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Pathway of effects of artificial light on non-target organisms at aquaculture sites in Canada

Séquence des effets de l'éclairage artificiel sur les organismes non ciblés sur les sites d'aquaculture au Canada

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ABSTRACT

A national Framework for Aquaculture Environmental Management (FAEM) is being developed to provide the basis for a coherent national approach to support the sustainability of the aquaculture sector in Canada. Of the various possible stressors, this document examines the pathways of effects of the alteration of light in aquaculture activities on natural aquatic ecosystems in Canada. Its content (i) briefly summarizes the benefits that fish farmers accrue by using 24 h light exposure, (ii) describes the light intensity, periodicity, wavelengths and arrays deployed, as well as outlines spatial and seasonal scales, (iii) based on available scientific literature, reports and speculates on the effects of light deployment on non-target marine biota, and (iv) identifies knowledge gaps and recommends possible research to address the effects of artificial light on aquatic ecosystems in Canada. It is concluded that artificial illumination of sea pens in the evening during late fall/early winter, a common practice to improve fish productivity, does not appear to pose a serious threat to Canadian aquatic ecosystems. Relative to many of the other aquaculture stressors, the risks imposed by artificial light appear to be minor.

RÉSUMÉ

Le cadre national pour la gestion de l’aquaculture qui est en cours d’élaboration fournira le fondement d’une approche nationale cohérente pour assurer la durabilité du secteur de l’aquaculture au Canada. Parmi les diverses sources possibles de stress, ce document traite des séquences des effets de l’altération de l’éclairage, dans le cadre des activités d’aquaculture, sur les écosystèmes aquatiques naturels au Canada. Son contenu (i) récapitule brièvement les avantages pour les aquaculteurs de l’exposition à la lumière 24 heures par jour, (ii) décrit l’intensité de l’éclairage, la périodicité, les longueurs d’ondes et les ensembles mis en place, en plus de préciser les échelles spatiales et saisonnières, (iii) expose, en s’appuyant sur la documentation scientifique, les effets de l’éclairage sur la biote marine non ciblée et émet des spéculations sur ce sujet, (iv) cerne les lacunes en matière de connaissances et recommande des pistes de recherches pour éliminer les effets de l’éclairage artificiel sur les écosystèmes aquatiques au Canada. Il a été conclu que l’éclairage artificiel des cages d’élevage en soirée à l’automne et au début de l’hiver, une pratique courante destinée à accroître la productivité des poissons, ne semble pas constituer une menace grave pour les écosystèmes aquatiques canadiens. Comparativement à de nombreuses autres sources de stress lié à l’aquaculture, les risques que pose l’éclairage artificiel semblent mineurs.

INTRODUCTION

The influences of aquaculture and aquaculture-related activities or stressors on natural ecosystems in Canada are of concern to ecosystem integrity. A national Framework for Aquaculture Environmental Management (FAEM) is being developed to provide the basis for a coherent national approach to support the sustainability of the aquaculture sector in Canada. This framework addresses environmental effects of aquaculture and aquaculture-related practices on four components of Canadian aquatic ecosystems: fish health, fish communities, fish habitat, and water quality. Stressors associated with aquaculture that may affect aquatic ecosystems include: alteration in light; release of chemicals and litter; release of pathogens; release or removal of fish; release or removal of nutrients, non-cultured organisms and other organic material; physical alteration of habitat structure; and noise. Identifying Pathways of Effects (POE) of these stressors on aquatic ecosystem components, including development of state-of-knowledge descriptions of stressor-effects, and descriptions of risk, is a key component to developing sustainable aquaculture practices in Canada. The focus of the current document is to examine the POE's of the alteration of light in aquaculture activities on natural aquatic ecosystems in Canada.

Artificial light that alters the natural patterns of light and dark in ecosystems may have adverse affects on various organisms and is of broad interest in terrestrial and aquatic environments (Longcore and Rich 2004). Sea turtles upon hatching at night from their natal beaches normally move towards the ocean surf though they have been reported to be misguided by anthropogenic light resulting in unsuccessful attempts to reach water (Witherington and Bjorndal 1991). Some species of insects and birds have been reported to be strongly attracted to tall lighted structures which can result in significant mortalities (Wiese et al. 2001). The less obvious influences of artificial light on the behaviour and community structure of species are not so well studied (Haymes et al. 1984; Nemeth and Anderson 1992; Longcore and Rich 2004; Marchesan et al. 2005).

