Monitoring and potential control of sea lice using an LED-based light trap

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Abstract: Sea lice are ectoparasitic copepods that threaten salmon farming aquaculture and the viability of wild salmon populations. To control infestations on farmed salmon, several chemotherapeutants have been developed, but these are invasive (often causing fish stress and loss in production), costly, may induce parasite resistance over time, and their impact on the environment is a major social concern. Here, we show that a light-emitting diode (LED)-based light trap can be used to monitor sea lice presence on fish and in the water. The performance of the light trap was tested in experimental tanks and in the ocean. Plankton net tows were also performed to compare catches with those from light traps. The light trap caught ~70% of salmon lice larval stages loaded onto a tank and ~24% of the adults. It also acted as a delousing agent by removing ~8% of adult salmon lice infective on Chinook salmon (*Oncorhynchus tshawytscha*) smolts in tank experiments. In the ocean, the light trap caught 21 sea lice (10 *Lepeophtheirus salmonis* and 11 *Caligus clemensi*), comprising free-swimming and attached stages, while plankton net tows failed to capture any. We conclude that light traps constitute an effective, noninvasive, environmentally friendly method to monitor sea lice.

Résumé : Les poux de mer sont des copépodes ectoparasites qui menacent l'aquaculture d'élevage du saumon et la viabilité des populations sauvages de saumons. On a mis au point plusieurs produits chimiques thérapeutiques pour contrôler les infestations chez les saumons d'élevage, mais ces substances sont perturbatrices (causant souvent du stress chez les poissons et provoquant une perte de production) et coûteuses; de plus, elles peuvent entraîner avec le temps une résistance du parasite et leur impact sur l'environnement constitue un sujet de sérieuse préoccupation sociale. Nous démontrons ici qu'on peut utiliser un piège lumineux comportant une diode électroluminescente (LED) pour surveiller la présence des poux de mer sur les poissons et dans l'eau. Nous avons testé la performance du piège lumineux dans des bassins expérimentaux et dans la mer. Nous avons aussi effectué des traits de filets à plancton pour en comparer les captures à celles des pièges lumineux. Le piège lumineux a capturé ~70% des larves et ~24% des adultes de poux du saumon introduits dans un bassin. Il a aussi servi d'agent d'épouillage en retirant ~8% des adultes de poux du saumon parasitant les saumoneaux de saumons chinook (*Oncorhynchus tshawytscha*) lors des expériences dans les bassins. En mer, le piège lumineux a récolté 21 poux de mer (10 *Lepeoptheirus salmonis* et 11 *Caligus clemensi*), à la fois des stades libres et fixés, alors que le filet à plancton n'en a capturé aucun. Nous en concluons que l'utilisation de pièges lumineux constitue une méthode efficace, non perturbatrice et respectueuse de l'environnement pour surveiller les poux de mer.

[Traduit par la Rédaction]

Introduction

Sea lice comprise a large number of ectoparasitic copepods that associate with a variety of vertebrate and invertebrate hosts in the marine environment (Pike and Wadsworth 1999; Costello 2006). Of these, the salmon louse, *Lepeophtheirus salmonis*, has received the most research attention because of its potential to cause extensive mortality in both farmed and wild salmonid fishes (Johnson et al. 2004; Costello 2006). Following settlement on a host, the salmon louse will feed on the skin components such as the mucus and blood (Pike and Wadsworth 1999). The resulting skin lesions, if sufficiently severe, can lead the host to osmotic imbalance and to a compromised immune system, increasing vulnerability to secondary infections (Pike and Wadsworth 1999; Mustafa et al. 2001; Wagner et al. 2008). Although the host may not die, the stress created by the infection often leads to morbidity, which reduces foraging effort and may increase the animal's vulnerability to predators (Wagner et al. 2003; Webster et al. 2007). In farmed salmon, the morbidity results in reduced growth rate, incurring substantial financial losses in revenue to the industry (Mustafa et al. 2001).

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In addition to the damage created to the salmon farming industry, infestations of sea lice are major threats to the viability of wild salmonid populations (Tully et al. 1999; McVicar 2004; Krkošek et al. 2007*a*) and are of potential concern to other species, like the Pacific herring (*Clupea pallasii*) (Morton et al. 2008). The free-swimming stages of sea lice are found in highest densities close to salmon farms (Costelloe et al. 1998; Penston et al. 2004, 2008), and their abundance can be correlated with the farms' production cycles (McKibben and Hay 2004; Penston et al. 2008). Mathematical models of salmon infestation dynamics in the Broughton Archipelago of British Columbia (Canada) have shown that sea lice from salmon farms constitute the main source of infections onto small juvenile wild salmon migrants (Krkošek et al. 2005, 2006, 2007*a*). This infestation pressure was historically absent in coastal waters because the young salmon migrate at a time (March–May) when adult salmon, the major carrier of offshore sea lice into coastal waters (Boxshall and Defaye 1993; Beamish et al. 2005), are seldom present (Groot and Margolis 1991; Krkošek et al. 2006, 2007*b*). Thus, salmon farms have broken the temporal barrier of juvenile wild salmon exposure to sea lice by acting as year-round sea lice reservoirs (Morton et al. 2004, 2005; Morton and Routledge 2005), potentially threatening the survival of affected wild salmon populations (Krkošek et al. 2006, 2007*a*, 2008).

The problems with sea lice epidemics have led to the development of various chemical and pharmacological treatments (Boxshall and Defaye 1993; Pike and Wadsworth 1999; McVicar 2004). Many of these treatments can induce stress on the fish, have a long withdrawal period, and the environmental effects are a major social concern (Pike and Wadsworth 1999; Naylor et al. 2003). In addition, sea lice can develop resistance to treatments, requiring a multiplicity of expensive interventions to mitigate the problem (Davies and Rodger 2000; Mustafa et al. 2001). As a result, the use of environmentally friendly methods to prevent infestations (e.g., site fallowing, development of vaccines, screening for resistant fish strains, freshwater or land-based aquaculture) has received increasing support from the scientific community and monitoring agencies (Boxshall and Defaye 1993; MacKinnon 1997; Naylor et al. 2003). Present-day salmon farming operations are overwhelmingly ocean-based, yet there is a lack of noninvasive, environmentally friendly methods to monitor sea lice presence on fish or in the water to help detect the onset of infestations at an early stage. Such methods could allow for preventive action, such as relocation of fish to another site by transport in fresh water to remove the sea lice.

Here, we describe the use of a light-emitting diode (LED)-based light trap in capturing sea lice in tanks and in the ocean. The experiments are based on laboratory and field results demonstrating sensitivity of parasitic copepods to light (e.g., Novales Flamarique et al. 2000; Mikheev et al. 2003; Yoshizawa and Nogami 2008) and capture of salmon louse nauplii and copepodids using a halogen light source equipped with an air lift system (Pahl et al. 1999, 2000). Visual behaviour experiments carried out in the laboratory with salmon lice showed that nauplii were attracted to lights turning off, copepodids to lights turning on, and adults to lights turning on and off (Novales Flamarique et al. 2000; see also Bron et al. 1993 for copepodid behaviour). The strength of the response increased with light intensity, and sensitivity to light was equivalent to that of their salmonid hosts (absolute perception threshold of copepodids ~10^{13} photons·m^{-2}·s^{-1}; Novales Flamarique et al. 1992; Novales Flamarique and Hawryshyn 1993, 1997). Based on these results, we hypothesized that a light trap with modulated intensity output could capture the free-swimming and attached stages of the salmon louse. A second hypothesis pertained to the use of a light trap as a delousing agent. According to this hypothesis, the light trap was expected to remove sea lice from infected fish.

