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# Aquaculture-related physical alterations of habitat structure as ecosystem stressors

# La modification physique de l'habitat par l'aquaculture comme facteur de stress écosystémique

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## ABSTRACT

Effects related to the addition or modification of physical structure due to bivalve and finfish cage aquaculture were reviewed. The on-bottom physical structures include anchoring devices for suspended and off-bottom bivalve farms or fish cage farms. In the case of on-bottom culture of oysters, it also includes the oysters themselves. For in-bottom clam culture, it includes the gravel that may be added to culture sites. Vertical structure added to the water column includes ropes and cage/net structures as well as buoys, etc. This infrastructure adds physical structure for colonisation by a large suite of hard-bottom associated species that may not otherwise find suitable habitat in a given area (e.g., muddy bottoms or water column). These have a variety of direct and cascading effects on the surrounding ecosystem. These structures also modify current regimes which may influence various ecosystem processes. Cage and netting structures may trap a variety of large organisms but data on this effect is rare. Modification of the physical environment via harvesting may have greater or lesser effects, depending on the methods used. In general, effects related to the addition or modification of physical structure are not well studied and most effects have not been quantified. Moreover, discussion of effects in the scientific literature is largely based on extrapolations from other systems. Shading adjustments may result from the physical structures used in all forms of culture operations blocking the sunlight. Clearing of waters by fouling organisms (and farmed bivalves) and increased turbidity due to waste from finfish culture sites may also alter light conditions in the water column and on the bottom. A number of specific knowledge gaps were identified, including the need for basic quantified descriptive studies, scale-dependent carrying capacity studies, the establishment of dose-dependent response curves to different stressors, the identification of appropriate indices for determining impacts, and all aspects related to finfish cage culture in freshwater.

# RÉSUMÉ

Les effets reliés à l'addition ou à la modification des structures aquacoles sur les sites d'élevage de bivalves et de poissons en cage ont été examinés. Les structures sur le fond comprennent les dispositifs d'ancrage pour la conchyliculture suspendue et surélevée ou l'élevage de poissons en cage. Dans le cas de l'ostréiculture, les huîtres sont également prises en compte. Pour la culture des palourdes, y compris le gravier qui peut être ajouté aux sites de culture. Les structures verticales ajoutées à la colonne d'eau incluent les cordes, les cages, les filets ainsi que les bouées, etc. Cette infrastructure ajoute une structure physique qui peut être colonisée par un grand nombre d'espèces qui sont normalement associées aux fonds durs et qui ne trouveraient pas autrement d'habitats convenables dans une zone donnée (par exemple, les fonds vaseux ou la colonne d'eau). Ces structures ont une variété d'effets directs et en cascade sur l'écosystème environnant. Elles modifient aussi les courants qui peuvent influencer divers processus de l'écosystème. Les cages et les filets peuvent piéger une grande variété de gros organismes mais les données sur cet effet sont rares. Les effets de la récolte sur l'environnement physique peuvent être plus ou moins importants selon la méthode utilisée. En général, les effets reliés à l'ajout ou à la modification de la structure physique ne sont pas bien étudiés et la plupart n'ont pas été quantifiés. De plus, la discussion de ces effets dans la littérature scientifique est fondée en grande partie sur des extrapolations à partir d'autres systèmes. Toutes les formes d'aquaculture peuvent causer de l'ombrage par le biais des structures physiques bloquant la lumière du soleil. La filtration des organismes salissants (et les bivalves en élevage) peut accroitre la pénétration de la lumière dans la colonne d'eau tandis que les déchets produits par l'élevage de poissons peut augmenter la turbidité de l'eau. Des lacunes au niveau des connaissances ont été identifiées, notamment la nécessité d'études quantitatives descriptives, d'études de capacité de support qui tiennent compte de l'échelle utilisée, le développement de courbes dose-réponse à différents facteurs de stress, l'identification d'indices appropriés pour déterminer les impacts et tous les aspects reliés à l'élevage en cage de poissons en eau douce.

# 1. INTRODUCTION

Aquaculture is expanding world-wide. Globally, total aquaculture production has grown from 3.9% of the total fisheries and aquaculture production of fish, shellfish, and other aquatic organisms in 1970 to 36% of the total in 2006 (47% of the total fish production). The Food and Agriculture Organization of the United Nations (FAO Fisheries and Aquaculture Department 2009) suggests that this trend will likely continue in the future, although the rate of growth of aquaculture production is slowing down. There have also been concomitant concerns about the potential environmental impacts associated with the industry (Black 2001, Davenport et al. 2003, Holmer et al. 2008). Initial concerns about aquaculture focused on finfish cage culture and the release of excess nutrients from cage sites, disease transmission, and the impacts of escapees on the receiving environment. A number of other concerns have subsequently been raised about finfish culture as well as for bivalve and other types of culture. More recently, focus has shifted to trying to better predict the carrying capacity of areas for aquaculture and it is becoming better recognized that interactions between aquaculture and the environment are complex and that there are both negative and positive environmental consequences arising from the practice.

In this report, the importance of one class of stressors arising from aquaculture, the physical alteration of habitat structure, will be discussed in the Canadian context. Thus, the review concentrates on finfish cage culture in marine and fresh waters and on bivalve culture in marine systems. The limited culture of algae and land-based farming are not examined, although it is acknowledged that the former practice is growing considerably and the latter is of considerable importance regionally.

The report starts with an overview of cage-based finfish and bivalve aquaculture practices in Canada followed by an overview of activity-specific pathways of effects. Following the Introduction, the report is divided into two main sections, one each for marine cage finfish farming and one for the farming of bivalves. Due to the paucity of information on freshwater finfish cage culture, this subject is included in the section of marine cage culture, providing information where it is available on freshwater systems. Given the diversity of methods used and the physical scale of some of the existing farms, the section on bivalve culture is the most complex and it is subdivided into suspended culture and intertidal/subtidal off-bottom and on-bottom culture sections. Within each section, four stressor classes are considered: 1) Shading adjustments, 2) Addition/removal of shoreline/bottom structure, 3) Addition/removal of vertical site infrastructure, and 4) Resuspension/entrainment of sediments. An overview of the main physical structures used in the types of aquaculture considered in this review and the areas in which the four stressor classes act are given in Figure 1.

To the extent possible, this review uses the terminology and structure requested by the Aquaculture Science Branch. In all cases, different stressor classes (placement/removal of site infrastructure, use of industrial equipment, and site and stock management) are discussed where relevant for each of the ecosystem components addressed in the documents. Ecosystem components highlighted with an asterisk indicate that this stressor category was not originally identified of importance for a given stressor category but was interpreted to be so by the author. For each ecosystem component, a number of points are addressed: i) Effects profile; ii) State of knowledge of direct effects; iii) Cascading effects and biological implications for ecosystem; iv) Magnitude of effects; v) Modifiers of effects; vi) Available evidence; vii) Uncertainties and knowledge gaps; and viii) Activity-specific links. For brevity, these are not included in the Table of Contents. The intricate links between many different ecosystem components often makes separating them difficult. In many cases, the information provided is redundant between sections and an attempt has been made to reduce this by referring to previous sections where appropriate [often to the first ecosystem component discussed for each class of aquaculture (Stressors on wild fish populations/communities) as following ecosystem components are often refinements of this first one]. At times, additional or more detailed information is provided in sections that seem more appropriate. For example, the ecosystem component, Habitat structure, cover and vegetation, follows the ecosystem component, Stressors on wild fish populations/communities, changes in which arise mostly via the addition or modification of habitat structure, which is both ecosystem component and the stressor category of interest in the present review. Thus, much of the relevant information on cascading effects is typically presented in the first ecosystem component discussed for a given type of aquaculture and stressor subcategory (stressors on wild fish populations/communities), whereas the Subcategory, habitat structure, cover and vegetation, concentrates on impacts on natural structured habitat (biogenic reefs or habitat created by benthic invertebrates, algae, and macrophytes).

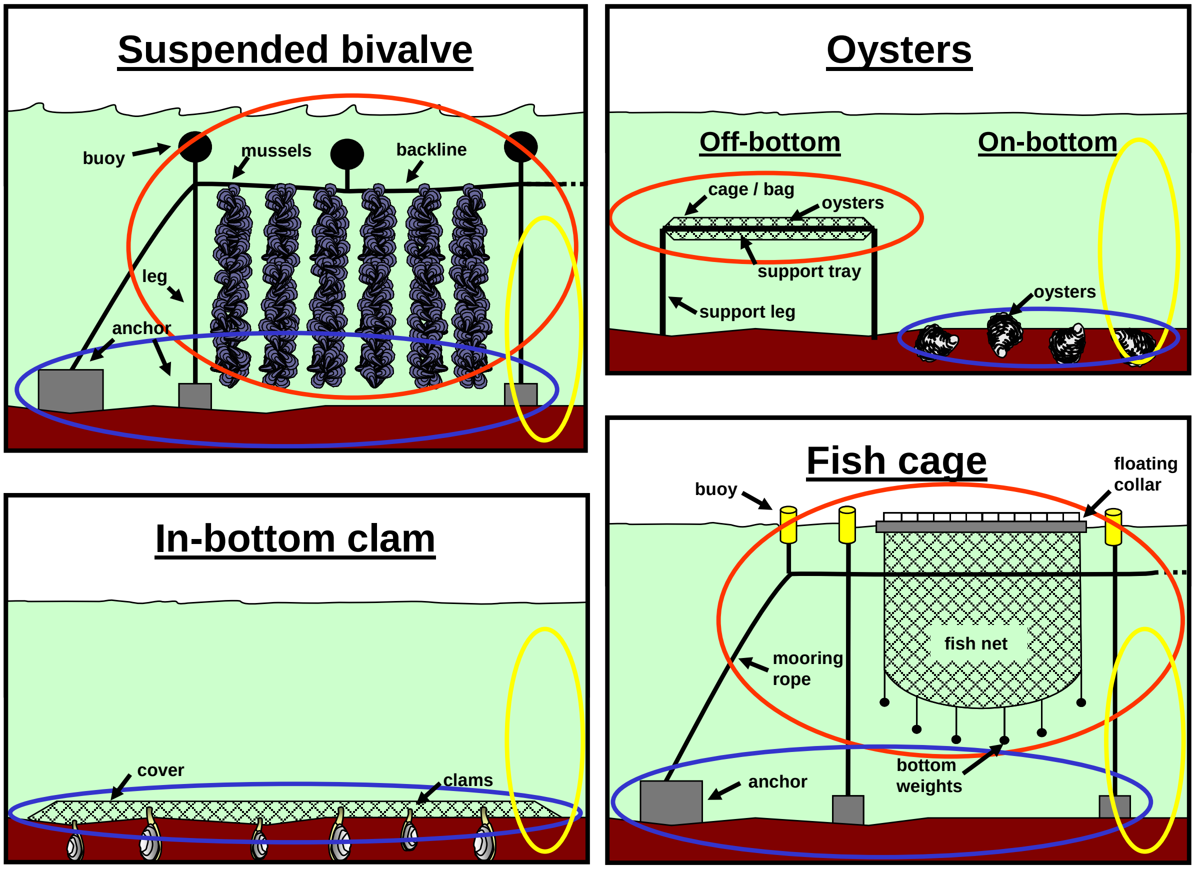

*Figure 1. Overview of the main physical structures of importance in the types of aquaculture considered in this review. Coloured ovals indicate areas in which stressor classes operate. Four stressor classes are considered: 1) Shading adjustments (yellow ovals), 2) Addition/removal of shoreline/bottom structure (blue ovals), 3) Addition/removal of vertical site infrastructure (red ovals), and 4) Resuspension/entrainment of sediments (also yellow ovals).*

## 1.1 OVERVIEW OF AQUACULTURE PRACTICES (FINFISH AND SHELLFISH) IN DIFFERENT ENVIRONMENTS

See Leggatt et al. (2010) for an overview of aquaculture practices. An outline of the techniques used for common species of bivalves cultured in Canada is given in an appendix at the end of this document.

## 1.2 OVERVIEW OF PHYSICAL ALTERATION OF HABITAT STRUCTURE

Bivalve and finfish aquaculture adds a considerable quantity of physical structure on the bottom and in the water column of waters around the world. With respect to the culture types used in Canada, this may include anchoring devices for suspended and off-bottom bivalve farms or fish cage farms. In the case of on-bottom culture of oysters, it also includes the oysters themselves and gravel may be added to clam culture sites. Vertical structure added to the water column includes ropes and cage/net structures, and buoys, etc., as well as, in the case of farmed bivalves, the bivalves themselves. This infrastructure and biological structure adds physical structure that may be colonized by a large suite of hard-bottom associated species that may not otherwise find suitable habitat in a given area (e.g., muddy bottoms or water column). These have a variety of direct and cascading effects on the surrounding ecosystem. These structures also modify current regimes which may influence various ecosystem processes. Modification of the physical environment via harvesting may have greater of lesser effects, depending on the methods used.

One issue of broad importance with respect to bivalve aquaculture is the potential transfer of exotic species associated with the physical structure of bivalves in introduction and transfers. Although of decreasing importance globally, the transfer of bivalves for aquaculture has historically contributed an inordinate proportion of exotic species in some areas (McKindsey et al. 2007). For example, Carlton (1992) has suggested that transfer of bivalves has been the single greatest source of exotic bivalves in western North America and Ruesink et al. (2005) suggest that the introduction of oysters for aquaculture purposes may account for the introduction of greater than 40% of exotic species in Europe, the western United States, and North Sea. Accordingly, recent risk analyses of bivalve aquaculture by Crawford (2003) and Forrest et al. (2009) suggest that the risk related to the transfer of exotic species is the greatest of all risks associated with the practice given the potential severity, spatial extent, duration and certainty of ecological effects.

## 1.3 SCOPE OF REVIEW

### 1.3.1 Aquaculture Practice Related Scope

Production from aquaculture is increasing throughout Canada and will likely continue to grow for the foreseeable future. Although originally concerned mostly with the stressors relating to biodeposition associated with aquaculture, Fisheries and Oceans Canada has now expanded research on the subject to include a more holistic understanding of the ecological interactions between the practice and the ecosystem. This is of particular importance for bivalve aquaculture which, because of its direct reliance on ecosystem services for many aspects of the husbandry (provision of food and clearing wastes) and the great areas it may occupy, is perhaps more tightly linked to the ecosystem than is finfish cage culture. The purpose of the current review is to summarize the stressors relating to the addition, removal, or modification of physical structure related to aquaculture activities. It must be highlighted that much of this information is already available in other forms within various recent CSAS documents (Jamieson et al. 2001, Chamberlain et al. 2005, Vandermeulen 2005, Anderson et al. 2006, Cranford et al. 2006, Johannes 2006, McKindsey et al. 2006a, Vandermeulen et al. 2006) and the current review largely summarizes the pertinent points from these reports with the addition of more recent information from the scientific literature. Important additions include Dumbauld et al. (2009) and Forrest et al. (2009) for bivalve aquaculture. An overview of the grow-out culture methods for bivalve culture and the equipment used is presented in Appendix 1.

The primary impacts arising from the addition, removal, or modification of physical structure related to aquaculture activities are the provision of habitat structure for aquatic organisms and the modification of current regimes. Both of these impacts may have various stresses on the surrounding aquatic ecosystems.

### 1.3.2 Type/Source of Literature Used

There is a great deal of peer-reviewed scientific literature on the interactions between aquaculture and the environment. Most of this is available within various books, scientific articles, reports, etc., that are found using the typical search engines (SCOPUS, Web of Science, ASFA, etc.). That being said compared to the quantity of work that has concentrated on benthic impacts related to food wastage and biodeposition by cultured species and the evaluation of carrying capacity of sites, the importance of physical structure modifications has received little attention. Given the scale of aquaculture sites, little or none of the work on physical habitat modifications has been done in controlled laboratory settings as any attempts are likely unrealistic. At best, multiple sites have been studied to infer generality of observations but this is uncommon. Most of the relevant literature reports “just so” details that leave room for considerable interpretation. Much of the interpretation reported in this review draws on logical extrapolations from more fundamental ecological research (for example, on rocky reefs) and thus has a solid footing in that sense but it is often not directly on aquaculture-related stressors. Several modelling studies have attempted to predict the behaviour of water masses in the vicinity of culture sites.

## 2. SUSPENDED BIVALVE AQUACULTURE

There are two main types of suspended bivalve aquaculture that are done in the water column: longline and raft systems. Details of these systems may be found in Boghen (2000) and McKindsey (2006a) and Drapeau et al. (2006) give a good review of industry standards with respect to line and sock spacing for suspended longline mussel aquaculture in Prince Edward Island (PEI). Only a brief overview is provided here. Longline systems involve a series of lines (typically 100-200 m long) anchored at both ends into bottom sediments with either anchors or a mass of concrete or steel (Figure 1). The lines are kept positively buoyant through the use of a series of buoys along the length of the longline (= backline). These are kept at a specific depth from the bottom by a series of “legs” or ropes with weights at the end. Thus, the buoys keep the longline off the bottom and the legs keep the longlines from being at the surface – a sort of balancing act. Aquaculture structures are then hung from these longlines, either nets, cages, tubes, or mussel socks (single dropper lines or a continuous mussel sleeve). Sites with longlines may cover very large areas (several square km) and at times nearly fill whole embayments. Rafts may be of various sizes and individual aquaculture structures are suspended below these, typically at fairly close intervals. The use of raft culture is mostly limited to western Canada although some experimental studies are planned to evaluate their efficacy for integrated multi-trophic aquaculture (IMTA) in eastern Canada.

*Table 1. Availability and quality of information supporting the linkages between 4 stressor types and various ecosystem components for suspended bivalve culture. Note that the table does not recognize the direction or severity of the stressor-effect linkage; the table must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Labels refer to the various sections in document. For example, Section 2.1.1 concerns the effects of suspended bivalve culture on shading adjustments on wild fish populations/communities. Graphical representations of pathways of effects for suspended bivalve culture are given in Figures 2, 3, and 6.*

| **Suspended bivalve culture** | **Ecosystem components** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Stressor type** | **Wild fish populations / communities** | **Habitat structure, cover, vegetation** | **Access to habitat / migration routes** | **Substrate composition** | **Food availability / supply** | **Primary productivity** | **Water flow** | **Oxygen (water column/benthos)** | **Contaminant concentrations** | **Suspended sediment concentration** |
| **Shading adjustments** | **2** | **2** | | | **1** | **3** | | | | |
| **Shoreline/bottom structure** | **4** | **4** | | **4** | | **→0** | | | | |
| **Vertical structure** | **5** | **5** | **?** | **5** | **3** | **3** | **5** | | | |
| **Resuspension/ entrainment** | **→0** | | | **5** | | | | **→0** | **2** | **→0** |

Key to table: 5 – Substantial peer-reviewed evidence from aquaculture setting. 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature. 3 – Substantial peer-reviewed evidence from non-aquaculture literature. 2 – Limited peer-reviewed evidence from non-aquaculture literature. 1 – Best guess. →0 – Effect not supported by literature. Empty cells indicate that the pathway was not considered.

The influence of suspended bivalve aquaculture, relative to intertidal aquaculture, is probably the best studied with respect to the impacts from bivalve aquaculture due to physical structure. Broad effects include current modifications and the associated cascading effects and the provision of three-dimensional habitat that acts as a substrate or habitat for many organisms that may then be used as food by others. The availability and quality of the evidence supporting the various linkages between stressors and ecosystem components is given in Table 1.

