

The predation of farmed salmon by South American sea lions (*Otaria flavescens*) in southern Chile

Juan Vilata, Doris Oliva, and Maritza Sepúlveda

Vilata, J., Oliva, D., and Sepúlveda, M. 2010. The predation of farmed salmon by South American sea lions (*Otaria flavescens*) in southern Chile. – ICES Journal of Marine Science, 67: 475–482.

The South American sea lion *Otaria flavescens* is abundant off southern Chile. Because Chilean salmon farming has experienced an explosive growth in the past two decades, interactions between *O. flavescens* and this industry have increased. Fieldwork, including *in situ* behavioural observations, was carried out at three salmon farms off southern Chile from May to July 2008. The aim was to analyse possible patterns in the interactions and to evaluate whether they were influenced by the endogenous circa-rhythms of the species, prey size, tidal flux, and the use of an acoustic harassment device (AHD). The results showed that the attacks by *O. flavescens* followed seasonal patterns, with salmon predated more in autumn and winter, and daily patterns, with more interactions at night. In addition, attacks were more frequent on larger salmon, suggesting the existence of a prey-size preference. More sea lions were sighted at the ebb and flow tide peaks, when currents are stronger, suggesting that currents linked to tidal flux might facilitate the access of the sea lions to the farmed salmon. Although the use of AHDs appeared positive at one site, there is a strong suspicion that their efficacy may be site-specific.

Keywords: AHDs, Chile, circa-annual rhythms, circadian rhythms, prey size preference, salmon farming, South American sea lion, tidal flux.

Received 25 May 2009; accepted 17 July 2009; advance access publication 6 November 2009.

J. Vilata: c/o José María Bayarri 8-24, 46014 Valencia, Spain. D. Oliva and M. Sepúlveda: Centro de Investigación y Gestión de los Recursos Naturales (CIGREN), Departamento de Biología y Ciencias Ambientales, Facultad de Ciencias, Universidad de Valparaíso, Valparaíso, Chile. Correspondence to J. Vilata: tel: +34 963 838296; fax: +34 963 309004; e-mail: juanvilata@yahoo.com.

Introduction

Interactions between fisheries and pinnipeds (seals and sea lions) are common in areas where fishing activities occur within the distribution of these species (Wickens, 1995). Salmon-farming areas that overlap with the range of any pinniped species also register frequent interactions with them (Kemper *et al.*, 2003; Kaschner and Pauly, 2004). This is so because the high density of fish stocked inside the salmon pens inevitably constitutes a strong attraction for these remarkably adaptable and intelligent predators (Schusterman and Kastak, 2000; Schusterman *et al.*, 2003; Lindemann *et al.*, 2006). Examples of interactions between pinnipeds and salmon farms are found in Norway, Scotland, Canada, Australia, the United States, New Zealand, and Chile (NSSG and Stewardson, 2007).

In Chile, the salmon-farming industry has grown almost exponentially, and it is currently the world's second-largest producer (612 000 t), closely behind Norway (654 500 t; FAO, 2006). From the start, Chilean salmon farms have been concentrated in the administrative region of Los Lagos, which hosts 80% of the total sites. However, the industry is expanding south, to the Aysén and Magallanes regions (Buschmann *et al.*, 2006). The main three species farmed are the Atlantic salmon *Salmo salar*, the coho salmon *Oncorhynchus kisutch*, and the rainbow trout *O. mykiss* (Kemper *et al.*, 2003; Buschmann *et al.*, 2006). The salmon are raised from smolt size to full commercial size (around 4–5 kg) in fish pens located in the open sea for ~18 months. Each site has a variable, from 6 to 20, number of fish

pens. Usually, a single salmon farm will have fish in different states of development stocked in different pens.

Two pinnipeds are found in this salmon-farming region; the South American sea lion *Otaria flavescens* and the South American fur seal *Arctocephalus australis*. There are no reports of the fur seal preying on farmed salmon in Chile, probably because it feeds mainly offshore (Thompson *et al.*, 2003). In contrast, the sea lions usually feed in coastal waters (Oliva *et al.*, 2003), predominantly on demersal and pelagic fish (George-Nascimento *et al.*, 1985; Koen Alonso *et al.*, 2000). With an estimated population of 35 000 (26% of the Chilean total), the region of Los Lagos hosts the largest population in Chile of South American sea lions (SSLs hereafter). Moreover, the population seems to be increasing (Oliva *et al.*, 2008).

