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Considerations in developing an integrated pest management programme for control of sea lice on farmed salmon in Pacific Canada

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Abstract

In the development of integrated pest management (IPM) plans for the control of sea lice there are some components that are common to many areas. However, effective plans must be tailored to regionally varying environmental and biological factors affecting the severity of sea lice infections. This paper describes factors that would be involved in the development of an IPM plan for sea lice in the Broughton Archipelago, British Columbia. Temperature, salinity and currents affect the production, dispersion and competence of larvae of sea lice, *Lepeophtheirus salmonis* (Krøyer), as they develop to the infective copepodid stage. This information can be coupled with oceanographic conditions in the Broughton Archipelago and emerging computer models to define zones of infection where infections of new hosts are most likely. Salinity and temperature depend, in part, on river discharge in estuarine systems. River discharge depends on precipitation, snow pack and ambient temperatures, which can be monitored to help forecast the intensity of sea lice infections associated with both farmed and wild hosts. One of the goals of IPM planning is to reduce reliance on pesticides to avoid development of resistance in targeted parasites and to minimize environmental residues. Recommendations for developing an IPM plan specific to the Broughton Archipelago are provided along with a discussion of the additional information needed to refine IPM plans in this and other areas.

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Introduction

Sea lice are ectoparasites of fish commonly found in marine environments. There are approximately 200 species of *Caligus* and 90 species of *Lepeophtheirus* (Pike & Wadsworth 1999). *Lepeophtheirus salmonis* and *Caligus clemensi* (Parker & Margolis 1964) infections have been observed on farmed Atlantic salmon, *Salmo salar* L., and numerous wild salmon of the genus *Oncorhynchus* in temperate latitudes of the Pacific Ocean. Of particular interest have been observations of sea lice on pink, *Oncorhynchus gorbuscha* (Walbaum) and chum, *O. keta* (Walbaum), salmon fry in the Broughton Archipelago of British Columbia (Jones & Hargreaves 2007). In the northern Atlantic, *L. salmonis* and *Caligus elongatus* (Nordmann) have been observed infecting wild Atlantic salmon and sea trout, *Salmo trutta* L. While the evidence regarding the origin of the infecting lice remains equivocal, concerns have been raised in both regions that sea lice infections are jeopardizing the health and viability of wild salmonid stocks (Krkošek, Ford, Morton, Lele, Myers & Lewis 2007). In Chile, infections by *Caligus rogercresseyi* have proven costly to Atlantic salmon producers (Bravo, Sevatdal & Horsberg 2008). However, no wild stocks of fish have been identified as being affected by sea lice in Chile. Johnson, Treasurer, Bravo, Nagasawa & Kabata (2004) noted that in British Columbia, sea lice have not significantly affected cultured Atlantic salmon, but they estimated that worldwide, sea lice cost producers approximately US $100 million per year. Thus, depending on the region where Atlantic salmon is farmed, sea lice control may be necessary to protect cultured fish and/or to protect wild stocks of fish.

Existing recommendations for development of IPM plans

Hosts, parasites and environments are constantly changing in both space and time. Therefore, one of the goals of IPM should be to reduce potential interactions when the hosts are most susceptible to infection and the parasites most vulnerable to treatment. IPM brings to bear a variety of tools to accomplish this. Use of chemotherapeutants is one of those tools, but overuse and/or incorrect use can lead to unintended consequences, such as development of resistant parasites in Scotland (Jones, Sommerville & Wootten 1992). Search (2004) discusses current thinking with respect to managing sea lice on farmed salmon with emphasis on minimizing the potential for development of resistance. The authors note that '*variety is the spice*' and recommend that farmers should exploit the maximum diversity of control measures available:

- Monitor sea lice on farmed fish.
- Avoid unnecessary use of anti-sea lice agents.
- Grow only 1-year class of fish at a time at any given site.
- Fallow between production cycles.
- Keep nets clean to increase water flow and minimize retention of lice larvae.
- Remove moribund fish, slow swimmers and runts on a frequent basis.
- Use cleaner fish, such as wrasse when they are available.
- Use chemotherapeutants at appropriate times and in accordance with the label.
- Synchronize control strategies through use of area-wide management plans.
- Rotate the use of chemotherapeutants having different modes of action.
- Monitor the efficacy of treatments to achieve early indications of resistance.

To date, most sea lice management plans rely on monitoring at prescribed intervals and treatment with chemotherapeutants when lice levels on farmed fish reach the following abundances. These requirements are imposed for the protection of wild sea trout and Atlantic or Pacific salmon. No government requirements for development of IPM plans consistent with the recommendations of Search (2004) were found.

- *British Columbia, Canada.* The BC Ministry of Agriculture, Food and Fisheries (BCMAFF 2003) Sea Lice Action Plan requires monthly monitoring of 20 fish from each of three randomly selected pens to detect the presence of motile lice. Increased monitoring, harvest, treatment or husbandry is required when sea lice abundance reaches three motile lice per fish at any time of the year.
- *Maine.* The Cobscook Bay, Maine IPM allows significant licensed veterinarian discretion. Monitoring of five fish from five cages at least every other week is required when water temperature is > 8 °C or monthly at between 4 and 8 °C. The plan requires treatment before the appearance of gravid *L. salmonis* on < 2 kg salmon. Treatment is required when one gravid female or five pre-adult *L. salmonis* are observed on five fish weighing ≥2 kg in two or more cages.
- *Norway.* Monitoring, followed by treatment of farmed salmon, is required between 1 December and 1 July when abundances of five motile lice of any stage or 0.5 gravid female lice/fish are observed. Between 1 July and 1 December, the benchmark is relaxed to require treatment when abundances reach 10 motiles of any stage or two gravid female lice per fish.
- *Ireland.* Between March 1 and May 1, treatment is required when the abundance of adult female lice reaches 0.3 per fish. During the remainder of the year, action is triggered when the abundance of adult female lice reaches 2.0 per fish.
- *Scotland.* No defined action level was identified. Management relies on area management agreements.

The Broughton environment, sea lice and hosts

Development of effective IPM plans requires understanding hosts, parasites and the environment within which they interact. The following discussion summarizes what is known regarding these needs in the Broughton Archipelago, British Columbia. This information will then be used to recommend additional tools and considerations that may reduce reliance on chemotherapeutants. While the focus is on conditions in the Broughton Archipelago, the principles can be applied to many areas, cultured species of fish and parasites. Figure 1 describes salient features of the Broughton Archipelago.