This research had three goals: (*i*) assess the capture efficiency of the light trap for various flashing protocols and durations in a tank loaded with either larval salmon lice or detached adult females, (*ii*) determine whether the light trap could attract and capture adult female salmon lice in a tank in the presence of salmon, and (*iii*) test whether the light trap could capture sea lice in the ocean. If the light trap was efficient at capturing sea lice, we expected significantly higher catches by a functional (operative) light trap vs. an identical one that was not operational (control) when performing parallel deployments. To assess whether the light trap performance in the ocean was commensurate with sea lice levels present, we conducted plankton net tows at deployment sites as a comparative sampling method.

Materials and methods

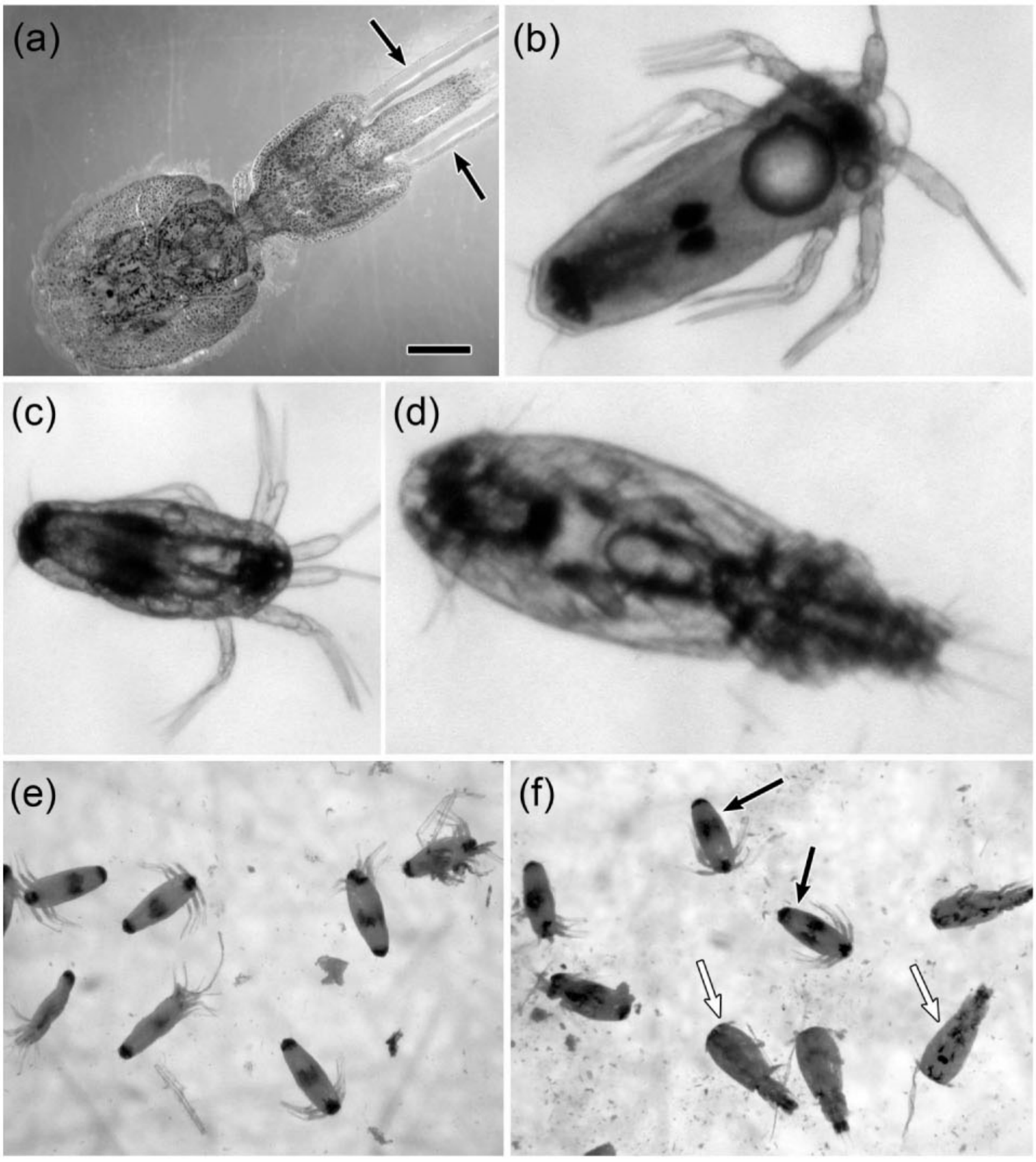
Source of salmon lice and maintenance of cultures

Gravid female salmon lice (*L. salmonis*) were obtained daily from wild adult salmon caught by fishermen at the Tyee Resort Fishing Lodge (Bamfield, British Columbia, Canada) in August–September 2005. The live salmon lice (Fig. 1) were transported in ocean water to the Bamfield Marine Sciences Centre. Here, the egg strings were removed from the females and placed in four 10 L flasks supplied continuously with 12 °C filtered ocean water (100 μm mesh size filter). The flasks were equipped with large aperture spouts covered with the same 100 μm filter netting to prevent escape of larvae. The netting was replaced twice every day to prevent clogging, as large numbers of larvae started to hatch on the same day that new egg strings were acquired. The larvae appeared healthy, and individual batches lasted over 1 week, indicating high quality of egg strings and (or) rearing conditions. The females (devoid of egg strings) were placed in two 20 L aquaria containing ocean water supplied via the same flow-through system. Salmon lice at various stages (Fig. 1) were obtained from this culture system for the tank experiments. New lice were used in each experimental trial.

Light trap and tank characteristics

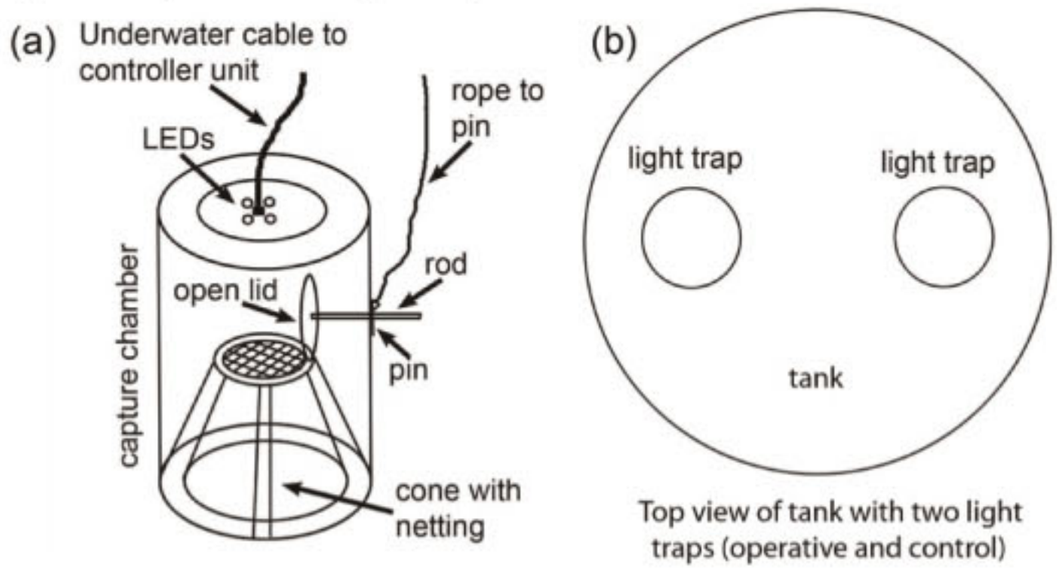
The light trap was designed around a hollow polyvinyl chloride (PVC) cylindrical capture chamber, 55 cm high and 27.5 cm in diameter, with a removable top housing four LEDs (white light emission LEDs, LXHL-MW1C, Philips Lumileds), which provided downward illumination (Fig. 2*a*). The LEDs and an electronic control unit, which controlled the intensity, duration, and onset of each diode's emission, were powered by a 12 V, 17 A·h sealed lead acid