## 2.1 SHADING ADJUSTMENTS

Considerable physical infrastructure is added in suspended bivalve culture (see preambles to sections 2.2 and 2.3), whether longline or raft systems. This includes both the physical structure of the farm equipment as well as the physical structure of the crop and associated fouling organisms. By general principles, we can assume that this physical structure will have a shading effect on the water column and bottom below it. This also creates a unique shaded environment on the underside and sides of the culture structure and associated crop/fouling communities. In general, light (or shading) has been shown to be important to the settlement and/or recruitment of a large variety of benthic/fouling organisms. As such, the addition of physical structure may have important effects on the types of communities that develop associated with and beneath farm structures. Decreased light will also impact the health of autotrophs (algae and plants) and thus impact those communities. Overall, the influence of this class of stressor on the ecosystem has received little attention and been poorly quantified. Extrapolation from other studies on shading (other forms of aquaculture and non-aquaculture) is needed. Shading adjustments due to reduced turbidity/plankton loads resulting from filter-feeding of farmed bivalves and associated organisms is only covered briefly. An overview of the main pathways of effects for this stressor class is given in Figure 2.

This review found only two studies that evaluated how suspended bivalve culture structures impact light intensities. Barranguet (1997) measured the incident light reaching the bottom at 5 m under a mussel farm and simultaneously that at a similar control site (same depth adjacent to farm site). On average, 14% of incident reached the bottom in the mussel site whereas 22% of the incident light reached the bottom in the control site. Eyre (2005) evaluated the depth-specific light intensity along a transect passing through a low-density (ca. 21 tonnes grown in a 16 ha site) longline mussel site in Western Australia on two occasions. No trends relative to the mussel site were observed.

### 2.1.1 Stressors on Wild Fish Populations/Communities*

**2.1.1.i. Effects profile.** Suspended bivalve culture adds considerable 3-D hard physical structure to the water column and thus directly and indirectly reduces the availability of light in the ecosystem directly under and surrounding culture structures. The intensity of light reduction (shading) may be modulated by regular husbandry practices (addition, removal, and cleaning of equipment and crops). This may have cascading effects on the functioning of the rest of the surrounding ecosystem, including altering the abundance and/or productivity of a number of species/communities and a variety of cascading effects resulting from this have been proposed.

Direct effects due to the addition of vertical physical structure for suspended bivalve culture have not been well studied. Although indirect and cascading effects on wild fish populations/communities may be imagined, these too have not been well studied.

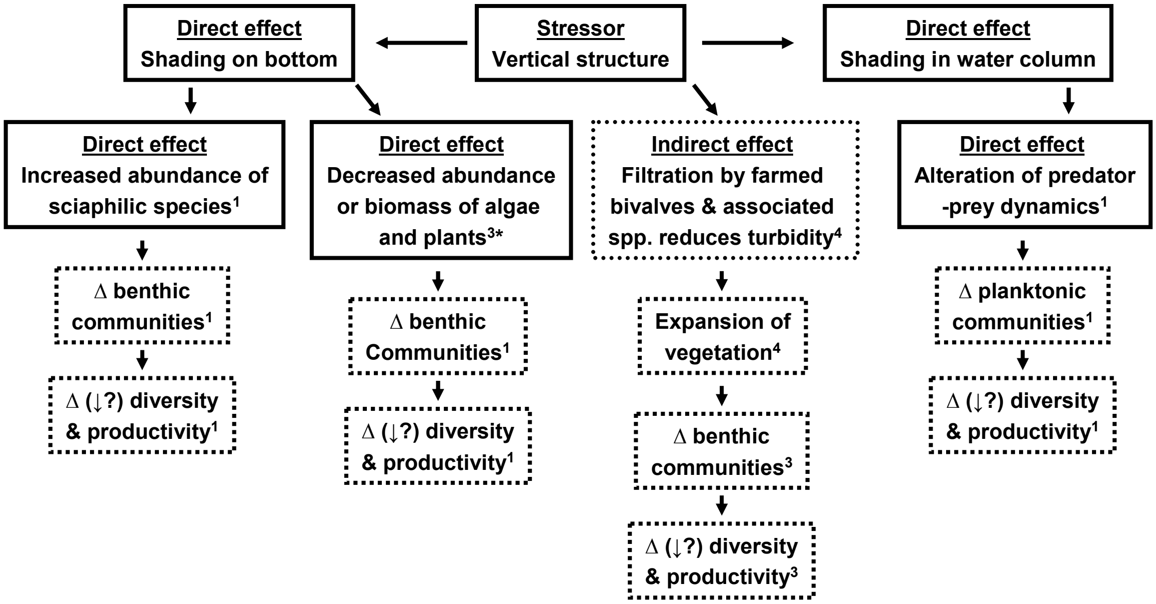

*Figure 2. Main pathways of effects for shading adjustments due to suspended bivalve culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**2.1.1.ii. State of knowledge of direct effects.** All else being equal, given that the structure associated with suspended bivalve culture logically reduce the quantity of light that reaches the sea bottom, this should increase the abundance of sciaphilic (shade-loving) species while decreasing the abundance of phytophyllic (light-loving) species. That being said, it is difficult to separate the influnce of physical structure and shading effects as many benthic species are both thigmophilic and sciaphilic, such as lobster (Cobb 1971). Thus, relevant sections that cover the addition of physical structure to the environment should also be consulted.

Shading by physical structures has been shown to impact a variety of biological communities, particularly of macrophytes (see sections 2.1.2 and 3.1.2), but also of sessile and mobile benthic and epibenthic assembalges, either directly or indirectly through loss of structural macrophytes. Examples include increased abundances of sponges, spirorbid polychaetes, and other colonial sessile forms (see review in Glasby 1999b). Shade may also influence the abundance of more mobiles species, including crabs, lobster and some fishes. In addition, shade may also impact the recruitment of fishes. For example, Hair et al. (1994) found that shade increased the abundance of fish recruits but not the number of species that recruited to artificial reefs. Cocheret de la Morinière et al. (2004) separated the effects of structure and shading for mangrove fishes and found that some species were principally attracted to the shading rather than to structure.

**2.1.1.iii. Cascading effects and biological implications for ecosystem.** Shade-induced alteration of benthic communities may directly or indirectly influence the organisms that depend on those modified resources. For example, Able (1999) and Duffy-Anderson and Able (2001) have shown that shade from overwater structures reduces the growth potential of fishes in the Hudson River estuary (note that these studies suggest that this was due to reduced seagrass abundances). Juvenile Pacific salmon continue to use shoreline and shallow water habitats to feed on epibenthic habitats and thus any change in their habitat quality may similarly affect them (Haas et al. 2002). Note that the results from the above-cited works discuss significant reductions in light due to piers and not the type of shading that could be expected from suspended bivalve culture.

In an unexpected way, Lo et al. (2008) suggest that shade produced by suspended bivalve culture (together with structure) in a Taiwan bay may account for increasing numbers of outbreaks by jellyfish as the abundance of the sessile medusa-producing stage. This is discussed in greater detail in sections 2.3.1.ii, 2.3.1.iii, and 3.3.1.ii. It is unknown whether such an effect could result in Canada.

**2.1.1.iv. Magnitude of effects.** Given the considerable structure that is added in suspended bivalve culture, effects may occur over wide spatial scales. In contrast, given that this subject has received so little attention, it is not likely to be of great importance. That being said, modifications due to shading that impact the abundance of important predators (jellyfish), as suggested by Lo et al. (2008), may have a number of important cascading effects on the greater ecosystem (Richardson et al. 2009).

**2.1.1v. Modifiers of effects.** Potential modifiers include spacing of culture structures (longlines, socks, cages, etc.), structure lengths, and fouling intensity on culture structures and products. These factors have not been well identified or studied.

**2.1.1.vi. Available evidence.** There is very little information (2 studies) on the degree of shading due to suspended bivalve culture and this study was not well replicated. All studies on shading that were identified in this review consider cases where the degree of shading examined is likely much greater than that which would be produced by suspended bivalve culture.

**2.1.1.vii. Uncertainties and knowledge gaps.** This subject is essentially unstudied – from shading levels to direct and indirect and cascading effects.

**2.1.1.viii. Activity-specific links.** Effects occur throughout the culture period and likely vary over time. Longlines maintained in the water environment will have little effect but effects will increase as (for example) mussels on culture structures and the associated epifauna grow, harvesting occurs, etc.

### 2.1.2 Stressors on Habitat Structure, Cover, and Vegetation

**2.1.2.i. Effects profile.** The considerable 3-D structure added in suspended bivalve culture logically reduces the availability of light in the ecosystem directly under and surrounding culture structures. Reduced light will impact benthic macrophytes (algae and seagrass: submerged aquatic vegetation - SAV) with consequent impacts on the functioning of the rest of the surrounding ecosystem.

Direct effects due to the addition of vertical physical structure for suspended bivalve culture have not been well studied. Although indirect and cascading effects on wild fish populations/communities may be imagined, these too have not been well studied.

Filtration by fouling species may contribute to increasing water clarity over considerable spatial scales, potentially increasing the area in which SAV may grow with consequent effects on associated communities. See also section 2.3.2.

**2.1.2.ii. State of knowledge of direct effects.** Direct effects due to shading from suspended bivalve culture are poorly studied. Crawford et al. (2003) examined 3 suspended bivalve culture farms in Tasmania and noted that SAV, in the one site that contained it, did not seem to be impacted by the longline oyster and mussel site. In contrast, although Eyre (2005) noted that seagrass shoot density was greatest at the sites that were most distant from a longline mussel site in Western Australia, no other eelgrass metrics showed a corresponding trend. This review found no evidence of impacts of shading from suspended bivalve culture on kelp or other macroalgae. According to Vandermeulen (2005), kelp seems to be less sensitive than eelgrass.

**2.1.2.iii. Cascading effects and biological implications for ecosystem.** Filtration by bivalves and their associated epifauna in suspended bivalve culture may greatly reduce the concentration of seston and increase water clarity (e.g., Prins et al. 1996, Meeuwig et al. 1998, Rice 2000) and various authors have suggested that this may be beneficial for benthic SAV (e.g., Dame 1993, 1996, Newell and Koch 2004, Newell et al. 2007). Although increased water clarity may promote the growth of “desirable” SAV, such as seagrass, and bring about what are generally considered to be positive benefits for the ecosystem (see section 2.3.2.iii), it may also stimulate the growth of nuisance species that may restrict water flow, cause plant mortality, and lead to sediment hypoxia (Peckol and Rivers 1995, Taylor et al. 2001). See also section 2.3.2.

**2.1.2.iv. Magnitude of effects.** Given that direct effects of shading are not discussed widely in the literature and that the only studies that have examined the issue have not detected significant effects, it is suggested that the importance of this issue for suspended bivalve culture is of no great magnitude. Increased water clarity due to filtration may have wide-scale effects on the ecosystem.

**2.1.2.v. Modifiers of effects.** Potential modifiers include spacing of culture structures (longlines, socks, cages, etc.), structure lengths, and fouling intensity on culture structures and products. These factors have not been well identified or studied. Also, SAV is not present in all culture sites. Obviously, presence or absence of SAV in culture areas (or beyond – if far-field effects) will be determine potential effects.

**2.1.2.vi. Available evidence.** There is no evidence of direct and limited modelling and correlative evidence of indirect effects of shading adjustments from suspended bivalve culture on SAV. There is no work on the effect of shading adjustments on habitat structure or cover. Modelling suggests that increased water clarity will have a positive impact on SAV communities.

**2.1.2.vii. Uncertainties and knowledge gaps.** Basic information on reduction of incident light due to suspended bivalve culture is missing. Direct effects are unknown and largely unstudied. Cascading effects are poorly known but of potential great importance to the functioning of the ecosystem given that they may result in changes in SAV over fairly large (bay-wide) scales. These latter effects should be better studied through modelling. No work has evaluated shading adjustments or their impacts in deeper suspended bivalve culture sites, such as those dominated by kelps in Newfoundland.

**2.1.2.viii. Activity-specific links.** Effects occur throughout the culture period and effects likely vary over time, depending on the age and spatial arrangement of culture structures in the environment, cleaning and other maintenance activities. Effects on SAV will only occur if it is present in culture sites (direct effects) but may occur if increased water clarity promotes SAV growth in previously inhospitable areas.

### 2.1.3 Stressors on Food Availability/Supply

**2.1.3.i. Effects profile.** Modification of light regimes may impact benthic communities (see section 2.1.1) and SAV (see section 2.1.2), both of which may influence the food available to different parts of the ecosystem. Shading modifications may also alter predator-prey relationships both on the bottom and in the water column.

These effects have not been well studied with respect to suspended bivalve culture and remain largely conjecture.

**2.1.3.ii. State of knowledge of direct effects.** Little is known about the direct effects of shading adjustments due to suspended bivalve culture on food availability. The abundance of some species may be increased or modified (see sections 2.1.1, 2.1.2). The influence of light on predator-prey dynamics is a very large and well-studied field of research, although not with respect to suspended bivalve culture.

Ambush predators (fish) have been shown to hide in shadows for planktonic prey in both freshwater (Helfman 1981, Lynch and Johnson 1989) and marine (Cocheret de la Morinière et al. 2004) systems and thus may use shade provided by suspended bivalve culture structures for foraging opportunities.

Many prey species have been shown to be associated with suspended bivalve culture structure (see section 2.3.1). Some of these are likely associated with these structures to take advantage of shading created by the structure to become less vulnerable to predation from a variety of predators.

Given that light conditions are so important in structuring planktonic communities in marine and freshwater systems (e.g., diurnal migrations to escape from predation, to profit from improved light conditions for hunting, see Zaret and Suffern 1976, Kerfoot 1985, Hays 2003), it is possible that shade may influence predator-prey dynamics in the plankton as well.

Water clarity (turbidity) has often been shown or suggested to influence predator-prey interactions in the water column between fish and plankton (Asknes et al. 2004, Van de Meutter et al. 2005, Varpe and Fiksen 2010) and plankton and plankton (Butler 1995, Tackx et al. 2003, Modéran et al. 2010). Thus, increased clarity due to filtration by farmed bivalves and associated epifauna may alter predator-prey dynamics in the plankton, potentially further shifting the plankton community towards one dominated by small types.

**2.1.3.iii. Cascading effects and biological implications for ecosystem.** Given that shading may affect a number of trophic pathways, cascading effects may occur (see section 2.1.1.iii).

**2.1.3.iv. Magnitude of effects.** Given the relatively large scale of suspended bivalve culture operations in some coastal areas, the magnitude of any such effects may be considerable. However, given that so little effort has been devoted to this, it is unlikely that such effects are detectable or thought to be of great importance. Further, given the transitive nature of effects on the water column (i.e., effects limited to the time the water mass passes through the shadow), it is likely that effects will also be equally limited. In contrast, increased clarity may occur over large spatial scales and impact interactions in the plankton.

**2.1.3.v. Modifiers of effects.** Potential modifiers include depth and background turbidity, current regimes, season, local plankton community structure, substrate type, etc. Husbandry practices (such as farm configuration and husbandry-maintenance) may alter the importance of shading effects.

**2.1.3.vi. Available evidence.** Impacts of shade and light regimes on various predator-prey interactions are well known theoretically and empirically. In contrast, the direct and indirect influence of structure related to suspended bivalve culture on such interactions is unknown and remains conjecture based on ecological principles.

**2.1.3.vii. Uncertainties and knowledge gaps.** There is no information on the impact of shading adjustments related to suspended bivalve culture on food availability or supply.

**2.1.3.viii. Activity-specific links.** Effects occur throughout the culture period and likely vary with season and seeding, maintenance, and harvesting regimes in a site.

### 2.1.4 Stressors on Primary Productivity

**2.1.4.i. Effects profile.** Vertical structure used in suspended bivalve culture allows for the growth of many filter-feeding species, both on that structure and on the species being farmed. These may impact turbidity and thus primary productivity. Shade directly due to shadows created by culture structures will only impact plankton for the time they pass through the shadow and are thus not likely of importance under normal circumstances.

Turbidity effects on primary productivity have been well studied outside of an aquaculture context whereas transitory impacts due to shadows on primary productivity have not been addressed in the literature.

**2.1.4.ii. State of knowledge of direct effects.** The impacts of turbidity on primary productivity are well studied (Cloern 1987, Brush and Brawley 2009) but not within an aquaculture context (but see Newell 2004). In contrast, this review identified no work that addressed the impacts of shading on primary productivity.

**2.1.4.iii. Cascading effects and biological implications for ecosystem.** Alteration of planktonic primary productivity due to increased water clarity may have feedbacks on the community and its components, including modified secondary production and altered plankton community structure, including species and size spectra changes, both of which may subsequently impact other communities.

**2.1.4.iv. Magnitude of effects.** Direct effects due to increased water clarity may be considerable as this may operate at a bay-scale whereas the impacts of shading from structures are likely negligible.

**2.1.4.v. Modifiers of effects.** Effects may be modified bye depth and background turbidity, current regimes, season, local plankton community structure, etc.

**2.1.4.vi. Available evidence.** Evidence for impacts of grazing on water clarity is very strong and has been described through various observational field studies, smaller manipulative studies, and modelling exercises. The impacts of this on other components have also been shown in a variety of studies. Impacts due to shading have not been evaluated.

**2.1.4.vii. Uncertainties and knowledge gaps.** The exact nature of changes due to reduced turbidity/increased clarity brought about by grazing by bivalves in culture and their associated epifauna are unknown. Impacts from shadows on primary productivity are unknown but assumed to be limited.

**2.1.4.viii. Activity-specific links.** Husbandry details (such as farm configuration and maintenance) may alter the importance of shading although it is not expected to have great effects. Husbandry practices may also alter grazing impacts and thus water clarity as the biomass of fouling species that contribute substantially to clearing the waters may be effectively controlled using a variety of methods.

## 2.2 ADDITION / REMOVAL OF SHORELINE/BOTTOM STRUCTURE

The structures of greatest importance are the blocks (typically cement) that serve to anchor the longline and raft systems in place. These may be very abundant in a site. For example, although the spacing of blocks along a longline varies with the seasons, grow-out cycle, husbandry practices, etc., it is common to have a block every 3 to 5 m along longlines. Consider the extreme situation in Tracadie Bay, PEI. Assuming that the mussel leases cover roughly half of the surface area of the bay, ca. 7 km$^2$ (Cranford et al. 2007), that mussel longlines are spaced at ca. 12.5 m intervals within the sites (Drapeau et al. 2006), and that half of this area is being farmed and using blocks at any one time (a conservative estimate), a back of the envelope calculation assuming a block spacing of 5 m suggests that there may be almost 60 thousand blocks in the bay at any one time. For even a more modest level of mussel aquaculture, such as that practiced in the 2.5 km$^2$ farm in Great-Entry Lagoon in the Magdalen Islands, Quebec, a similar calculation based line spacing there (18 m line spacing with 200, 91 m long, longlines in each of 2 sections, Weise et al. 2009) and assuming that half of the lease is being farmed at any one time suggests that there are ca. 4 thousand blocks on the bottom of the lagoon. Thus, longline suspension farming adds considerable physical structure to the bottom of culture sites. Depending on their configuration, raft structures tend to have a very limited number of blocks or are attached to the bottom with screw anchors. Although there is some information on the influence of blocks for longline systems, little information is available with respect to these structures for raft culture and the review is largely limited to information from longline systems. In addition to blocks, in some sites there may also be an abundance of old discarded or lost rope and other equipment on the ocean bottom. This latter subject has not been considered with respect to suspended bivalve culture but general reviews on the subject may be found in section 5.3.1.ii. An overview of the main pathways of effects for this stressor class is given in Figure 3. Figure 4 shows general effects relating to the addition of anchors for suspended bivalve culture.