Broughton Archipelago environment

The Broughton Archipelago is a dynamic estuarine system located adjacent to Queen Charlotte Strait. Inputs of fresh water from major rivers such as the Klinaklini are associated with rainfall, snowmelt and glacial runoff in the BC Cascades, lying east of the archipelago. This input causes generally westward surface flows of low salinity water, which are compensated for by higher salinity intrusions of deep water from the Queen Charlotte Strait (Foreman, Stucchi, Zhang & Baptista 2006).

Salinity

Figure 2b describes salinity at the Sargeaunt Pass salmon farm located at the confluence of Knight Inlet and Tribune Channel. The data was collected by Marine Harvest Canada using a YSI Model 33 salinometer calibrated at 0.0 and 30 Practical Salinity Units (PSU) each day. Salinity at Sargeaunt Pass was highly variable under the influence of Klinaklini River runoff that significantly reduces salinity in the eastern portions of the estuary to depths of 10 to ~40 m from May to November (Brooks 2005; Foreman *et al.* 2006). In contrast, the Arrow Pass farm, located near the Queen Charlotte Strait (Fig. 2a) had nearly constant salinity of *ca* 32 PSU during 2007. Figure 3 compares freshwater discharge from the Klinaklini River at the head of Knight Inlet (unpublished DFO data) with salinity recorded at the same time in the upper 5.5 m at Sargeaunt Pass. At depths ≤5.5 m, the correlations between river runoff and salinity are significant and > 0.80. However, as depth increases, the correlation breaks down and is not statistically significant at depths > 10.5 m. The model predictions are reasonably well correlated with the tidal stage variable displayed at the bottom of Fig. 2b, indicating stronger ebb tides (more and higher magnitude negative values) than flood tides (positive values).

Broughton seawater temperatures

Figure 4 describes temperatures recorded in Sargeaunt Pass at three depths during the spring and early summer of 2006. The recorded values illustrate the

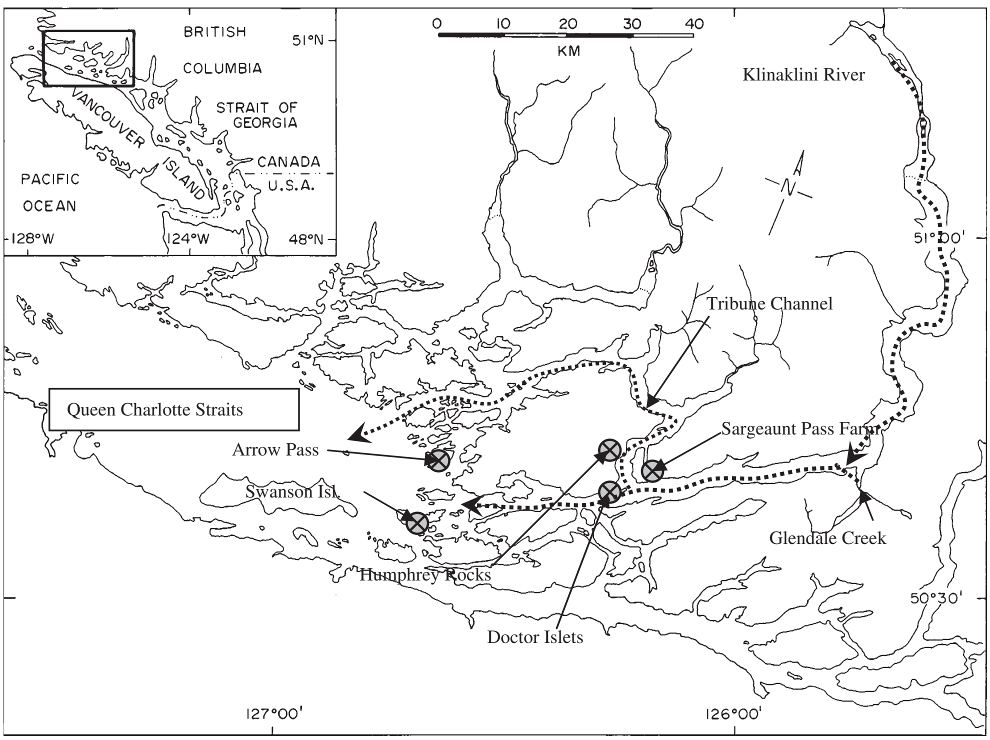

Figure 1 Broughton Archipelago of British Columbia. Major surface flows and features discussed in this paper are identified.

