–26 in northern Norway, in order to minimise the risk of infestation to out-migrating juvenile salmon (Overton et al., 2019). By way of comparison, in British Columbia (BC), Canada, 20 fish should be sampled from each of three selected pens on a farm once or twice per month (Fisheries and Oceans Canada, 2014). A sea louse threshold of three mobile *L. salmonis* per fish is specified and if this is exceeded during the wild salmonid out-migration period (March to June) then farms in BC are required to conduct a delousing treatment or harvest. During the rest of the year, an exceedance will trigger a louse notification event to the regulator (Fisheries and Oceans Canada, 2017).

However, it is widely accepted that setting such thresholds, across a range of domains, can lead to an erosion in their utility as effective metrics – the "targets" and "measures" of

Goodhart’s (or sometimes, Campbell’s) Law (Manheim, 2018). The impact of this effect on measurements associated with the current COVID-19 pandemic is a recent and important example of the challenges involved (Giles, 2020; Hancké, 2020) where, for example, a focus on ensuring that the maximum number of hospital beds were available led to a much higher level of deaths in care homes than would otherwise have been the case. In this study, we investigate the extent to which the setting of sea lice management targets, particularly when those are at low levels, can affect the veracity of reported *L. salmonis* infestation levels on salmon farms.

2. Material and Methods

We analysed publicly available sea louse datasets from Norway and BC, Canada. The data were reported by farm staff who sampled salmon and returned counts of sea lice according to their life stages. They reported the mean abundance of adult female (AF) and total mobile (TM) *L. salmonis* at each sampling event to the relevant authorities.

In Norway, sea lice related data reported by salmon farms have been archived on the *BarentsWatch* information system (BarentsWatch 2021). We used the weekly mean AF and TM abundance of *L. salmonis* from all farms that recorded infestation in a given week. The dataset consisted of a total of 270,211 observations recorded between 2012 and 2021, from all production areas (Supplementary Table S1). From 2017, the lower sea louse limit of 0.2 AF per salmon was applied between weeks 16 - 21 and weeks 21 - 26, in Production Areas 1 to 7 and Production Areas 7 to 13, respectively (Overton et al., 2019). Details of the locations of Production Areas in Norway can be found in Figure 1 of Overton et al, 2019; in general, these number from “1” in the south of the country, to “13” in the most northerly region.

In BC, the Canadian Department of Fisheries and Oceans (DFO) requires the uploading of sea louse counts from salmon aquaculture facilities (Fisheries and Oceans Canada, 2017). We used the AF and TM mean abundance of *L. salmonis* reported on the DFO web site (Fisheries and Oceans Canada, 2017). This dataset consisted of a total of 13,034 observations taken between 2011 and 2021, from the seven DFO fish health zones in BC (Supplementary Table S2).

The purpose of this paper is not to carry out an in-depth examination as to the causal mechanisms that may be generating biases in sea lice reporting data. Rather it was to explore the data for evidence of such biases, to report these (primarily through simple visual summaries), and provide access to the original data sets so that other researchers may seek to better explain the main sources of reporting bias.

3. Results

Our initial analyses involved looking at the apparent demographics within the *L. salmonis* populations on farms in Norway and BC. It can be seen (Table 1) that the reported median proportion of AF to TM *L. salmonis* was much lower (0.18) in Norway to the proportion reported in BC (0.43). However, it should also be noted that the overall median abundance of mobile infestation in Norway (0.35) was almost half that observed in BC (0.58) over the years for which data were available. This large difference in AF proportions prompted further exploration, with the distribution of reported AF proportions being shown in Figure 1 (right-hand panels). The data from Norway were randomly sub-sampled to provide the same number of data points, both to make the histograms more comparable and to avoid the heavy over-plotting that would occur in the left-hand panels had we attempted to visualise the 270,000 data points present in the case of Norway. There is a clear right skew in the AF/TM proportions data from Norway, while those from BC are more normally distributed. Both histograms show the expected 'peaks' at the 0 and 1 ends of the distribution, though this is much less evident at the right tail (i.e., all mobile *L. salmonis* observed were AF) of the distribution for Norway. The differences in the underlying association between reported AF and TM abundance values is perhaps more starkly illustrated by the scatter plots of these data (left-hand panels of Figure 1). A simple linear regression for the data from BC indicates a strong association ($R^2 = 0.90$) between these two stages of *L. salmonis* with a best-fitting slope of around 0.51. In contrast, the Norwegian data indicate that this association is much less robust ($R^2 = 0.48$), while the gradient of the line of best fit is only around 0.15. There also appears to be some sort of 'plateau' evident in the reported AF values from Norway, at around the 0.5 AF *L. salmonis* abundance level. This is further illustrated in the scatterplots of AF/TM proportions as a function of AF and TM abundance that are provided in Figure S1 (Supplementary Materials).