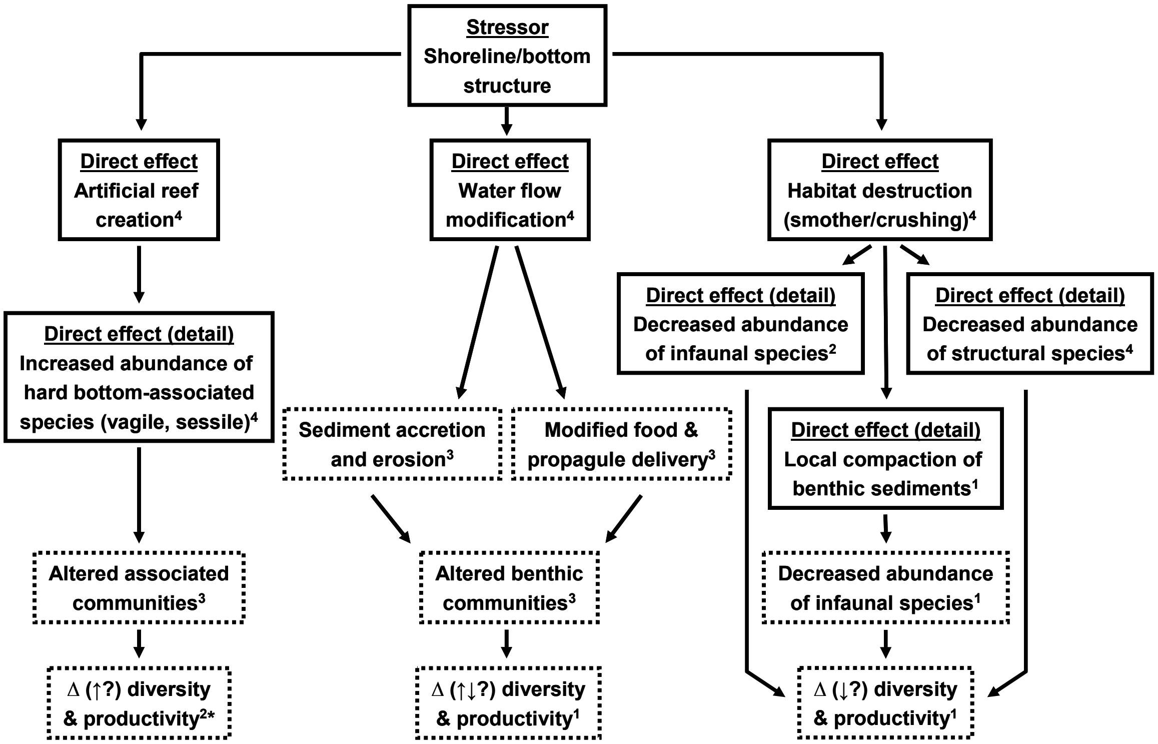

*Figure 3. Main pathways of effects for shoreline/bottom structure adjustments due to suspended bivalve culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks.*

### 2.2.1 Stressors on Wild Fish Populations/Communities

**2.2.1.i. Effects profile.** The addition of physical structure to the benthic environment directly alters the abundance/productivity and composition of benthic communities under blocks and the abundance/productivity of some benthic species (mobile and sessile) associated with the provision of hard substrate. This may in turn alter the abundance/productivity of other populations/communities in the ecosystem.

Direct effects from the presence of suspended aquaculture-related benthic structure on fish populations and communities are poorly known and indirect (cascading) impacts due to structure on benthic communities and productivity are unknown and only presumed. It is suggested that modelling would be best able to address these gaps.

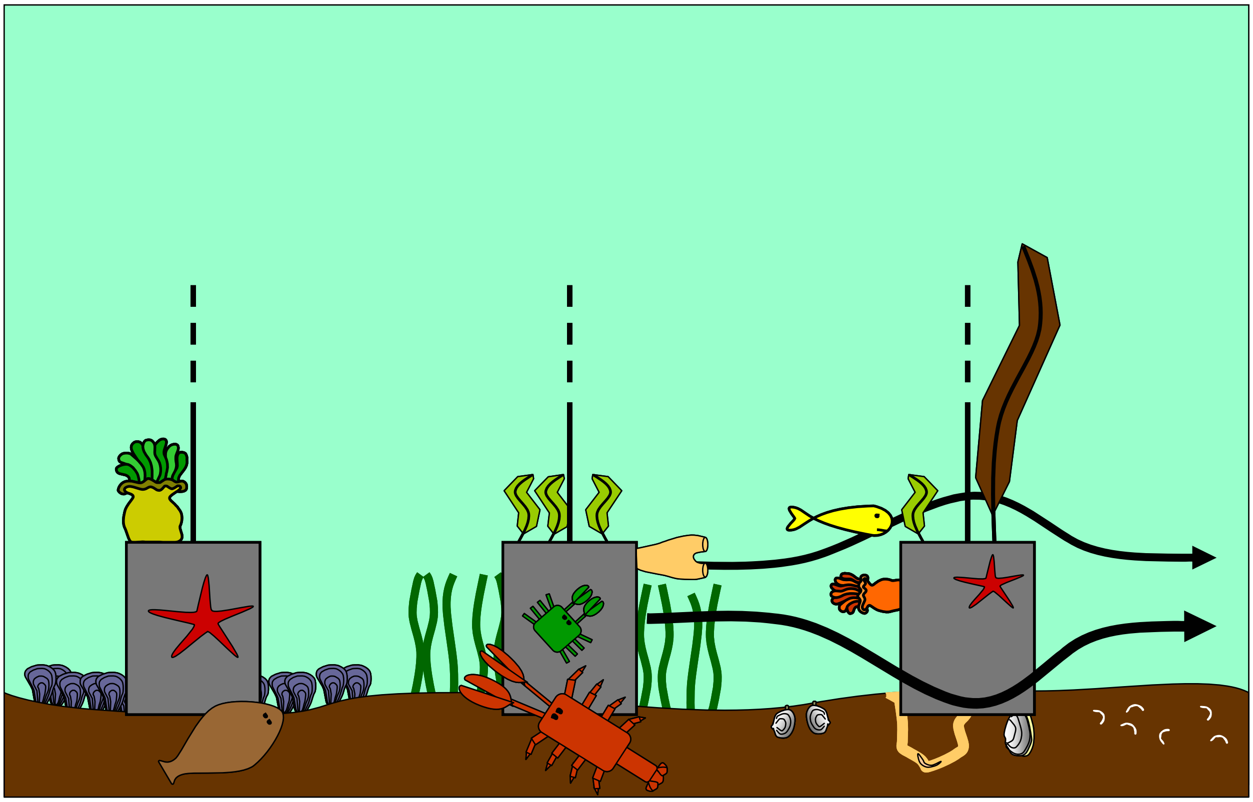

*Figure 4. General potential effects resulting from the addition of physical structure (anchor blocks) to the benthic environment. Anchor blocks necessarily crush or smother biogenic structural species, such as mussel or oyster reefs or eelgrass, if present, or benthic infaunal communities. The blocks also provide habitat for a variety of sessile and mobile species, including prey species for predators. Blocks may also modify currents and thus food and propagule delivery to the bottom, thus potentially modifying benthic communities. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**2.2.1.ii. State of knowledge of direct effects.** There is limited information on the importance of bottom-associated physical structure associated with suspended bivalve aquaculture either in the Canadian context or internationally. However, there is considerable information on the importance of artificial structures used as reefs to enhance specific areas for fisheries species (Jensen et al. 2000, Seaman 2000, Brickhill et al. 2005) and much can be gleaned from the relevant artificial reef literature. The strength of the evidence on the likelihood of these effects occurring is very high.

The presence of artificial structure in the form of blocks associated with suspended bivalve aquaculture on the sea floor may have various direct effects on wild fishes. The most direct effect is the crushing/smothering of benthic organisms directly under the position of the blocks. However, other types of communities may develop under the blocks, as has been shown in natural boulder fields (Cruz Motta et al. 2003). The importance of this effect has not been evaluated but could be estimated from extrapolation from benthic surveys in culture sites. There are also direct effects on benthic macrofauna. For example, field studies by D'Amours et al. (2008) and Clynick et al. (2008) found increased abundances of a variety of taxa of macrofauna (e.g., fishes, starfish, crabs, lobster) associated with mussel culture sites in PEI and the

Magdalen Islands, respectively, and Carbines (1993) reports the same observation from New Zealand mussel farms. Although some of this increased abundance may be due to attraction of predators from increased culture-related biodeposition in the form of faeces and pseudofaeces as well as drop-off of the mussels themselves (see review in McKindsey et al. 2006a), subsequent manipulative field experiments showed that, for lobster, it is the physical structure of the anchoring blocks that is important and not the provision of food (Figure 5). This latter observation was done in an area with a soft-bottom and it is not clear how lobster and other mobile species commonly associated with benthic structure react to the addition of structure in hard-bottom environments.

Bottom structures also provide considerable surface area for sessile and other hard-substrate associated organisms (plant and animal) that are not normally found on soft sediment bottoms, as is often the case in coastal embayments where bivalve aquaculture is practiced. Thus, diverse fouling communities may develop on these structures (Carbines 1993, personal observations). In general, primary and secondary productivity of hard bottom substrates is greater than that of soft bottom ones (Cusson and Bourget 2005, Cowles et al. 2009) and this is also likely true with respect to anchoring blocks used in bivalve culture. Given this and the greater surface area of blocks added for aquaculture relative to the area of seafloor occupied by the blocks, it is likely that they will, overall, increase local diversity and productivity.

Some of these effects are immediate (such as the attraction of lobster and crabs, which arrive shortly after blocks are installed) whereas others are longer-term (development of fouling communities and increases in primary and secondary productivity).

This review found no information as to the quantities of lost aquaculture equipment that may be on the bottom within and outside of culture sites nor to its importance as habitat for wild fish populations/communities. Anecdotal observations suggest that the presence of such material is very site-specific and that it creates suitable habitat for a variety of hard bottom species.

**2.2.1.iii. Cascading effects and biological implications for ecosystem.** Given that blocks may directly augment secondary productivity (see section 2.2.1.ii) this would also suggest that any increased productivity would be transferred up the food chain and possibly enhance the secondary productivity of more important fisheries species. This is the fundamental background and logic behind the idea of installing artificial reefs (Seaman 2000, Brickhill et al. 2005). However, it is unclear how the actual “productivity” of the surrounding ecosystem is influenced by this.

The presence of blocks on the bottom sediments may also have more subtle effects on the benthos arising from the modification of benthic currents which will alter the surrounding benthic sediments and associated fauna directly via this mechanism and indirectly via modification in the delivery of propagules and/or food around the blocks. This effect has been observed for blocks of similar size to those used in aquaculture on both hard and soft bottom communities (Cusson and Bourget 1997, Guichard and Bourget 1998, Guichard et al. 2001). It has not been evaluated in the context of aquaculture. The impact of the placement and removal of blocks on the resuspension of sediments is sporadic and related to husbandry practices and likely of little consequence to the surrounding environment as it is a simple “pulse” stressor.

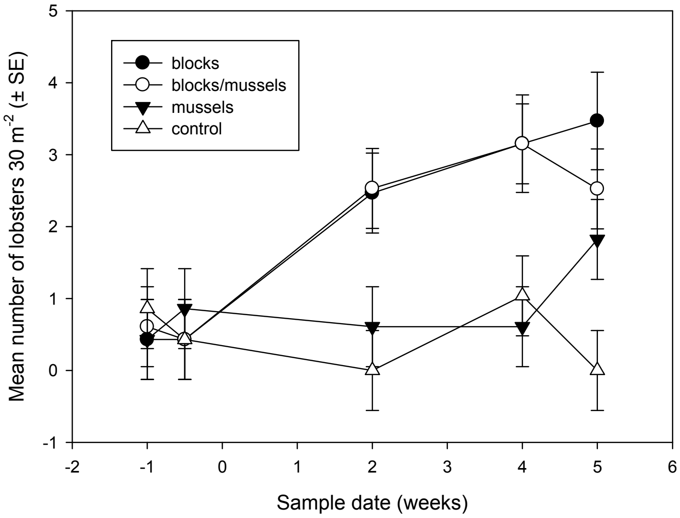

*Figure 5. Unpublished data (McKindsey, in prep) from a manipulative experiment to evaluate effect of habitat structure (cement blocks) and food (mussels) on the abundance of lobster. A total of 12 sites were used with triplicates for each of 4 treatments: with and without mussels and with and without blocks. The abundance of lobsters increased with the presence of blocks but not with the addition of mussels.*

Given the size of many suspended aquaculture farms, increases and losses of biodiversity/productivity associated with the placement of blocks on the seafloor may have considerable cascading effects on wild fish populations/communities. Cascading effects include: the addition of blocks provides habitat structure (see section 2.2.2) for lobster and fouling organisms (see sections 2.2.1 - wild fish communities and 2.2.4 - primary productivity). With the exception of limited work on the attraction of macroinvertebrates and fishes to cement blocks in suspended bivalve culture and the fouling communities that are associated with blocks, the other cascading effects are unstudied.

**2.2.1.iv. Magnitude of effects.** Effects are potentially extensive given the great areas that may be concerned. Simple island biogeographic theory predicts that a greater abundance of islands of suitable habitat will increase the total abundance of organisms and species diversity (MacArthur and Wilson 1967). Experimental field studies on artificial reefs has shown this to be true although the spacing of reefs (from sources and between individual modules) and the number of modules (blocks) within an environment will impact the actual form of the response (Lindberg et al. 1990, Jordan et al. 2005, Strelcheck et al. 2005), as will the scale of the blocks used (Guichard et al. 2001). This has not been studied with respect to aquaculture.

**2.2.1.v. Modifiers of effects.** Proposed effects are clearly affected by bottom type (greater impact on soft bottoms), depth and turbidity (no algal or limited growth at depth or in turbid conditions; source of propagules, etc.), current regimes, seasonally, etc. The frequency at which benthic structure is added/removed is also likely important. It is unclear how these modifiers may impact any suggested effects and they have not been examined to date.

**2.2.1.vi. Available evidence.** There is limited field evidence for most plausible effects resulting from the addition of bottom structure for aquaculture and almost no manipulative experiments have been used to remove likely confounding effects (e.g., structure vs addition of biodeposits in all their forms, ranging form faeces through the fall-off of product and associated fouling organisms). Although there is much related evidence from the ecological literature with respect to the importance of habitat structure, most cascading effects remain conjecture. That being said, there is much solid ecological work using both observational and manipulative experiments here in Canada and elsewhere that supports suggested links.

**2.2.1.vii. Uncertainties and knowledge gaps.** It is unclear how postulated effects arising from the addition of benthic habitat structure will directly and indirectly influence benthic communities and how this will scale-up (e.g., does the addition of 10 thousand blocks have 10 thousand times the effect of adding a single block?). Some experimental work on artificial reefs suggests that it is not a simple scaling exercise (Jordan et al. 2005). Also, do larger blocks, such as those sometimes used to anchor longline systems and rafts have proportionally larger effects? Further observational and manipulative field work with modeling efforts would be the most logical way to proceed to address these uncertainties.

The greatest uncertainty with respect to the addition of benthic physical structure is the influence of this on productivity. For example, there are direct impacts on benthic species that are smothered/crushed by blocks whereas the abundance of many block-related species (lobsters, fouling organisms, under-block species) is increased but the overall impact of these effects and how they influence the productivity of the system as a whole is unknown. This information would provide a much greater understanding of the role of suspended bivalve aquaculture in the ecosystem. It is also unknown how the movement, addition, and removal of blocks throughout the culture period will impact any of the proposed effects.

Most studies on the importance of artificial reefs on secondary productivity are confounded in a number of ways and it is unclear whether or not artificial reefs augment the productivity of fishes or serve simply to aggregate them (Pickering and Whitmarsh 1997, Bortone 1998, Powers et al. 2003). Most studies to date have been largely descriptive in nature (Baine 2001, Jensen 2002, Seaman 2002) and there is a lack of rigorous scientific data to determine whether artificial reefs have a net positive or detrimental effect on marine ecosystems (Grossman et al. 1997). An apparent increased “productivity” may result from a concentration of suitable habitat, the sum of which may have been found elsewhere in the ecosystem. According to Carr and Hixon (1997), the only way to show that an artificial reef, such as blocks used in an aquaculture site, actually increases the productivity of fishes and other assemblages is by showing that their survival and growth is greater on the reef than on the natural habitat on which they are found. This is however exceedingly difficult experimentally given the lack of knowledge of the natural history of many of the species involved and the natural variation in the environment (Pondella et al. 2002). Further, the confounding influence of cultured bivalves (and associated epifauna) suspended in the water column providing a food resource to benthic predators through fall-off (Leonard 2004) makes ascribing effects to the addition of benthic physical structure difficult.

**2.2.1.viii. Activity-specific links.** The smothering/crushing of benthic organisms from the addition/movement of blocks occurs throughout the culture period, is related to farm husbandry practices, and the effect is almost immediate. The longer blocks are left in place, the greater the effect on the development of associated hard bottom benthic and macrofaunal communities; although it is assumed that such communities will come to relative equilibrium at some point.

### 2.2.2 Stressors on Habitat Structure, Cover, and Vegetation

**2.2.2.i. Effects profile.** The addition of benthic structure may directly impact biogenic species by crushing or otherwise smothering them. In contrast, the added structure (e.g., blocks) may also serve as a new substrate for biogenic structural species

Effects of the addition of benthic structure on habitat structure, cover and vegetation, and the indirect influence of this on other populations/communities remain largely unstudied in the context of aquaculture. Many of the arguments developed in Section 2.2.1 may be extended to the current section as they result from cascading effects from the addition of biogenic species.

**2.2.2.ii. State of knowledge of direct effects.** There is very limited information on the direct influence of the addition of benthic structure on biogenic species in the aquaculture context and, with the exception of anecdotal observations, no published information is available from Canada. Most understanding must thus be extrapolated from ecological principles.

Both vegetation and animal species may be directly affected by the addition of structure although different types of structural species and vegetation will clearly profit from this provision of physical structure to varying degrees (e.g., *Zostera marina* and other structural species that do not rely on hard sediments will not profit from the addition of cement blocks whereas kelp and sponges may). No information was found in this review with respect to the destruction of benthic habitat structure, cover, and vegetation due to the addition of benthic structure. It is assumed that the addition of such structure will have a negative impact on underlying biogenic structural species. Carbines (1993) described rich assemblages of algae associated with mooring blocks in a suspended mussel culture site in New Zealand, an observation that is also common in eastern Canada where other biogenic structural species (sponges, oyster, anemones, tunicates, etc.) may also be abundant (personal observations). Given the increased 3-D surface area of the structure added in aquaculture, it is likely that the resulting community will be greater than that smothered in either soft- or hard-bottom systems, with concomitant increases in abundance, diversity, and productivity. That being said, a number of factors may result in the communities growing on blocks to differ from those associated with natural hard bottoms (e.g., Leichter and Witman 1997, Glasby 1999a).

**2.2.2.iii. Cascading effects and biological implications for ecosystem.** The presence of physical structure in the form of biogenic foundation species generally has many cascading effects on the flora and fauna directly associated with those species as well as on the ecosystem as a whole because of the way they modify environmental conditions, resource availability, and species interactions (Dayton 1972, Bruno and Bertness 2001, Bruno et al. 2003, Gutiérrez et al. 2003). For example, structure provided by these species creates suitable habitat that is rapidly colonized by other species, as has been shown in a number of observational and manipulative experiments around the world and here in Canada (e.g., Dean and Connell 1987, Edgar 1990, McKindsey and Bourget 2001, Castilla et al. 2004). Theoretical work (e.g., Bruno et al. 2003) suggests that facilitation at the local level should also have cascading effects on the rest of the system, stimulating heightened productivity at larger spatial scales. Alteration of currents by bottom structures may directly impact biogenic reef structures and vegetation by crushing and/or smothering and indirectly by modifying current regimes which may influence species directly or indirectly by modifying benthic sediments and the delivery of propagules and/or food (see section 2.2.1.iii).