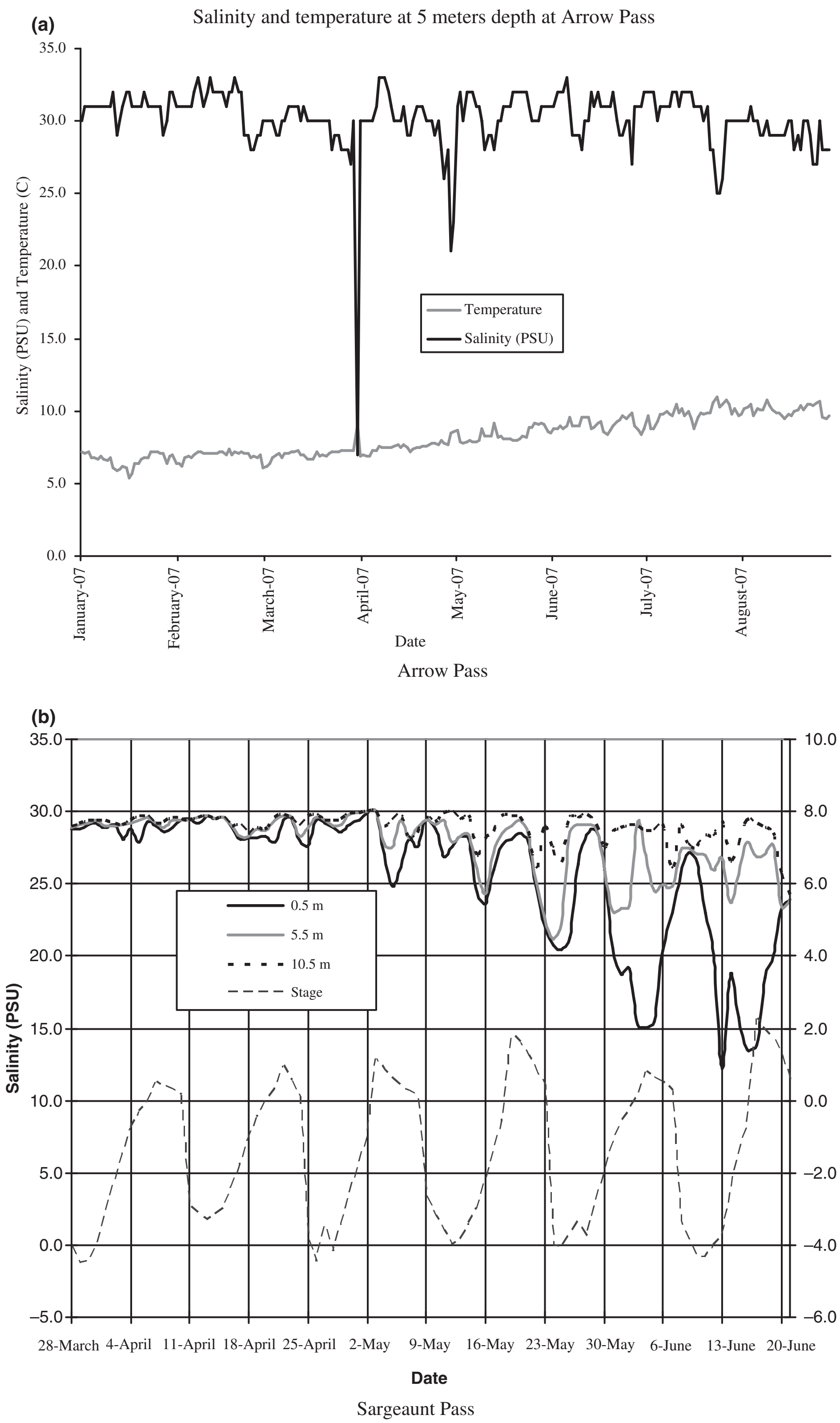

Figure 2 Salinity and temperature at the Arrow Pass salmon farm (a) located near the Queen Charlotte Strait and at Sargeaunt Pass (b).

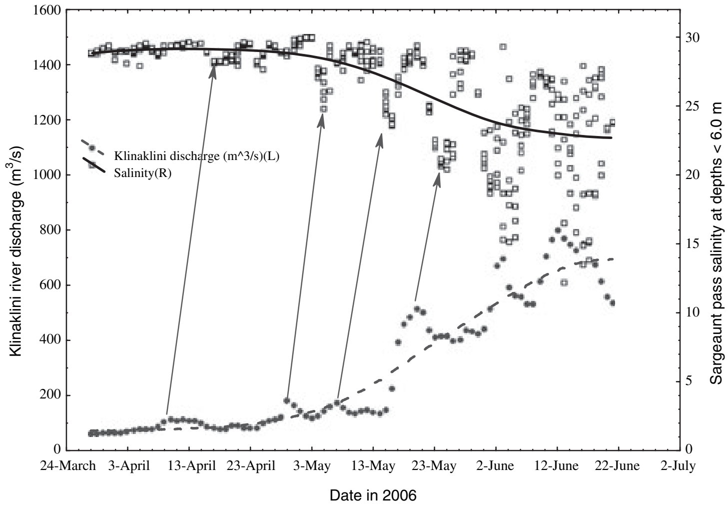

Figure 3 Comparison of Klinaklini River discharges(m^3 s^{-1}) with salinity (PSU) at depths ≤5.5 m at Sargeaunt Pass. The arrows relate increased river discharge with minimum values of salinity recorded during neap tides.

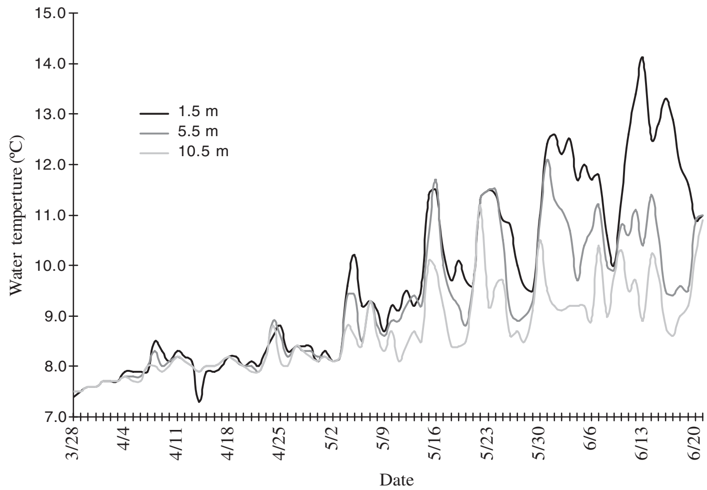

Figure 4 Temperatures at 1.5-, 5.5- and 10.5-m depths at the Sargeaunt Pass salmon farm in the Broughton Archipelago between 28 March and 20 June, 2006.

same variability and period seen in the salinity data under the influence of cold snow and glacial melt in Klinaklini River water. Winter sea water temperatures of 7.5 °C increased during late April reaching highs of 14 °C in surface water by the middle of June. Note that temperatures vary from 10 to 14 °C over 2-week periods during June. The same degree of variability was not observed at Arrow Pass, located near the Queen Charlotte Strait (Fig. 3a) where the temperature at 5-m depth varied only between 9 and 10 °C during the same period.

Broughton currents

Table 1 describes the mean and net current speeds measured at 15-m depth at 15 Broughton Archipelago salmon farms over full lunar cycles. The empirically derived net speeds integrate the effects of wind, tidal currents and estuarine flows. Peak current speeds at 9 of 15 farms were ≥50 cm s^{-1} (one knot). Maximum current speeds at the other farms varied between 30 and 50 cm s^{-1}. Included in Table 1 are estimates of the advection of sea lice larvae downcurrent during development to the infective copepodid stage at 9 °C (a minimum distance) and the maximum total distance larvae are carried before the copepodids die at 7.5 °C. The data was collected at 15-m depth and may underestimate surface current speeds (i.e. < 5-m depth). Brooks & Stucchi (2006) presented the results of modelling the dispersion of continuously released sea lice nauplii (considered inert particles) from two

Table 1 Net surface (15-m depth) current vectors at 15 salmon farms in the Broughton Archipelago