The extent to which such a 'plateau' might exist was further explored and in Figure 2 the histograms of actual reported values for AF and TM *L. salmonis* abundance are shown for farms in Norway (under the two different target/threshold conditions) and in BC. What appears to be clear is that there is an abrupt decrease in the frequency of values over 0.5 AF for much of the Norwegian data (middle-left panel of Figure 2), something which seems even more apparent for values over 0.2 AF *L. salmonis* (upper-left panel) during the period that this threshold was in effect. In all cases the y-axes have been shown on a square-root scale; these drops would appear even more 'dramatic' if the data had been shown on a regular scale and as such, without mixing our geological metaphors too much, we will refer to this as a 'cliff effect'. Of interest is the fact that no such 'cliff effects' were observed in the TM *L. salmonis* abundance data from Norway, nor do they appear to be present in either the AF or TM abundance data for farms in BC. It should be noted that for farms in BC the relevant threshold limit is 3.0 TM *L. salmonis* (bottom-right panel of Figure 2).

Once these 'cliff effects' had been observed in the aggregate data from Norway, it was important to explore their presence over space and time. The graphics in Figure 3 illustrate this for production areas (of which there are 13 in Norway) and over the 10 years for which data were available. In all cases for this set of analyses, data were restricted to times during which the 0.5 AF limit was applicable in Norway (which accounted for almost 95% of the Norwegian data). When considering production areas (Figure 3 upper-left panel), it can be seen that the more southerly areas (i.e., 2 to 7) typically had median proportion values that were lower than was the case for the more northerly areas (i.e., 8 to 13). The southern areas also tended to have a higher overall median abundance of total mobile *L. salmonis*. (Production Area 1 appears to be something of an outlier, having both a low overall TM abundance and a low median proportion of AFs to TM.) Looking at three exemplar production areas (Figure 3 upper-right panel), the 'cliff effect' is particularly obvious at 0.5 AF in PA 4 and in PA 7. However, any effect is more difficult to detect in PA 11.

In terms of years (Figure 3 lower-right panel), the 'cliff effect' is again particularly evident in the data from 2020, and to a lesser extent in 2015. However, it is difficult to detect evidence of this effect in the earliest year (2012). In contrast to the production area data, the trend between overall median TM abundance and proportion of AF is not so evident. If anything, there appears to be a modest trend towards higher proportions of AFs, as the overall median abundance increases over the years; thought any effect is much weaker than the opposing trend that was observed when considering production areas. It tends to be that case that the distribution of values will have an impact on annual aggregate comparisons. In more recent years there were fewer records that reported an AF abundance measure of zero and in general these years showed lower variance, which has the potential to confound our interpretation when considering earlier years which tended to report a much higher level of variability in AF counts.

4. Discussion

We explored the abundance of AF and TM *L. salmonis* in data from Norway and BC, Canada, and found that the estimated proportion of AF to TM was substantially different between the two regions. Our analyses indicated that a ‘cliff effect’, a precipitous drop in the counts of female sea lice per salmon, coincided with the AF limits in Norway. It seems likely that this effect is also the main cause of the lower overall proportion of AF to TM *L. salmonis* in Norway. In addition, the ‘cliff effect’ was more pronounced in the southern production areas of Norway than in the northern areas, and in the most recent years.

There are differences regarding these data and the contexts from which they were collected in Norway and BC. In the first place, the data from Norway are much more extensive. This is partly due to the fact that there are many more farms operating in Norway than in BC, but also because the Norwegian data were reported on a weekly basis, while those data to which access was available from BC were initially based on monthly reporting with increased temporal regularity in the more recent years. If our focus has been primarily on population dynamics this may have been problematic. However, when looking at absolute numbers and the proportions of AF, the frequency of reporting seems unlikely to have a major impact on interpretation. It is also possible that environmental factors could be playing a role in differences. Both seawater temperature and salinity are known to affect sea louse population dynamics, with warmer waters resulting in shortened development times (Stien et al., 2005) and low salinities leading to higher mortality rates particularly in the earlier stages of the sea louse life cycle (Groner et al., 2016). However, it is not clear how such effects on dynamics would result in significantly differing proportions of AF in the overall population.