Fig. 1. Photomicrographs showing the sea lice (*Lepeophtheirus salmonis*) stages used in tank experiments. (*a*) Adult female salmon louse with egg strings (arrows). (*b*) Nauplius (bottom side) showing characteristic lipid sac (circular structure) and lack of mouth parts. (*c*) Nauplius (upper side) showing typical banding pattern (see Schram 2004). (*d*) Copepodid with characteristic pointed rostrum. (*e*, *f*) Nauplii (*e*) and mixture of nauplii (black arrows) and copepodids (white arrows) (*f*) caught by the light trap. Magnification bar in panel (*a*) represents 7.3 mm (*a*), 0.082 mm (*b*), 0.13 mm (*c*), 0.09 mm (*d*), and 0.38 mm (*e*, *f*).



battery (Polar Batteries). The bottom end of the capture chamber consisted of a removable cone lined with 100 μm mesh netting, whose top was equipped with a removable metal grid (to select for the animals being caught, e.g., zooplankton or larger animals like fish) and a lid, connected to a metal rod, that could be closed remotely by release of an external pin (Fig. 2*a*). At the end of a given deployment and prior to retrieving the light trap from the water, the lid was closed by pulling on a rope that dislodged the pin, resulting in the capture of the animals that were present in the light trap. At the surface, the catch was carefully washed off the cone netting and from the inside of the chamber with filtered sea water into a collection bucket. Random samples of the live catch were analyzed with a light microscope in the field and in the laboratory for presence of sea lice. The catch was then filtered through 100 μm netting and the fil-

Fig. 2. Schematic diagrams of (*a*) the light trap capture module and (*b*) the disposition of light traps inside the tank viewed from above.



tered content washed into a glass vial with 100% ethanol for long-term storage. A detailed inspection for sea lice was carried out in the laboratory at the Institute of Ocean Sciences or at Simon Fraser University (Burnaby, British Columbia). The tank trials consisted of submerging two identical light traps at equidistant locations from the centre of a ~5800 L tank (2.43 m diameter × 1.25 m height; Fig. 2*b*). The bottom of each light trap was suspended at approximately 80 cm from the bottom of the tank. The tank was surrounded by semidark cloth whose light transmission produced a diffuse spectral background with intensity (6.2×10^{16} photons·m^{-2}·s^{-1}) resembling that at crepuscular periods in the upper layers (1–3 m) of the ocean (see Novales Flamarique and Hawryshyn 1997; Novales Flamarique and Hárosi 2000; Novales Flamarique et al. 2000). The light trap intensity, 80 cm from the bottom of the capture chamber, was 4.3×10^{20} photons·m^{-2}·s^{-1} (the intensity was kept the same throughout the study), and the spectral range was 400–740 nm (see Novales Flamarique et al. 2007 for the LED emission spectrum). Light measurements were acquired with a USB-2000 spectroradiometer equipped with a 600 μm diameter light guide and cosine collector under the control of OO Irradiance software (Ocean Optics, Florida). Both the intensity and spectrum characteristics of the light trap emission were within the visual sensitivity range of the salmon louse (Novales Flamarique et al. 2000). Light trap capture efficiency trials were carried out by loading the tank with a given concentration of salmon lice, alone or with fish (details below). At the end of each trial, the tank was drained and its surfaces power-washed to remove any residual lice; the tank was then filled and loaded with new animals for the ensuing trial.

Tank experiments with detached salmon lice

To test the ability of the light trap to capture salmon lice, deployments (n = 8 replicates per treatment) were carried out in a tank loaded with these parasites, and the capture efficiency was assessed after 2 h for the following light flash frequencies: 0 (always on), 90 s on : 90 s off, 90 s on : 30 s off, and 90 s on : 15 s off. In addition, 8 h deployments were also carried out for the 0 frequency condition to test whether capture changed significantly from 2 h deployments. In all cases, deployments involved two identical light traps (a functional one, with LEDs operative, and a control, with no light emission). For each series of experiments, the two light traps were alternated in their role (operative vs. control) to account for any differences in experimental design (e.g., small differences in relative position of each light trap in the tank).

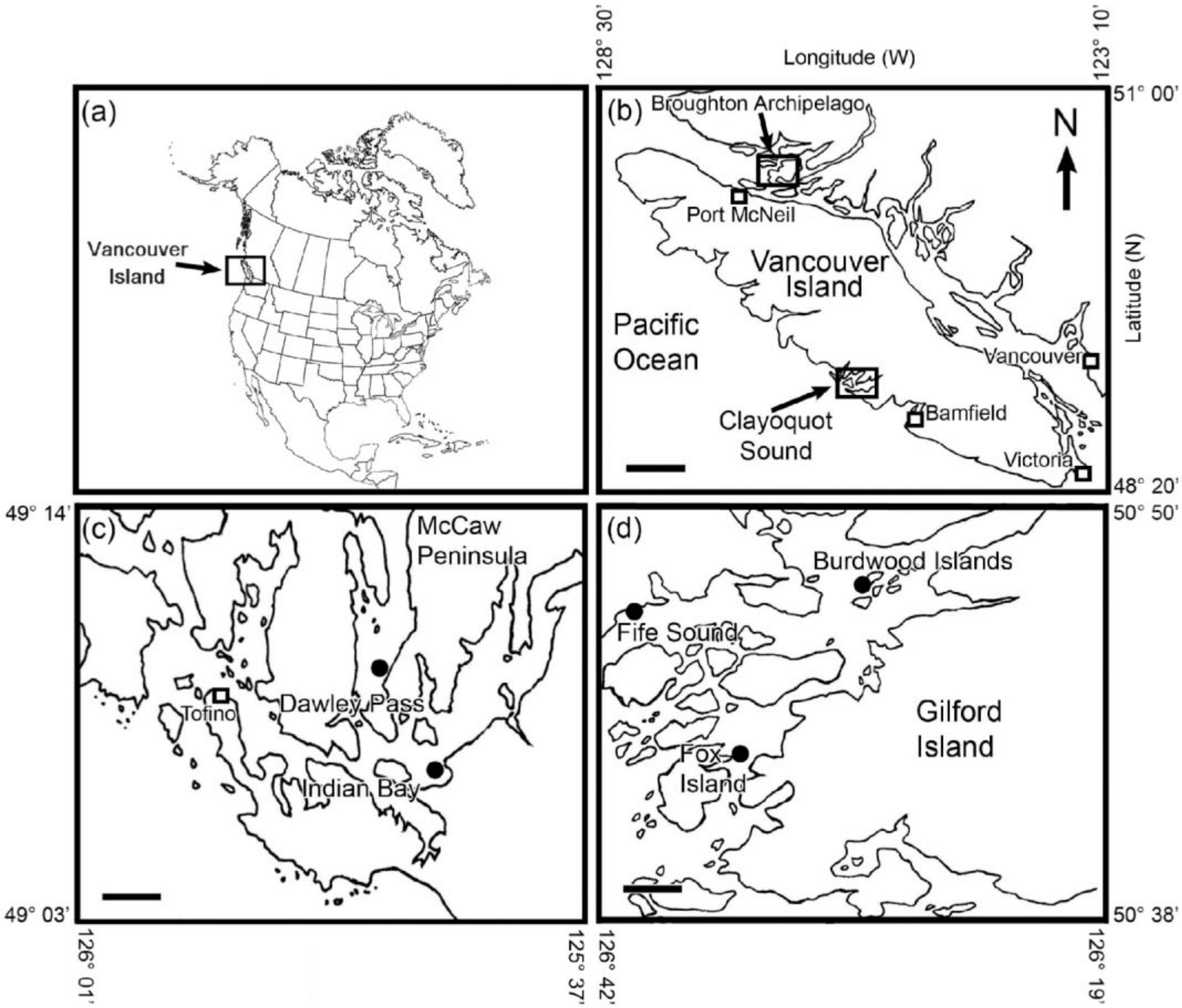
Prior to immersion of the light traps, the tank was loaded with a known concentration of larvae (2 per l; ratio ~2:1 nauplii II to copepodid) or adult female lice (0.13 per l). The larval concentrations used in this study were about four times those reported in some areas of coastal Scotland (~500·m^{-3}) by Penston et al. (2004). Larval loads were estimated by averaging the number of nauplii and copepodids in ten consecutive 20 mL water samples taken randomly from a homogeneous flask culture and computing the required volume to arrive at the desired concentration inside the tank. Adult concentrations were obtained by loading individual salmon lice females (390 per trial). At the end of each trial, the lice captured by each light trap were counted. In the case of larvae, this involved washing the light trap with filtered ocean water and collecting the salmon lice in a bucket. The water was then refiltered through a 100 μm net and the catch washed into a glass cylinder. If larval count exceeded 500, the concentration was estimated by counting the number of larvae in ten 20 mL water samples of the swirled (homogeneous) culture. Larvae were counted with replacement at 40× magnification using a slide grid on the microscope stage. We did not compute mortality of salmon lice during the experiments, as we did not expect it to be significant because of the high quality of the culture and rearing conditions. The light trap efficiencies reported are therefore conservative estimates, should there have been any mortality during the experiments.