	Net speed, cm s^{-1}	Resting direction degrees true	Average speed, cm s^{-1}	Minimum distance to copepodid (4.2 days)	Maximum distance (copepodids die in 10.8 days)
Arrow Pass	2.0	193	3.9	7.3 (3.9)	18.7 (10.1)
Blunden Pass	0.2	251	2.2	0.7 (0.4)	1.9 (1.0)
Bocket Point	2.2	24	4.5	8.0 (4.3)	20.5 (11.1)
Deep Harbor	1.2	210	1.2	4.4 (2.4)	11.2 (6.0)
Doctor Islets	1.4	261	5.6	5.1 (2.8)	13.1 (7.1)
Eden	1.6	77	7.0	5.8 (3.1)	14.9 (8.0)
Glacier Falls	4.3	82	6.7	15.6 (8.4)	40.2 (21.7)
Humphrey Rock	3.1	41	6.6	11.2 (6.0)	28.9 (15.6)
Midsummer Island	1.6	283	4.3	5.8 (3.1)	14.9 (8.0)
Port Elizabeth	2.6	73	4.3	9.4 (5.1)	24.3 (13.1)
Sargeaunt Pass	1.8	126	6.4	6.5 (3.5)	16.8 (9.1)
Smith Rock	2.0	85	8.4	7.3 (3.9)	18.7 (10.1)
Swanson Island	1.9	264	7.7	6.9 (3.7)	17.7 (9.6)
Upper Retreat	2.2	36	4.8	8.0 (4.3)	20.5 (11.1)
Wicklow	0.5	166	10.5	1.8 (1.0)	4.7 (2.5)
All farms	1.91			6.9 (3.7)	17.8 (9.6)

The vectors indicate the direction and speed at which seston (including lice nauplii) would be displaced from each farm as a function of time. The minimum distance at which nauplii moult to the infective copepodid stage is provided for a temperature of 9.0 °C (4.2 days) and the maximum typical distance at which copepodids die if they do not find a new host (10.8 days) is provided assuming a larval development time of 5.8 days at 7.5 °C. Distances are in km from each farm. Distances in nautical miles are provided in parentheses.

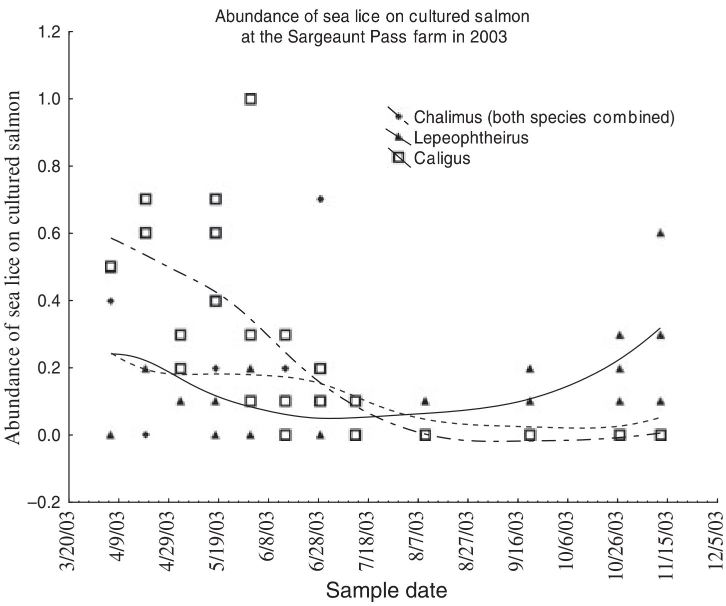

Figure 5 Abundance (mean number of lice/cultured fish) at the Sargeaunt Pass salmon farm in 2003. The farm was not treated during the period of these records. The regression lines were derived using the least square fitting routine in Statistica™ Version 6 software.

Broughton farms using the model of Foreman *et al.* (2006), which did not include the effects of sea lice behaviour or of wind. That exercise predicted that nauplii released from the Doctor Islet salmon farm would be swept down Knight Inlet and out of the archipelago before moulting to the infective copepodid stage. However, nauplii released from the Glacier Falls farm moulted to the copepodid stage in the vicinity of the Burdwood Group and could infect farmed salmon and/or wild fish located in the western portions of the archipelago. Gillibrand & Willis (2007) published and tested a model designed for lochs in Scotland. Their model, which does include sea lice behaviour and wind, in addition to tidal and river driven currents, predicts that in an idealized loch, larvae moult to the infective stage at distances of 7–12 km from their point of hatching.

Lepeophtheirus salmonis and *Caligus clemensi*

Johnson & Albright (1991) reported the response of Pacific *L. salmonis* to temperature and salinity. Pike & Wadsworth (1999), Bricknell, Dalesman, O'Shea, Pert & Mordue Luntz (2006) and Tucker, Sommerville & Wootten (2000)have characterized Atlantic *L. salmonis* larval responses to temperature and salinity. No studies describing the response of larval *C. clemensi* to temperature and salinity were found. For purposes of developing IPM plan recommendations, it will be assumed that both *L. salmonis* and *C. clemensi* respond in a similar way to temperature and salinity.

Effects of salinity on the survival of *L. salmonis*

Johnson & Albright (1991) observed almost no development of *L. salmonis* to the copepodid stage at salinities < 30 PSU. Bricknell *et al.* (2006) found that survival of Atlantic free-swimming copepodids was 'severely compromised' at salinity < 29 PSU and Tucker *et al.* (2000) observed reduced settlement of Atlantic copepodids at 24 PSU in comparison with 34 PSU. Using data from Johnson & Albright (1991), Brooks & Stucchi (2006) developed a statistical model resulting in a family of curves describing *L. salmonis* survival as a function of salinity and time from naupliar hatching. The results predict very low survival at salinities < 30 PSU.

Effects of temperature on the development of *L. salmonis*

Temperatures at < 5-m depth in the Broughton Archipelago vary between 6 °C in winter and 14 °C in summer (Brooks 2005; Figs 2a,b & 4). Using data from a variety of sources, Brooks (2005) developed a statistical model estimating the time for *L. salmonis* development from hatching to the infective copepodid stage ($T_{n-c} = 19.95 - 2.587^{*}T + 0.092^{*}T^{2}$). At typical springtime temperatures of 7.5–9.0 °C, the model predicts that nauplii will be dispersed for 4.2–5.8 days before becoming infective. However, at summer temperatures of 13–14 °C, the development time is reduced to *ca* 1.9 days. Brooks (unpublished data) developed a similar model for predicting the brood generation time (BGT) for *L. salmonis* (BGT = 345–273*LogT °C). At 7.5 °C, this model predicts a BGT of 106 days. The BGT is reduced to only 32 days at 14 °C.