Perhaps a more likely cause of some of these differences is associated with treatment methods. Sea louse management strategies can be categorised as either ‘immediate’, ‘continuous’ or ‘preventative’ (Brakstad et al. 2019; Jensen et al., 2020). For those methods designed to have an ‘immediate’ effect it is possible that some of the ‘cliff’ effect is due to increase treatment intervention at or close to the point at which the threshold for AF abundance is being reached. In Norway, there has been a much wider range of treatment regimens in place, in particularly the widespread use of cleaner fish (Overton et al., 2019; Coates et al., 2021). Cleaner fish are known to feed preferentially on larger sea lice, especially adult females, and it may be that this could lead to lower AF proportions in the overall population. This hypothesis could be further studied by comparing AF proportions on farms or areas with a heavy / slight use of cleaner fish, but such a comparison is beyond the scope of this short paper. In addition, while this may partially explain the lower AF proportions in Norway, it is not clear how this might provide a basis for the ‘cliff effect’ reductions that occur at the 0.2 and 0.5 threshold levels.

One final cause behind these differences could relate to the counting methods that are adopted in various countries. In general, sampling regimes do not vary greatly but some countries encourage higher sample sizes or more complete coverage of all pens on a given site. Studies on farmer-based versus auditor-based counting have shown that differences can occur (Elmoslemany et al., 2013), and a tendency for farms in BC to under-report when compared to external auditors was recently published (Godwin et al., 2021). However, these studies did not report any systematic patterns that would lead to the wide divergence in AF proportions or to the ‘cliff effects’ that were observed in the present analyses.

It seems likely that there is a natural human tendency to want to report a value that is within the limits of a specified threshold. While a successful case has been brought against a Norwegian operator for reporting incorrect sea louse numbers (Thorvaldsen et al., 2019) it would seem that in many cases this is not ‘premeditated’. The fact that our ‘cliff effect’ was more strongly observed when the 0.2 AF limit was in place than was the case for the 0.5 limit, would suggest that the more ambitious the target, the more likely that under-reporting will occur. This is precisely one of the points that Goodhart’s Law is highlighting; making the point that, if we wish to maintain the utility of a given measure, it is important not to embed that measure in some target-setting agenda, particularly if the target is difficult to achieve.

The use of a higher, more attainable, target for TM in the case of BC, appears to have avoided some of the problematic reporting of AF levels observed in Norway. However, In addition to the reporting issues noted here, the setting of ambitious targets may also lead to over-treating, which in turn tends to drive resistance in sea louse populations (Jensen et al., 2020), particularly in the absence of a significant wild host refugia (McEwan et al., 2015; Bateman et al., 2020). For regulators this is a complex issue, as the threshold values set for farms are primarily intended to avoid effects on wild salmon stocks. As such, increasing a threshold simply to make it more 'attainable' may undermine the very purpose of setting such a limit in the first place.

The issue of which sea louse stage(s) and level(s) should be set as threshold targets should therefore be carefully considered by regulators. Even when one sea louse stage is selected as the target threshold, it is important that data for multiple stages are reported so that appropriate data quality checks can be put in place. For example, in Scotland, AF is the stage for which recommendations relating to good practice are specified; they are also to only sea lice data that are publicly reported by farms. This means that checking for inconsistencies, such as we were able to carry out in the current study, would not be possible against the Scottish data. In addition, the assumption that reporting data for only one life stage is adequate seems questionable in light of the limited correlation between mobile and AF population numbers seen in Norway. Adult, or even gravid, female sea lice form the basis of threshold targets in Chile (Sernapesca 2022), Ireland (O'Donohoe et al., 2020) and the Faroe Islands (Kragesteen et al., 2019). It seems likely that the lessons from this study should be taken into account when considering sea louse data from these jurisdictions. It is important that regulators keep in mind the potential unintended consequences of setting levels that are too ambitious or that focus on reporting only a single life stage when looking to better manage sea lice on salmon farms.

Declaration of Competing Interest

None.