The use of female salmon lice only for experiments with non-larval stages (as opposed to both females and males) merely reflects the fact that we collected only females with strings from wild salmon. Our observations on adult salmon lice swimming behaviour have not indicated differences between the sexes.

Tank experiments with salmon lice and fish

The aim of this series of experiments was to assess whether detached adult female salmon lice would enter the light trap despite the presence of host fish and whether the light trap could act as a delousing agent by capturing salmon lice previously loaded onto fish. Two types of experiments were carried out. In the first type (n = 3), the tank was loaded with 25 Chinook salmon (*Oncorhynchus tshawytscha*) smolts and 175 detached adult female salmon lice in the presence of two light traps (operative and control) deployed as per the experiments without fish (see previous section). The operative light trap was programmed to flash intermittently 90 s on : 30 s off for 2 h (based on the analysis of results from the previous section). At the end of each trial, the numbers of lice in each light trap were counted and the tank drained and prepared for the next trial as explained previously. In the second type of experiment (n = 3), Chinook salmon smolts (n = 15) were infected with 10 adult female lice each and monitored in aquaria for 30 min (to ensure that no lice-shedding took place), after which they were released into the tank. Two light traps (one operative (90 s on : 30 s off light cycle) and a control) were then deployed in the tank for 2 h as per previous experiments. The number of salmon lice on the fish, inside the light traps, and

Fig. 3. Maps showing the research locations for light trap deployments and net plankton tows in Clayoquot Sound and the Broughton Archipelago (British Columbia, Canada). (*a*) Location of Vancouver Island within North America. (*b*) Location of both research areas (rectangles) in relation to Vancouver Island and major cities (squares), as well as the location of the Bamfield Marine Science Centre. (*c*, *d*) Enlargement of the study areas in Clayoquot Sound (*c*) and the Broughton Archipelago (*d*). Solid circles indicate the specific sites of deployments (light traps and plankton net tows). The scale bars on the bottom left of maps (*b*–*d*) correspond to 47 km (*b*), 2.6 km (*c*), and 3.6 km (*d*).



remaining in the tank were counted at the end of each trial. The Chinook smolts used in these experiments had average weight and total length ± standard deviation (SD) of 41 ± 5.4 g and 16 ± 4.8 cm, respectively. Each trial used naïve fish.

Statistical analyses

For a given treatment (deployment type), capture efficiencies from the control (nonfunctional) light traps were subtracted from the corresponding operative ones. These numbers were compared between treatments by Student's *t* test or one-way analysis of variance (ANOVA). Capture results ($n = 8$) for the 2 and 8 h treatments with a light trap continuously on (zero flash frequency condition) were compared by Student's *t* test for both larval and adult salmon lice independently. The 2 h treatments were analyzed by one-way ANOVA followed by a Tukey's grouping test with $\alpha = 0.05$ (this analysis encompassed all trials together, for both larval stages and adults). Catches from control light traps were independently analyzed by one-way ANOVA with $\alpha = 0.05$.

Light trap testing in the ocean and comparison with catches from plankton net tows

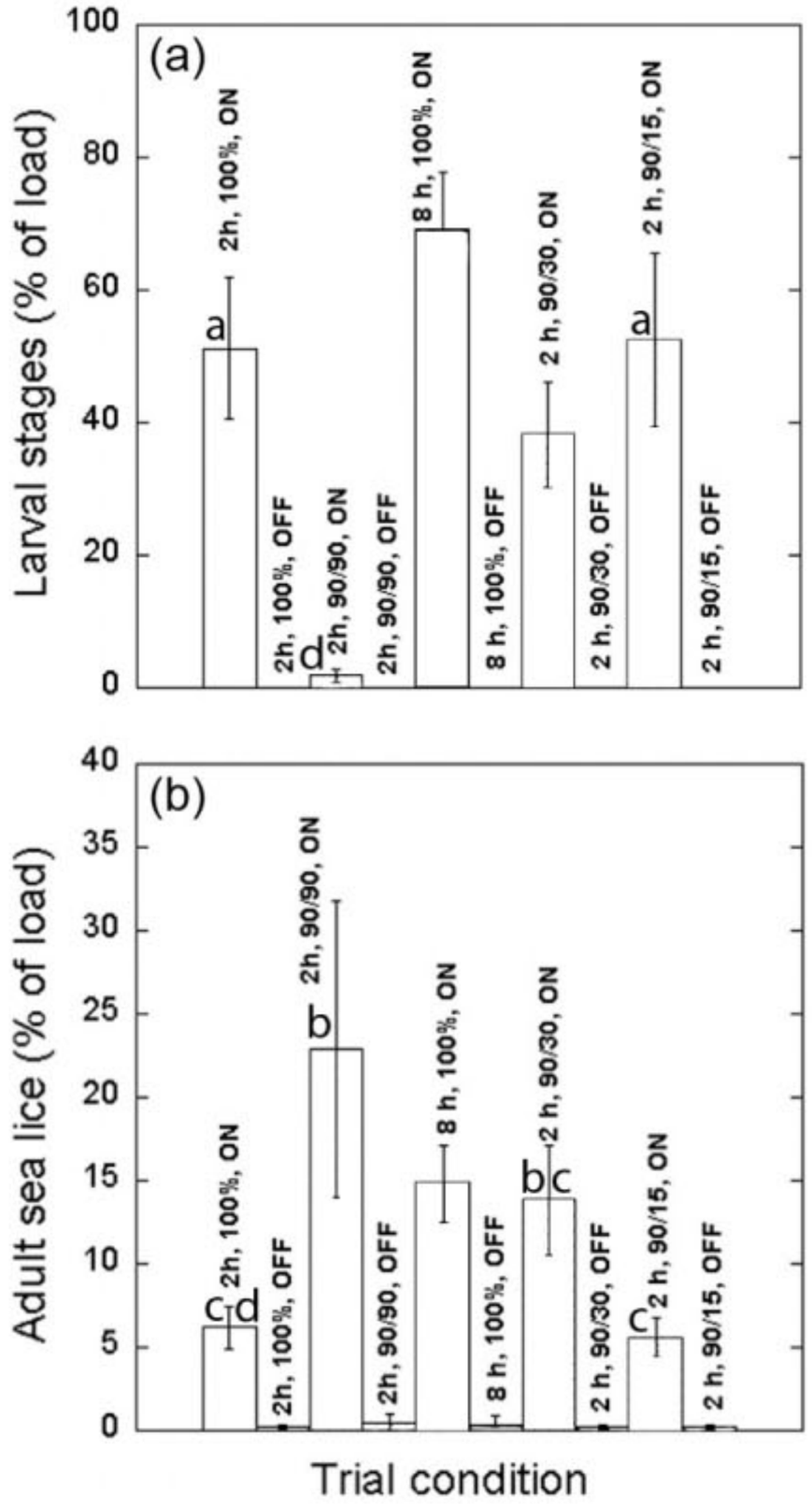
To investigate whether the light trap could capture sea lice in the ocean, we deployed it at various locations in Clayoquot Sound and in the Broughton Archipelago (British Columbia, Canada; Fig. 3) and carried out simultaneous