Hosts of *L. salmonis* and *C. clemensi*

Caligus clemensi has been reported on 13 species of marine fish in British Columbia including coho, *Oncorhynchus kisutch* (Walbaum), pink and chum salmon (Parker & Margolis 1964). *Lepeophtheirus salmonis* has generally been considered specific to salmonids. However, Bruno & Stone (1990) reported that saithe, *Pollachius virens* (L.), was host to both *L. salmonis* and *C. elongatus* and that motile sea lice actively transferred from healthy fish to dark moribund fish. In the Pacific, Jones, Prosperi-Porta, Kim, Callow & Hargreaves (2006a) reported *L. salmonis* on three-spine sticklebacks, *Gasterosteus aculeatus* L., throughout the Broughton Archipelago with high prevalence of both *L. salmonis* and *C. clemensi* (83.6% and 42.8%, respectively). Abundance on the sticklebacks increased from east to west in the archipelago and appeared positively correlated with increasing salinity. The abundance of *L. salmonis* on sticklebacks ranged from 1.3 to 73.2, with the lowest numbers observed in areas of lowest salinity and the highest abundance in area 'K' adjacent to Queen Charlotte Strait. It should be noted that in this study and in the laboratory study of Jones, Kim & Dawe (2006b), gravid female *L. salmonis* were not observed on three-spine sticklebacks. Evidence from the Broughton Archipelago (see Fig. 6) and the reports of Bruno & Stone (1990) and Jones *et al.* (2006b) indicate that some portion of new infections are associated with direct transfer of motile lice from one host to another. This emerging lice vector is substantiated by the sentinel cage data in Scotland presented by Raffell, Buttle & Hay (2007). Three-spine sticklebacks are a euryhaline species found in nearshore waters where juvenile pink and chum salmon also migrate (Hart 1973). Stickleback and other, as yet unidentified peripatetic hosts (see Raffell *et al.* 2007), may be important for sustaining sea lice over winter allowing direct transfer of motile stages to salmon fry the following spring. The numbers of resident salmonids, three-spine sticklebacks and other hosts of *L. salmonis* and *C. clemensi* in the Broughton Archipelago are unknown.

Pink salmon fry

Pink salmon fry migrate to the marine environment shortly after emerging. They leave their natal streams weighing < 0.5 g and grow rapidly given adequate food availability at rates of 3.5–7.6% of

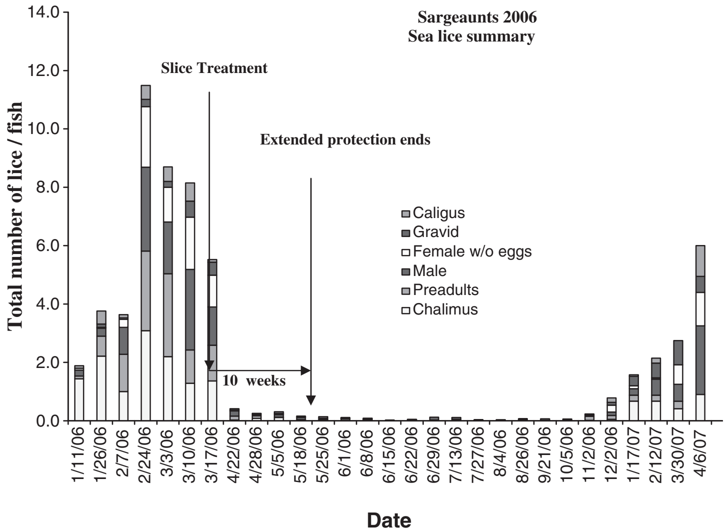

Figure 6 Sea lice at the Sargeaunt Pass salmon farm in 2006. SLICE® was administered for 7 days beginning on 7 March, 2006. The 10-week period of extended SLICE® protection is indicated.

body weight per day. They move offshore at total lengths of 4.5–7.0 cm (Heard 1991). Peter van Will (DFO, personal communication) provided data demonstrating a high degree of variability in the timing of pink salmon fry migration from Glendale Creek, which produces 89% of the archipelago's pink salmon in odd years and 39% in even years (Brooks & Jones 2008). In 2003, fry began migrating from the watershed before the first week in March. In 2005 and 2006, migration began during the first week in March and continued until mid April. However, in 2007, because of cold weather, fry did not start migrating from Glendale Creek until the first week in April and some fish did not leave the watershed until the third week in May. Heard (1991) reported that hatching of pink salmon occurred after accumulating 530–610 degree days and that emergence required 900–980 degree days. This information coupled with monitoring of water temperatures in major pink salmon spawning areas provides a basis for predicting when pink salmon fry will migrate, which is important for timing sea lice control measures.

Effects of lice on pink salmon fry

Management of sea lice on farmed salmon in the Broughton Archipelago has been undertaken as a precautionary approach to protecting pink and chum salmon fry during their outmigration. Brooks & Jones (2008) reviewed the controversy regarding the effects of sea lice on pink salmon fry and concluded that numerous studies have demonstrated a general resistance to sea lice infections among species of *Oncorhynchus* including pink salmon fry (Johnson & Albright 1992a,b; Johnson 1993; Fast, Ross, Mustafa, Sims, Johnson, Conboy, Speare, Johnson & Burka 2002a; Fast, Sims, Burka, Mustafa & Ross 2002b; Jones *et al.* 2006b, 2007; Jones, Fast, Johnson & Groman 2007; Webster, Dill & Butterworth 2007; Jones, Fast & Johnson 2008b; Jones, Kim & Bennett 2008a).

However, until the question of sea lice effects on wild salmon populations are resolved, producers will probably be required to manage lice on farmed salmon.