Acknowledgements

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Appendix A. Supplementary material

Supplementary material associated with this article can be found in the online version.

Data Availability

The data used in this study and the R code for Figures 1 - 3 are available at https://github.com/jaewoonjeong/proportionAFinTM

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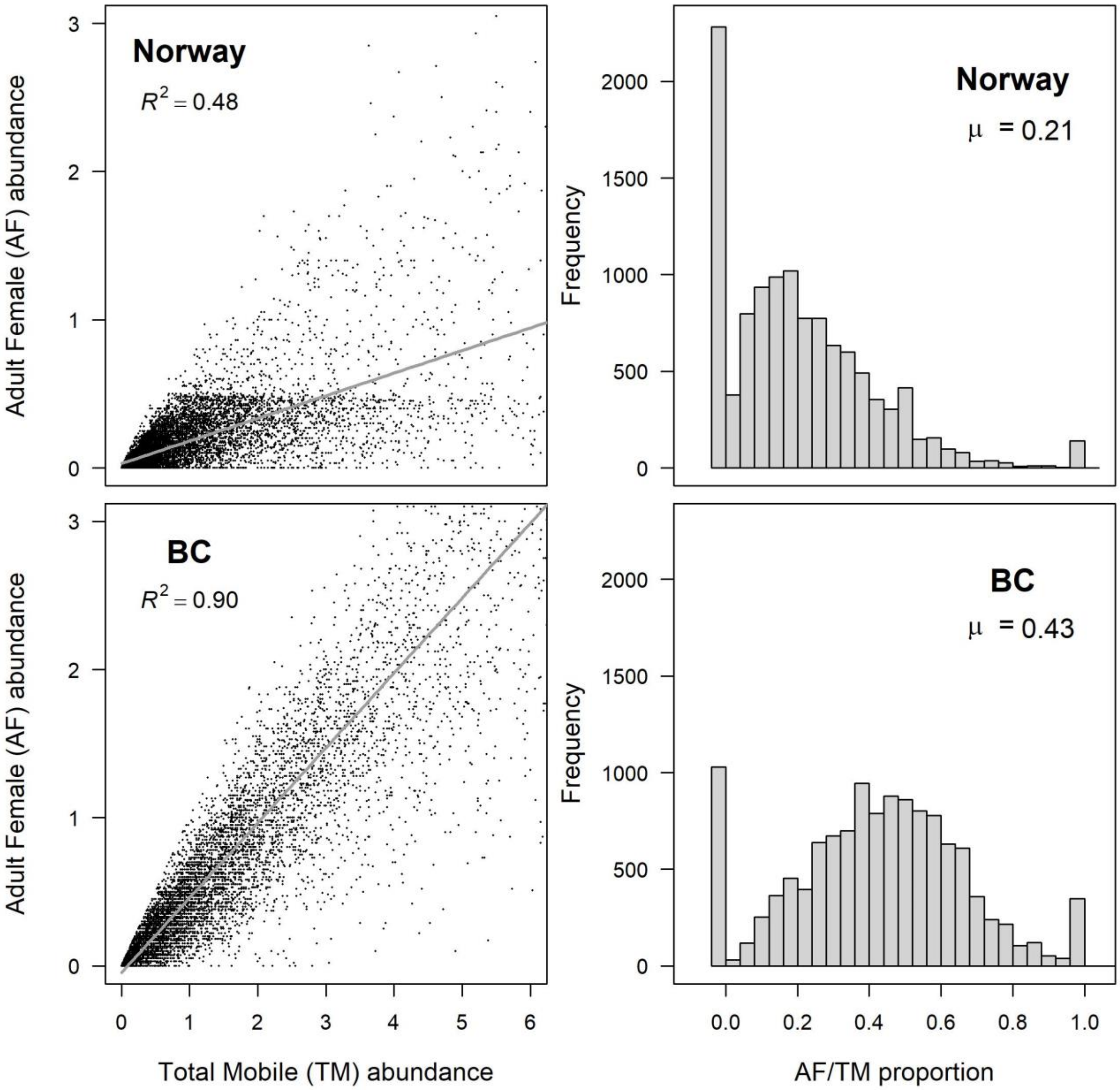
Table 1. Summary statistics (median and mean) for Adult Females (AF), Total Mobiles (TM), and proportion of AF in TM for the datasets from Norway and British Columbia (BC), Canada. IQR and CI represent interquartile range and confidence interval, respectively.