plankton net tows. Deployments in Clayoquot Sound took place during October 2005, while those in the Broughton Archipelago were conducted in April–June 2006, 2007. The net tows were carried out at the same sites and on the same dates as light trap deployments (Clayoquot Sound) or in very close proximity (within 0.5 km) of light trap deployments on the same dates (Broughton Archipelago). Although light trap and plankton tow catches could only be compared qualitatively, we consider the light trap to be a highly efficient capturing device if the number of sea lice caught is several times the number captured in standard plankton tows in the vicinity of ideal sea louse habitat (as per our sampling locations and protocol).

Six light traps were deployed at a depth of 1–3 m near salmon farms (with individual net pen dimensions: 30 m × 30 m × 20 m; ocean bottom depth: 40–60 m), inside an experimental net pen (dimensions: 4 m × 4 m × 2 m; ocean bottom depth: 10–15 m) with infected juvenile pink salmon (*Oncorhynchus gorbuscha*) (Fox Island, Broughton Archipelago), and at non-farm locations (ocean bottom depth: 30–60 m). To improve the chances of catching sea lice, which exhibit diel vertical migrations (Heuch et al. 1995), we deployed the light traps for one complete tidal cycle starting at ~1500 h and ending at ~0800 h the next morning. Light traps are particularly efficient under mesopic and scotopic conditions, when the light trap's emission contrasts most against the (low) background illumination. The LED lights were continuously on during deployments, as we primarily aimed to catch the larval stages of sea lice. We used laboratory space on the boat (e.g., on the Canadian Coast Guard's CCGS *Vector*) or on farm platforms to retrieve the catch, carry out preliminary microscopy examinations, preserve the animals for long-term storage, and redeploy the light traps. Similar observations and storage procedures were carried out on catches originating from the plankton net tows.

We used a Scientific Committee on Oceanographic Research plankton net (0.5 m mouth, 2 m length, and 200 mm mesh size) with flow meter to conduct horizontal and vertical net tows. Horizontal tows involved dragging the net in undulating fashion (between the surface and 1 m) on the nearshore side, upstream into the observed current, at 0.5–1 $m \cdot s^{-1}$ for approximately 2 km. This method was employed in an attempt to maximize potential sea lice encounter on the assumption that the larvae would be distributed in the upper 1 m layer of the ocean (see McKibben and Hay 2004) and near shore (as this is where schools of infected juvenile wild salmon have been observed; Morton et al. 2004; Krkošek et al. 2005). Vertical net tows to 50 m were carried out in selected areas to access any potential sea lice that could be dwelling deeper in the water column, as these may be attracted to the light traps but would not be sampled by the horizontal surface tows. It should be noted that genetic analyses of the Pacific salmon louse have shown it to be markedly different from its Atlantic counterpart, and this may explain alterations in physiology (e.g., osmoregulatory capacity, see Yazawa et al. 2008). Thus, we had no a priori indication that the sea lice pursued would exhibit the same behaviours as those reported for corresponding Atlantic morphs. In total, 40 net tows (~4400 m^3 of water filtered through the net) and 34 light trap deployments were carried out. Taxonomic identification of sea lice was performed following published guides (Johnson and Albright 1991; Schram 2004; Galbraith 2005).

Fig. 4. Average light trap catches (± standard deviation) in the tank for (*a*) larval stages and (*b*) adult females, expressed as a percentage of the load. Above each bar graph are the lighting conditions of the operative light trap (ON) and the control light trap (OFF, no LED emission). The following nomenclature applies to the lighting regimes: 100%, ON (light on all the time); 100%, OFF (light off all the time, control); 90/90, 90/30, 90/15 are the cycling flashing regimes for the operative (ON) light trap corresponding to 90 s on : 90 s off, 90 s on : 30 s off, and 90 s on : 15 s off, respectively. The amount of time (2 or 8 h) for each type of deployment is also indicated. Statistically similar treatments ($p > 0.05$) share the same letter (top of bar graph). The control light trap (OFF) averages are shown for illustrative purpose; they were subtracted from the corresponding functional light trap (ON) values prior to statistical analyses.



Results

Success of light trap in capturing salmon lice in tanks

The light trap was successful at capturing the larval and adult stages of the salmon louse used in the study (Fig. 4). The larval stages were a mixture of nauplii and copepodids (Figs. 1*e*, 1*f*), as these varied in developmental stage within

a culture flask. Nauplii comprised ~60%–95% of all catches, which mirrored the range in the culture flasks.

The larval stages were primarily attracted to a light that was on all the time ($F = 62.48$, $p < 0.0001$; Fig. 4*a*). When the light cycled between 90 s on and 15 s off (2 h, 90/15, ON), lice capture was statistically similar to that when the light was permanently on (2 h, 100%, ON; Fig. 4*a*). If the off part of the cycle was increased by 15 s (2 h, 90/30, ON), capture was significantly lower compared with the 2 h, 90/15, ON condition. A further increase of 60 s in the off cycle (2 h, 90/90, ON) led to a precipitous decline in capture efficiency (Fig. 4*a*). If the light trap was kept continuously on for 8 h (8 h, 100%, ON), the capture efficiency increased significantly over the corresponding 2 h condition ($t = -3.93$, $p = 0.0018$), resulting in an average capture of 70%. In all experiments, the control light trap, with the light permanently off but otherwise operative, captured a minute number of salmon lice (<0.07%; see OFF results, Fig. 4*a*).