**2.2.2.iv. Magnitude of effects.** Given the extent of areas that may be impacted by the addition of benthic structure within suspended aquaculture sites, the magnitude of any effects may be proportionally large. However, this subject has not been addressed with respect to aquaculture. Section 2.2.1.iv discusses possible effects in more detail.

**2.2.2.v. Modifiers of effects.** See section 2.2.1.v.

**2.2.2.vi. Available evidence.** There is only limited evidence for the effects described in this section and most of it remains strictly observational and limited to direct effects. However, suggested pathways are supported by a strong theoretical basis developed through solid ecological work using observational and manipulative studies done around the world and are thus likely to exist.

**2.2.2.vii. Uncertainties and knowledge gaps.** See section 2.2.1.vii.

**2.2.2.viii. Activity-specific links.** See section 2.2.1.viii.

### 2.2.3 Stressors on Substrate Composition

**2.2.3.i. Effects profile.** Benthic substrate composition is modified directly by the addition of 3-D physical structure used in aquaculture to the bottom and indirectly via modification of current regimes and by biological modification of the underlying substrate.

These effects have been little studied in the context of aquaculture. See also section 2.2.1.

**2.2.3.ii. State of knowledge of direct effects.** There is limited knowledge with respect to the direct impacts of the addition of benthic structure used in suspended bivalve aquaculture on substrate composition. The most obvious direct impact is the addition of 3-D hard substrate to benthic environments which may have more or less natural benthic structure (as compared to soft-sediment and rocky hard-bottom communities). Heavy structures may also compress underlying sediments which will likely remain somewhat so for an unknown period of time after the removal/displacement of the structures.

**2.2.3.iii. Cascading effects and biological implications for ecosystem.** There is no information with respect to the indirect and cascading impacts due to the addition of benthic structure used in suspended bivalve aquaculture on substrate composition. However, some predictions may be made based on the findings from various ecological studies. Depending on current regimes, various sediment types may be eroded and deposited at different locations around 3-D structures such as the cement blocks used in suspended bivalve culture. Although not studied in the context of aquaculture, this effect has been reported from observational (Cusson and Bourget 1997, Barros et al. 2001) and manipulative (Guichard et al. 2001) ecological field studies and has been shown to be scale-dependent with respect to block-size (Guichard et al. 2001) and current regimes (Davis et al. 1982, Johnson 1998). Biodeposition from organisms associated with added benthic structure may also influence benthic sediments, as has been shown both in observational and manipulative ecological studies (Norkko et al. 2001, Miller et al. 2002). Effects are also likely with respect to sloughed off or dying organisms associated with benthic structure enriching and modifying sediments locally. Burrowing by lobster and other macro-organisms under added blocks (personal observations) and variation in benthic communities due to variation in sediment types brought about by the above-mentioned factors add further complexity to the variation in benthic sediment structure. Together, this suggests that benthic structure added for suspended bivalve culture may increase the diversity of benthic fauna by creating a mosaic of sediment types, each of which will support different assemblage types (see Gray and Elliott 2009 for a review).

**2.2.3.iv. Magnitude of effects.** Although considerable benthic structure may be added in suspended bivalve aquaculture, the magnitude of effects on benthic sediments due to this is predicted to be limited relative to other effects resulting from the addition of bottom and vertical structure.

**2.2.3.v. Modifiers of effects.** Proposed effects will be affected by bottom type (greater impact on soft bottoms), depth, current regimes, season, etc. The configuration of the benthic structure will also likely influence sediment impacts.

**2.2.3.vi. Available evidence.** Other than personal observations, this review found no published evidence of benthic structure in suspended bivalve culture impacting benthic sediments. Suggested impacts are based on extrapolations from the ecological literature, a considerable amount of which is based on data from Canada and other temperate regions.

**2.2.3.vii. Uncertainties and knowledge gaps.** It is uncertain how the spatial configuration of added benthic structure will influence bottom sediments, their importance, and even if predicted effects exist.

**2.2.3.viii. Activity-specific links.** The longer benthic structure is left in place, the greater the effect will be until equilibrium is reached.

### 2.2.4 Stressors on Primary Productivity

**2.2.4.i. Effects profile.** Modification of benthic communities by the addition of benthic 3-D structure for suspended bivalve culture may influence various benthic processes that may alter nutrient fluxes/recycling and thus impact primary productivity in the water column. These effects have not been examined in the aquaculture context.

**2.2.4.ii. State of knowledge of direct effects.** Direct effects of the addition of benthic structure on primary productivity in the water column seem unlikely. This review found no suggested effects.

**2.2.4.iii. Cascading effects and biological implications for ecosystem.** Added benthic structure may influence benthic communities and sediments (see sections 2.2.1, 2.2.2, and 2.2.3). A number of studies have shown that variation in these parameters modify nutrient fluxes, and thus Redfield ratios and oxygen consumption (Reay et al. 1995, Cowan and Boynton 1996), and this may alter the composition and primary productivity of planktonic communities with further cascading effects on the rest of the ecosystem. Although a number of studies have shown the importance of suspended bivalve culture on nutrient fluxes here in Canada (Richard et al. 2007a, Richard et al. 2007b) and internationally (e.g., Baudinet et al. 1990, Hatcher et al. 1994, Stenton-Dozey et al. 2001, Christensen et al. 2003, Giles et al. 2006, Nizzoli et al. 2006), this is usually assumed to be due to organic loading from the cultured product and associated organisms and not to effects arising from the addition of benthic structure.

**2.2.4.iv. Magnitude of effects.** The magnitude of any potential effects due to the addition of benthic physical structure on primary productivity is likely to be small. This is particularly true when effects due to the addition of benthic structure are compared to those due to biodeposition from the placement of vertical structure and product.

**2.2.4.v. Modifiers of effects.** Proposed effects will be affected by bottom type, depth, current regimes, season, configuration of added benthic structure, the extent of suspended bivalve culture farms, the timing of the addition and removal of blocks, other husbandry variables, etc.

**2.2.4.vi. Available evidence.** No direct evidence is available to support the suggested links due to the addition of benthic structure in suspended bivalve culture. All links are predicted based on ecological principles with solid theoretical and empirical foundations.

**2.2.4.vii. Uncertainties and knowledge gaps.** Although suggested pathways are based on a wealth of solid ecological work, none of the proposed effects have been evaluated for suspended bivalve aquaculture.

**2.2.4.viii. Activity-specific links.** The longer a benthic structure is left in place, the greater effects will be until an equilibrium is reached.

## 2.3 ADDITION/REMOVAL OF VERTICAL SITE INFRASTRUCTURE

Considerable vertical infrastructure is added in suspended bivalve culture, whether longline or raft systems. In longline systems, this includes the “legs”, longline and buoys of the system, as well as the dropper or continuous lines used to support product in mussel culture, the cages/nets, etc., used in scallop and oyster culture, and the tubes at times used for oysters and ropes used at times for scallop culture (see Boghen 2000, and McKindsey et al. 2006a for a review of suspended bivalve culture methods). For raft systems, there is the raft structure itself as well as the infrastructure to support whatever product is being grown. Also of great importance in both raft and longline systems is the product itself which acts as a surface for various physical and biological processes. While the length/quantity of dropper and continuous lines, cages and nets, etc., used to support product and the product itself vary seasonally and with husbandry practices, the remaining vertical infrastructure is more permanent (although buoys and legs with block anchors are added and removed throughout grow-out cycles in longline systems). Consider again the more and less extreme examples in Tracadie Bay and Great-Entry Lagoon. If we assume (see section 2.2) there are 60 and 4 thousand blocks in Tracadie Bay and Great-Entry Lagoon, respectively, and that the associated legs are ca. 2.5 and 5 m long in the 2 sites (personal observations), respectively, this suggests that there is ca. 150 and 20 km rope used for legs in each site. Given that there is at least 1 buoy for each anchor block (usually many more), there is also at least as many buoys as anchor blocks in each site. Assuming that the mussel leases in Tracadie Bay cover roughly half of the surface area of the bay, ca. 7 $km^2$ (Cranford et al. 2007), and that mussel longlines are spaced at ca. 12 m intervals within the sites (Drapeau et al. 2006), a back of the envelope calculation suggests that there are over 500 km of rope used as backlines in the bay. (Unlike blocks and buoys, which are added and removed throughout the farming process, backlines are typically left in place. Given that each of 2 sections of the mussel farm in Great-Entry Lagoon consists of 200, 91 m longlines, there are ca. 36 km of rope used for backlines in that site. Again assuming that half of the leased area in Tracadie Bay is farmed at any time and that individual mussel dropper lines are spaced at ca. 40 cm intervals and each is ca. 1.8 m long (Drapeau et al. 2006), a similar calculation suggests that there are ca. 2250 km of socking material (and product) in the bay. With respect to Great Entry Lagoon, each longline supports ca. 366 m of continuous sleeves (Weise et al. 2009) and if we assume that half of the longlines are being used at any given time then a quick calculation shows that there are ca. 73 km of socking material in the site. Socking material varies among sites and with farming methods with dropper socks typically being made of polypropylene mesh for growout and rope being used for spat collection and for growout in mussel farms that use continuous socking methods. Raft systems, although quite compressed in space, typically have much greater density of product and thus infrastructure and thus may also represent considerable physical structure in the water column.

Many of the potential and documented effects of suspended bivalve culture are due to filtration and biodeposition by the cultured bivalves. However, many organisms grow associated with the water column structure added in suspended bivalve culture, including many other filter feeding organisms (e.g., Tenore and González 1976, Khalaman 2001b, LeBlanc et al. 2002) which likely have an effect similar to that of the bivalves being cultured with respect to grazing on plankton (Petersen 2007), providing structure (Paine and Suchanek 1983), contributing larvae to the meroplankton community (Broekhuizen et al. 2002), and biodeposition (McKindsey et al. 2009). Given that the effects of grazing, larval production, and biodeposition were presented at the CSAS Pathway of Effects meeting, limited reference is made to related effects in the present document. An overview of the main pathways of effects for this stressor class is given in Figure 6.

### 2.3.1 Stressors on Wild Fish Populations/Communities*

**2.3.1.i. Effects profile.** Suspended bivalve culture adds considerable 3-D hard physical structure into the water column and thus directly and indirectly increases the abundance of “benthic” organisms in this environment. This may have cascading effects on the functioning of the rest of the surrounding ecosystem, including altering the abundance and/or productivity of a number of species/communities. A large number of other effects have also been proposed.

Direct effects due to the addition of physical structure in the water column have been fairly well studied. In contrast, indirect and cascading effects on wild fish populations/communities have not been studied and are largely conjecture. It is suggested that modelling would be best able to address these gaps.

**2.3.1.ii. State of knowledge of direct effects.** Bivalves growing in suspended culture may create favourable habitats for other invertebrates by providing refuges from predation and adverse environmental conditions (Gutiérrez et al. 2003) and a direct source of food for other invertebrates. Indeed, fouling associated with suspended bivalve culture is a universal concern for the industry (Enright 1993) with the main fouling taxa being macroalgae, barnacles,

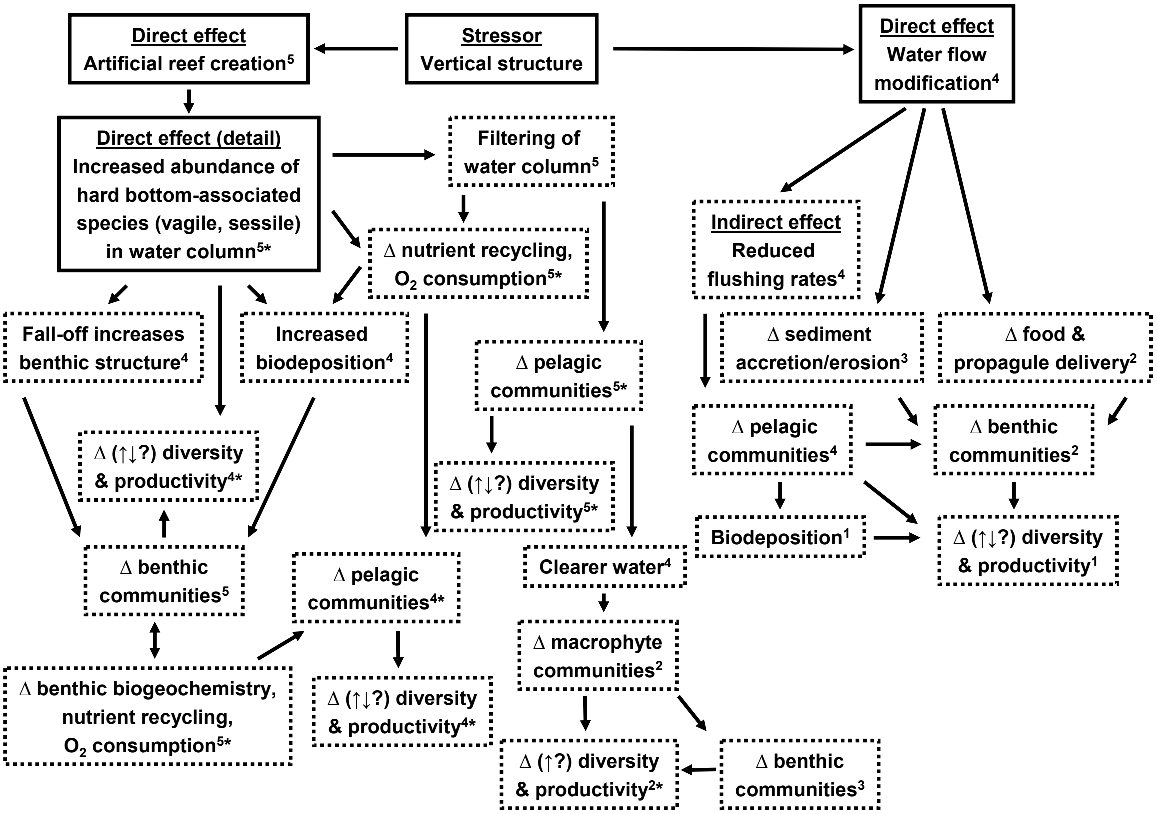

*Figure 6. Main pathways of effects for adjustments due to the addition/removal of vertical structure relating to suspended bivalve culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear.*

hydroids, tunicate ascidians, and mussel spat (Heasman 1996). Thus, a large number of studies have reported diverse assemblages of algae, invertebrates and thigmophilic fishes associated with suspended bivalve culture from both Canada and internationally (Tenore and González 1976, Khalaman 2001a, b, LeBlanc et al. 2003, McKindsey et al. 2006a, Murray et al. 2007). In eastern Canada, macroalgae has been reported to grow associated with mussel longline culture in Nova Scotia (Lawrence et al. 2000), kelp (*Laminaria longicrursis*) frequently colonizes suspended mussel lines in Newfoundland (MR Anderson, personal communications), and various algae colonize mussel longline systems (backlines, buoys, cages, bivalves in suspension, etc.) in both Prince Edward Island and Quebec (personal observations). Macroalgae has also be reported to grow on mussel lines in Tasmania (Crawford et al. 2003) and Russia (Khalaman 2001a). At times, the biomass and diversity of the associated organisms may be considerable. For example, Guenther et al. (2006) reported over 30 species recruiting to pearl oyster valves grown in nets in longline culture over a period of 16 weeks. Leblanc et al. (2003) found a dozen large and dominant taxa with a total dry weight of about 20 g from mussel socks in a Prince Edward Island suspended mussel farm and this was only in the first year of grow-out when epifauna communities were not that developed. In a more extreme example, Tenore and González (1976) reported over 100 species on mature mussel socks in Spanish raft mussel culture and up to 430 g dw of fouling organisms (mostly holothurians) $m^{-1}$ mussel sock. Fouling by some species, especially exotic tunicates, may contribute even greater biomass to the suspended culture infrastructure. For example, Grant et al. (1998) report a mean biomass of ca. 1350 g of *Ciona intestinalis* $m^{-1}$ mussel ropes from South Africa mussel rafts and McKindsey et al. (2009) and Ramsay et al. (2008) report mean biomasses of the same species of ca. and 360 g and generally > 1000 g $m^{-1}$ from experimental mussel lines in Prince Edward Island, respectively. Although most studies have concentrated on species diversity, abundance and biomass measures, a recent study by Robichaud et al. (submitted) done in a series of 8 Prince Edward Island embayments found that the abundance, biomass, and productivity of organisms associated with socks in suspended mussel culture were roughly equivalent to that of the underlying sediments.

Many studies have shown that suspended bivalve culture sites act as a focus for a large number of invasive species, including tunicate ascidians, algae, molluscs, etc. This mass of artificial structure, relatively free from benthic predators, may act to perpetuate infestations once they are established (see review in McKindsey et al. 2007).

Cnidarians (jellyfish) have a benthic stage (polyp) that requires a hard substrate and that produces the swimming stage (medusa). Richardson et al. (2009) have suggested that a large addition of appropriate artificial hard substrate in the water column, such as that created by the physical structure and shading provided by aquaculture structures (Hoover and Purcell 2009), may thus lead to the proliferation of medusae. This appears to have occurred in Taiwan, where the jellyfish (*Aurelia aurita*) often irrupted in blooms when the embayment was filled with oyster aquaculture rafts but which disappeared from the system when the culture structures were removed from the embayment (Lo et al. 2008). Of several possibilities examined by Lo et al. (2008), the direct provision of physical structure that enhanced the abundance of polyps, followed by the reduction of flushing times due to the physical presence of culture structures, was the factor that seems to best account for the observed changes in ecosystem functioning.

A number of studies have also shown suspended bivalve culture sites to have increased abundances of a variety of fish and macroinvertebrate species (see section 2.3.1.iii). Although this may be because the physical structure of the suspended bivalve culture sites attract the fish and other large taxa, that the structures act as “fish aggregation devices” or FADs (Bombace 1989, Rountree 1989, Nelson 2003), it seems more probable that this is a cascading effect from the presence of the diverse assemblage associated with suspended bivalve culture sites and thus is discussed in section 2.3.1.iii. See also the discussion on artificial reefs in Section 2.2.1.

Fall-off of mussels and other bivalves grown in suspended culture may be considerable and add physical structure to the benthic environment. For example, Leonard (2004) showed that an average of 130 g $m^{-2}$ of mussels (whole mussels only, does not include broken shells or empty shells in traps) fell daily to the bottom under mussel lines in the Magdalen Islands in the end of July, 2004. Kaspar et al. (1985) reported the build-up of live mussels and shell material under a mussel farm in New Zealand and Inglis and Gust (2003) found that living mussels and mussel shells covered 55% of the bottom within farm sites but were absent from non-farm sites in New Zealand, thus substantially increasing the physical structure within farm sites. Also in New Zealand, de Jong (1994) reports that the most noticeable visual impact of mussel farms is the reef-like structure that develops beneath them. In that study, clumps of mussels up to 20-30 cm thick covered 38% of the seafloor beneath mussel line and reached a density of 250 $m^{-2}$.

Although not quantified, Iglesias (1981) and Freire and González-Gurriarán (1995) also noted an abundance of mussels, shell and shell fragments in the Ría de Arosa, Spain.

For some taxa, such as mussels, oysters, and scallops, spat are typically collected from the wild for growout in eastern Canada, the larvae recruiting directly to various structures placed into the water column to this end (see McKindsey et al. 2006a). This harvest of individuals from wild populations may be considerable but its impact is unknown.