	Norway (N = 270,211)		BC, Canada (N = 13,034)	
	Median (IQR)	Mean (95% CI)	Median (IQR)	Mean (95% CI)
Adult Females (AF)	0.06 (0.00 - 0.20)	0.17 (0.00 - 0.90)	0.23 (0.05 - 0.81)	0.85 (0.00 - 5.88)
Total Mobiles (TM)	0.35 (0.08 - 0.99)	0.89 (0.00 - 5.01)	0.58 (0.17 - 1.77)	1.76 (0.00 - 11.33)
Proportion of AF in TM	0.18 (0.05 - 0.33)	0.21 (0.00 - 0.67)	0.43 (0.27 - 0.58)	0.43 (0.00 - 1.00)

Fig. 1. Scatter plots of Total Mobile (TM) versus Adult Female (AF) (left-hand panels) and histograms of the AF in TM proportions (right-hand panels) in datasets of mean farm abundance records from Norway and British Columbia (BC), Canada. In the upper panels, a subset of data points from Norway when the threshold in effect was 0.5 AF were randomly selected to provide the same number of data points as for BC. The correlation coefficients (R^2) associated with linear regression analyses are indicated, as are the mean proportions (μ) of AF in TM.

Fig. 2. Histograms of adult female (left panels) and total mobile (right panels) abundance levels, where *L. salmonis* limits of 0.2 AF (top panels) and 0.5 AF (middle panels) in Norway, and 3.0 TM in British Columbia (BC), Canada (bottom panels) were applicable. Red vertical lines represent these varying sea lice limits. (The y-axes are square-rooted, and the leftmost black bars include counts that are strictly zero. All histograms are right-truncated.)

Fig. 3. Effect of production area (top panels) and year (lower panels) on the proportion of adult females (AF) in total mobiles (TM) from farms in Norway. Scatter plots of the median abundance of TM versus the median proportion of AF in TM by production area and by year are shown in the left-hand panels. Density plots from three exemplar productions areas and from three years are shown in the right-hand panels. Red vertical lines represent the sea lice limit of 0.5 AF in Norway, and the dataset includes only records from times during which this limit was applicable. (The y-axes on the density plots are square-rooted, and all plots are right-truncated. The production areas (PA) in Norway are broadly numbered from "1" in the south, to "13" in the north.)