Artificial light and its use to stimulate fish growth and/or suppress sexual maturation have received strong attention from both industrial and scientific perspectives in coldwater mariculture (Oppedal et al. 1997, 2001, 2007; Hansen et al. 2001; Skjæraasen et al. 2004). Laboratory experiments on salmonids and gadoids have demonstrated the efficacy of continuous light during many life cycle stages (Hansen et al. 2001; Trippel and Neil 2003; Davie et al. 2007). For salmonids, considerable success has been achieved by transferring this technology from controlled laboratory conditions to sea cages (Fernö et al. 1995; Endal et al. 2000; Harmon et al. 2003; UN-GESAMP 2008).

Countries in the northern hemisphere that apply continuous lighting on sea cages include Canada, Norway, Scotland, Ireland and Iceland. The economic benefits for salmonid aquaculture are manifested in the additional somatic growth achieved by abstaining from gametogenesis and the avoidance of reduced fillet quality that would have occurred had maturation progressed normally. The high incidence of precocious individuals in mariculture is a consequence of high energy diets that support fast somatic growth. Selective breeding has been unsuccessful in generating fast growth in the absence of maturation (G. Friars, pers. comm.). Hence, fish farmers have resorted to lengthening day length during a time-critical period of the year (autumn). They do this by using lighting arrays either within or above sea cages and thereby mask the capacity of subadults from recognizing the shortening of day length that commonly begins the physiological processes triggering gametogenesis. What normally would end up as a mature fish in the spring would by the correct application of 24 h light remain infertile and its gonads would remain small and undeveloped.

The objectives of this contribution are to (i) briefly summarize the benefits that fish farmers accrue by using 24 h light exposure, (ii) describe the light intensity, periodicity, wavelengths and arrays deployed, as well as outline spatial and seasonal scales, (iii) based on the available scientific literature, report and speculate on the effects of light deployment on non-target marine biota, and (iv) identify knowledge gaps and recommend possible research to address the effects of artificial light on aquatic ecosystems in Canada.

OVERVIEW OF BENEFITS OF ARTIFICIAL LIGHT TO AQUACULTURE

For Atlantic salmon (*Salmo salar*) culture, implementation of 24 h light in sea cages from late November to mid April is a widespread practice in Atlantic Canada in the coastal areas where sea pens exist (R. Griffin, Cooke Aquaculture Inc., pers. comm.). Use of lights on salmon smolts in the first autumn of entry in the Bay of Fundy increased body weight and reduced incidence of sexual maturation compared to control cages (Harmon et al. 2003). In Harmon's study, after taking into account cost of purchasing, wiring and operating lights the savings gained per cage (70 m circumference) was estimated to be $100,000 over a production cycle. Approaches used in the past to reduce incidence of sexual maturation, such as food deprivation at critical seasonal time periods and induction of sterility by triploidy, failed to achieve the results desired by salmon farmers (Benfey 2001). Either food deprivation was ineffective or triploidy resulted in slower growth and higher incidence of deformities (Benfey 2001); however, a rigorous examination of the utility of triploidy in salmonid culture is still lacking.

Fish farmers in the past have noted the existence of annual variation in the maturation problem, and this may have been associated with annual variations in sea temperature where warm years would support rapid growth and greater incidence of maturation. However, in order to avoid maturation, fish farmers have elected to implement lights annually as the cost of running lights offsets the rare chance that early maturation may not be prevalent in unlit cages. When implementing continuous light, Cooke Aquaculture Inc. noted a reduction in incidence of sexual maturation from 4-10% to <1% per cage (R. Griffin, pers. comm.). A light regime of 20 h light: 4 h darkness may also be suitable to reduce incidence of sexual maturation. However, from an operations perspective, farm site managers believe it is simpler to maintain continuous light than a light/dark cycle.