Sea lice on Pacific salmon returning to the archipelago

Beamish, Neville, Sweeting & Ambers (2005) found that pink, chum and sockeye salmon returning to the Broughton Archipelago had average lice intensities ranging from 41.5 to 52. The prevalence of lice on pink salmon was 100% resulting in identical lice abundance and intensity of 51.1 lice in Queen Charlotte Strait. About twice as many *L. salmonis* as *C. clemensi* were observed on returning salmon and one-third of the *L. salmonis* lice were gravid females. In 2000, 3 600 000 pink salmon returned to the Broughton Archipelago. Given an average fecundity of 700 eggs per gravid female on wild salmon (Pike & Wadsworth 1999), these results suggest that returning adults brought 28 billion *L. salmonis* eggs into the estuary ($3\ 600\ 000 \times 51.1 \times 0.66 \times 0.33 \times 700$). During average years when 900 000 pink salmon return, the number of eggs would be in the order of 7 billion. Saksida, Constantine, Karreman & Donald (2007) reported a mean *L. salmonis* abundance of 1.59 ± 0.46 female lice on farmed Atlantic salmon. This analysis will conservatively assume that the female lice on cultured fish were gravid with 300 eggs per female (Pike & Wadsworth 1999). Production of Atlantic salmon in the Broughton Archipelago between 2000 and 2006 has averaged 19 119 046 ± 2 735 023 kg [Proprietary data provided by the British Columbia Pacific Salmon Forum (BCPSF) with permission from Marine Harvest Canada and Mainstream Canada]. Assuming that these fish weighed an average of 5.5 kg at harvest suggests that in a typical year, there were 3 476 190 Atlantic salmon being raised in the archipelago. The contribution of eggs during the single brood cycle that is likely during the spring migration of pink salmon fry would be 3 476 190 × 1.59 × 300 = 1.66 billion, or about 24% of those contributed by the returning wild pink salmon during the previous autumn in an average year. This result does not include sea lice on three spine sticklebacks or any of the other returning or resident wild salmon – nor does it include the contribution of *Caligus* from numerous wild hosts. The results suggest that while farmed salmon make a quantifiable contribution to the overall lice load in the archipelago, wild salmon and other hosts also contribute lice. This is important for IPM planning because while sea lice on farmed fish can be managed, the contribution from wild sources cannot be controlled.

Sea lice on Atlantic salmon in the Broughton Archipelago

The foregoing information indicates that large numbers of sea lice are brought into the eastern portions of the archipelago when adult pink salmon return in the autumn (September to early November). Runoff in coastal rivers is low in late autumn and winter leading to surface salinities in the eastern portions of the estuary of 25–30 PSU. Lice detach from their anadromous hosts as they enter natal streams – or they die in the fresh water. The traditional understanding of sea lice vectors involves maturation of females followed by larval development in the plankton resulting in copepodid infection and development on new hosts. Raffell *et al.* (2007) suggested that peripatetic (wandering) hosts were involved as lice vectors and that Atlantic sticklebacks might play that role and the same may be true in the Pacific. An alternate hypothesis to the copepodid vector is proposed here. In this strategy, lice detach from returning Pacific salmon in autumn and early winter. They find residence on farmed salmon, other opportunistic hosts, or in alternate nearshore environments where they overwinter. These motile lice are then available to directly infect new hosts or to release larvae in late winter.

Patterns of sea lice infection and development on farmed salmon

Intensive monitoring of farmed Atlantic salmon in compliance with the provincial Sea Lice Action Plan provides a useful record for testing the natural control hypotheses. Sea lice abundance on untreated Atlantic salmon at the Sargeaunt Pass farm was highest during winter when salinity was high and river discharge low (Brooks 2005). In response to increased river discharge, abundance declined significantly in June and remained low (≤0.2 lice per fish) until October after which *L. salmonis*, presumably from returning Pacific salmon, increased steadily. A similar pattern was reported for the nearby Humphrey Rocks farm.

Figure 6 describes sea lice on Atlantic salmon at the Sargeaunt Pass salmon farm during 2006. The last two pens were treated beginning on 7 March, 2006. Assuming 10 weeks of extended protection associated with the SLICE® treatment, the fish would be protected until 21 May, 2006. In fact, the cultured fish remained essentially lice free until 2 November, 2006 when the abundance of lice began increasing. The additional 6-month lice free period is hypothesized to have been caused by reduced summer salinity (Fig. 2b). The composition of the lice community is also interesting in that more pre-adults and adult lice were recorded on all dates than were chalimus. Pre-adult, male and gravid female lice were recorded on 2 December, 2006 before any chalimus were observed. The composition of the developing lice community suggests direct infection by several pre-adult and adult stages of lice. Figure 7 describes sea lice abundance at the Arrow Pass salmon farm located near the Queen Charlotte Strait (Fig. 1). Motile abundance peaked there in spring and generally declined during summer. In 2005, abundance increased in spring and peaked in

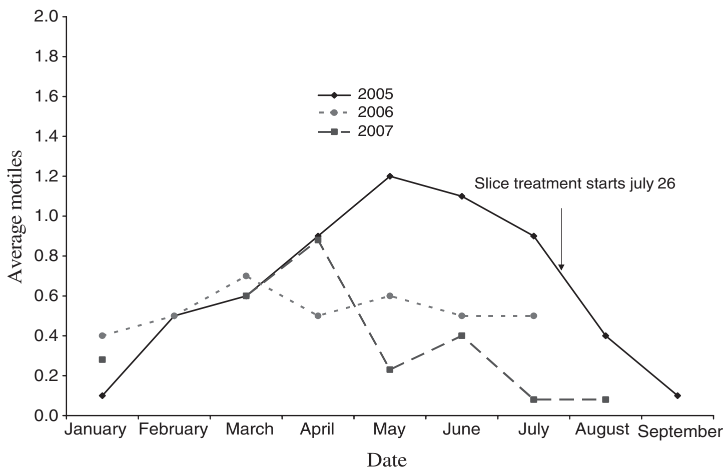

Figure 7 Motile sea lice counts on farmed Atlantic salmon at the Arrow Pass salmon farm from January 2005 to August 2007. SLICE® medicated feed was provided on 26 July, 2005 for 7 days, but no treatments were made in other years.

May at 1.2 motiles per fish. Treatment was planned in anticipation of a continued increase and the fish were treated in late July 2005. However, the abundance of lice started declining naturally after May suggesting that summer salinity in eastern parts of the estuary depressed larval development as they were carried from low salinity areas toward Arrow Pass. This is an example of a treatment that may not have been necessary.

Use of chemotherapeutants to control sea lice on farmed salmon in the Broughton Archipelago

Emamectin benzoate (SLICE®) is the only chemotherapeutant generally used in the Broughton Archipelago. It is an avermectin that acts to block nerve transmission in arthropods resulting in paralysis and death when administered in salmon feed at a dose of 0.05 mg kg^{-1} fish biomass for 7 days. SLICE® is effective against all stages of *Lepeophtheirus* sp. and *Caligus* sp. when administered at 3–15 °C (Stone, Sutherland, Sommerville, Richards & Varma 2000). Hobson (2005) concluded that SLICE® provides $>90\%$ efficacy for more than 64 days after commencing treatment and provided $>80\%$ reduction in gravid females for at least 70 days. These reports indicate that SLICE® effectively reduces lice on Atlantic salmon for 70 days from the start of treatment. The eggs on gravid female lice do not have nervous systems and therefore may not be directly affected by this treatment. Dr Richard Endris (Schering-Plough, personal communication) reports that the effect of SLICE® on the viability of sea lice eggs has not been determined. Thus, it is possible that eggs attached to moribund female lice could remain viable, affecting the timing of treatment, which is an important consideration in IPM planning.