**2.3.1.iii. Cascading effects and biological implications for ecosystem.** Organisms growing on farmed bivalves in suspension may filter great quantities of water to feed, consuming a variety of seston, phyto- mero- and zooplankton (e.g., Duarte et al. 2008, Grant et al. 2008). This may have great impacts on the pelagic ecosystem with concomitant impacts on fish, macrophytes, benthic organisms, etc. (Prins et al. 1998, Gibbs 2004, Newell 2004) and a limited number of attempts have been made to model such effects (e.g., Jiang and Gibbs 2005, Ferreira et al. 2009). This topic is not covered further here.

Organisms growing on or otherwise associated with bivalves grown in suspension culture may provide habitat or otherwise attract other organisms, including algae, other invertebrates, as well as fish and more mobile macroinvertebrates. Recently, Robichaud et al. (submitted) observed that a greater abundance of invertebrates is associated with mussel socks fouled with *Styela clava* than socks that are not fouled by this structure-providing species in an observational study done in Prince Edward Island. Similarly, Khalaman (2001b) showed that macroinvertebrate communities associated with farmed mussels with large abundances of the ascidian *Styela rustica* had a greater average species richness than did macroinvertebrate communities associated with farmed mussels with fewer *S. rustica* in Russia. A number of studies have also shown that various species of toxic phytoplankton may grow associated with algae growing on farmed mussels in eastern Canada (e.g., Lawrence et al. 2000, Levasseur et al. 2003).

The organisms associated with suspended bivalve culture may provide direct benefits for commercial fishery and other species. For example, Brooks (2000) suggests that the epifauna associated with mussel rafts in Washington may support greater than 11 times the biomass of prey for commercial fish species than that of the underlying benthos. Carbines (1993) found a positive correlation between algal cover and the number of young spotties (*Notolabrus celidotus*) on mussel lines and noted that fish also associated with encrusting invertebrates and algae on mooring ropes in New Zealand mussel farms. This study used a manipulative experiment to show the functional relationship between algal cover and fish abundance. More recent studies done on mussel farms in New Zealand found a variety of demersal fish species associated with mussel lines; although some pelagic species were also present, they did not make regular use of the farms (Morrisey et al. 2006). In Washington, Brooks (2000) suggests that mussel rafts there attract schools of Shiner Perch (*Cymatogaster aggregata*) that feed on the mussel line-associated community. Brehmer et al. (2003) used remote methods to examine the distribution of fish and fish schools in a French Mediterranean mussel growing area and found a greater number of fish schools within mussel culture sites than outside of the them although the schools within the mussel sites were smaller than those outside of them. In all of these studies, it is unknown whether the effect of fish aggregation is due to the fish being attracted by the structure provided by the added vertical structure, the farmed product, or the abundance of associated food items. In a review paper of artificial reefs in the Mediterranean, Bombace (1989) suggested that the organisms associated with mussels growing on mussel lines attract and concentrate various nektobenthic fish species (Gilthead, Sea Bream, Meagre, White Sea Bream, Saddled Bream, Sea Bass) and that catches of these species were thus increased in the areas surrounding the farms.

Žydelis et al. (2009) examined the interactions between Surf Scoters and Barrow's Goldeneyes and suspended bivalve culture (oysters) in Baynes Sound, BC. The abundance of both seaducks was best predicted by, among the variables considered, the presence of aquaculture structures. Normally, both of these seaducks feed almost exclusively on mussels in rocky habitats. Previous work done in the area (Kirk et al. 2007) showed that the mussels growing on culture structures and oysters being farmed were larger at times, had lower shell mass, weaker byssal attachments, and were at greater densities than those in intertidal areas. These factors make them attractive to mussel-eating ducks (Dunthorn 1971, Davenport et al. 2003) and Bustnes (1998) has shown that common eiders are able to discriminate and select mussels with these same characteristics. Overall, this suggests that the seaducks thus benefit from the presence of the fouling organisms associated with suspended bivalve culture in that area (Kirk et al. 2007, Žydelis et al. 2009).

Bivalves and their associated fauna that drop from suspended culture operations enhance the amount of food available to benthic predators and provide structure. Many authors have reported a greater number and/or biomass of benthic predators that likely prey directly on bivalves from suspended culture within bivalve culture sites relative to control sites. These include starfish (Saranchova and Kulakovskii 1982), crabs (Miron et al. 2002), and benthivorous fish (Gerlotto et al. 2001). More recently, tunicates have been observed to form dense populations directly under fouled longlines in Prince Edward Island (A Ramsay, personal communications). Gerlotto et al. (2001) observed increased fish density and production around mussel lines in the Mediterranean that they attribute to increased prey availability at the farm site as benthivorous fish were observed feeding on mussels in the studied mussel site. D'Amours et al. (2008) reported increased abundance of a number of fish and macroinvertebrate species within 4 suspended mussel farms in Prince Edward Island. Although some of these species, such as lobster, were likely more abundant because of the added physical structure on the bottom (see section 2.2.1.i), other were more likely more abundant because of mussel and associated species falling from the mussel lines. Clynick et al. (2008) evaluated the abundance of several fish and macroinvertebrate species at 2 suspended mussel farms in the Magdalen Islands and found variable results; some species were more abundant in farms at some times whereas others were not. Romero et al. (1982) studied the spatial distribution of crabs relative to the location of mussel culture sites in the Ría de Arosa, Spain. Over 4 seasons, they found that both the abundance and biomass of the 3 dominant crab species (accounting for 99% of the total crab abundance and biomass) was consistently (when significant) greatest within mussel farms with, on average, greater than twice the number of crabs within mussel sites than in control sites. A subsequent study done in the same area showed that the diet of one crab species switches from algae being the most important component in a control site to mussels being the most important component in a mussel culture site (Freire et al. 1990). Similarly, Freire and González-Gurriarán (1995) studied the ecology of a second crab species and found that it too increased the proportion of mussels in its diet within mussel farms. This effect is not limited to crabs. Olaso Toca (1979, 1982) studied the distribution of echinoderms in the same ría and observed 10 times the biomass of echinoderms (mostly starfish and sea cucumbers) within mussel sites relative to control locations, the starfish feeding on the mussels that had fallen from the rafts overhead and the sea cucumbers feeding on settling particulate matter. The abundance of sea urchins is also greater under these mussel rafts than in areas distant from them (Olaso Toca 1979, 1982). This has also been observed for oyster rafts in British Columbia (Brian Kingzett, pers. comm.). Although this latter effect has not been quantified, it appears to result from urchins that have recruited to the raft falling off and accumulating in the immediate vicinity of the oyster rafts. Inglis and Gust (2003) report that mussels on the bottom serve to aggregate the predatory starfish, *Coscinasterias muricata*, under mussel lines in Pelorus Sound, New Zealand, where they feed on fallen mussels. They suggest that this food source likely increases the starfish's reproductive output by enhancing growth and gonad maturation rates. Using modeling, they further suggested that this aggregating behaviour could also enhance fertilization success as it is a function of the distance between reproductive adults in broadcast spawners such as *C. muricata*.

The physical structure provided by the mass of bivalves and associated fauna that fall from suspended bivalve operations provides a habitat for species normally associated with hard-bottom communities. For example, Kaspar et al. (1985) found that this structure allowed for the development of a community with tunicates, calcareous polychaetes and sponges, species normally associated with hard-bottom reefs. In general, hard-bottom communities are generally more diverse, have a greater biomass (Ricciardi and Bourget 1999) and are more productive (Cusson and Bourget 2005) than soft-bottom ones. Thus suspended bivalve culture may have indirect positive effects on local ecosystem diversity and productivity. Iglesias (1981) discusses the importance of this physical structure increasing habitat heterogeneity to augmenting the diversity of fishes under mussel rafts relative to control sites and further mention how active predators are particularly abundant within culture sites, feeding on the associated organisms there. In fact, Iglesias (1981) typically found a greater number and biomass of fishes in mussel sites than in control sites and Chesney and Iglesias (1979) found the same trend for fish community richness, diversity and biomass although there were temporal variations in these trends in both studies. Kaspar et al. (1985) similarly discuss the importance of how such a changed habitat is important for providing food to a variety of pelagic and epibenthic predators.

With respect to algae that fall from suspended cultured bivalves, kelp lost from mussel lines during storms or harvest drops to the bottom under the lines and represents an attractive food source for bottom feeders such as sea urchins. Winter video surveys of the rocky bottoms under a mussel lease on the Northeast coast of Newfoundland show clusters of urchins feeding on healthy new growth of kelp under the lines (M.R. Anderson, personal communications). Crawford et al. (2003) reported similar clumps of filamentous algae fallen from mussel lines in Australia as the only visible effect of farms at these open coastal sites.

As pointed out by many authors (e.g., Stenton-Dozey et al. 2001, Giles et al. 2006), sedimentation by suspended bivalve aquaculture-associated fauna may contribute considerably to the total flux of material to the bottom. Recently, McKindsey et al. (2009) did a manipulative experiment that showed the presence of *Ciona intestinalis* on mussels lines in Prince Edward Island effectively doubled biodeposition rates within mussel lines relative to that due solely to farmed mussels. Increased biodeposition related from farmed bivalves and their associated fauna will have a number of implications for the ecosystem due to the enrichment of underlying sediments, ranging from influencing benthic community structure and productivity through altering nutrient recycling with cascading effects on planktonic communities (see Anderson et al. 2006, Cranford et al. 2006, McKindsey et al. 2006a).

The importance of the removal of spat from natural populations is largely unknown. The only reference this review found is an NGO report that suggests that scallop spat removal has little impact on natural populations although no evidence for this is offered (Anonymous 2006). Although hard bottom communities are often recruitment-limited (Underwood and Fairweather 1989), larval supply is extremely variable at a variety of temporal and spatial scales (Connell 1972, McQuaid and Lawrie 2005) and is typically not limiting for farmed species in areas where they are abundant and so this may be true. In contrast, more subtle effects may be apparent, such as promoting shifts in the genetic composition of farmed populations. Although this does not appear to have happened for pearl oysters (Arnaud-Haond et al. 2003) within sites, translocation of captured spat among sites has been shown to have homogenized the genetic structure of oysters among sites (Arnaud-Haond et al. 2004). Similarly, Gardner et al. (1996) suggest that genetic similarity of Greenshell mussels (*Perna canaliculus*) in New Zealand are due to aquaculture practices rather than natural gene flow among sites, a finding that was partially confirmed by Apte et al. (2003).

Hinojosa and Thiel found that styrofoam, presumably mostly from mussel culture operations, is the dominant type of floating marine debris in northern Chile (2009). Similarly, Fujieda and Saski (2005) found that the bulk of the stranded foamed plastic on beaches in a Japanese bay was from local oyster culture operations and Cho (2005) suggest that the great quantity of styrofoam on South Korean beaches is also from aquaculture and that almost 40 thousand tonnes of marine debris is produced annually from aquaculture practices. A number of studies have shown that consumption of such material by wildlife may lead to a variety of effects, ranging from sublethal physiological ones to death (Carpenter et al. 1972, Moore 2008, Barnes et al. 2009, Jacobsen et al. 2010, Boerger et al. 2010).

Many studies have highlighted the importance of the transfer of bivalves and equipment associated with bivalve farming to the introduction and transfer of exotic species (McKindsey et al. 2007). A recent study by Astudillo et al. (2009) pointed out the potential importance of detached buoys from aquaculture sites in Chile as vectors for the dispersal of associated organisms, particularly exotic species, which seem to thrive in many aquaculture sites. This is particularly true for marine suspended bivalve culture sites (McKindsey et al. 2007). Given the great abundance of buoys in suspended bivalve culture sites and the great prevalence of exotic species in many farms in Canada (Figure 7), buoys may be a potential vector of considerable importance in this country as well. Cascading effects from exotic species are covered in McKindsey et al. (2007).

The possibility that the presence of physical structures in an ecosystem may enhance the production of jellyfish to the point that blooms develop has a large number of potential cascading effects on the rest of the ecosystem. These are outlined in Richardson et al. (2009) and range from effects algal communities through microzooplankton up to important fisheries species. Effects linked to the Taiwan example include impacts on all types of organisms in the water column (Lo et al. 2008), although some of these are obviously confounded by the elimination of the oysters that were also removed from the lagoon (Lin et al. 2009).

**2.3.1.iv. Magnitude of effects.** Given that considerable structure is added in suspended bivalve culture, effects may be similarly great. The direct impacts of added structure may greatly augment diversity locally and indirect effects may influence both benthic and pelagic ecosystems, potentially causing regime shifts in local ecosystems.

**2.3.1.v. Modifiers of effects.** Potential modifiers include depth and turbidity, current regimes, season, larval supply, substrate type, etc. The frequency and timing for seeding and socking as well as cleaning and other husbandry practices (such as double socking) are likely of great importance. These factors have been little examined to date. A notable exception is the great volume of work done to control fouling species (e.g., LeBlanc et al. 2007, Mallet et al. 2009).

*Figure 7. Typical buoy from a mussel farm site in Prince Edward Island (Malpeque Bay) with heavy fouling by the invasive tunicate,* Styela clava *(Photo: C. McKindsey)*

**2.3.1.vi. Available evidence.** Many observational studies have documented the influence of suspended bivalve culture on associated communities. However, most studies have been done on a single or limited number of dates and so data is limited to a series of snapshots of what is present at a given time. Cascading effects from direct effects are less well studied although most proposed pathways are based on solid ecological foundations. To date, the only experimental work to try to establish dose-dependent relationships between organic loading due to suspended bivalve culture and benthic responses is the work by Callier et al. (2009). Their work done in the Magdalen Islands found a clear response to benthic loading. Unfortunately, the variation in biodeposition levels studied was not great and there were several potentially confounding variables in the study.

**2.3.1.vii. Uncertainties and knowledge gaps.** It is unclear how management approaches may alter the development of associated communities and how communities undergo succession. This is particularly true with respect to the cleaning of stock and equipment *in situ* and the effects of this on the communities associated with vertical structure, the sea bottom, and the pelagic milieu. Uncertainties surround the cascading effects and modelling should be used to better understand larger-scale implications. As most studies on this subject have been limited to observational studies done at a single or limited number of times and that studies are typically done in areas with the oldest bivalves in a site or that have been farmed the longest (but see Tenore et al. 1982, Miron et al. 2005, Callier et al. 2007), a better understanding of the succession of associated communities is needed. Dose-dependent responses to organic loading need to be determined under a variety of conditions to predict benthic and ecosystem effects as well as determine the ecological carrying capacity of areas for suspended bivalve culture. The influence of spat collection on the ecosystem, especially in the immediate vicinity of capture sites, is completely unknown and should be evaluated.

**2.3.1.viii. Activity-specific links.** Effects occur throughout the culture period and effects likely increase with time. Husbandry practices, especially harvesting and cleaning, likely greatly impact community development and related effects due to fall-off.

### 2.3.2 Stressors on Habitat Structure, Cover, and Vegetation

**2.3.2.i. Effects profile.** Biodeposition from farmed bivalves and associated organisms may enrich the benthic environment, potentially smothering or otherwise covering biogenic structure. However, fall-off of farmed bivalves and associated organisms may directly increase benthic biogenic structure. Indirect effects of filtration leading to decreased turbidity and nutrient release may stimulate growth of algae and seagrasses.

**2.3.2.ii. State of knowledge of direct effects.** Direct effects due to biodeposition and fall-off by and of farmed bivalves and their associated epifauna are fairly well known and are covered by Keeley et al. (2009) and McKindsey et al. (2011).

**2.3.2.iii. Cascading effects and biological implications for ecosystem.** Filtering by farmed bivalves and their associated epifauna may reduce the concentration of both phytoplankton and inorganic particles from the water column thereby reducing turbidity and improving water clarity (Meeuwig et al. 1998, Rice 2001). Concomitant increased light penetration may enhance the production of benthic plants, such as seagrasses, algae, and microphytobenthos (Newell and Koch 2004). Increase light penetration to the sediment surface may be deleterious if “nuisance species” of macroalgae become established resulting in profuse growth, restricted water flow, and plant decay may cause sediment hypoxia (Peckol and Rivers 1995, Taylor et al. 2001).

Aggregations of suspension-feeding bivalves and their associated fauna increase nitrogen cycling rates, remineralizing particulate nitrogen as ammonium which is made available for plant growth (Dame et al. 1984, Dame et al. 1989). Deposited fecal matter also contributes considerable amounts of phosphorous to bottom sediments (Dame et al. 1989) promoting phosphate releases from sediments under anaerobic conditions (Nixon et al. 1980), thus potentially encouraging plant growth.

Macrophyte communities, particularly those associated with seagrass, are vital to the ecological structure, function, and productivity of aquatic ecosystems. With animals in almost every major phylum represented along with numerous associated species of macroalgae, seagrass, and epiphytes, such communities are the most diverse of the soft-bottom marine communities (McRoy and MacMillan 1977) and combine exceptionally high primary and secondary productivity (Williams and Heck 2001). The structural complexity of these communities both above and below the substrate function to provide increased growth opportunities (Irlandi and Peterson 1991, Irlandi et al. 1995), refuge from predation (Irlandi 1994, Irlandi et al. 1995), increase prey-capture opportunities for ambush-predators, and enhance recruitment success, while increasing sedimentation of suspended particles, cycling nutrients, and stabilizing sediments by decreasing water velocities (Williams and Heck 2001, Newell and Koch 2004). Seagrass communities also function as nursery areas for a variety of organisms, particularly various life stages of many commercial fish species, by providing opportunities for increased growth and survival (Heck et al. 2003). Macrophyte communities are also critical for supporting waterfowl populations which may feed heavily or almost exclusively on seagrass (Seymour et al. 2002, Hanson 2004). Thus altering these communities through direct and cascading effects may have great effects on the ecosystem as a whole.

Indirect effects due to biodeposition and fall-off by and of farmed bivalves and their associated epifauna are fairly well known and are largely covered in Chamberlain and Page (in press) and in section 2.3.1.

**2.3.2.iv. Magnitude of effects.** Given the importance of benthic structure to ecosystem functioning and productivity and the considerable structure that is added in suspended bivalve culture, effects may be similarly great and occur over larger scales.

**2.3.2.v. Modifiers of effects.** Potential modifiers include depth and turbidity, current regimes, season, substrate type, etc. Husbandry practices such as the frequency and timing for seeding and stocking as well as cleaning and other husbandry practices are of great importance to fall off. For example, mussel fall-off is often much greater in summer and harvesting at that time will greatly increase the abundance of mussels and associated fauna under mussel culture structures at that time. These factors have been little examined to date.

**2.3.2.vi. Available evidence.** Observations of the formation of reef-like benthic structures are fairly common in the literature although they are not always observed. There is little or no direct evidence of increased water clarity due to filtering by farmed bivalves and associated organisms allowing for the development of greater populations of benthic macrophytes.

**2.3.2.vii. Uncertainties and knowledge gaps.** Cascading effects are poorly known but of potential great importance to the functioning of the ecosystem. These should be better studied empirically and through modelling.

**2.3.2.viii. Activity-specific links.** Fall-off is ongoing but greatly increased during harvesting and immediately following the placement of new product in the leases for grow-out. Filtering capacity increases throughout the grow-out period as organisms recruit and grow.

### 2.3.3 Stressors on Access to Habitat/Migration Routes

**2.3.3.i. Effects profile.** The vertical infrastructure added in suspended bivalve culture creates a complex web in the water column. This has the potential to limit displacement by marine mammals, potentially entrapping and killing them.

Direct effects due to the addition of physical structure in the water column have been observed, although only rarely. Indirect effects are unknown.