Farming of marine finfish species such as Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), and haddock (*Melanogrammus aeglefinus*) is not as economically viable as salmon and, thus, only limited numbers are present in sea cages in Canada. Atlantic cod, a key candidate species for mariculture, also exhibits early puberty (Taranger et al. 2006; Trippel et al. 2008). Males may achieve maturation in the first year and females in the second year, yet presently time to harvest is 3 years at best. Consequently, repeated years of reproduction for cod held in sea cages is the norm. Considerable losses in somatic growth may be the consequence of early puberty. Moreover, cod in Norway have been reported to spawn and release viable embryos while reared in sea cages (Jørstad 2008). No such 'embryo escape' study has been conducted in Canada. Therefore, concerns associated with early puberty of cod are shared by both fish farmers and those vested in maintaining the genetic integrity of wild cod stocks existing in coastal areas (e.g., COSEWIC).

Seasonal changes in day length are an important trigger for onset of sexual maturation in fishes and are manifested in changes in endocrinology. Research has shown that salmon may require less light to inhibit sexual maturation than cod and this appears to be a function of species-specific sensitivities of the pineal organ to light (Porter et al. 1999, 2000). Synthesized by pineal photoreceptor cells, melatonin is a hormone which affects the brain/gonadal axis, and, hence, its diel/seasonal cycling triggers onset of gametogenesis.

Cod respond well to photoperiod control if kept in covered tanks because the light level stays constant, but cod do not respond well to continuous light in sea cages when ambient light is present (Porter et al. 2000). Similar to Atlantic salmon, the melatonin levels of cod must decrease to a certain point before they can be reduced further through photoperiod control. Porter et al. (2000) found cod exhibit diel melatonin production, and this persisted even after two weeks of constant light. The levels were lower than their natural light counterparts, but still followed the same ambient light pattern of melatonin levels. There was no significant difference between the melatonin levels of cod kept in natural light and those under continuous light. This research suggests that melatonin production in Atlantic cod is less sensitive to light than that of Atlantic salmon, and that more intense light levels may be required to achieve the same effect.

In Atlantic Canada, application of continuous light on cod farms failed to halt sexual maturation but delayed it by three to four months (Trippel et al. 2008). Similar results were reported in a Norwegian study (Taranger et al. 2006). It was unclear whether lights enhanced growth in the Canadian study (low sample sizes) but continuous light did increase growth of cod in Norway.

In Canada, other than for finfish no other aquaculture sector (e.g., blue mussel (*Mytilus edulis*) culture off Prince Edward Island) uses continuous light to enhance growth and/or suppress maturation (Karayücel and Karayücel 2000; Landry et al. 2006).

SCOPE OF REVIEW

Activities Causing Stressor (Artificial Light)

Variable lighting arrays are used in Canadian finfish aquaculture to suppress maturation. Lighting arrays currently deployed for Atlantic salmon cages in southwestern New Brunswick are commonly composed of three 400 W underwater lights in each 70 m polar circle cage (cage depth ~7 m). Lights are situated such that one is located at each of 1, 2 and 3 m below the surface (R. Griffin, Cooke Aquaculture Inc., pers. comm.). Earlier research by Harmon et al. (2003) revealed that two lights suspended above the surface are sufficient though industry has implemented a third light as a back-up in case one light becomes non-functional. In Shelburne County, Nova Scotia, where the water is more turbid, salmon farmers are using double the light intensity, i.e., six 400 W lights). Another salmon farming operator in the Bay of Fundy currently uses four 400 W lights each located near the side walls of a 70 m net pen (Ocean Legacy, pers. comm.). Light readings at night in the experimental work by Harmon et al. (2003) showed that illumination near the cage edge was very similar between lit and control cages (~2-3 lux) (Table 1).

In British Columbia, salmon farmers deployed nine 400 W lamps over a cage measuring 30 m on a side and ~30 m deep (lights were suspended 2.5 m above the water's surface) (Hay et al., 2004). In Norway and Scotland, several studies have been undertaken to examine the amount of light required to suppress sexual maturation in Atlantic salmon. In pioneering work, Hansen et al. (1992) suppressed salmonid maturation by using three halogen lamps (2.1 kW total) on a 125 m^3 cage from 15 October to June 24 suspended 1-2 m above the surface such that the minimum light intensity at the bottom of a cage was 10 lux. In research conducted in Scotland, four metal halide lights (Kockum Sonics, Leighton Buzzard, Beds, UK) were used per 10 m^2 cage and were located 2 m above the water's surface (Porter et al. 1999). Lights were turned on 50 min before dusk and turned off 50 min after dawn. Light intensities near the cage corners ranged from 8-16 lux, whereas the ambient photoperiod cage was <0.2 lux at midnight (Table 2).