When similar experiments were carried out with adult female salmon lice, the results were very different (Fig. 4*b*). Adult female salmon lice were primarily attracted to a flashing light, and the highest average catches (~24% of the load) were obtained when the off part of the cycle approximated the on portion (see 90/90, ON; Fig. 4*b*). Capture was statistically similar, however, when the off part of the cycle was reduced by 60 s (2 h, 90/30, ON) but significantly lower when the off part of the cycle was reduced to 15 s (2 h, 90/15, ON; Fig. 4*b*). Capture efficiency for the latter condition was similar to that for a continuously operating light trap, whether for 2 h (2 h, 100%, ON) or 8 h (8 h, 100%, ON). Capture efficiency for the 8 h condition (8 h, 100%, ON) was significantly greater than that for the 2 h condition (2 h, 100%, ON) ($t = -9.71$, $p < 0.0001$). Compared with the catches of larval stages with the light permanently on (in the range ~52%–84% of the load), adult captures with a flashing light were less than half. The control light traps for all treatments (encompassing larval and adult salmon lice trials) had statistically the same low capture efficiency ($p > 0.05$).

Delousing properties of the light trap

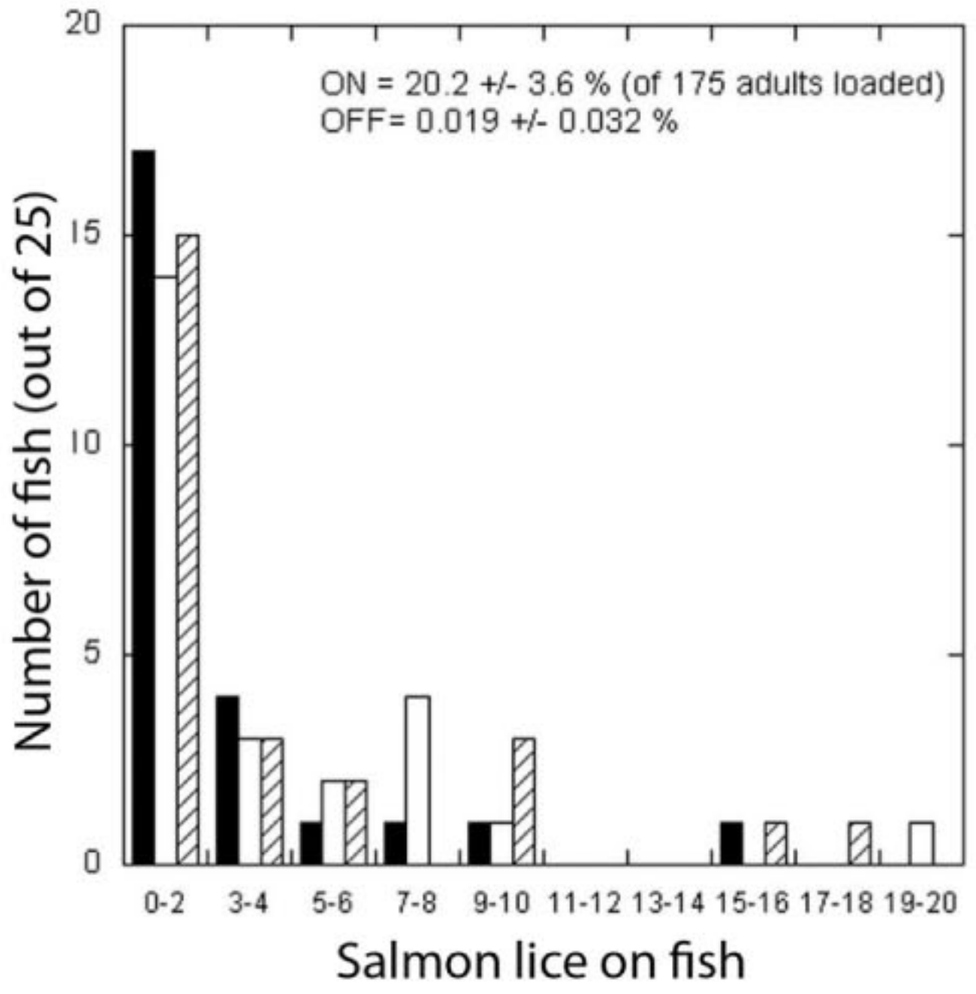
In experiments where 175 adult salmon lice were loaded into the tank in the presence of 25 Chinook smolts and a 90 s on : 30 s off flashing light trap for 2 h, capture by the light trap was 20% of the load (Fig. 5). By comparison, on average 50% of the salmon lice were attached to the fish at the end of the 2 h exposure, with a small fraction of fish carrying large individual loads (15–20; Fig. 5). The remaining lice (~30%) were on the floor or the walls of the tank.

When similar experiments were carried out with three sets of 15 smolts preloaded with 10 adult lice per fish, the light trap retrieved on average 8% of the load (12 ± 2.65 lice), 85% remained on the fish (127 ± 4.58 lice), and the remainder (7%, 11 ± 2.64 lice) were on the floor or the walls of the tank.

Light trap capture of sea lice in the ocean

In total, the light trap caught 21 sea lice: 10 *L. salmonis* and 11 *Caligus clemensii*. These were distributed as follows: 3 adults, 2 nauplii, and 1 copepodid *L. salmonis* in Dawley Passage (Clayoquot Sound); 3 adult, 3 subadult, and 2 chalimus *C. clemensii* near the Burdwood Islands (Broughton Archipelago; the chalimus were associated with herring scales); 2 adult and 1 subadult *C. clemensii* in Fife Sound (Broughton Archipelago); and 4 subadult *L. salmonis* near Fox Island (Broughton Archipelago). In contrast, no sea lice were caught with the plankton net tows.

Fig. 5. Average number of salmon lice on three sets of 25 Chinook salmon smolts released into the tank in the presence of 175 detached adult female salmon lice and two light traps (operative and control: the operative light trap flashing 90 s on : 30 s off) for 2 h. The salmon lice caught by each light trap (operative, ON) and control (OFF) are indicated at the top of the panel. Each distribution is depicted by its own pattern bar.



Discussion

The light trap as a tool to monitor sea lice in nature

Light traps have long been used by researchers to characterize fish and zooplankton communities in both freshwater ecosystems and in the ocean (Kawaguchi et al. 1986; Doherty 1987). Laboratory experiments with lobster larvae (Pahl et al. 1999) suggested that a light trap with permanent emission and equipped with an air lift system located at the entrance to the capture chamber could be used to catch phototopositive zooplankton larvae like those of the salmon louse (Bron et al. 1993). Salmon lice larvae were indeed successfully caught using such a trap, equipped with a halogen light source, deployed at night in Atlantic salmon net pens off the coast of Maine, USA (Pahl et al. 2000). Unfortunately, the lack of control light traps in these studies precluded an unequivocal conclusion that it was the light emission, and not the air lift system, that was responsible for the catch (as drifting zooplankton could easily be trapped by the action of the air lift system). Nonetheless, these pioneering studies suggested a role for light traps in monitoring, and potentially controlling, sea lice numbers (Pahl et al. 2000). With this in mind, and based on detailed studies of salmon louse vision (Novales Flamarique et al. 2000), we designed a new LED-based light trap with flashing capabilities to improve capture of all stages of sea lice.

The enclosure tests demonstrated that salmon louse larvae were highly attracted to a continuous light source (catches ~70% of the load), whereas the adults preferred a flashing light source and were less likely to enter the light trap (catches ~24% of the load). In the ocean, however, the light trap caught primarily the non-larval stages, suggesting that free-swimming larvae were less abundant than attached stages during our sampling times. In the Broughton Archipelago, plankton net tows have only caught sea lice larvae (11 individuals) in the early spring (March–April) despite 4 years of effort (M. Galbraith, unpublished data). By mid-April, juvenile wild salmon migrants are observed to be heavily infected with salmon lice (Morton et al. 2004; Krkošek et al. 2005), and the larvae are no longer found in plankton net tows (this study). The three larvae caught in Clayoquot Sound may have been the result of a potential seasonal increase in sea lice due to the return of adult wild salmon in the fall.