**2.3.3.ii. State of knowledge of direct effects.** A number of marine mammals and sea birds are attracted to suspended bivalve culture sites because of the availability of food there (Meire 1993). The physical structure added to the water column in suspended bivalve culture may be a hazard to marine mammals and sea birds, largely due to entanglement. The extensive nature of suspended bivalve culture may also displace marine mammals. Markowitz et al. (2004) found that Dusky Dolphins (*Lagenorhynchus obscurus*) avoided areas occupied by mussel culture longlines in the Marlborough Sounds, New Zealand. Würsig and Gailey (2002) suggest that this may be due to the suspended structure inhibiting the ability of the dolphins to aggregate their fish prey. Similarly, Pearson (2009) found that this same species in Admiralty Bay, New Zealand, modified its behaviour to avoid travelling within areas with suspended mussel culture.

In Australia, Bottlenose Dolphins (*Tursiop* sp.) were reported to be excluded from parts of their home range by longlines for oyster culture (Watson-Capps and Mann 2005). Ribeiro et al. (2007) studied the distribution of Chilean Dolphins (*Cephalorhynchus eutropia*) in a bay in Chile and found that suspended mussel culture influenced dolphin habitat use such that the mammals were less often than would be predicted (based on surface area and habitat type) in areas with the greatest density of suspended mussel culture but were not less prevalent in areas with lower concentrations of mussel culture. Both area types were associated with foraging activities and not socializing or resting, suggesting that suspended bivalve culture modified the dolphin's habitat use within the area. Large amounts of litter from bivalve culture may also be found on the seabed under mussel farms and on nearby shores (Cole 2002). Lloyd (2003) suggests that the risk of entanglement is probably greatest for thin ropes and those that are not under tension. Lloyd (2003) also suggests that baleen whales, which cannot echolocate, may be particularly susceptible to such entanglement. Thus more off-shore areas used for spat collection may also create hazards for whales. In an extreme example, Lloyd (2003) discusses how Bryde's Whales (*Balaenoptera brydei*) have been killed after becoming entangled in mussel spat collectors in New Zealand. There are no solid data on these potential effects. This subject is discussed in detail in McKindsey et al. (2006a).

Suspended bivalve culture sites are used as resting places for a variety of sea birds (Butler 2003) although the physical structure of farms may displace some species of sea birds, including divers and grebes, and anti-predator netting may trap birds (Pillay 2004).

Aggregation of macroinvertebrates due to vertical structures may be reversible as D'Amours et al. (2008) suggest that increased abundances of starfish at intermediate distances from culture sites in Prince Edward Island represent outward migration of these organisms following harvesting. It is unclear as to what impact vertical structure related to suspended bivalve culture has on access to habitat and migration routes by fishes.

**2.3.3.iii. Cascading effects and biological implications for ecosystem.** Given the limited effects of suspended bivalve culture on migration routes and habitat access, cascading effects are likely slight.

**2.3.3.iv. Magnitude of effects.** Given the limited effects of suspended bivalve culture on migration routes and habitat access, the magnitude of effects is likely slight.

**2.3.3.v. Modifiers of effects.** Effects on marine mammals are likely most problematic in areas where marine mammals are most abundant (e.g., near pinniped haul out sites or in feeding/migration areas for cetaceans). Effects are likely variable seasonally and among areas.

**2.3.3.vi. Available evidence.** Most evidence of vertical structure used in suspended bivalve culture impacting access to habitat and migration routes comes from observations collected from various researches throughout the world. Experimental evidence is completely lacking.

**2.3.3.vii. Uncertainties and knowledge gaps.** As many such interactions are poorly reported (Würsig and Gailey 2002), the overall importance of this effect is largely uncertain.

**2.3.3.viii. Activity-specific links.** Effects will vary with activities such that off-shore spat collection will likely impact one group of organisms whereas vertical structure in grow-out situations or where spat is collected in coastal areas will impact others.

### 2.3.4 Stressors on Substrate Composition

**2.3.4.i. Effects profile.** Biodeposition in the form of faeces (from farmed bivalves and associated organisms) and the farmed bivalves and associated organisms themselves will influence the structure of the underlying substrate in a number of ways. Alteration in currents may also impact substrate composition.

Impacts from biodeposition have been largely studied (Keeley et al. 2009, McKindsey et al 2011).

**2.3.4.ii. State of knowledge of direct effects.** Direct effects related to biodeposition have been well documented with respect to changes to sediment biogeochemistry (e.g., Cranford et al. 2006, Hargrave et al. 2008) and the creation of benthic reef-like hard bottom structure (see section 2.3.1.ii).

**2.3.4.iii. Cascading effects and biological implications for ecosystem.** Indirect effects related to changes in sediment biogeochemistry due to organic loading from suspended bivalve culture-related biodeposition have been well documented with respect to changes in benthic infaunal communities (e.g., Cranford et al. 2006, Callier et al. 2008, Cranford et al. 2009) and the creation of benthic reef-like hard bottom structure (see section 2.3.1.ii, McKindsey et al. 2006a). They are not discussed further here. Vertical structure-mediated alterations to water flow may also lead to changes in sedimentation rates within farm areas as flow is typically reduced in those areas (see 2.3.7). These aspects are discussed in section 2.3.7.

**2.3.4.iv. Magnitude of effects.** Given the large scale of suspended bivalve culture operations, effects may be similarly great. Altered sediment structure will have a large variety of cascading effects throughout the ecosystem.

**2.3.4.v. Modifiers of effects.** Potential modifiers include depth, season, background current regimes, substrate type, degree of fouling and fall-off, husbandry practices, etc. See 2.3.1 for further details.

**2.3.4.vi. Available evidence.** There is a wealth of observational studies examining the link between suspended bivalve culture and benthic communities. There has been very limited experimental work to try to establish dose-dependent relationships between organic loading due to suspended bivalve culture and benthic responses.

**2.3.4.vii. Uncertainties and knowledge gaps.** Dose-dependent responses of benthic communities to biodeposition are needed to construct predictive models for benthic responses.

**2.3.4.viii. Activity-specific links.** The longer benthic structure is left in place, the greater the effect will be until an equilibrium is reached. It is assumed that the effects will increase throughout the grow-out period. Harvesting will likely greatly change benthic sediment structure due to fall-off and on-site cleaning.

### 2.3.5 Stressors on Food Availability/Supply

**2.3.5.i. Effects profile.** The vertical structure associated with suspended bivalve culture serves as a structure for the growth of bivalves and the organisms associated with them. These provide a direct resource to pelagic and benthic organisms, modify benthic structure that alter benthic communities, and compete directly with, prey on, and contribute to pelagic communities.

These effects have been fairly well established although dose-dependent effects are needed to advance modelling efforts to better predict impacts and carrying capacity.

**2.3.5.ii. State of knowledge of direct effects.** Much information is available about the influence of vertical structure used in suspended bivalve culture on the availability of food in the water column and on the bottom. This has been covered in Section 2.3.1.

**2.3.5.iii. Cascading effects and biological implications for ecosystem.** Alterations in food supply related to the addition of vertical structure have been shown to alter benthic and pelagic components of the ecosystem. This has been covered in Section 2.3.1.

**2.3.5.iv. Magnitude of effects.** Given the size and number of farm sites in some areas, effects are potentially wide-spread.

**2.3.5.v. Modifiers of effects.** Potential modifiers include depth and turbidity, current regimes, season, larval supply, substrate type, etc. Husbandry practices (such as double socking, cleaning regimes, timing of socking, etc.) are likely of great importance but have been little studied to date.

**2.3.5.vi. Available evidence.** Direct effects have been fairly well studied using observational studies but indirect or cascading effects have been much less well studied. Most predicted pathways remain supposition based on ecological principles.

**2.3.5.vii. Uncertainties and knowledge gaps.** Dose-dependent responses of benthic and pelagic communities to the level of suspended bivalve culture are needed to develop models to predict impacts and determine ecological carrying capacities of areas for suspended bivalve culture.

**2.3.5.viii. Activity-specific links.** Effects occur throughout the culture period and likely increase with time. Effects are typically greatest with older product (Tenore et al. 1982, Callier et al. 2007)

### 2.3.6 Stressors on Primary Productivity*

**2.3.6.i. Effects profile.** Vertical structure used in suspended bivalve culture allows for the growth of many filter-feeding species, both on that structure and on the bottom, that may prey directly on phytoplankton or alter nutrient fluxes and oxygen consumption/generation and thereby alter plankton community composition.

Grazing by the suspended component has been fairly well studied with respect to aquaculture whereas that of the benthic component has been less-well studied. However, considerable basic ecological data on the subject is available.

**2.3.6.ii. State of knowledge of direct effects.** Direct effects of the provision of vertical structure in suspended bivalve culture on primary productivity are likely limited.

**2.3.6.iii. Cascading effects and biological implications for ecosystem.** Cascading effects of the provision of vertical structure for suspended bivalve culture on primary productivity are related to the development of rich filter-feeding communities in both the water column and on the bottom, both of which prey on plankton and may alter nutrient fluxes and oxygen consumption/generation that may influence phytoplankton productivity and community composition. These aspects are discussed at length in a number of papers (e.g., Anderson et al. 2006, Cranford et al. 2006, McKindsey et al. 2006a) and only highlights are presented here.

Cultured bivalves have been shown to impact phytoplankton communities directly through grazing (Dame 1993, Prins et al. 1998, Smaal et al. 2001, Sarà 2007, Petersen et al. 2008). A number of studies done in Canada and elsewhere have shown bivalves grown in suspended culture and their associated fauna augment the flux of nutrients from the culture structures themselves (Mazouni et al. 2001, Mazouni 2004, Nizzoli et al. 2006, Richard et al. 2006, Richard et al. 2007b) as well as from the underlying sediments (Baudinet et al. 1990, Hatcher et al. 1994, Christensen et al. 2003, Richard et al. 2007a). Together, these two sources of nutrients may have considerable impacts on phytoplankton communities, changing its structure and potentially resulting in a net gain in phytoplankton primary production (Asmus and Asmus 1991). Richard et al. (2007b) have also suggested that greater than expected nutrient fluxes and oxygen consumption measured in a scallop culture site in the Magdalen Islands was due to fouling of pearl nets that may favour oxygenation and degradation of trapped organic matter by stimulating the nitrification process. These same studies have generally found that increased oxygen consumption due to increased respiration by bivalves and associated organisms may reduce oxygen concentrations in the pelagic and benthic environments.

Many cultured bivalves are quite plastic in their physiology, allowing them to react swiftly to an increase in phytoplankton abundance by increasing filtration rates. This rapid response to food availability coupled with a constant supply of nutrients directly or indirectly from farmed bivalves may allow bivalves in a system to reduce the intensity and extend the length of phytoplankton blooms (Herman and Scholten 1990), potentially leading to increased overall primary production in the phytoplankton. Dame (1996) further suggests that this may increase the stability and productivity of coastal ecosystems, increasing their functional and structural sustainability.

Petersen (2004) has suggested that suspended mussel aquaculture encourages the development of a community dominated by picoplankton through selective grazing by mussels and associated epifauna and enhanced nutrient regeneration, which may be the case in Prince Edward Island (Cranford et al. 2006). Thus, waters with a predominance of small plankton, as observed in Prince Edward Island, may give tunicates, many of which are invasive, a competitive advantage (Petersen 2007). There are many cascading effects on the ecosystem from this and these are discussed in McKindsey et al. (2007).

**2.3.6.iv. Magnitude of effects.** The magnitude of any potential effects due to the addition of vertical physical structure on primary productivity is likely to be great given the scale of culture sites and the fundamental ecological importance of grazing and nutrient regeneration in coastal areas.

**2.3.6.v. Modifiers of effects.** Effects are greatly modified by hydrodynamics (flushing due to winds, tides, rivers, etc.), bottom type, depth, season, configuration of added vertical structure, the extent of suspended bivalve culture farms, etc.

**2.3.6.vi. Available evidence.** Evidence for this is very strong. Observational field studies have described basic patterns. Manipulative field and lab mesocosm studies have supported predicted effects and elucidated processes.

**2.3.6.vii. Uncertainties and knowledge gaps.** The relationships between grazing, nutrient regeneration/supply, and phytoplankton communities need further refinements. This is particularly true with respect to the importance of fouling organisms in these processes. Links between these factors and ecosystem stability and exotic species are of great importance. It is unknown how harvesting and temporal variation affect these effects.

**2.3.6.viii. Activity-specific links.** It is assumed that effects on primary productivity are ongoing throughout the grow-out period. Harvesting will reduce pelagic fluxes and oxygen consumption from suspended culture units and the benthic environment.

### 2.3.7 Stressors on Water Flow

**2.3.7.i. Effects profile.** The great quantity of physical vertical structure placed in the water column for suspended bivalve culture greatly influences current regimes within sites. Fall-off from suspended bivalve culture increased bottom heterogeneity, slowing flow across the bottom and increasing sedimentation rates.

Other than recognizing the importance of this for carrying capacity calculations, these effects are not well understood, nor are the direct and indirect effects of this.

**2.3.7.ii. State of knowledge of direct effects.** Suspended bivalve culture is known to influence and be influenced by hydrodynamic circulation at a large range of spatial scales (see Figure 8). Bivalve culture systems present a porous barrier and are hierarchical, with individual bivalves and their associated fouling organisms nested within culture units (socks, cages and stacks of cages, pearl nets and strings of pearl nets, etc.), these being nested within culture gear (longlines or rafts), which are nested within farms, and so on (Plew et al. 2005, Fréchette 2008, Stevens et al. 2008). An understanding of processes operating at each scale as well as the relations between these scales is needed to predict how hydrodynamics may operate to influence the settlement and recruitment of organisms within culture systems and to understand further cascading effects on the rest of the ecosystem. At the largest scale, interactions are likely dominated by hydrodynamic processes whereas, at smaller spatial scales, biological processes such as settlement and feeding that operate at the cm scale, become more important.

At a bay-scale, Makita and Saeki (2004) modeled the impact of longline suspended oyster culture in a Japanese bay and suggest that, although the physical structures increase retention time within culture sites, they do not reduce inflow and outflow volumes. Rather, they influence the relative exchange of different areas within an embayment to the total volume of water that is exchanged. This reduces exchange within the bay and creates areas of the bay that are much better flushed than others. In contrast to this, Lo et al. (2008) suggest that flushing times for an entire bay in Taiwan were greatly impacted by the presence of aquaculture structures (mostly suspended oyster culture but also some fish culture) such that flushing rates were 3-7 days normally but 5-13 days when culture structures were present in the bay. Similarly, Plew (in press) suggests that mean current speeds in 2 embayments with suspended mussel farms in New Zealand are reduced by 2.8 to 7.3% relative to what they would be had mussel culture not been occurring there. By extending the model domain to include the area outside of the 2 bays showed that suspended bivalve culture in the larger area reduced mean current speeds in the 2 embayments by a further 3%.

At a farm scale, Riethmüller et al. (2006a) suggest that a farm of rafts in the Ría de Vigo, Spain, slows currents by about 30%. Boyd and Heasman (1998) suggest that each row of mussel rafts in a site in South Africa may reduce ambient current speeds by 3.2%; thus 10 rows will reduce flow by ca. 28%, which is consistent with their field observations. At a smaller scale, a substantial wake of ca. 30 to 50 m has been reported to develop behind mussel rafts in the Ría de Vigo, Spain (Riethmüller et al. 2006a, Herman 2007). However, because the inter-raft distances in this site are about 100 m, little reduction of flow is observed before subsequent rafts. Riethmüller et al. (2006a) suggest that the wake and subsequent mixing in the site makes the current spacing of 100 m between rafts an optimum distance to ensure adequate food renewal and area use. Horizontal and vertical mixing in the site is quite intense (Riethmüller et al. 2006a) and likely ensures sufficient food supply to the mussels on the rafts (Riethmüller et al. 2006b, Herman 2007). According to Boyd and Heasman (1998), current velocity within South African mussel rafts drops to about 17% (1.25 cm $sec^{-1}$) of the ambient flow. In the Rías Baixas, Spain, Pérez Camacho et al. (1995) found current speeds within 3 mussel rafts varied between 1.8 and 3 cm $sec^{-1}$ and Pérez-Camacho and Labarta (cited in Duarte et al. 2008) considered normal currents “near” rafts to be 2-3 cm $sec^{-1}$. However, as Duarte et al. (2008) suggest drag in mussel rafts increases proportionally with the square of current speed, relative decreases in current speed will be greater with increasing ambient current speeds. More recently, Petersen et al. (2008) studied hydrodynamics within and around mussel rafts in the Ría de Vigo, Spain, and observed a zone of high turbulence but reduced advection at the upstream corners of the raft with average velocities within the raft being only 20 to 30% those outside of the raft. That current speeds drop below ambient values but the currents within the rear of rafts are greater than those measured in the centre suggests that there are lateral inputs (Blanco et al. 1996). Predictions from modelling efforts by Riethmüller et al. (2006a) of a raft site in the Ría de Vigo were largely supported by field measurements although the authors make many suggestions for further work on the subject, especially with respect to effects under different current and upwelling regimes.

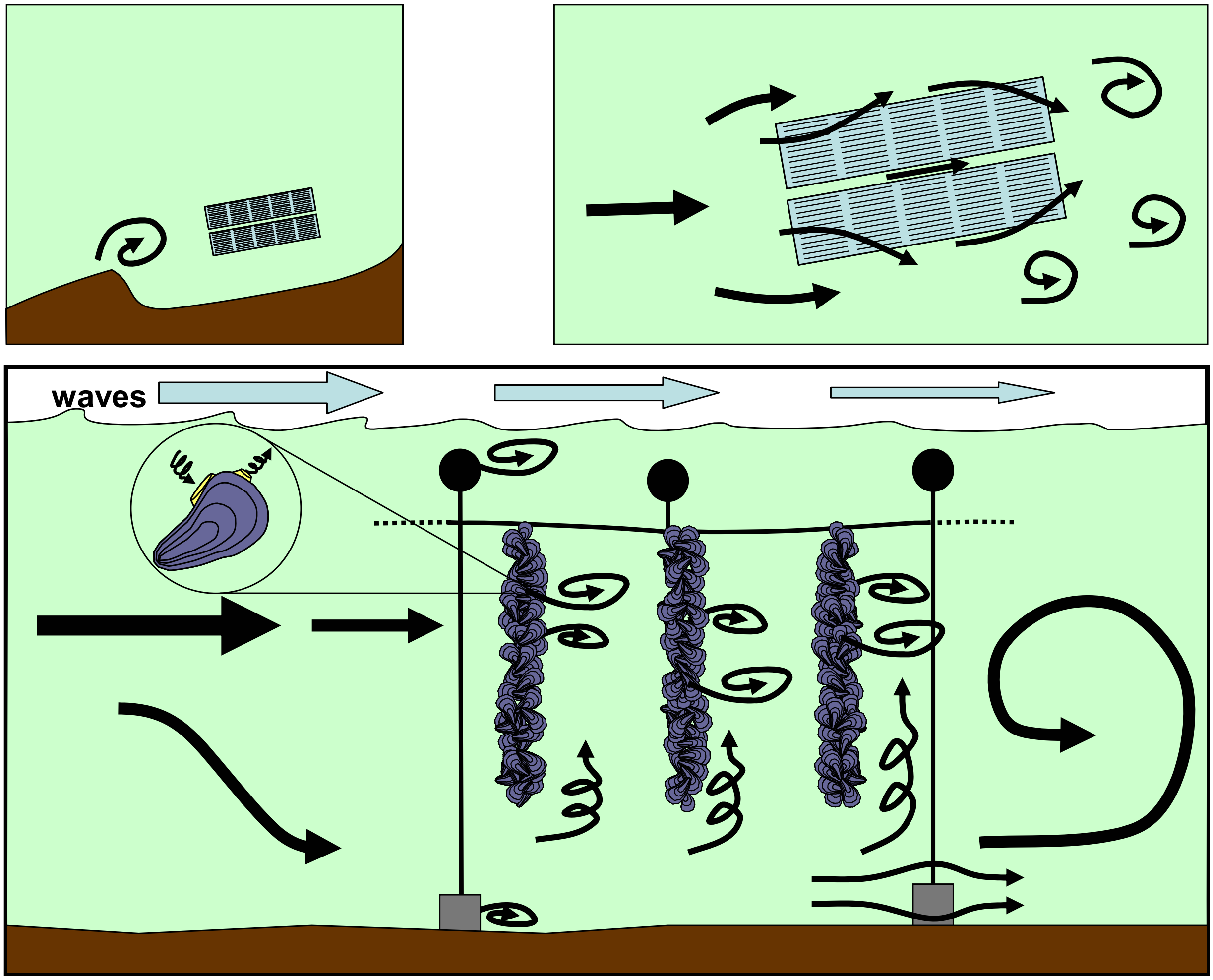

*Figure 8. Overview of how suspended bivalve culture may influence hydrodynamic processes over a range of spatial scales ranging from a bay or coastal-scale to the cm-scale. In addition to the processes shown, culture structures may also reduce flushing locally and of embayments. Modified from Plew et al. (2005) and Stevens et al. (2008).*

At a large scale, longline suspended bivalve culture systems in open areas will deflect currents around sites with increased current speeds to the sides and below (Plew et al. 2005). It is unclear how these currents are affected in more coastal and restrained systems where vertical infrastructure occupies a much greater proportion of the areas under culture. In general, reduced currents are reported within longline farms relative to areas outside of them. For example, Plew et al. (2005) and Gibbs et al. (1991) have reported 36-63% (8 cm $sec^{-1}$) and 70% (1.5 cm $sec^{-1}$) reductions in water flow velocity, respectively, within New Zealand longline mussel farms. Recent modelling work for a number of farm sites in New Zealand (Plew 2011) shows that currents within farms are reduced by an average of 25 to 45% in most farm sites, although they may be reduced to a greater degree in some and even increased in others due to deflection of water by other farms. Stevens (2010) suggested that the small (100 m scale) farms in that general area would decrease flow by ca. 5%. Strohmeier et al. (2005, 2008) found 70-80% reductions (1.2 to 1.7 cm $sec^{-1}$ in the 2005 study and 2.6 cm $sec^{-1}$ in the 2008 study) in longline mussel farms in Norway. Pilditch et al. (2001) observed a 40% reduction in flow speed in a longline scallop culture site in eastern Canada, and Grant and Bacher (2001) modelled a

54% attenuation in current velocity in a longline scallop system in China. However, this latter study modeled current attenuation due to friction from the suspended mussel socks only. Recent work by Plew (2011) shows that deflection of currents under suspended mussel sites may increase the importance of benthic drag and thus flow. For example, an evaluation of the drag due to a farm in New Zealand showed that bed friction about 9% of the total friction. At a smaller scale, sheer stress may be increased by about 66% if flow is not directed around farms or decreased by about 40% if it is (Plew 2011). This latter finding has important implications for understanding benthic loading in culture areas.