In more recent work in Norway, Dempster et al. (2009) used two submersible lamps (Idema Aqua A/S, N-1344 Haslum) in a submersible scale sea cage. Each light had a 400 W power rating (Powerstar, HQI-BT 400 W/D Colour temperature: 32,000 lm, Osramn, Lysaker, Norway) and were at 7 m depth, 6 m between lamps.

Experimental research conducted in the Bay of Fundy to suppress sexual maturity of Atlantic cod has utilized six 400 W lights (2.4 kW) (Trippel et al. 2008), as well as six 800 W lights (4.8 kW) in 70 m polar circle cages (Trippel et al. 2009) (Figures 1 and 2). For light trials that deployed six 400 W lights, the light levels at night ranged from 160 lux in the centre of the ring of lights suspended at 2 m depth at the centre of the cage to 9 lux at the middle of the cage bottom. Light levels ranged from 22-30 lux along the cage sides (Trippel et al. 2008).

Given that the pineal organ of Atlantic salmon is very light sensitive, the sea cage operator is able to achieve the desired physiological outcomes with minimal use of artificial night light. Although cod mariculture is being pursued from a scientific perspective, the number of sea cages in eastern Canada containing cod is relatively few. Hence, although up to four times the amount of light may be required to suppress maturity in sea cages containing cod only a few experimental/industrial cod cage sites existed in the Atlantic provinces in 2009 (five sites). Even so, the ineffectiveness of an intensive lighting array for cod is giving way for research into fish sterilization, for example triploidy (Peruzzi et al. 2007; Trippel et al. 2008; Feindel et al. 2009), and given the levels of mortality associated with cod spawning, this form of infertility may be more suitable for cod than for salmon culture.

As a note for future research, often times experiments are carried out by matching the power (in Watts) of two individual light sources that differ in wavelength emission in tests of colour preference of an animal. These experiments may not be designed properly as the two sources (matched in power) will differ in quantal intensity (photons) which is likely more important to the receiving animal (I.N. Flamarique, pers. comm.). A more appropriate way to quantify light for fish studies is to measure the irradiance (photons m^{-2} s^{-1}) as a function of wavelength and integrate over the wavelengths of interest. There are many spectroradiometers with this capacity available commercially (e.g., Ocean Optics).

The use of simulated natural daylight (white light) is a common light fixture available to commercial fish farmers, though bulbs emitting blue light are also available. The reason why fish farmers may be attracted to blue/green light is that a similar effect of illumination on fish may be achieved (Figure 1) but with lower intensity bulbs. This is because water absorbs light differentially. The red end of the light spectrum is absorbed in shallow water while the blues and greens penetrate the deepest. In Canada, light transmission through coastal waters does not peak in the blue but in the green-yellow (i.e., 540-560 nm) (Flamarique and Hawryshyn 1993). From the data listed in Table 3, it can be seen that peripheral light at a cage edge commonly ranges from 10 to 150 times greater than ambient night-time light. There is no indication of how light intensity decays spatially around a lit cage, however, given the rapid decline from cage centre to periphery it is anticipated that further declines will be even more pronounced.

Scope of Species Examined

The species examined in this report are limited as there have been relatively few studies directed at the effects of anthropogenic light on non-target organisms around sea cages in Canada or elsewhere. Some organisms that will be highlighted include sea lice, zooplankton, lobster, shrimp and herring, though due to data scarcity the synthesized information is mainly founded on speculation.

Type/Source of Literature Used

Literature used in this document was primarily peer-reviewed scientific documents located through various search engines (ASFA, Scopus, BIOSIS, Web of Science). As well, government documents, reports, and websites from federal, provincial and international agencies were used as appropriate. Personal communications with aquaculture industry personnel and researchers were also used to gather relevant information. No review of this type has been previously conducted on the environmental impact of anthropogenic light of fish farms on wild organisms; hence previous reviews in the scientific literature to build upon were unavailable.