In 1997, Sepúlveda and Oliva (2005) found that nearly 90% of the Chilean salmon farms in Los Lagos had reported attacks by SSLs. Based on the results of enquiries to salmon farmers, it was established that SSLs showed a preference for attacking those sites holding the largest fish, and that the attacks were more frequent at night and in winter, following the natural circadian and circa-annual activity patterns of the species. However, the study of Sepúlveda and Oliva (2005) was based principally on enquiries and did not include field observations.

Another factor that may influence the patterns of attack is the intensity of the tidal flux, which increases the vulnerability of fish to predation by sea lions (SSGA, 1990). Currently, the most widespread design for salmon pens is a square fish net arranged in two

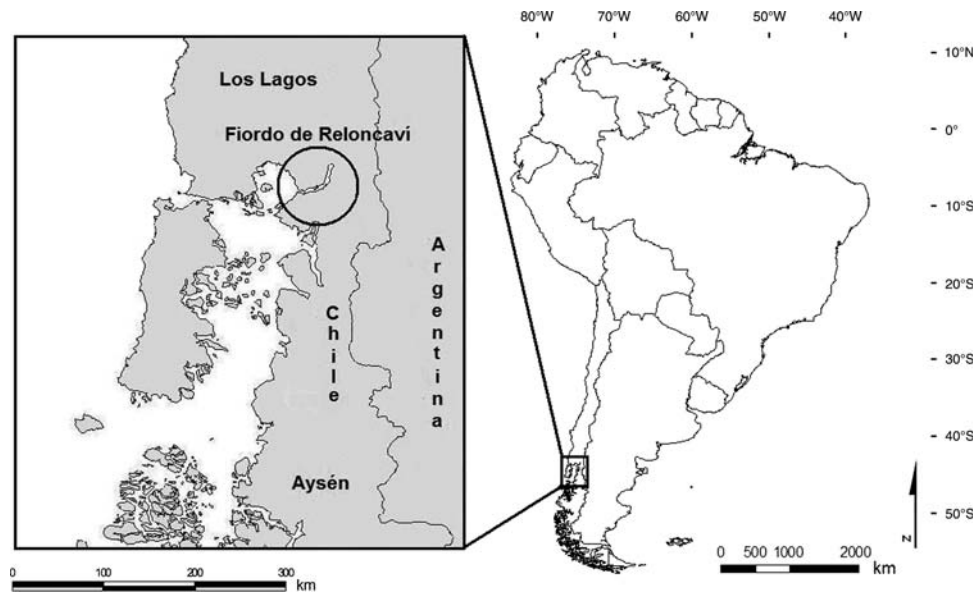


Figure 1. Study area showing the location of the Reloncaví fjord within the region of Los Lagos in southern Chile.

adjacent rows, forming a parallelepiped surrounded by an outer antipredator net. The two nets are separated by a certain distance usually not less than 1.5 m, and are held under tension by weights to keep them apart (Beveridge, 2004). Under normal conditions, this is sufficient to prevent the access of an aquatic predator. However, stormy weather or a strong tidal flux might cause the antipredator net to adhere to the inner fish net, cancelling out the physical-barrier effect and increasing fish vulnerability (Kemper *et al.*, 2003). In southern Chile, this phenomenon could be especially important, because the range between low and high tide usually reaches 7 m (Häussermann *et al.*, 2006).

Given the limitations of antipredator nets as a defence against pinniped incursions, and the high economic losses caused by these interactions (Oliva *et al.*, 2003), additional protection has been sought by salmon farmers: the use of acoustic harassment devices (AHDs). AHDs were created with the aim of producing a sound deterrent to marine mammals that would keep them away from an area or structure (Kemper *et al.*, 2003). Their effectiveness is controversial: most authors find it to be low to nil because of the progressive habituation of the predatory animals (Jefferson and Curry, 1996; Sepúlveda and Oliva, 2005; Nelson *et al.*, 2006). However, technical improvements have allowed the development of new AHDs with enhanced characteristics such as increased power, an increased number of sound sources, and a random schedule of activation that might improve their performance (Kemper *et al.*, 2003).