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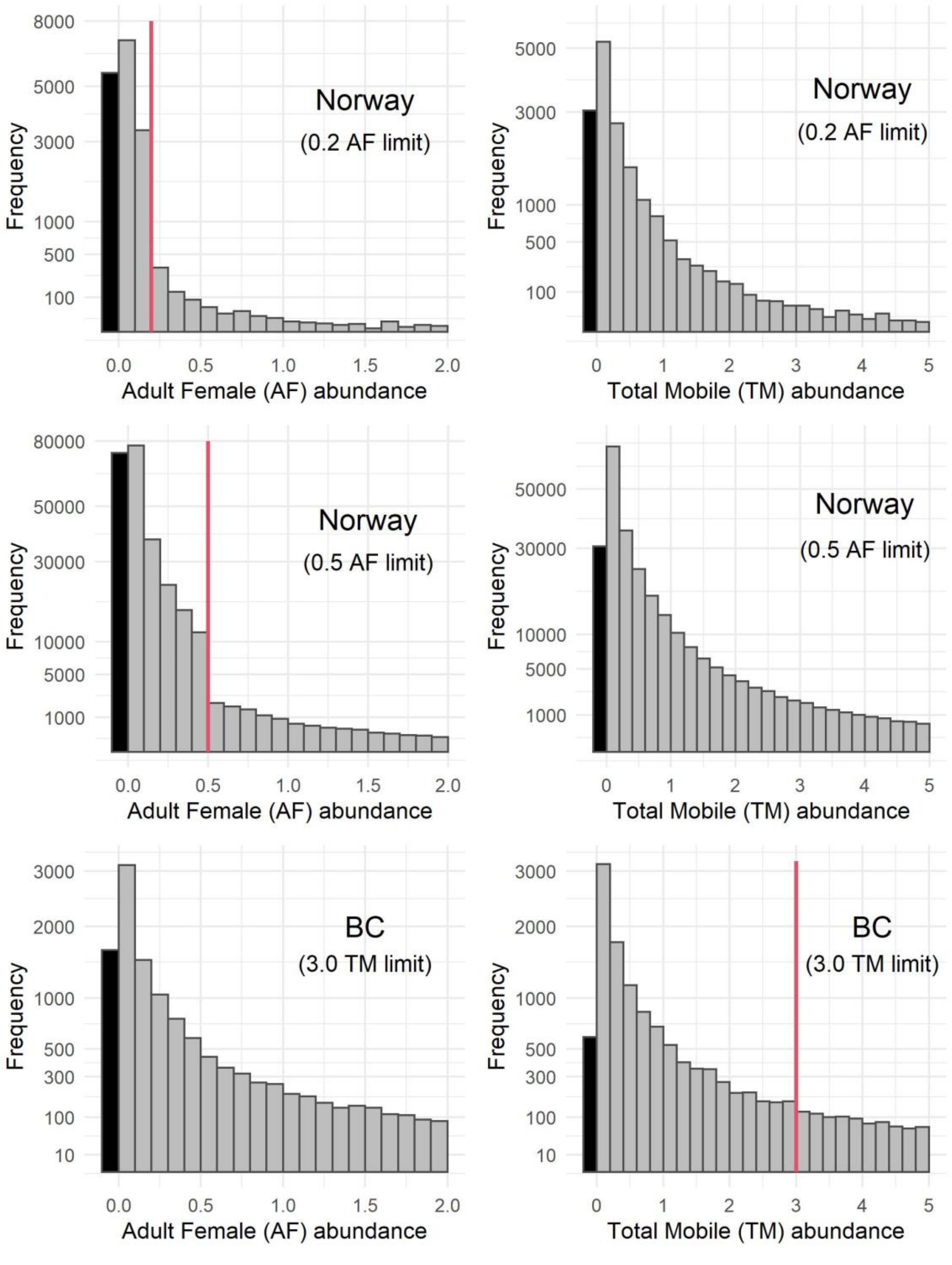

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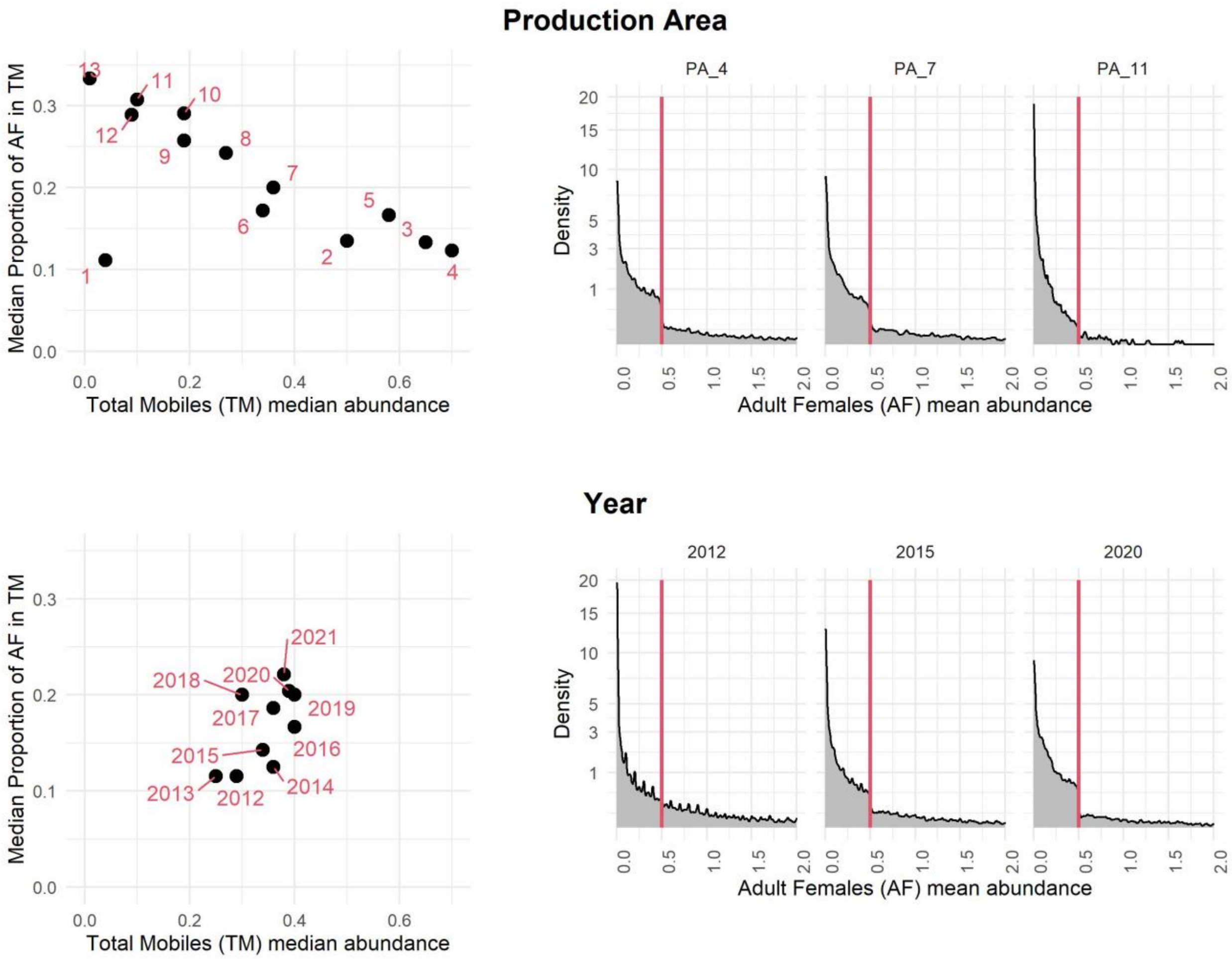