LINKAGES BETWEEN ACTIVITY, STRESSOR AND EFFECTS

A paucity of literature exists on the effects of artificial night light on the reactions of marine organisms in Canada. This review is thus somewhat limited to a few studies that addressed this issue and provides some speculation on the potential effects of illumination during night on these and other biota. The section is divided into effects of night light on non-target organisms within and in the near vicinity of sea cages.

WITHIN SEA CAGES

Sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi*) are ectoparasitic copepods that attach themselves to salmon and often cause fish stress and loss in production. In British Columbia, research has been undertaken to monitor and entrap sea lice using a light-emitting diode (LED) based light trap (Flamarique et al. 2009). When deployed, it captured sea lice larval stages and adults and also assisted to delouse some fish. Would the use of artificial light on salmon cages thus attract sea lice and thereby increase infestation over unlit cages? This is a research issue that clearly requires some attention. This may be the single largest negative effect of lights. It would reduce the quality of farmed salmon and in the event of an escape would lead to sea lice infested salmon in natural waters. Although unreported in the light trials of Peterson and Harmon (2005), these investigators did not detect sea lice on salmon in either experimental or control cages (R.H. Peterson, pers. comm.) and the degree to which fish in these trials were treated with SLICE or other anti sea lice treatments is unknown. Moreover, Browman et al. (2004) showed changes in light intensity are involved in sea lice host detection at spatial scales on the order of meters, but it is not the primary sensory modality underlying host location at smaller scales (cm to mm).

Zooplankton fauna of a wide variety of species were also attracted to the light traps (I.N. Flamarique, pers. comm.). If wild food organisms are attracted to lit cages, they may become vulnerable to predation by caged Atlantic salmon. To test this hypothesis examination was made of ~600 stomach contents of salmon held in lit and unlit cages at the northern end of Vancouver Island (Hay et al. 2004). The gut contents varied in time and within and among pens but very little wild feed was consumed by salmon at any of the sites. The principal wild organisms taken were caprellids, small crustaceans that are part of the ‘fouling’ community that grew on the webbing of cage nets. Only one fish was found in the stomachs and this was a small sand lance (*Ammodytes hexapterus*). It is uncertain from these results if wild organisms were more abundant in lit compared to unlit sea cages, though in either case they were not reflected in the diet of caged salmon. If wild plankton are attracted to lit cage sites then this practice may exacerbate the attraction of potentially parasite and disease infected zooplankton that are preyed upon by farmed fish. However, the results of Hay et al. (2004) suggest this is an unlikely outcome.

During the winter, *Pandalus* shrimp are often abundant in Passamaquoddy Bay. Literature could not be found on their reactions to illumination and so this shrimp may be attracted, repulsed or unaffected by lit salmon cages. Vertical distribution differences between day and night were found for two of seven species of shrimp off Oregon (Pearcy 1977). Sampling for shrimp during day and night near the perimeter of lit and unlit sea cages may provide further information in this regard. Cultured Atlantic cod held in sea pens in Back Bay, New Brunswick did not noticeably have any other food items in their stomachs other than recently ingested or partially digested pellets (E.A. Trippel, unpublished data). Thus, it is unlikely that *Pandalus* shrimp are seriously impacted by 24 h lighting as they are a preferred food item of wild cod and would likely have been evident in the stomachs of cultured cod had they entered the sea pens.

Biofouling of nets may also restrict entrance of certain sizes of fish into sea pens and possibly influence availability of potential prey for salmon in the pen. In deployment of LEDs on traps, Flamarique et al. (2009) routinely caught larval stages of important crustaceans (e.g., shrimp, crab and lobster) which are seemingly photopositive (Pahl et al. 1999).

NEAR-FIELD ENVIRONMENTAL EFFECTS

Large crustaceans such as the American lobster (*Homarus americanus*) are typically photophobic (Calinski and Lyons 1983; Annis 2005) and consequently adult and juvenile lobster may avoid lit cages. The extent of this response would be a function of light penetration beneath the cage and the distance from net bottom to seabed. In many cases, net bottoms are several meters above the seabed and since light penetration in these circumstances does not reach the ocean floor, it is unlikely that lobsters would be influenced by anthropogenic light. To the author’s knowledge there is no study on the comparative distribution of lobsters (or shrimp) around lit and unlit cages. It is worth noting that the alteration of the sediment quality within any light field would likely have a greater impact on lobsters. The most important concern under near-field environmental effects is whether or not species diversity and abundance are diminished from a zone beyond the edge of the cage, i.e., the environmental footprint of the cage is enlarged when it is lit in the winter. This possibility has not been systematically studied, but information could be extracted from routine benthic surveys and knowing where the light intensity decays to background levels.