There are also finer spatial differences of current velocity within both rafts and longline systems such that current velocity reduction is typically greater in the centre of the culture unit than on either the upstream or downstream sides (Blanco et al. 1996, Strohmeier et al. 2005) and varies vertically. This suggests that there are lateral inputs (Blanco et al. 1996). As water flowing under culture systems will increase turbulence at the base of the culture structures, this will increase the depth of a mixing layer that will increase in importance as water passes through/under the vertical structure of farms (Plew et al. 2005). Studies have shown that both dropper line and larger-scale spacing (i.e., longline and raft) as well as farm size and configuration may have a great influence of current velocity attenuation (Boyd and Heasman 1998, Smith et al. 2006, Aure et al. 2007, Duarte et al. 2008, Stevens et al. 2008), as will dropper line diameter (Plew et al. 2005). At a smaller scale, it seems that filtering by cultured bivalves (and likely associated fouling species?) does not influence the drag exerted by mussel socks although it does slightly increase down-stream turbulence (Plew et al. 2009).

It has also been suggested that shell deposits on the bottom due to fall-off may slow flow across the sediments, thereby increasing sedimentation rates (de Jong 1994, Lloyd 2003).

**2.3.7.iii. Cascading effects and biological implications for ecosystem.** Change in currents may influence flushing and thus the provision/replenishment of planktonic food/communities in sites, nutrient exchange with oceanic waters, oxygen concentrations in the water column, etc. These are discussed for the Taiwan bay example discussed above with respect to flushing by various authors (e.g., Huang et al. 2008, Lo et al. 2008, Lin et al. 2009, Plew 2011), although effects observed are confounded with a variety of factors, including the removal of a large abundance of filter-feeders and reduced localized biodeposition.

**2.3.7.iv. Magnitude of effects.** Effects may be quite great, especially in areas where culture sites are large/abundant.

**2.3.7.v. Modifiers of effects.** Impacts on flow are largely determined by husbandry practices, including stocking density and farm configurations. This includes the density of bivalves on culture structures (socks or cages, etc.), of culture structures along longlines or on rafts, of longlines or rafts in farms, of farms within locations, etc. The great size of some fouling organisms (e.g., solitary tunicates) will logically increase drag through farms and thus impact flow and related effects.

**2.3.7.vi. Available evidence.** Much empirical and modelling work has shown that water flow is impacted by the presence of vertical structure used in suspended bivalve culture. In contrast, little work has evaluated how modifications at different spatial scales interact or what effect they have on the organisms in the surrounding environment.

**2.3.7.vii. Uncertainties and knowledge gaps.** Interactions between the effects on flow at different spatial scales and their effects on the surrounding ecosystem are mostly unknown.

Interactions between husbandry practices (stocking density and cleaning) and flow have not been evaluated but are likely of great importance in determining site carrying capacities.

**2.3.7.viii. Activity-specific links.** Effects occur throughout the culture period but likely vary with respect to the timing of stocking and harvesting as well as cleaning.

## 2.4 RESUSPENSION/ENTRAINMENT OF SEDIMENTS

Benthic structure is added, moved, and removed throughout culture periods and this may lead to resuspension of sediments. The physical structure, both benthic and pelagic, related to suspended bivalve culture may also impact the resuspension and entrainment of sediments. Sediment structure may also be modified through a variety of biological mechanisms (biodeposition, fall-off, etc.). Resuspension due to the placement of benthic structure is punctual in nature (a “pulse” impact”) and thus unlikely to have significant effects on the ecosystem. Other factors that may influence sediments have been discussed in the preceding sections (2.2 and 2.3) and are not discussed further here. All sections requested are addressed below but mainly refer to the appropriate preceding sections.

### 2.4.1 Stressors on Wild Fish Populations/Communities

See sections 2.2.1 and 2.3.1

### 2.4.2 Stressors on Substrate Composition

See sections 2.2.3 and 2.3.4

### 2.4.3 Stressors on Oxygen (Water Column and Benthos)

See sections 2.2.4 and 2.3.6

### 2.4.4 Stressors on Contaminant Concentrations

**2.4.4.i. Effects profile.** Increased biodeposition linked to the presence of bivalves and their associated fauna may lead to the accumulation of contaminants in benthic sediments.
Direct effects due to the addition of physical structure in the water column have been observed, although only rarely. Indirect effects are unknown but likely.

**2.4.4.ii. State of knowledge of direct effects.** Many of the organisms associated with suspended bivalve culture, including the cultured bivalves themselves and associated epifauna, are filter feeders. As such, they may filter great quantities of water and concentrate contaminants in the seston and plankton in faeces and pseudofaeces, thus increasing the concentration of these contaminants in benthic sediments. This has been shown to occur in Spain (Otero et al. 2005) and the Magdalen Islands (G. Tita, personal communications), although the former case concerns contaminants from a near-by tanning facility, the latter case concerns naturally occurring arsenic.

**2.4.4.iii. Cascading effects and biological implications for ecosystem.** There are many impacts of contaminants in sediments (Gray and Elliott 2009).

**2.4.4.iv. Magnitude of effects.** Effects will be cumulative over time. Given the restrictions on site licensing in Canada, it is expected that these will be limited.

**2.4.4.v. Modifiers of effects.** The most important modifiers are background contaminant levels, stocking density, and age of culture sites.

**2.4.4.vi. Available evidence.** There is much literature showing the importance of filter-feeders on the bioconcentration of contaminants in sediments. Few have examined this effect with respect to suspended bivalve culture.

**2.4.4.vii. Uncertainties and knowledge gaps.** The importance of these effects is generally poorly studied and thus not well-known.

**2.4.4.viii. Activity-specific links.** The process will occur throughout the culture period with effects becoming more important through time.

### 2.4.5 Stressors on Suspended Sediment Concentration

See sections 2.2.1, 2.3.1, and 2.3.2.

## 3. ON-BOTTOM / OFF-BOTTOM OYSTER AQUACULTURE

Oyster culture, as practiced in Canada, concentrates on 3 main methods: suspended bivalve culture with oysters in cages or on tubes (see Section 2.1A), off-bottom culture using tables, racks, trays, floating bags, stakes, or shallow off-bottom longline systems, and on-bottom culture where adults are seeded directly on the bottom for grow-out. The depth at which these latter two methods is done at is typically less than that used for suspended bivalve culture and off-bottom culture sites are also generally in more protected areas and thus the physical and biological processes are somewhat different than those normally encountered in suspended bivalve culture. Moreover, off-bottom and bottom culture systems typically use only single layers of grow-out structures and so there is not the same extensive 3-D structure in the water column as that in suspended bivalve culture. That is not to say that culture using these methods is not extensive, Indeed, some of the largest culture areas for oysters, such as Arcachon in France (Castel et al. 1989) or Willipa Bay in Washington state (Tallis et al. 2009), are dominated by these methods. About 32% of the 1530 hectares of intertidal beach area in Baynes Sound (between Denman Island and Vancouver Island, British Columbia) is tenured for beach culture, most of which is for oyster culture (B.C. Ministry of Sustainable Resource Management 2002). Further, as off-bottom and bottom culture is typically practiced in more shallow systems, at times in intertidal locations, the potential environmental effects of the practice are somewhat different. This is also true with respect to harvest methods which often include considerable direct physical disturbance of the seabed. Two thirds of the greater than 1 million tonnes of mussels produced around the world are grown in on-bottom culture and, with the exception of China, oysters are similarly grown mostly in on- and off-bottom culture (Davenport et al. 2003). In Canada, mussels are not cultured in on- and off-bottom systems, the practice being mostly limited to the grow-out of oysters and this review will concentrate on culture of this species. To date, much more research has concentrated on the impact of off-bottom oyster culture relative to on-bottom culture (Forrest et al. 2009) and this review reflects this bias. In particular, there have been very few studies on the impact of oyster culture in intertidal habitats (Bouchet and

Sauriau 2008). The availability and quality of the evidence supporting the various linkages between stressors and ecosystem components is given in Table 2.

*Table 2. Availability and quality of information supporting the linkages between 4 stressor types and various ecosystem components for oyster culture. Note that the table does not recognize the direction or severity of the stressor-effect linkage; the table must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Labels refer to the various sections in document. For example, Section 3.1.1 concerns the effects of off-bottom oyster culture on shading adjustments on wild fish populations/communities.*

| **On/Off-bottom oyster culture** | **Ecosystem components** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Stressor type** | **Wild fish populations / communities** | **Habitat structure, cover, vegetation** | **Access to habitat / migration routes** | **Substrate composition** | **Food availability / supply** | **Primary productivity** | **Water flow** | **Oxygen (water column/benthos)** | **Contaminant concentrations** | **Suspended sediment concentration** |
| **Shading adjustments** | **2** | **4** | | | **1** | **1** | | | | |
| **Shoreline/bottom structure** | **4** | **4** | **5*** | **4** | | **→0** | | | | |
| **Vertical structure** | **5** | **5** | **?** | **5** | **3** | **3** | **5** | | | |
| **Resuspension/ entrainment** | **→0** | | | **5** | | | | **→0** | **2** | **→0** |

Key to table: 5 – Substantial peer-reviewed evidence from aquaculture setting. 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature. 3 – Substantial peer-reviewed evidence from non-aquaculture literature. 2 – Limited peer-reviewed evidence from non-aquaculture literature. 1 – Best guess. →0 – Effect not supported by literature. Empty cells indicate that the pathway was not considered. Asterisk indicates that this is the purpose of adding the structure (i.e., to control organisms from consuming farmed bivalves).

## 3.1 SHADING ADJUSTMENTS

Limited physical structure is added to the environment in on-bottom oyster culture, although some may be removed (see section 3.2). The added structure is limited to the oysters themselves or, at times, bags of oysters that may be placed on intertidal or shallow subtidal beaches. These will have direct effects on various processes that are largely covered in section 3.2 and this information is not repeated here.

In contrast, considerable infrastructure is added in off-bottom oyster culture (see section 3.3), ranging from stakes to tables or racks and various types of longlines strung between stakes in shallow or intertidal areas. The influence of these structures on the environment has been quite well studied (see Forrest et al. 2009). However, little effort has evaluated the impact of shading modifications and the little work that has addressed this issue has clearly been confounded with biodeposition from the oysters themselves and associated fouling organisms and/or hydrodynamic modifications. It is anticipated that shading adjustment impacts due to grazing and subsequent reductions in turbidity and water clearing will be similar to those outlined in section 2 and is not repeated here. An overview of the main pathways of effects for this stressor class covered in this review is given in Figure 9.

This review found several studies that evaluated how off-bottom oyster culture structures impact light intensities. Rumrill and Poulton (2004) measured incident light levels in intertidal oyster longline plots with longlines separated by 0.75 and 1.5 m and in a reference location. In short, they found a decrease of ambient light of up to about 40% on the bottom in the 1.5 m treatment but light levels in the 0.7 m treatment did not vary much from that observed in the reference location and ambient light at 60 cm from the bottom did not differ among treatments. By pulling a light meter on a sled along a transect under longlines spaced 75 cm apart, they also found that some longlines reduced ambient light by about 10% whereas others had little effect. Rumrill and Poulton (2003) did a further study and found that light intensity was reduced under oyster longlines but did not vary substantially between plots with lines spaced at 0.5 and 1.5 m intervals. Vaudrey et al. (2009) deployed light sensors between 0.9 x 0.9 m cages on 15 cm feet used for depurating oysters in Connecticut and found no impact on benthic light levels. It must be said that all of these studies were, to the extent that they may be evaluated by the published methods, not very robust and that responses were very variable. A manipulative study by Laffargue et al. (2006) measured light levels under 4 treatments, one with oyster racks and bags with oysters, another with oyster racks and bags with oyster shells, and two without oyster structures. When the experimental pond was filled to 0.8 m, light levels on the bottom under the oyster and oyster shell treatments were 4% of subsurface light whereas that on the bottom in areas without oyster structures were 69% of subsurface light. Skinner (personal communications) measured light intensity (Photosynthetic Photon Flux Density - PPFD) under 3 types of floating oyster bag structures in New Brunswick and found that light intensity was decreased by almost 50% by the least opaque bag material to greater than 90% by the most opaque material.

### 3.1.1 Stressors on Wild Fish Populations/Communities*

**3.1.1.i. Effects profile.** Off-bottom oyster culture adds considerable 3-D hard physical structure to the water column and thus directly and indirectly reduces the availability of light in the ecosystem directly under and surrounding culture structures. The intensity of light reduction (shading) may be modulated by regular husbandry practices (addition, removal, and cleaning of equipment and crops. This shading adjustment may have direct and cascading effects on the functioning of the rest of the surrounding ecosystem, including altering the abundance and/or productivity of a number of species/communities.

Direct effects due to the addition of vertical physical structure for off-bottom oyster culture have not been well studied. Although indirect and cascading effects on wild fish populations/communities may be imagined, these too have not been well studied and are largely conjecture.

**3.1.1.ii. State of knowledge of direct effects.** All else being equal, given that the structure associated with off-bottom oyster culture reduces the quantity of light reaching the sea bottom, this should increase the abundance of cryptic and sciaphilic species while decreasing the abundance of phytophyllic species (but see section 2.1.1.ii).

Shading by physical structures has been shown to impact the abundance of a variety of more benthic species. For example, Laffargue et al. (2006) evaluated the effect of off-bottom (trestle) oyster culture on the swimming activity of sole (*Solea solea*) in a 600 $m^2$ mesocosm with 3 habitat types (zones with trestles with bags of live oysters, trestles with bags of oyster shell, no aquaculture infrastructure, and a zone between these areas, also with no culture structures) in the Bay of Biscay, France. Most fish studied stayed associated with off-bottom structures in the day but foraged in all habitats at night time, suggesting that the fish sought out shade in the day time. Work in the Bay de Veys, France, has shown that the abundance of the European Green Crab (*Carcinus maenas*) is augmented within culture areas relative to nearby control areas (Dubois et al. 2007). It is likely that this species uses this shelter as a base from which it may forage on the surrounding habitats. In contrast, the gammarid amphipod *Urothoe poseidonis* was found solely in the reference site. This latter species, however, is largely restricted to clean sands, a habitat that may be compromised under oyster racks due to siltation and organic loading. Although not quantified, tunicates of a variety of species recruit preferentially to the bottom of a variety of structures, including oyster bags on racks, presumably because of the darker conditions there. A large variety of organisms have been reported from oyster bags (see section 3.3.1), presumably because of the structure the physical structure the bags provide but a good number of the species reported from the bags are also sciaphilic species.

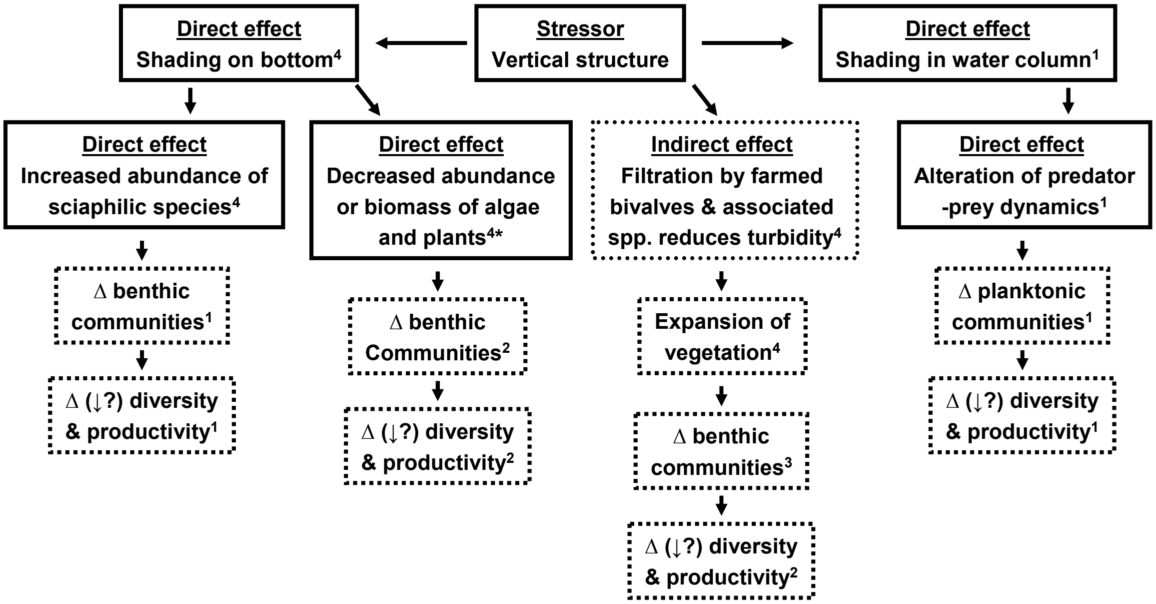

*Figure 9. Main pathways of effects for shading adjustments due to off-bottom oyster culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**3.1.1.iii. Cascading effects and biological implications for ecosystem.** The impact of shade-seeking species on the surrounding habitat may be substantial. For example, that green crabs are normally hard-bottom dwelling species (Behrens Yamada 2001) but are limited to under oyster tables in muddy areas, at least during low tide in the day (Dubois et al. 2007) suggests that the shading provided by off-bottom oyster culture structure may provide them a refuge they would not enjoy in otherwise featureless mud and sand flats. Given that they are also known to have a severe impact on some infaunal species, such as Softshell Clam (*Mya arenaria*) (see Floyd and Williams 2004), the shading may bring about indirect cascading effects on the surrounding benthic communities mediated though predation by green crabs.