Development of resistance to chemotherapeutants by sea lice

Organophosphates such as dichlorvos were used in Norway until 1995. In some areas of mid-Norway, dichlorvos lost its effectiveness in 1991–1992. Similarly resistance to azamethiphos occurred in mid- and southern Norway during 1995–1996. In Chile, organophosphates were used from 1982 until the end of the 1980s, when ivermectin was introduced. Schering-Plough Animal Health (2000) also reported resistance in *L. salmonis* to azamethiphos, pyrethroids, deltamethrin, cypermethrin and hydrogen peroxide. Altered (mutated) forms of acetycholinesterase have been identified as the resistance mechanism to this class of compounds (Search 2004). SLICE® was introduced to counter this developing resistance. However,Bravo *et al.* (2008) report evidence of resistance in *C. rogercresseyi* to emamectin benzoate during 2006 and 2007 in Region X of Chile, suggesting that this treatment must also be used judiciously.

Summary of important factors in developing an IPM plan for the Broughton Archipelago

The following points are considered important in developing an IMP plan for the Broughton Archipelago.

- At spring temperatures of 7.5–9.0 °C, nauplii will be dispersed for 4.2–5.8 days during development to the infective stage. The BGT at these temperatures is ~106 days. However, at summer temperatures of 14 °C it is predicted to be as short as 32 days. This suggests that there is little potential for more than a single generation of lice in winter and early spring, but that several generations of lice could be produced in warmer areas of the archipelago – at least when salinity is acceptably high. Note that at Arrow Pass, typical of farms located near the Queen Charlotte Strait, the maximum temperature recorded was *ca* 10 °C resulting in a BGT of 72 days. When coupled with the 10 weeks of extended protection provided by SLICE®, this suggests that gravid females will not be found on treated fish newly infected by copepodids for approximately 20 weeks (5 months).
- During spring in the Broughton Archipelago, new copepodid infections should be expected at distances of 6.9–17.8 km from the point of hatching. However, the variation in Table 1 indicates significant differences between farms and each farm should be analysed separately.
- Sea lice originating on farms located near the Queen Charlotte Strait or at Doctor Islets in Knight Inlet will probably be swept into the Queen Charlotte Strait prior to moulting to the copepodid stage. Larvae released at Glacier Falls, Humphrey Rocks and Sargeaunt Pass in March and April can infect both cultured and wild fish as they pass around Tribune Channel while being carried toward the straits.
- Salinity at depths ≤5.5 m at Sargeaunt Pass may be suitable for development of *L. salmonis* during winter and until the end of April. With the assumptions that lice larvae remain in the upper 5.5 m of water, it appears that in many years salinity in the eastern portions of the archipelago is too low for development of lice after the end of April.
- Salinity in the area of Sargeaunt Pass can probably be predicted based on Klinaklini River discharges. The lag from discharge to effects at Sargeaunt Pass decreases from 2 weeks when discharges are low to only a few days at higher river discharges.
- Pink salmon fry begin their outmigration as early as the first week in March and the migration from Glendale Creek typically extends until the end of April. However, in cold years, the migration may be delayed for up to a month (April to the end of May).
- Sea lice originating on Atlantic salmon farms in the archipelago are a quantifiable source of lice. However, it is now known that there are numerous other sources of lice. The relative proportion of farmed and wild lice is currently unknown, but the analysis provided herein suggests that the wild contribution may be substantial.
- Under constant re-infestation pressure, emamectin benzoate (SLICE®) has been shown to significantly reduce all stages of lice on treated fish by up to 90% for ~10 weeks after starting treatment.
- The presence of resting stages for lice, on sticklebacks or in an unknown environmental compartment, seems a logical evolutionary adaptation to sustain the significant reproductive potential of lice on returning Pacific salmon. However, other than the presence of large lice loads on three-spine sticklebacks and mounting evidence of direct infection by motile stages of lice, this hypothesis has not been tested.

Development of an IPM plan for the Broughton Archipelago

The following considerations are intended to expand the recommendations made by Search (2004). They are not intended to replace those recommendations.

Existing management of sea lice in the Broughton Archipelago

An IPM programme has not been developed for the Broughton Archipelago. Sea lice management to protect out-migrating pink salmon fry relies primarily on sea lice monitoring and required treatment in accordance with the provincial Sea Lice Action Plan. Efforts to develop an area-wide management plan continue, but no such plan is currently in place. Significant efforts to understand the interaction between farmed salmon, sea lice and wild stocks of pink and chum salmon continue with studies funded by the Pacific Salmon Forum (PSF) and the Canadian Department of Fisheries and Oceans (DFO) with support from industry. Interim findings of the PSF are available at http://www.pacificsalmonforum.ca/pdfs-all-docs/BCPSFInterimReport.pdf and DFO research is regularly published in the peer reviewed literature. Many of the following traditional recommendations for managing lice are accomplished in compliance with the provincial Net Pen Waste Management Policy:

- Sea lice are monitored on farmed fish one or more times each month.
- Single year classes are raised at all Broughton salmon farms.
- Farms are fallowed until sediment free sulphides decline to < 1300 μM $S^{=}$. Copepodids remain viable for 7–10 days and fallowing requirements for waste management purposes usually last for several months.
- Nets at Broughton Archipelago salmon farms are typically treated with copper-based antifouling compounds to maintain flows adequate for fish health and to minimize stress on the anchoring system.
- Moribund fish are removed at least weekly from salmon farms.
- Because of its efficacy against all stages of lice; extended period of protection (10 weeks); and low environmental toxicity (Scottish Environmental Protection Agency 1999, 2004; Schering-Plough Animal Health 2002; Telfer, Baird, McHenery, Stone, Sutherland & Wislocki 2006) SLICE® has been the chemotherapeutant of choice in the Broughton Archipelago. It is administered under supervision of a veterinarian using an Emergency Drug Release (EDR) issued by Health Canada.