Based on the above, the objectives of this paper are (i) to describe the behaviour of SSLs in their interactions with salmon farms, (ii) to assess whether there is any discernible circadian and/or circa-annual rhythm in the distribution of the attacks, (iii) to investigate whether prey size has any effect on the pattern of the SSL attacks on salmon farms, (iv) to check whether this pattern of interactions is linked to the peaks of tidal flux, and (v) to evaluate the efficiency of AHDs by comparing the pattern of predation by SSLs at farms with and without this protective system. This project was the first in Chile in which these interactions between SSLs and salmon farms were studied directly *in situ* through fieldwork observations.

Material and methods

Study area

The fieldwork was carried out in the region of Los Lagos from May to July 2008 at three salmon farms, sites 1 ($41^{\circ}39'S$ $72^{\circ}40'W$), 2 ($41^{\circ}41'S$ $73^{\circ}38'W$), and 3 ($41^{\circ}43'S$ $72^{\circ}41'W$). The three sites are located near the fishing village of Caleta La Arena, in the Reloncaví fjord (Figure 1). Atlantic salmon (*S. salar*) was the species being farmed at all three sites. At the beginning of the fieldwork in May 2008, sites 1 and 2 held salmon that had almost reached commercial size (average body weight 4.31 ± 0.19 and 4.07 ± 0.27 kg, respectively), whereas site 3 held salmon that were much smaller (1.52 ± 0.27 kg).

Influence of circadian rhythms and behaviour of SSLs at interaction events

Observations were made to characterize the behaviour of SSLs during the interactions and to assess whether they were influenced by a circadian pattern. This effort was split into daylight (DT, hereafter) and night (NT) observations. In all, there were 25 shifts of observations, of which 21 were by day (from 08:00 to 15:30) and four were at night (from 23:00 to 07:00). During DT shifts, field Olympus 8×40 DPSI binoculars were used to detect the animals approaching the centre. During night shifts, a digital, infrared Yukon Ranger 5×42 , night-vision monocular, was used.

All the SSLs detected within a 20-m perimeter around the salmon farms were registered. For each sighting event, the number of SSLs present and the duration of sightings were noted. Sightings were also classified according to their distance to the antipredator net: <5 , 5–10, and 10–20 m. After compiling the data from all shifts, two sample groups were obtained, one for DT observations and another for night observations. To make daylight and night observation effort comparable, the number of SSLs observed in each shift was transformed into an hourly rate: $SSL\ h^{-1}$. The number of sightings was also transformed into $sightings\ h^{-1}$. Because the data were not normally distributed, a Mann–Whitney *U*-test was used to test for significant differences

between DT and NT activity samples. Analyses were performed separately for SSL h^{-1} and sightings h^{-1} .

Prey-size preference and circa-annual feeding pattern

To assess whether SSLs show any prey-size preference and whether their circa-annual feeding pattern is reflected in their attacks on salmon farms, data on SSL predation rates were gathered from the company's logbooks. The data showed the rates of salmon mortality detailed by cause, including predation by SSL, at the three study sites. Data on the average growth of salmon at each site were also collected and plotted against monthly time-intervals from January 2007 to June 2008, for each site.

Linear regression was chosen to analyse the possible relationship between predation and salmon body weight. As the AHD was installed at site 2, and site 3 had been harvested recently (September 2007), only the data from site 1 were used. Two regressions were fitted, one for autumn and winter (February–June) 2007 and another for the same period of 2008.

Tidal flux

To assess the influence of the tidal flux on the interactions, modelling software (WXTide32 version 4.7, freeware) was used to compile all high tide peaks during the period of fieldwork. Each hour of observation was used as a datum and assigned to a tidal interval ranging from 0 to ± 6 h, where "time 0" ($H = 0$, from now on) was an hourly interval consisting of the 30 min before and after the high tide peak. A runs-up and runs-down test for trend data was subsequently performed for SSL h^{-1} and sightings h^{-1} in these intervals (Sokal and Rohlf, 1995).

Effectiveness of the AHD

On 21 March 2008, a commercial AHD, model Airmar dB Plus 11® (Airmar Technology Corp., Milford, USA), was installed at site 2. According to Lepper *et al.* (2004), the device generates a sequence of pulsed, sinusoidal tonal bursts with a frequency of 10.3 kHz. Each tonal burst lasts 1.4 ms, with a 40-ms interval between bursts. The transmitter was located at an approximate depth of 10 m and linked to eight sensors distributed at even distances throughout the site (J. Zamorano, pers. comm.).