The levels of light and quality of ambient light that are needed to support phytoplankton and hence zooplankton are of potential significance in order to evaluate if there are consequences on primary productivity of a light intensity up to 30 lux at the edge of the cage. Assessment of these light levels is an area for future investigation in connection with published literature on the subject.

Purse seining techniques for squid in New England have been reported to use light to aggregate individuals around a vessel (Taber 1977). Many squid fishermen in Peru and South Korea use lights to lure these animals so there is a real possibility for impact on these species (both larvae and adults). Consequently, squid could be attracted to lit cages, though this potential attraction would also be a function of other habitat/environmental requirements (e.g., coastal vs. deep water habitat preferences and seasonal timing of use of artificial light).

Cage farming has been reported to attract large numbers of both pelagic and demersal wild fish due to a result of uneaten or lost food and profuse fouling around the cages (Dempster et al. 2002; Akyol and Ertosluk 2010). Finfish may also be influenced by artificial night light. The knowledge of the ecology and visual behaviour of local fish in natural conditions, and in relation to artificial light, is a fundamental premise to provide improved advice on their reaction to lit cages. There is a significant literature base on the use of artificial light for selective light fishing, though this tactic is not commonly used in Canadian waters. Norwegian spring spawning herring (*Clupea harengus*) have been photomanipulated at harvesting (Beltestad and Misund 1989) and light manipulation has been used to capture other fish species (Joseph 1975; Enderein and Wickstroem 1991; Deudero 2002). Negative phototaxic reactions may be exploited to guide fish into catching gear, for example for the polar cod (*Boreogadus saida*) (Ben-Yami 1976). Detailed experiments have been undertaken to examine the responses to artificial light of variable intensity and wavelength on aggregation, phototaxis, and photokinesis in several commercial fish species in the Mediterranean Sea in order to provide guidelines for more selective fishing that leads to less by-catch (Marchesan et al. 2005). Knowledge of the swimming behaviour of pelagic fish in relation to light has been used in purse seine operations where herring are "scared" up into the purse by subjecting the school to light from below (Joseph 1975).

Atlantic herring undergo seasonal migrations along the eastern Canada/U.S. coast and often enter into the Bay of Fundy in large numbers in summer supporting a weir fishery in southwestern New Brunswick. Herring are mainly in the upper layers of waters of Passamaquoddy Bay during summer and nearer to the surface when light intensity is low (Battle et al. 1936). Since farmers only use photoperiod manipulation from late November to mid April the potential disrupting effect of lights on herring distribution is seriously diminished as there is little spatial-temporal overlap.

Atlantic mackerel (*Scomber scombrus*) observed swimming in lit cages at night in November (E.A. Trippel, pers. comm.) may be filter feeding and taking advantage of the light intensity that in turn may have attracted zooplankton to the cage (Sutherland et al. 1995). This may be analogous to bats observed preying on moths near lamp posts at night (Frank 1988). Thus, Atlantic mackerel may enter a cage site and then leave, though these fish are commonly present in August/September in the Bay of Fundy and thus the effect of artificial light is minimal for this species. Research has shown that the level of light, length of exposure, and the environmental setting governs the type of behaviour exhibited by Mediterranean fishes (e.g., curiosity/attraction vs. frightened/flee) (Marchesan et al. 2005). Consequently, studies on behavioural reactions to light need to be taken into context of the potential stressor.

Moreover, lights could displace juvenile fish of importance (like wild salmon) either disrupting their migratory behaviour or making them venture into deeper water (leaving their protective shoreline habitat) following zooplankton or being attracted by the lights themselves. However, the use of lights does not correlate with typical spring/summer presence of juvenile wild salmon.