What is not being accomplished in the Broughton Archipelago

- Monitoring to specifically assess efficacy of chemotherapeutants is not accomplished and the field bioassays suggested by Search (2004) are not being conducted.
- Cleaner fish have not been identified or used in the archipelago.
- Treatments since 2002 have relied almost exclusively on SLICE® without rotation with pyrethroids or other chemotherapeutants with a different mode of action. The loss of resistant strains that might be selected from treated *L. salmonis* or *C. clemensi* resident on farmed salmon in the archipelago to the much larger Queen Charlotte Straits and the dilution of resistant strains by the influx of lice on returning adult salmon from the Pacific Ocean probably minimizes the potential for the proliferation of resistance in the archipelago's sea lice population. Nonetheless, the significant negative consequences of resistance suggest that vigilance and rotation of chemotherapeutants having different modes of action is warranted. A monitoring programme to provide early warning of resistance is recommended.
- An area management plan coordinating sea lice management efforts by all producers in the archipelago has not been developed and implemented. Such a plan should be developed to enhance protection of both cultured and wild fish.

Additional recommendations for developing a Broughton Archipelago IPM plan

The purpose of this paper has been to examine the parasites, hosts and environment in an effort to manage sea lice in a way that optimizes natural (environmental) controls and avoids unnecessary treatments with chemotherapeutants. This task is multidisciplinary in that it requires specific knowledge of the environment, the parasites and the hosts. However, the benefits of developing and applying the information in a truly integrated IPM plan are significant. The following discussion will focus on sea lice and the Broughton Archipelago. However, the principles can be applied to any horizontally transmitted disease vector in any environment.

Understanding the hydrodynamics within the management area

Ultimately, field verified three dimensional computer models, such as those of Foreman *et al.* (2006) and Gillibrand & Willis (2007), predicting the movement of seston within a management area are ideal. Development of sophisticated computer models is expensive and takes time, which is not always available when confronted with a new disease outbreak. As a starting point, current meters can provide site specific information at low cost and window-shade drifters, set at appropriate depths, can be tracked to estimate the dispersal of disease agents from their sources or to backtrack from identified zones of infection to evaluate likely source areas. Drifter studies can be carried out at every farm in a region on a variety of tides and winds with minimal cost using small boats, crews of two and hand-held GPS equipment. This information is useful in achieving a basic understanding of the management area's hydrodynamics while more sophisticated approaches, such as computer modelling, are developed.

IPM recommendations specific to the Broughton Archipelago

Sea lice and many other diseases are horizontally transmitted. If the goal of the management programme is to protect cultured stocks, then managers need to backtrack to determine the likely source(s) of infectious agents originating in upstream areas. If managers are interested in minimizing the potential for the spread of lice from one farm to another, then they need to determine the zones of infection associated with nauplii released from each farm in the management area. These zones will be defined by currents; the minimum time to develop to the infective stage; and the maximum time the infective stage is competent. These determinations require an understanding of the life cycle of the parasite and currents in the management area. If the management objective is to protect wild stocks of fish from disease vectors originating on farmed fish, then the problem becomes one of minimizing the interaction of wild stocks in space and/or time within the parasite's zone of infection. The consequences of this in the Broughton Archipelago are:

- Sea lice must be more aggressively managed in the eastern portions of the estuary from where they will be dispersed westward into other areas of the archipelago where pink salmon fry are present, before being diluted in the Queen Charlotte Strait.
- Sea lice larvae released from salmon farms located adjacent to the Queen Charlotte Strait will most probably be swept out of the archipelago before they develop to an infective stage. In the straits, nauplii and copepodids will probably be diluted to concentrations too low to cause epizootic disease.
- The Foreman *et al.* (2006) model is currently being modified to include the effects of wind and sea lice behaviour on dispersal of nauplii. The model should then be used to identify zones of infection associated with the dispersal of lice larvae from every farm in the archipelago. This will inform the IPM plan with respect to identifying cause (hatching of nauplii) and effect (new copepodid infections) relationships between existing farms and other farms or wild stocks of fish that might be jeopardized by infection. Where reasonable evidence suggests that lice are dispersed out of the area of concern, then treatment should not be required, but should be allowed if the health of the cultured stock is affected. This model will also be useful in siting of new farms to minimize their interaction with existing farms.
- Based on the response of *L. salmonis* to salinity and the Broughton Archipelago salinities reported by Brooks (2005) and described in Figs 2a,b & 4, it appears that salinity at farms located in the eastern portions of the archipelago is too low to support development of *L. salmonis* after the end of April in most years. Salinity in this area responded within days to a week to freshwater discharge from the Klinaklini River, which is gauged. The timing and magnitude of these river discharges varies from year to year (DFO data provided by Dario Stucchi). Useful long-range predictions of river discharge and salinity (months prior to the need for action) could be based on snow pack and late-winter and early spring weather conditions (temperature and rainfall). The natural summertime decline in lice described in Figs 5–7 is characteristic of many farms in the Broughton Archipelago and suggests that treatment is not necessary after the beginning of May or more conservatively after the end of May. Low salinity should be allowed to naturally control lice in summer.
- Salmon producers in the Broughton Archipelago should be encouraged to routinely collect high quality temperature and salinity data at every farm for purposes of documenting this hypothesized natural control. Data collection should be accomplished using a well designed protocol with adequate quality assurance provisions. Because wind appears to play a significant role in predicting ocean currents, producers should also be encouraged to install and maintain automatically recording anemometers at each farm.

- The date when pink salmon fry emerge from gravel and enter the marine environment in any given year can be estimated based on the accumulated number of degree days over the preceding winter. Assuming that nauplii take 4–6 days to reach the copepodid stage, and that copepodids are viable for another 7 days, implies that gravid female lice need to be controlled on those farms where the migration of fry coincides with predicted zones of infection after the middle of February in warm years to mid April in cold years. Protection should continue until local salinities are reduced to a level that will not support larval lice development (probably in May) and/or to June when pink salmon fry have grown substantially. Therefore, gravid sea lice on farmed fish in the eastern portions of the archipelago need to be aggressively controlled from the middle of February until the middle of May (i.e. about 3 months). Sea lice on farmed fish before or after this period have little potential to adversely affect pink salmon fry. Supporting this argument is Fig. 6 showing that treatment of lice in mid March at the Sargeaunt Pass farm during 2006 resulted in a lice free cultured stock for nearly 8 months. Figure 7 appears to represent an unwarranted treatment at Arrow Pass. Lice abundance on the cultured salmon did not reach the trigger level of 3.0 motiles per fish at any time and were declining when the fish were treated near the end of July. The data from other farms and the 2007 lice profile for this farm suggests that natural controls would have resulted in reductions in lice without treatment.
- Research documenting the response of *C. clemensi* to temperature and salinity is needed. The evidence provided in this report supports loss of larval competence at reduced salinity. However, clear documentation of specific responses for both *L. salmonis* and *C. clemensi* to salinities between 20 and 30 PSU is needed to improve confidence in these recommendations.

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