To assess the effectiveness of the AHD, the salmon mortality resulting from predation by SSLs registered at site 2 was compared with that registered at site 1, during the period in which the AHD was in use at site 2 (the austral autumn of 2008). Site 1 was selected because, unlike site 3, the average body mass of the salmon stocked there was similar to that at site 2 ($U = 96$, $p = 0.52$). Differences between sites 1 and 2 in terms of SSL h^{-1} and sightings h^{-1} and their average salmon body weight were assessed using Mann–Whitney U tests.

Results

Influence of circadian rhythms and behaviour of SSLs in the interaction events

DT shifts ($N_1 = 21$) amounted to a total of 111 h, and NT ($N_2 = 4$) to 24 h (Table 1). During DT shifts, 179 sightings were registered and 390 SSLs were observed: an hourly rate (h^{-1}) of 1.61 sightings and of 3.52 SSLs sighted. Similarly, during the NT shifts, 50 sightings were registered and 159 SSLs were sighted, providing rates of 2.09 sightings h^{-1} and 6.65 SSL h^{-1} . The number of SSLs sighted per hour was significantly greater at night ($U_{(4,21)} = 103$, $p < 0.01$); sightings were also significantly more during NT shifts

($U_{(4,21)} = 72$, $p < 0.05$). Furthermore, the mean group size, as indicated by the relationship of the number of sighted individuals to the number of sightings, was significantly larger at night ($U_{(4,21)} = 79$, $p < 0.01$).

During the interaction events, most SSLs were sighted at a distance of 5–10 m from the antipredator net (43.2%). Only 151 SSLs of a total of 549, i.e. 27.5%, were sighted swimming at < 5 m from the predator net. SSLs were seen in direct contact with the antipredator net in eight of these events: three during DT shifts, 1.7% of the DT sightings, and five during NT shifts, 10% of the NT sightings. Each of these direct contact events involved just one animal at a time.

The group size in the 229 sighting events (DT and NT sightings combined) ranged from 1 to 11 (Figure 2), with an average of 1.72. Sightings of a single SSL accounted for 38.4% of the total. Group sizes of 1–4 accounted together for 90.4% of the sightings. Only eight events (3.5%) had a group size > 7 .

Prey-size preference and circa-annual feeding rhythms

Figure 3a shows the monthly rates of salmon predation and the average body weight of the salmon kept at each site, from February 2007 to June 2008. The total salmon predation by SSLs during this period (17 months) was 168.04 t at site 1, 50.44 t at site 2, and 24.90 t at site 3, i.e. 8.25, 2.62, and 3.09% of the total production at sites 1, 2, and 3, respectively.

The predation pattern is highly irregular at site 1 (Figure 3a): the lowest records were in October 2007 and February 2008. Following these minima, predation increased sharply, reaching a maximum of 42.3 t in June 2008. At site 2 (Figure 3b), predation was high from March to June 2007, after which it dropped, to increase again in November and December. In January 2008, there was a peak, but thereafter it decreased, and from March on it stayed low. At site 3 (Figure 3c), predation was most prevalent during autumn and winter 2007, with two peaks in April and July. Thereafter, predation declined rapidly, and from October 2007 on, it was practically negligible.

The linear regression analysis shows no association between salmon body weight and predation by SSLs in 2007 ($r^2 = 0.65$, $p = 0.097$; Figure 4a). In contrast, in 2008 (Figure 4b), increased predation was linked significantly with the increment in salmon body weight ($r^2 = 0.85$, $p = 0.025$).

Tidal flux

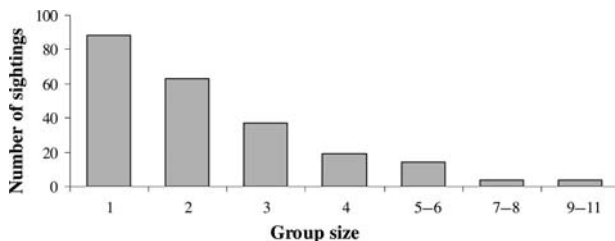
Figure 5 shows the numbers of SSLs observed and sightings at each hourly interval of the tide. The curves have a similar shape with two peaks, one before high tide ($H = 0$) and another thereafter. The successive positive and negative changes in both SSL h^{-1} and sightings h^{-1} differ significantly from random (SSLs: $\mu_{0.05} = 0.54$, $Z = -2.31$, $p = 0.02$; sightings: $\mu_{0.05} = 0.46$, $Z = -2.31$, $p = 0.02$). Therefore, the rates of SSL h^{-1} and sightings h^{-1} are cyclic, with most animals present just before the high tide, and a second peak at the ebb tide.