The prominent capture of nauplii by a light trap with uninterrupted emission suggests that the long-term response to continuous light is opposite to the immediate response following dark adaptation previously reported (Novales Flamarique et al. 2000). Alternatively, the nauplii used by Novales Flamarique et al. (2000) may have been at an earlier developmental stage (I), whereas the ones used here (predominantly stage II) already exhibited the visual behaviour of the copepodid, the next stage of development. Whatever the case, larval catches under continuous illumination were consistent with reported catches in salmon net pens (Pahl et al. 2000, though the physical factor responsible for the catches in this study is debatable, as explained previously) and with the overall migration of sea lice to surface waters during the day (Heuch et al. 1995), when ambient illumination is highest.

Our experiments also showed that despite preference for a flashing light, female adult salmon lice were also drawn to a continuous source of illumination. The tank trials further illustrated that the light trap captured a percentage of adult lice even if these were originally attached to hosts. Such a finding was corroborated by results in the ocean, where the majority of deployments took place in close proximity of farms, at least one of which (an experimental sea lice farm near Fox Island) had juvenile pink salmon infected with salmon lice. It has been previously observed in tanks (but see also Saksida et al. 2007 for comments on sea lice displacements in nature) that attached sea lice will move among host fish (Ritchie 1997; Hull et al. 1998), suggesting the possibility that some lice detached from their hosts to enter the light trap. The alternative is that motile sea lice that could not find a new host after detachment (despite the large numbers of fish present in the net pens) were attracted to the light trap. Either way, the light trap acted as a delousing agent.

Our results demonstrate that light traps could be used to monitor sea lice on fish and in the water column. The work of Pahl and collaborators indicated that abundance of larvae (copepodids) on sampled fish was similar to larval abundance determined by use of their light trap (Pahl et al. 2000). This, in turn, suggested that larval abundance in the water column was closely related to settlement numbers on the fish (Pahl et al. 2000). Light traps could therefore be deployed to monitor the number of sea lice larvae in the water as an indicator of infection levels. If sea lice densities derived from light trap catches attained a given threshold (e.g., much less than eight, as this was the average number on fish when chemotherapeutic treatment was initiated in British Columbia (Saksida et al. 2007) during years when infestations occurred on juvenile wild salmon (Morton et al. 2004; Orr 2007)), alternative corrective action could be undertaken by transporting the fish in freshwater to another location. The trigger for corrective action is a complex decision that varies with jurisdiction, but given that five motile salmon lice per small juvenile pink salmon could collapse populations of this species (Krkošek et al. 2007*b*), it would be prudent from a conservation perspective to take corrective action when the light trap captures five larvae. In our experience, short-term exposure (in the order of hours) of large juvenile (smolt) Pacific salmon of various species to fresh water had no effect on subsequent food consumption and growth. Since Atlantic salmon (*Salmo salar*) can naturally spawn multiple times throughout life, alternating in the process from salt- to fresh-water residency, we expect that short-term transport of farmed fish in fresh water would have little effect on their long-term physiology and growth.

The light trap as a sea lice sampling tool has several advantages over sea lice counts on fish or plankton net tows (which are the two methods presently used to sample for sea lice). First, the light trap eliminates fish handling and the associated stress to the animals, which often leads to potential losses in production (Mustafa et al. 2001). Second, in contrast with plankton net tows, the light trap does not require time-consuming and expensive operation of boats. Third, the light trap can be deployed in areas where it is extremely difficult or impossible to carry out plankton net tows (e.g., next to floats, in net pens, along intricate shoreline), adding another appealing feature as a research tool. Fourth, because the light trap catches live animals, sea lice nauplii and copepodids can be more readily distinguished from other zooplankton larvae based on colouration (Schram 2004) instead of the more intricate morphological criteria (Galbraith 2005) required to identify fixed specimens (which readily lose their colour). Plankton net tows also produce live catches, but these often include phytoplankton content requiring tedious sorting of the catch (especially during the spring bloom) before zooplankton analysis can proceed. Alternatively, light trap catches could be processed by real-time polymerase chain reaction (PCR) using species-specific gene markers to expedite the identification and quantification process (McBeath et al. 2006).

Cost analysis of light traps versus other procedures

To assess whether the use of light traps could be financially worthwhile in salmonid production operations, it is instructive to perform a basic analysis of costs incurred with these devices and compare them with those incurred via alternative sea lice prevention methods. We have therefore calculated the average cost per net pen per production cycle (i.e., salmon growth for 2 years in salt water) due to sea lice infections in the case of (*i*) a farm that takes no action, (*ii*) a farm that uses light traps operating at 72% (delousing) efficiency, (*iii*) a farm that uses light traps operating at 8% efficiency, (*iv*) a farm that treats with emamectin (Slice) once per production cycle, (*v*) a farm that treats with Slice once

Table 1. Net pen costs associated with sea lice infection per production cycle for a salmon farm that undergoes one of the following treatments: no treatment (NT), deploys light traps performing at 72% capture efficiency (LT(72%)), deploys light traps performing at 8% capture efficiency (LT(8%)), treated with Slice (S), treated with Slice and deploys light traps performing at 72% capture efficiency (S+LT(72%)), or treated with Slice and deploys light traps performing at 8% capture efficiency (S+LT(8%)).

	Treatment					
Loss factor	NT	LT(72%)	LT(8%)	S	S+LT(72%)	S+LT(8%)
Reduced growth	0.2	0.056	0.184	0.12	0.032	0.11
Reduced feed CR (%)	5	1.4	4.6	2.9	0.81	2.7
Downgrade (%)	1	0.28	0.92	0.58	0.16	0.53
Secondary diseases (%)	1	0.28	0.92	0.58	0.16	0.53
Cost of above factors per net pen per production cycle (CAN$)						
Reduced growth	72 000	20 160	66 240	43 240	11 520	39 600
Reduced feed CR	11 250	3 150	10 350	6 525	1 823	6 075
Downgrade	1 800	504	1 656	1 044	288	956
Secondary diseases	14 400	4 032	13 248	8 352	2 304	7 648
Procedural costs per net pen per production cycle (average over first three cycles) (CAN$)						
LT	0	2 487	2 487	0	2 487	2 487
LT + salaries (operation)	0	28 201	28 201	0	28 201	28 201
Slice treatment	0	0	0	18 000	18 000	18 000
Total costs per net pen per production cycle (CAN$)						
Total (no LT salaries)	99 450	30 333	93 981	77 161	36 152	74 766
Total (with LT salaries)	99 450	56 047	119 695	77 161	62 136	100 480

Note: Calculations are based on deployment of five light traps (LT) per net pen. Slice treatment is assumed to occur once during the production cycle. The nonprocedural cost factors considered were as follows: reduced growth (in terms of loss of weight per fish, kg·fish^{-1}), reduced feed conversion ratio (CR) (requiring added feed to produce a marketable fish), downgrade of fish meat from premium to standard, and fish losses produced by secondary infections.

per production cycle and uses light traps operating at 72% efficiency, and (*vi*) a farm that treats with Slice once per production cycle and uses light traps operating at 8% efficiency. The choice of light trap capture efficiencies was based on our results from tank trials where ~70% of larval stages were caught and 8% of female adults on fish were caught. The 72% efficiency assumes removal of 70% of larval stages from the water and 8% of the remainder (presumed attached to fish); thus, the efficiency factor is 0.7 + (0.3)(0.08) ~ 0.72 or 72%. The other efficiency considered (8%) was the lowest found in our tank studies, when capturing attached adults. In this case, we proceeded conservatively and applied this efficiency factor to all stages.