The rationale for undertaking this review stems mainly from elucidating if the presence of artificial light causes significant environmental degradation that is manifested in non-target organisms. The interactions between light intensity, underwater light transmission properties and water clarity define the potential threat of light pollution beyond the periphery of sea cages. The financial costs associated with purchasing lighting arrays, replacing bulbs and the energy to run them necessitate that fish farmers remain prudent in their use. Why have light shine far beyond the edge of a sea cage? Optimum deployment of light is in the best interest of the industry.

Deployment of lights is limited to fall/winter which is not as potentially serious as compared to year-round use. Measurements of light values around sea cages demonstrated that very little additional light is observed outside the cage perimeter. Consequently, light may be no more a detriment to habitat alteration than the physical presence of the cage and netting. Animals and sea plants may be influenced that are immediately below the cage, but then illumination of many cages does not penetrate to the benthic zone and so this is unlikely. Passive planktonic organisms may drift through the lit cage site. Unless they exhibit self propelled movement in which they are able to actively maintain a position in a lit cage then they too will not be seriously influenced. Moreover, the animals that can be influenced by night light must be those small enough to enter the webbing of sea cages. Mesh size consequently plays a role in precluding certain individuals from entering a sea cage and ultimately whether they will be strongly influenced by night light.

To a large extent, the Bay of Fundy is resident to a greater diversity of marine life in summer and early autumn, as this is the period when fish and cetaceans along the New England coast often migrate north into Canadian waters, followed by a return migration in late fall. If lights in coastal aquaculture sites are not turned on until late November this mitigates the potential deleterious effects on these marine organisms.

INTERACTIONS WITH OTHER STRESSORS ASSOCIATED WITH AQUACULTURE

Artificial light appears to be not associated with other stressors of aquaculture that may impact aquatic ecosystems that include: release of chemicals and litter; release of pathogens/parasites; release or removal of fish; release or removal of nutrients, non-cultured organisms and other organic material; physical alteration of habitat structure; and noise. Of these, perhaps, the release of pathogens could be linked to illumination. Sea lice appear to be attracted to light and the use of artificial illumination at night may increase the incidence of sea lice on Atlantic salmon in sea cages.

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF EFFECTS

Artificial illumination of sea pens in the evening during late fall/early winter, a common practice to improve fish productivity, does not appear to pose a serious threat to Canadian aquatic ecosystems. Relative to many of the other aquaculture stressors, the risks imposed by artificial light appear to be minor.

SUMMARY OF KNOWLEDGE GAPS AND RECOMMENDED RESEARCH

The following knowledge gaps should be addressed to better predict the consequences of artificial light on aquatic environments.

- Conduct laboratory and field research to develop a knowledge base of the behavioural responses of key aquatic organisms to artificial light deployed in night conditions.
- Conduct a study of light intensity decay beyond the cage periphery to better define the zone of enlightenment for different lighting arrays in waters of different turbidities.
- Establish a permitted threshold of light intensity at the cage periphery based on an intensity decay function in the waters beyond.
- Examine whether sea lice infestation on Atlantic salmon and other species is greater in lit than unlit cages.
- Undertake measurements of primary productivity beyond lit cages.
- Conduct a biological survey of the presence and abundance of various pelagic and benthic species around lit and unlit sea cages during day, night and different seasons.
- Concerns with using artificial light in aquaculture are necessarily amplified four-fold for cod versus salmon.
- Examine the efficacy of 20 h light (extended day length; lights off 0000-0400 h) relative

to 24 h light in reducing early puberty in farmed fish.
- Pursue the development of functional sterile fish to preclude the need for night illumination of sea cages.

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TABLES

Table 1. Two 400 W Seebrite lights simulating the natural light spectrum were placed in each of three 70 m polar circle cages, approximately 5 m below the surface and were centered in the cage separated by 7 m. Lights were turned on November 21. Light intensity at outer edges was measured after dark on December 6 at three points around lit cages and two points around unlit cages. At each point readings were taken every 0.25 m to a maximum depth of 3.0-4.5 m, depending on the cast. Source: modified from Harmon et al. (2003) and Peterson and Harmon (2005).