Effectiveness of AHDs

According to the company's logbooks, 13.17 t of salmon were predated by SSLs at site 2 from April to June 2007. In contrast, for the same period of 2008 just 7.75 t were predated, significantly less ($U = 1474.5$, $p = 0.011$). At site 1, where no AHD was installed, there was a distinct increase in predation as autumn and winter 2008 approached, growing from 3.34 t in March to 42.33 t in

Table 1. Rates of SSLs sighted and of sightings-per-hour by day (DT) and night (NT).

Date	DT/NT	Time (h)	Sightings	SSLs sighted	Sightings h ⁻¹	SSLs h ⁻¹
21 May 2008	DT	5.67	6	6	1.06	1.06
23 May 2008	DT	6.25	4	4	0.64	0.64
24 May 2008	DT	6.50	5	5	0.77	0.77
26 May 2008	DT	7.17	16	30	2.23	4.19
27 May 2008	DT	4.08	12	13	2.94	3.18
28 May 2008	DT	5.17	6	17	1.16	3.29
29 May 2008	DT	7.17	11	16	1.53	2.23
30 May 2008	DT	6.75	6	9	0.89	1.33
31 May 2008	DT	4.58	8	12	1.75	2.62
01 June 2008	DT	7.25	18	45	2.48	6.21
04 June 2008	DT	7.25	19	29	2.62	4.00
05 June 2008	DT	2.67	4	6	1.50	2.25
06 June 2008	DT	7.17	12	30	1.67	4.19
09 June 2008	DT	4.33	5	16	1.15	3.69
10 June 2008	DT	5.67	11	34	1.94	6.00
12 June 2008	DT	8.33	9	23	1.08	2.76
13 June 2008	DT	4.08	10	20	2.45	4.90
15 June 2008	DT	4.00	7	38	1.75	9.50
23 June 2008	DT	3.00	4	26	1.33	8.67
25 June 2008	DT	3.83	6	11	1.57	2.87
Total DT		110.92	179	390	1.61	3.52
18 June 2008	NT	8.00	15	49	1.88	6.13
23 June 2008	NT	5.67	15	50	2.65	8.82
30 June 2008	NT	6.25	12	33	1.92	5.28
06 July 2008	NT	4.00	8	27	2.00	6.75
Total NT		23.92	50	159	2.09	6.65
Total (DT+NT)		134.84	229	549	1.70	4.07

**Figure 2.** Group size at the sighting events, May–July 2008 ($n = 229$).

June 2008. At site 2 in 2008, the predation registered in March (3.36 t) was greater than that in June (2.52 t; Figure 3a).

During the period January–March 2008, there was no significant difference between sites 1 and 2 in terms of the biomass of salmon predated by SSLs ($U = 1570.5$, $p = 0.49$). During the period April–June 2008, i.e. after installation of an AHD at site 2, the biomass of salmon predated was significantly greater at site 1 than at site 2 ($U = 265.0$, $p < 0.001$).

Discussion

We have presented evidence that the interactions of SSLs with salmon aquaculture are not random, but follow patterns linked to daily and annual circa-rhythms, the intensity of the tidal flux, and prey size. These factors are discussed below.

Circadian rhythms and characterization of the sightings

The results show more SSLs present in the immediate vicinity of salmon farms at night. This preference for nocturnal interaction has also been found for other pinnipeds, such as the New Zealand fur seal (*Arctocephalus forsteri*; NSSG and Stewardson,

2007), the Mediterranean monk seal (*Monachus monachus*; Güçlüsoy and Savas, 2003), and the harbour (or common) seal (*Phoca vitulina*; Tillapaugh, 1991). Such a pattern fits with the current knowledge of the circa-rhythms of *O. flavescens*, which has been considered a predominantly nocturnal feeder (Thompson *et al.*, 1998; Sepúlveda *et al.*, 2001). Moreover, salmon farmers affirmed that *O. flavescens* attacks farms mainly at night (Sepúlveda and Oliva, 2005).