Our cost analysis (all currency is in Canadian dollars) is based on that published by Mustafa et al. (2001) for sea lice costs to the aquaculture industry in eastern Canada. These authors identified four major costs incurred through sea lice infections: (*i*) reduced growth of salmon (at a loss of 200 g·fish^{-1}), (*ii*) reduced feed conversion rate (requiring 5% more feed at a cost of \$1.25·kg^{-1} of feed), (*iii*) downgrading of salmon product from premium to standard, at a cost of \$1·kg^{-1} of fish, and (*iv*) secondary diseases emanating from lice infection, resulting in a loss of 1% of total fish harvested. These factors, unaltered, guide the calculations for the nontreated farm (Table 1).

Our analysis also produces new cost factors for the various treatments, which arise by multiplying those above (see Mustafa et al. 2001) by efficiency coefficients pertinent to each treatment. In the case of light treatments, for instance, we assume that the costs will be reduced by the capture efficiency factor of the light trap. This is based on the results of Pahl et al. (2000), who showed that the number of sea lice on fish (and therefore, we assume, the infection pressure, ensuing damage, and costs to the culturist) was directly proportional to the number of sea lice larvae in the water (and assessed by light trap capture). Thus, the use of a light trap with 72% efficiency would lower the cost factor due to reduced salmon growth by 0.2 kg·fish^{-1} – 0.2 kg·fish^{-1}(0.72) = 0.056 kg·fish^{-1}. In the case of Slice, Saksida et al. (2007) showed that treatment with this neurotoxin was effective for a maximum of 5 months. Thus, in our analysis we used 1 – 5/12 ~ 0.58 to calculate the reduced factors associated with this treatment (Table 1). When both Slice and light traps are combined, the reduced cost factors are obtained by applying the light trap efficiency factor to the portion of the production cycle when Slice is ineffective. For instance, the new factor associated with reduced salmon growth when Slice and a 72% efficient light trap are combined becomes 0.2 kg·fish^{-1}(0.58)(1 – 0.72) ~ 0.032.

The calculations leading to the costs presented in Table 1 further assumed typical net pen dimensions of 30 m × 30 m × 20 m (volume: 18 000 m^3), fish stocking density of 10 kg·m^{-3}, market fish size of 4 kg, and the sale of salmon for \$8·kg^{-1}. For instance, the cost due to reduced growth per net pen in a nontreated farm per production cycle would be 18 000 m^3(10 kg·m^{-3})(1 fish·4 kg^{-1})(0.2 kg·fish^{-1})(\$8·kg^{-1}) = \$72 000. For the same net pen, the cost due to reduced feed conversion would be 18 000 m^3(10 kg·m^{-3})(0.05)(\$1.25·kg^{-1}) = \$11 250; the cost due to product downgrade would be 18 000 m^3(10 kg·m^{-3})(0.01) (\$1·kg^{-1}) = \$1800; and the cost due to secondary infection losses would be 18 000 m^3(10 kg·m^{-3})(0.01)(\$8·kg^{-1}) = \$14 400.

There are additional intrinsic costs to Slice treatment and (or) the operation of light traps. Slice treatment is estimated at \$0.10 kg^{-1} of fish (Bright and Dionne 2005). Our prototype light trap costs \$1200 to manufacture. Given the dimensions of the cone of light emitted, a maximum of five light traps need be deployed per net pen for a cost of \$6000 per net pen (or \$2000 per production cycle). The light trap is powered by a battery that costs \$92, and each light trap has four LEDs that cost \$20 each. Both components (battery and LEDs) last 5–6 years, for a cost of 5[92 + 4(20)] = \$860 (or \$287 per production cycle). In our estimates, we have also included \$200 for miscellaneous repairs per production cycle. The operation of our light trap is self-evident, requiring no training costs. The remaining cost for light trap operation would be labour (for aquaculture operations that could not incorporate light trap retrieval and redeployment as part of the operating crew's work load). Given that the battery can power the four LEDs for >48 h at half the intensity used in this study (which would be sufficient for attracting sea lice within the net pen dimensions considered here, see below), we estimate that the total cost of one extra person to operate five light traps per production cycle would be \$50 000·$year^{-1}$(9 h·35 h·$week^{-1}$)(2 years·$cycle^{-1}$) = \$25 714. This calculation is based on retrieval and redeployment of each light trap in 36 min (which is a conservative estimate, since the task can be completed in 30 min) and deployments lasting on average 2 days (three deployments per week). Thus, the total cost with and without the extra salary for deploying five light traps per production cycle would be \$28 201 and \$2487, respectively.

Our light trap-related cost estimates are based on deployment of five units per net pen. Given the dimensions of the light trap, we can calculate an exit cone of light of 28°. Thus, this cone will be 5 m wide at 20 m depth. For a 30 m × 30 m net pen with a converging bottom (as is normally the case, resulting in less than 25 m × 25 m cross-section at 20 m depth), five light traps will expand a strip of cross section 5 m wide. Although such a strip of light will not cover the total cross sectional area of the net pen at any depth, only a maximum of five light traps need be considered for deployment because (*i*) fish and sea lice (attached and free-swimming) move within the net pen and will inevitably encounter one of the light cones, and (*ii*) horizontally scattered light 80 cm from the bottom of the capture chamber will travel ~51 m in any radial direction before it becomes invisible to a salmon louse. (This is based on an extinction coefficient of 0.3 m^{-1}, a scattered horizontal light intensity that is one-quarter of the downwelling light (see Novales Flamarique et al. 1992; Novales Flamarique and Hawryshyn 1993), and assuming an emission that is half the intensity of that used in this study.) All our laboratory and field trials indicate that such a light environment will draw sea lice to the light traps, especially at night. In fact, a single light trap positioned in the centre of the net pen with a downwelling light emission 10^{-5} times that used in this study (~10^{15} photons·m^{-2}·s^{-1}) would be visible to a salmon louse anywhere within the net pen at night (assuming the previous extinction factor and ratio of sidewelling to downwelling light). This makes our cost analysis for the light trap (which is based on deployment of five units) excessive in terms of necessary costs. When deploying light traps in salmon farms, care should be taken to place them strategically to minimize the number of units necessary and to refrain from attracting sea lice from beyond the net pens. In this regard, vertical light penetration appears to be the most forgiving dimension in that nauplii and copepodids are commonly found close to the surface, well within ~20 m depth (i.e., within the depth limit of most commercial net pens; Heuch et al. 1995).

Table 1 shows that deployment of light traps with 72% capture efficiency is the most effective single treatment of all considered, decreasing costs by \$69 117 (including the extra worker's salary) and \$43 303 (without such salary) per net pen per production cycle compared with the nontreated condition. The savings, when including the extra worker's salary, are approximately twice those achieved by Slice treatment (\$22 289). Treatment with an 8% efficient light trap results in reduced costs (when compared with the nontreated condition) only if the worker's salary is not included in the calculations. In this case, the culturist would save \$5469 per net pen per production cycle.

Our analysis of reduced costs using light traps of different capture efficiencies suggests that these devices should be implemented into sea lice monitoring–prevention programs in farms and in ecologically sensitive areas. Given the assumption that efficiencies measured in tank experiments will transfer to deployments in nature (an assumption that is qualitatively congruent with the difference in catch between light traps and plankton tows obtained in this study), our conservative analysis (see also Mustafa et al. 2001) indicates that light traps constitute a cost-efficient, noninvasive, environmentally friendly method to monitor sea lice in nature.

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