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Table S1. Number of weekly observations in each year by production area in Norway. A total of 233 observations (<0.1%) had to be discarded as details of production area were not recorded.

Production area	**Year**										
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
1	293	266	284	402	400	343	316	300	377	319	**3,300**
2	1,281	1,517	1,623	1,838	1,634	1,646	1,563	1,746	1,697	1,739	**16,284**
3	4,521	4,194	4,691	4,778	4,972	4,598	4,644	4,468	4,641	4,396	**45,903**
4	3,640	4,140	3,981	4,357	4,274	4,415	4,148	4,460	4,461	4,177	**42,053**
5	1,112	1,279	1,320	1,453	1,372	1,415	1,437	1,439	1,315	1,504	**13,646**
6	3,139	3,479	4,002	4,352	4,005	4,364	4,315	4,258	4,619	4,613	**41,146**
7	1,274	1,382	1,401	1,329	1,328	1,486	1,615	1,708	1,779	1,957	**15,259**
8	1,889	2,027	2,371	2,586	2,243	2,484	2,823	3,131	3,097	3,004	**25,655**
9	1644	2082	2127	1974	1931	2252	2371	2334	2758	2804	**22,277**
10	1020	1348	1543	1566	1756	1782	1836	1855	1900	1943	**16,549**
11	610	775	807	968	968	1176	1146	1035	1243	1242	**9,970**
12	850	1280	1560	1623	1645	1868	1826	2097	1988	1999	**16,736**
13	86	145	85	92	128	158	117	133	144	112	**1,200**
Unknown	107	19	24	7	7	14	12	20	13	10	**233**
Total	**21,466**	**23,933**	**25,819**	**27,325**	**26,663**	**28,001**	**28,169**	**28,984**	**30,032**	**29,819**	**270,211**

Table S2. Number of observations by DFO fish health zone for each year in British Columbia (BC), Canada.

Fish Health Zone	**Year**											
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
2.3	192	100	166	187	228	181	182	164	165	261	414	**2,240**
2.4	125	84	93	133	156	91	212	147	279	293	425	**2,038**
3.1	47	23	6	15	63	53	46	64	59	95	77	**548**
3.2	214	135	73	116	119	189	178	264	332	387	134	**2,141**
3.3	210	121	188	210	198	245	410	398	451	430	567	**3,428**
3.4	81	62	46	83	81	126	179	267	261	218	167	**1,571**
3.5	82	43	75	84	84	105	131	122	109	112	121	**1,068**
Total	**951**	**568**	**647**	**828**	**929**	**990**	**1,338**	**1,426**	**1,656**	**1,796**	**1,905**	**13,034**