Nonetheless, this pattern of activity might be influenced by external causes, such as the minimal human presence at salmon farms at night, and the fact that the salmon tend to move to the bottom of the fish pen then (Oppedal *et al.*, 2001; Juell *et al.*, 2003), both of which increase their vulnerability (Ross, 1988). Moreover, the use at night of artificial lighting inside the fish pens to enhance the growth of the fish (Boeuf and Le Bail, 1999; Endal *et al.*, 2000) appears to attract many of the phototropic wild fish on which SSLs feed (Koen Alonso *et al.*, 2000). The fish will be rendered more visible by artificial illumination, which may enhance the feeding efficiency of *O. flavescens* (Schusterman and Kastak, 2000).

A remarkable result is that the average SSL h⁻¹, and hence the average group size, was almost double at night (6.65) than by day (3.52; Table 1). If night groups were larger, then it would be reasonable to expect a greater predation pressure at night. Unfortunately, it was not possible to quantify separately the amount of salmon predated by day and night because salmon mortality was checked every 24 h or at even longer periods. The greater number of SSLs at night could be explained by cooperative foraging behaviour, which might improve an individual's foraging efficiency (Berta *et al.*, 2006). Although cooperative foraging behaviour has not been reported for *O. flavescens*, anecdotal

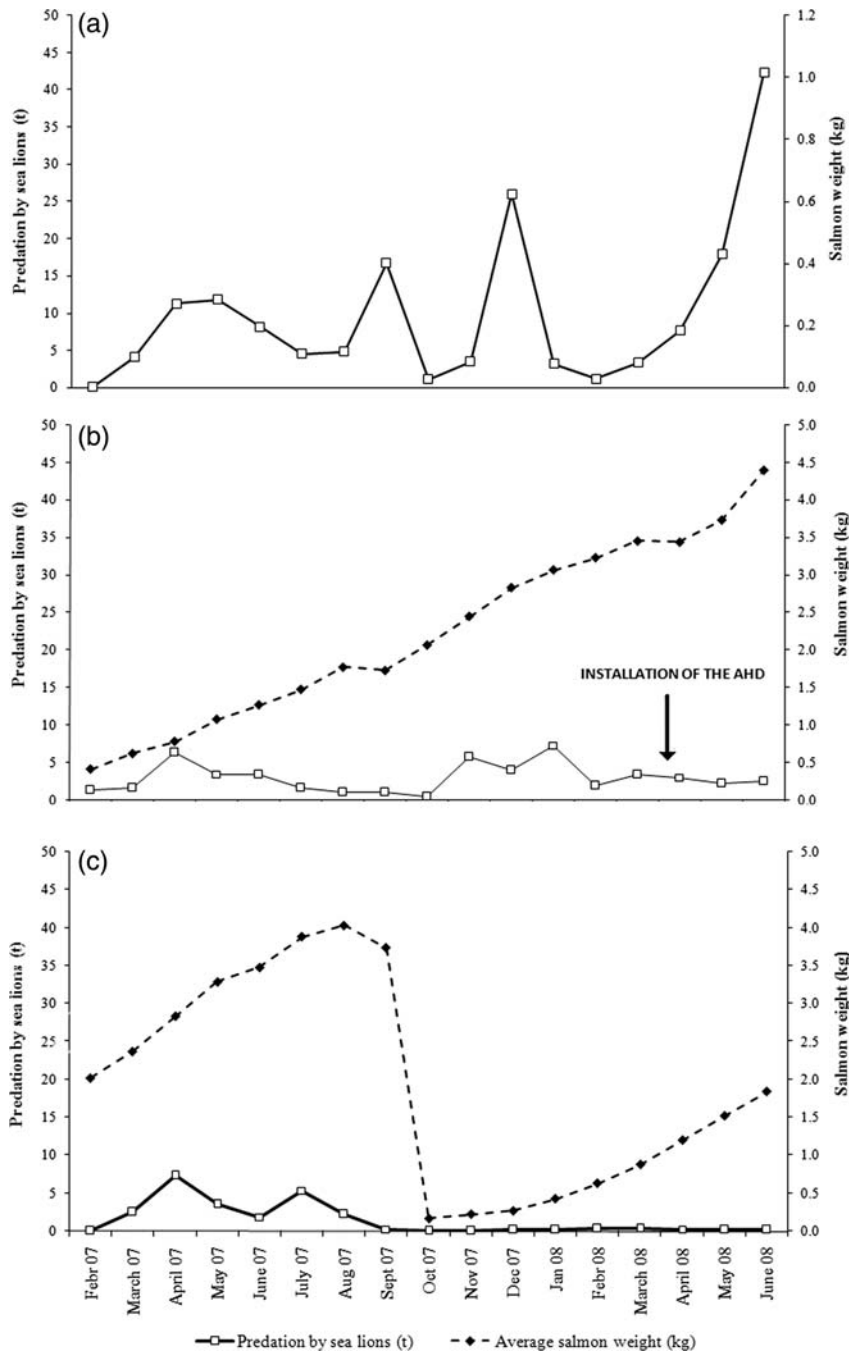


Figure 3. Predated biomass of salmon (t) and the monthly mean body weight (kg) of salmon at (a) site 1, (b) site 2, and (c) site 3, February 2007–June 2008.