	Cage	Cast #	Mean of readings taken every 0.25 m to depth of 3.0-4.5 m (lux)	Cage mean (lux)
Lit	1	1	3.365	3.131
		2	3.178	
		3	2.851	
	2	1	2.573	2.529
		2	2.535	
		3	2.480	
	3	1	2.527	2.386
		2	2.375	
		3	2.257	
Control	1	1	2.144	2.147
		2	2.150	
	2	1	2.062	2.116
		2	2.170	
	3	1	2.173	2.198
		2	2.222	

Table 2. Light intensities (lux) measured at the water's surface, 1 and 5 m depths in sea cages with ambient lighting and additional night-time illumination. Source: Porter et al. (1999).

Depth	Ambient photoperiod cage		Additional night-time illuminated cage		
	Noon	Midnight	Noon	Midnight (below lights)	Midnight (cage corner)
Surface	12,000	<0.2	12,000	9200	16
1 m	775-9000	<0.2	775-9000	340	9
5 m	42-240	<0.2	42-240	34-50	8

Table 3. Summary of light intensity at cage periphery and natural ambient light levels outside of cages as reported in several studies.

Species cultured	Light intensity at cage periphery	Ambient night light	Source
Atlantic salmon	2-3 lux near the cage edge	2 lux	Harmon et al.(2003)
Atlantic salmon	10 lux at both of the cages		Hansen et al. (1992)
Atlantic salmon	8-16 lux near the cage corners	<0.2 lux	Porter et al. (1999)
Atlantic cod	22-30 lux along cage sides		Trippel et al. (2008)

FIGURES

Figure 1. Aquastar aquaculture machine systems, submersible photoperiod lighting 800 W 220 V-50 HZ bulb type: halogen metal with Ignitor 11 cm diameter 100 cm length, bulb life: 12,000 h, colour yield - 90 CRI colour temperature: 6500 degrees K glass type: boro silicate. 5 mm). Six of these were used in a 70 m polar circle cage holding Atlantic cod in the Bay of Fundy, near Back Bay, New Brunswick (Trippel et al., 2009). Electricity to power lights is either generated by a gas powered generator on the cage site or by underwater cables to a commercially available source. Photo credit: O.A. Puckrin.

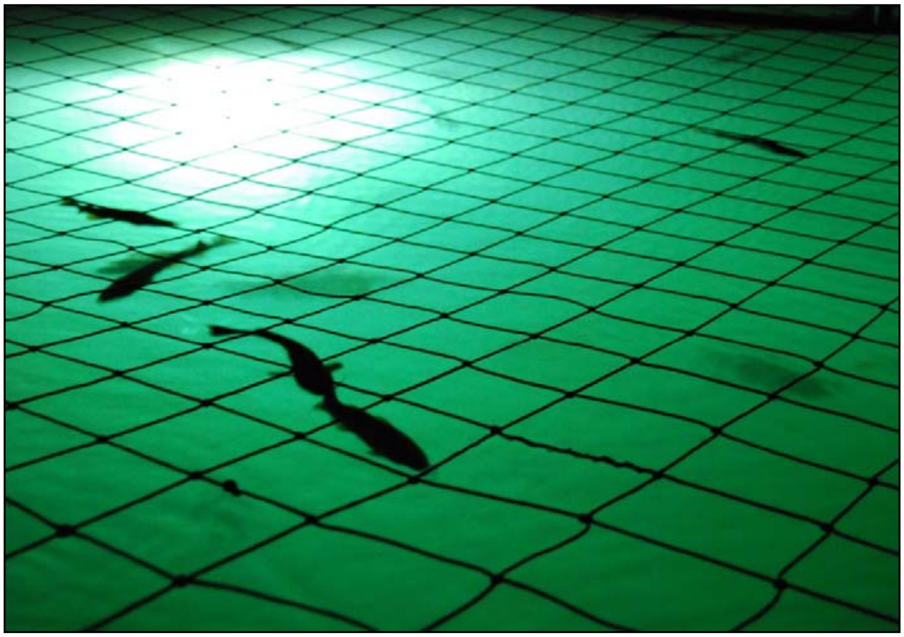

Figure 2. Photograph at night of a 70 m circumference sea cage holding Atlantic cod in Kelly Cove, New Brunswick (diameter 21.2 m, depth 7.5 m). This cage was lit by six 400 W Aquastar submersible lights (three lights were at depth of 2 m and three lights at 4 m, placed in two 7 m sided triangles, one offset from the other) (Trippel et al,. 2008). Photo credit: E.A. Trippel.