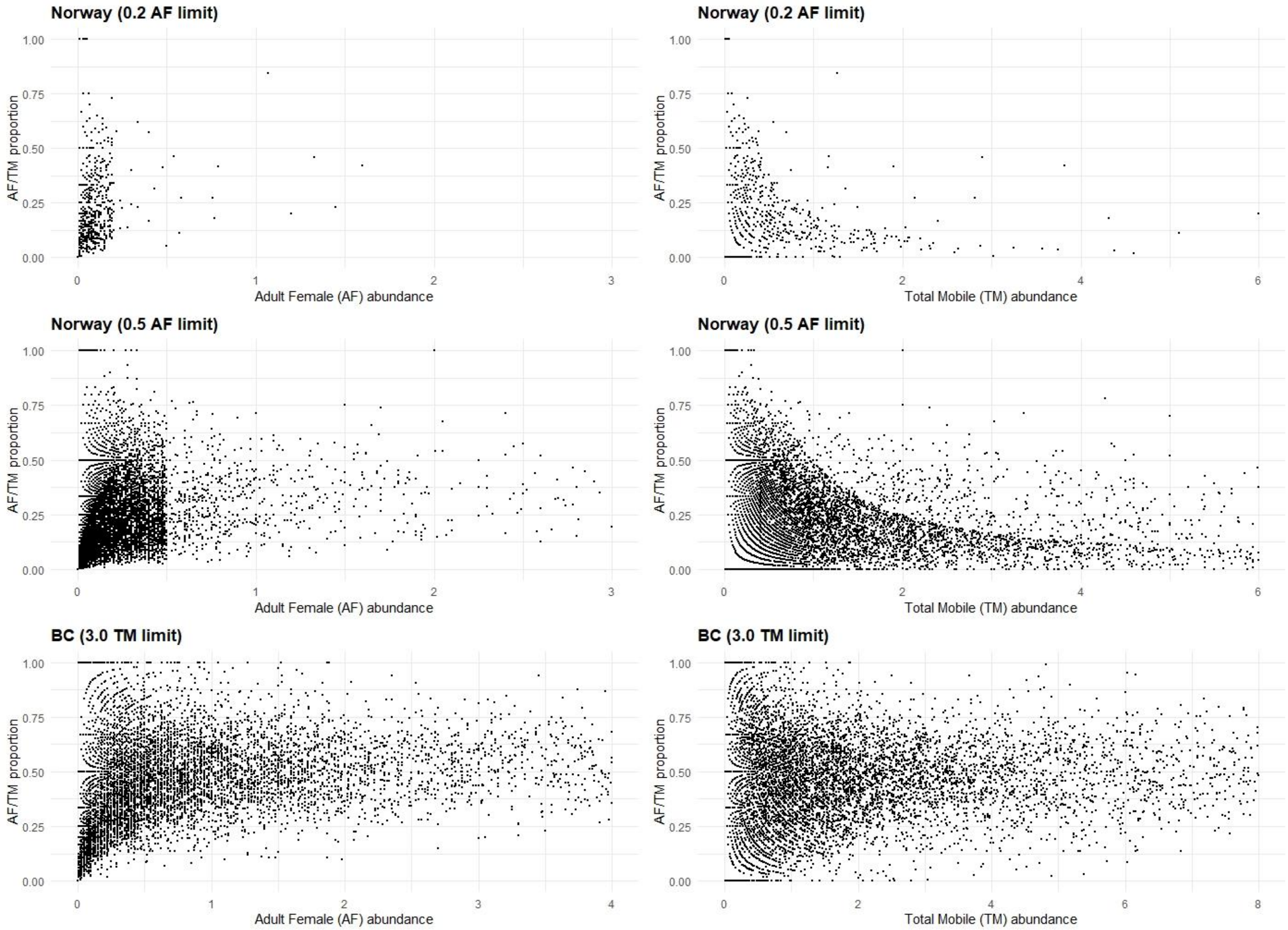

Figure S1. Scatter plots of proportion of adult female (AF) to total mobile (TM) as a function of AF abundance (left panels) and TM abundance (right panels). *L. salmonis* limits of 0.2 AF (top panels) and 0.5 AF (middle panels) in Norway, and 3.0 TM in British Columbia (BC), Canada (bottom panels) were applicable. In the middle panel, a subset of data points from Norway when the 0.5 AF threshold was in effect, were randomly sampled to provide the same number of data points as for BC. (All scatter plots are right-truncated.)