experience during the study suggests that SSLs do show this kind of behaviour. Furthermore, cooperative behaviour of SSLs during interaction events has also been reported repeatedly by salmon farmers (Sepúlveda and Oliva, 2005).

Prey-size preference and circa-annual feeding rhythms

Our results suggest that SSLs preferably predate larger salmon, as proposed previously (Oporto and Leal, 1991; Sepúlveda and Oliva, 2005). The linear regression of the total biomass of salmon predated by SSLs against the average body weight of salmon supports this conclusion (Figure 4). The absolute maximum predation for

all three sites, registered at site 1 in June 2008 (Figure 3a) happened precisely when the salmon were at their maximum commercial size (4–5 kg), immediately before being harvested. Similarly, at site 3, predation peaked during autumn and winter 2007, when the salmon were mature. In October 2007, the salmon were harvested and substituted by smolts, and predation stopped (Figure 3c). The most important aspect of the predation curve at site 2 is that in autumn 2008 the mortality was lower than in the same period of 2007, although the salmon were larger in 2008. Interestingly, the period coincides with the installation of a new AHD at that site.

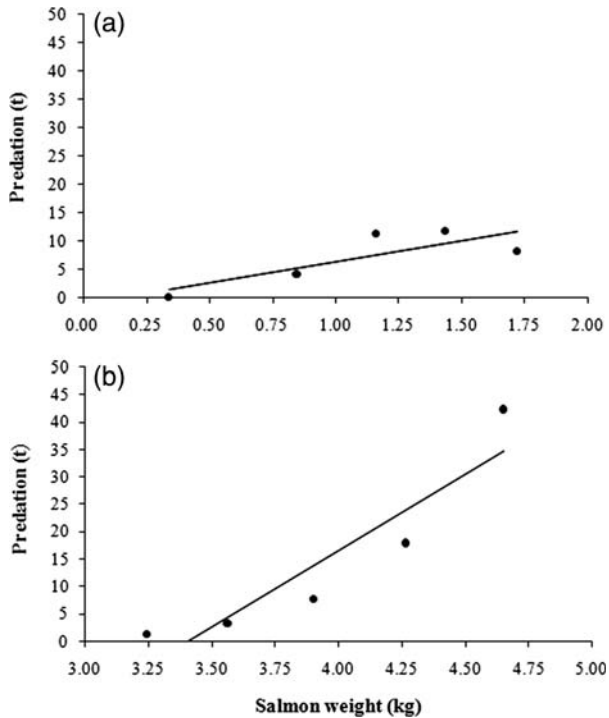


Figure 4. Predation of salmon (t) plotted against individual salmon weight (kg) at site 1 in autumn and winter of (a) 2007, and (b) 2008.

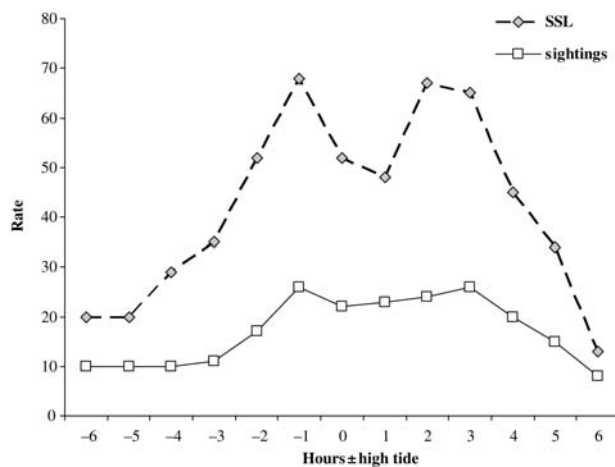


Figure 5. Number of sightings ($n = 229$) and of SSLs sighted per hour ($n = 549$) at hourly intervals after the high tide peak ($H = 0$).

A seasonal effect might be acting here too: SSLs show circa-annual activity patterns shaped by their breeding season (December–March), when foraging activity is greatly reduced. Therefore, it is reasonable to expect limited interaction then, followed by an increase from March. It is important to remember, of course, that when compared with the total production of salmon, the predation by SSLs is negligible.

Tidal flux

Our results show a relationship between sightings h^{-1} and SSLs h^{-1} and the height of the tide around the sites. This association with tidal flux has been proposed by several authors for

other pinnipeds (Ross, 1988; SSGA, 1990). According to those authors, the strong currents associated with ebb and flow tides break down the defensive systems so that SSLs can reach the salmon inside the fish pen. Several Chilean salmon farmers have reported this phenomenon. Other pinnipeds take advantage of tidal cycles to increase their chances of catching fish too (Zamon, 2001; London, 2006).

Another explanation for the increase in sightings of SSLs at the study sites close to high tides could be the lack of available space in their colonies then. The implication is that there will be more animals in the water (Bornemann *et al.*, 1998), and presumably many of them are engaged in foraging. In fact, surveys of the region (Oliva *et al.*, 2008) found that, during high tides, the numbers of SSLs at the colonies *per se* were severely reduced.

Effectiveness of AHDs

At the beginning of 2008, predation at site 2 was relatively high. Unexpectedly, instead of it increasing until autumn, it dropped, and stayed low until the end of the fieldwork in June 2008 (Figure 3b). This contradicts expectations, according to the circa-annual foraging pattern of SSLs. Simultaneously, at site 1 nearby, predation increased sharply from March to June 2008 and was more intense than in the same period of the previous year. The AHD was installed at site 2 in March 2008, whereas site 1 remained unprotected. Hence, the intense rate of predation at site 1 and the simultaneous decrease at site 2 are most likely explained by the presence there of the AHD.

However, the AHD had been active for only three months by the time the fieldwork finished, perhaps too short a time to allow definitive conclusions to be drawn. Moreover, an AHD of the same model installed over the same period at another salmon farm farther south proved to be totally ineffective (P. Figueroa, pers. comm.). Such contradictory information and the available literature show that despite their wide use in aquaculture (Kastelein *et al.*, 2006), the effectiveness of AHDs is still in doubt. Although several authors have found that they are at least partially effective (Yurk and Trites, 2000; Quick *et al.*, 2004; Fjälling *et al.*, 2006), others found them to be ineffective (Jefferson and Curry, 1996; Nelson *et al.*, 2006). In some cases, the use of AHDs not only was ineffective in deterring pinnipeds, but actually acted as attractants, because the animals learned to associate the sound with the presence of easily accessible fish (Nelson *et al.*, 2006).

Consequently, until this situation is clarified, salmon farmers should not rely solely on the use of AHDs as their main source of protection against interaction with pinnipeds. Other factors such as good management of the antipredator nets, selection of a good location for the farm, and the implementation of good management practices for recording fish mortality might be equally or more relevant in protecting the sites from pinniped interactions.

Acknowledgements

This work is part of the first author's MSc thesis at the University of Aberdeen (UK). We thank all those who managed and facilitated our fieldwork at the salmon farms, particularly Roberto Berndt, Mónica Alarcón, Maribel Cárcamo, and Jaime Cantero, and Ítalo Astudillo, from AquaChile Lda. Additionally, the fieldwork would not have been possible without the collaboration and goodwill of many AquaChile staff: Juan Donozo, Ariel Cabrales, Jaime Zamorano, Nelson Carruz, Óscar González,

Williams Hurtado, María Inelia Vargas, Ariel Gutiérrez, Aldo Vargas, Nicolás Hernández, Jaime Carretero, and many more. JV particularly thanks Thelma Fletcher and David Lusseau, who coordinated the course at Aberdeen during the academic year 2007/2008, and Paul D. Thompson, supervisor of the MSc thesis. The other two authors acknowledge the funding from FIP 2006-34 and Innova Chile 07CN13IPM-170. Finally, we express our gratitude to Lee Hastie and Colin McLeod of the University of Aberdeen, and Enrique A. Crespo of the Universidad Nacional de la Patagonia (Argentina) for reviewing the first draft.

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doi:10.1093/icesjms/fsp250