**3.1.1.iv. Magnitude of effects.** Given the considerable structure and extent of culture sites in some areas, effects may occur over wide spatial scales. However, research to evaluate this possibility remains to be done.

**3.1.1.v. Modifiers of effects.** Potential modifiers include spacing of culture structures (racks and trestles, longlines, cages, etc.), and fouling intensity on culture structures and products. These factors have not been well identified or studied.

**3.1.1.vi. Available evidence.** There is limited information on the degree of shading due to off-bottom oyster culture, some of which is poorly reported or executed. Evidence of impacts due to shading are largely confounded with various other factors, such as biodeposition, sediment modification, the addition of structure.

**3.1.1.vii. Uncertainties and knowledge gaps.** This subject is largely unstudied. Experiments are needed to separate the various potentially important factors to determine which ones are of greatest importance.

**3.1.1viii. Activity-specific links.** Effects occur throughout the culture period and likely vary over time. Rotation of culture equipment and stock will greatly impact shading adjustments and their impacts.

### 3.1.2 Stressors on Habitat Structure, Cover, and Vegetation

**3.1.2.i. Effects profile.** Shading adjustments due to habitat structure in off-bottom oyster culture may negatively impact submerged aquatic vegetation (SAV) directly or indirectly via reduced turbidity and/or increased water clarity brought about by the filtration of the water column by farmed bivalves and their associated epifauna. Much research has been directed at this effect although results are often confounded by other factors (biodeposition, accretion and erosion, altered hydrodynamics, harvesting effects, etc.).

**3.1.2.ii. State of knowledge of direct effects.** Direct effects due to shading adjustments and other factors have been discussed in section 3.3.2.ii. However, most of these studies have been confounded by other factors that may also account for the observed effects. Manipulative experiments are needed to evaluate the different factors independently to determine which ones may be the important ones in impacting SAV.

A recent study by Marc Skinner (Fisheries and Oceans Canada at the Canadian Rivers Institute, University of New Brunswick) does a good job of this. He studied the impact of floating bag oyster culture in New Brunswick on Eelgrass (*Zostera marina*). First, he examined incident light levels directly under culture structures as compared to several reference areas. He found that

PPFD under culture structures was only about 10% that measured in reference stations. He then did manipulative experiments to separate the influence of biodeposition from shading and, to some extent, hydrodynamic effects, by comparing different bag structures (i.e., more or less opaque) with different densities of oysters and reference areas with no structure over 3 months. Within 2 months, clear effects were evident that only increased over the duration of the experiment. In short, eelgrass shoot density and photosynthetic performance were reduced in all treatments proportionally to shading. The measured PPFD was only above the minimum mid-day light requirements for *Z. marina*, as calculated by Thom et al. (2008), for the reference locations in all of his studies; PPFD measured in existing culture sites and all other treatments in the manipulative study were just below or considerably below this level.

As pointed out in section 2.1.2, clearing of waters via filtration by farmed bivalves and associated fouling species has been suggested to increase the depth to which SAV may grow and increase its productivity (Newell and Koch 2004).

At large temporal and spatial scales, Deslous-Paoli et al. (1998) reviewed studies from the Thau Lagoon, France, comparing historic and contemporary data on macrophyte distributions, and concluded that *Zostera* spp. has extended its distribution from shallow regions to areas up to 5 m in depth in some areas of the lagoon. The authors attribute this increased distribution to reduced turbidity in culture regions as a result of farmed bivalve (mostly off-bottom oyster culture) filter feeding. Given that the associated tunicate epifauna filter roughly 50% of the water that filtered oysters do (Gangnery 2003), the physical structure provided by off-bottom oyster culture contributes considerably to increasing water clarity and thus expansion of eelgrass in the system. On a near-field scale, SAV could also be found between culture trestles but were completely absent underneath. Deslous-Paoli et al. (1998) indicate that this indicates a shading effect of these structures but the impact of biodeposition and other factors may also be important. (In stark contrast to these suggestions, De Casabianca et al. (1997) also compared current data and historical accounts to suggest that macrophyte communities in the Thau Lagoon, France have shifted from a dominance of *Zostera* to communities composed of opportunistic algae (*Ulva* and *Gracilaria* spp.) over the past century. These authors conclude that this succession was caused by elevated levels of nitrogen and increased turbidity in these areas resulting from eutrophication by extensive off-bottom culture of oysters and mussels.)

**3.1.2.iii. Cascading effects and biological implications for ecosystem.** Impacts on eelgrass, which is considered to be an “ecologically significant species” (DFO 2009), may have a number of cascading effects on the surrounding ecosystem. The importance of this habitat has been described in many reviews (e.g., Chambers et al. 1999, Jackson et al. 2001, Heck et al. 2003, Williams 2007) and is not elaborated upon here. Similarly, many other types of SAV fill a role similar to that of eelgrass (Heck et al. 2003) and so similar effects may also arise from harmful alteration or destruction of these habitats.

**3.1.2.iv. Magnitude of effects.** Given the vast areas over which this type of culture may occur, impacts to eelgrass and other types of SAV and cascading effect from this may also be great.

**3.1.2.v. Modifiers of effects.** The most important modifiers are likely husbandry practices, especially density and crop rotation. The importance of the degree to which floating bag structures are allowed to move with their moorings may also be important. Other modifiers include depth and turbidity, current regimes, season, substrate type, etc. These latter factors have been little examined to date.

**3.1.2.vi. Available evidence.** There is considerable evidence of direct effects on SAV although much of this is confounded with other factors. Impact on SAV-associated organisms are well studied but not in the aquaculture context.

**3.1.2.vii. Uncertainties and knowledge gaps.** Studies to separate out competing factors are needed to determine the importance of different factors working concurrently in natural systems. These should be best studied empirically. Studies on rates for impact and recovery as well as crop rotation are needed.

**3.1.2.viii. Activity-specific links.** The activities with the greatest impact on eelgrass are likely related to harvest methods, maintenance, stocking density, and crop rotation.

### 3.1.3. Stressors on Food Availability/Supply

Effects of shading adjustments on food availability and supply for off-bottom oyster culture are basically unknown and unstudied but are likely to be similar to those outlined in section 2.1.3 and this section should be consulted to this end.

### 3.1.4 Stressors on Primary Productivity

Effects of shading adjustments on primary productivity for off-bottom oyster culture are largely unknown and unstudied but are likely to be similar to those outlined in section 2.1.4 and this section should be consulted to this end.

## 3.2 ADDITION/REMOVAL OF SHORELINE/BOTTOM STRUCTURE

The physical impact of bottom structure is mostly limited to the legs of tables, etc., that are used to support the tables, bags, etc., that hold the cultured oysters in off-bottom oyster culture. This review found no reference to the potential effects of these structures. Potential pathways of effects would be similar to those outlined in Section 2.2 and are not considered further here. Instead, this section of the review concentrates on the influence of the physical structure associated with on-bottom culture of oysters with reference to bottom culture of mussels, where appropriate. Removal of bottom structure due to the use of carbaryl, a general arthropocide, to control the abundance of burrowing shrimp in on-bottom oyster culture (see Simenstad and Fresh 1995) is not covered in this review as the practice is not used in Canada (McKindsey et al. 2006a) and is being phased-out in the United States (Dumbauld et al. 2009). An overview of the main pathways of effects for this stressor class is given in Figure 10.

### 3.2.1 Stressors on Wild Fish Populations/Communities

**3.2.1.i. Effects profile.** The addition of physical structure in on-bottom oyster culture is principally limited to the addition of physical structure provided by the oysters themselves and the cage/bag structures that are used in some cases and placed directly on the bottom. This increases the abundance of many benthic and reef-associated species locally and may have cascading effects on planktonic communities and the greater ecosystem.

Direct effects from the presence of oysters in on-bottom culture have not been well studied but ecological research on oyster restoration and on natural reefs support proposed pathways. Indirect effects have been even less-well studied but proposed pathways are supported through ecological work. Directed research coupled with modelling would best address this gap.

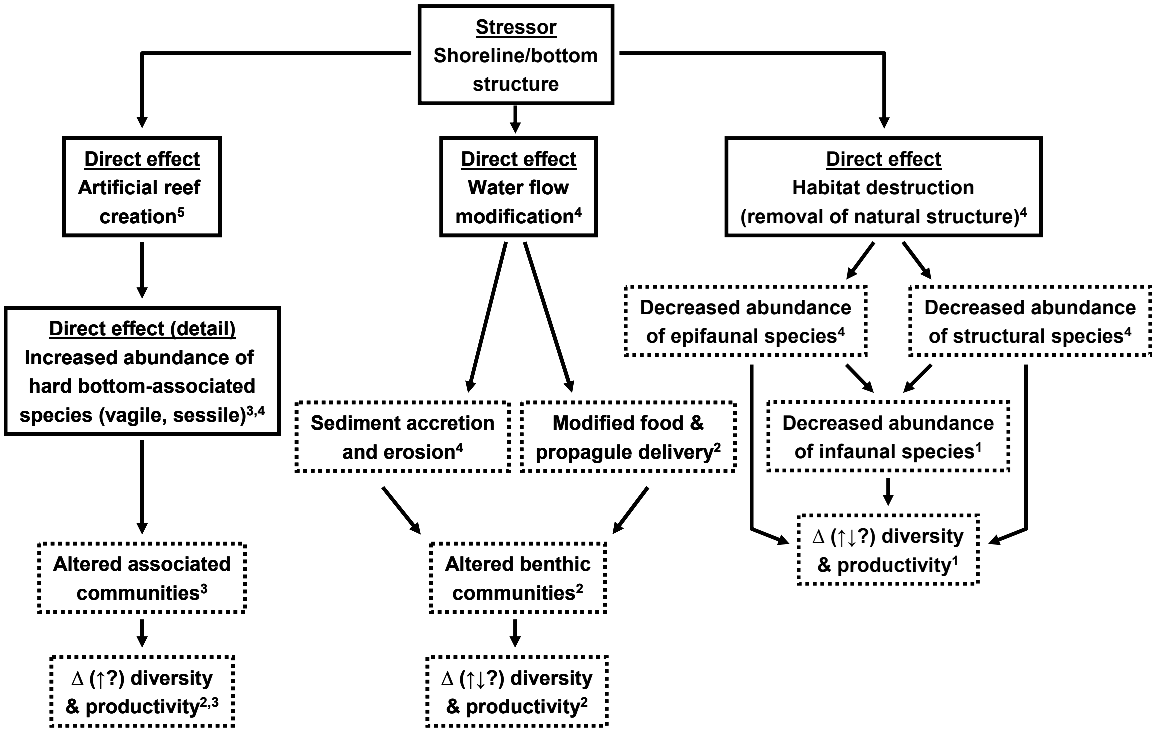

*Figure 10. Main pathways of effects for adjustments due to modification of shoreline/bottom structure due to on-bottom oyster culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**3.2.1.ii. State of knowledge of direct effects.** Oysters are typical foundation species (sensu Dayton 1972) in so much as the physical structure they provide may change fairly homogeneous 2-D habitats into complex 3-D ones that provides space for many associated organisms that would otherwise not be present. Manipulative studies have shown that it is the physical structure of bivalves and not the biological services they provide that augment diversity and abundance at local scales (Suchanek 1979, Ricciardi et al. 1997). Many studies have noted increased abundances of many species associated with natural oyster reefs relative to other habitats (see reviews in Coen et al. 1999, Luckenbach et al. 1999, Milewski and Chapman 2002, National Research Council 2004, Ruesink et al. 2005).

Most authors suggest that on-bottom oyster culture will have similar effects on the environment as do natural and restored oyster reefs. This is probably only somewhat true given that the 3-D structure of natural and restored reefs is greater than that allowed to occur in farmed sites and reef structure differs among species. A number of studies have shown that oyster reef structure has an important influence on the number and types of organisms associated with them (Breitburg 1999, Lenihan 1999). Thus Dumbauld et al. (2009) suggest that the ecological role of cultured oysters as habitat, particularly non-native species, must be studied separately and not strictly inferred from studies of natural and restored bivalve reefs. A critical review of studies on the direct impacts of on-bottom oyster culture finds that most discussion within the studies actually refers to publications that have examined oyster reefs and not oyster culture.

For studies that examine on-bottom oyster bag or cage culture, Dealteris (2004) compared the organisms > 5 mm associated with *C. virginica* modified rack and bag culture (multiple cages of oyster stacked on top of each other and placed on the bottom) in Rhode Island to those found in similar areas with *Z. marina* and areas with a non-vegetated seabed. Over 4 sampling dates (seasons), they found the average number of taxa to vary between about 15 and 23 cage$^{-1}$ and the total abundance of associated species between about 1000 and 2500 individuals. This included 10 fish species, 12 macrocrustaceans, and a number of molluscs, including commercially and recreationally important species. Species richness was greatest in cages and least in non-vegetated areas with eelgrass between these two. Cages typically had an order of magnitude greater abundances of fish, crustaceans, molluscs and also generally greater abundances of sessile organisms such as sponges, hydroids, bryozoans, and ascidians relative to the other habitats evaluated. Organism abundance was highly correlated (r = 0.94) with the amount of emergent surface area available with the culture gear having by far the greatest surface area (Kilpatrick 2002). This author estimated that the culture gear provided 60 times the surface area relative to an eelgrass bed and pointed out that, whereas eelgrass may be ephemeral, the culture gear is there year-round. Species unique to culture gear included: American Eel (*Anguilla rostrata*), Oyster Toadfish (*Opsansus tau*), Rock Gunnel (*Pholis gunnellus*), Atlantic Tomcod (*Microgadus tomcod*) and American Lobster (*H. americanus*). It was concluded that observed differences were due to differences in habitat composition, structure, and complexity which increased refuge areas and densities of fouling and forage organisms, suggesting the potential of this type of oyster culture of increasing secondary productivity (Dealteris et al. 2004). A further study examined modified rack culture effects in Rhode Island and its influence on fish communities (Tallman and Forrester 2007). This study compared fish density, growth, and disappearance on 3 culture sites, 6 natural rocky reefs, and an artificial reef. Autumn trap surveys in 2005 and 2006 showed that Cunner (*Tautogolabrus adspersus*) were more abundant on reefs than in culture sites, whereas Scup (*Stenotomus chrysops*) and Tautogs (*Tautoga onitis*) were most abundant in culture sites. A mark and recapture study of scup showed that, while its growth was greatest on natural reefs, its rate of disappearance was lowest in culture sites. The authors suggest that this supports the notion that the grow-out cages create favourable habitat for fishes normally associated with natural hard bottoms. Erbland and Ozbay (2008) studied similar grow-out methods in Delaware and compared the macro-epifauna (mostly fish and crabs) associated with culture systems to that associated with created oyster reefs. The study showed that the abundance of macrofauna associated with the culture gear was about twice that associated with the constructed reefs, both abundance and richness were greater in the culture gear (14 of 18 species were more abundant in culture gear than in the reefs), evenness was less, and diversity did not differ between the 2 treatments.

Powers et al. (2007) sampled “biogenic structure” (mostly algae but also some erect epifauna) associated with on-bottom Quahog (*Mercenaria mercenaria*) culture with polypropylene mesh bags as well as with seagrass (*Zostera* marina and *Holdule wrightii*) and a sand flat in North Carolina. Epifaunal biomass in the 2 culture sites studied was consistently greater on aquaculture mesh than sand flats and did not differ from that associated with seagrass on most sample dates. It is likely that on-bottom bag culture for oysters would have a similar effect.

Trianni (1995) examined epifauna and infauna in 4 habitat types in Arcata Bay (Humboldt Bay, California) and found that diversity was increased in sites with on-bottom oyster culture relative to one with a muddy bottom due to the increased abundance of epifauna associated with the oyster valves. Unfortunately, the thesis gives very little clear information. Work on oyster reefs shows that a great diversity of organisms is associated with the physical structure of oyster valves. In general, basic ecological principles suggest that the addition of hard substrate, such as oysters in bottom culture, will augment local diversity and productivity but this has not been evaluated for on-bottom oyster culture.

A limited number of studies have shown greater diversities and abundances of fishes associated with on-bottom oyster sites relative to areas without structure and/or similar to those with some type of natural structure. For example, Hosack et al. (2006) studied faunal associations in each of 3 benthic habitat types in each of 3 locations in Willapa Bay, Washington, on each of 3 dates and found a greater diversity of fish and decapods in on-bottom oyster farms with two to three year old oysters relative to eelgrass or muddy areas but abundances did not differ among habitat types. Epibenthic invertebrates were equally abundant in oyster culture sites and eelgrass sites and more abundant than those in mudflat sites. Holsman et al. (2006) examined migration and habitat use by Dungeness Crab (*Cancer magister*) and Red Rock Crab (*Cancer productus*) in 3 littoral habitat types (unstructured, *Z. marina*, and on-bottom oyster culture) in 4-5 sites on 2 dates in Willapa Bay. Trapping found the greatest abundance of Dungeness Crabs in unstructured, followed by eelgrass and then oyster habitats; Red Rock Crabs showed the opposite trend. In contrast, underwater video done within a single site in each of the 3 habitats showed greater migration of Dungeness Crab through unstructured habitat than through the other 2 habitats whereas larger Dungeness Crabs were observed in the oyster habitat. Semmens (2008) studied the movement and survival of acoustically-tagged Chinook Salmon (*Oncorhynchus tshawytscha*) smolts in 4 different habitats in an ca. 4000 m$^2$ enclosure in Willapa Bay. The study found that the smolts had a greater preference for remaining within native eelgrass (*Zostera marina*) habitats and survived longer than in three other types of habitats that are characterized by non-native species: Pacific Oysters (*C. gigas*), non-native eelgrass (*Zostera japonica*), and non-native Smooth Cordgrass (*Spartina alterniflora*). This study seems to reflect a general trend of on-bottom oyster habitat being a lower quality habitat than eelgrass for Pacific salmon (see review in Dumbauld et al. 2009).

Increased recruitment to oyster aquaculture may also have negative impacts on some species. For example, the native western North American oyster (*Ostrea lurida*), is in decline and Trimble et al. (2009) have done a series of studies that, together, suggest that this may in part be due to preferential settlement by recruits of the species to *Crassostrea gigas* grown in intertidal aquaculture and the *O. lurida* dying of desiccation there.

**3.2.1.iii. Cascading effects and biological implications for ecosystem.** A great many studies have examined various cascading effects related to oyster reefs in areas around the world (see reviews in Coen et al. 1999, Luckenbach et al. 1999, Milewski and Chapman 2002, National Research Council 2004, Ruesink et al. 2005). However, as for direct effects, studies from artificial or natural reef communities may give an indication of the importance of effects of on-bottom oyster culture but actual effects and interactions among species are commonly a function of the physical structure of reefs (Grabowski 2004, Grabowski and Powers 2004, Grabowski et al. 2008). Very little research has actually focused on the cascading effects of on-bottom oyster culture on the ecosystem.

Many studies have evaluated infaunal communities among habitat types, including those in on-bottom oyster leases and found variable results. For example, Hosack et al. (2006) found the abundance of infauna in on-bottom sites to be intermediate to that in *Z*. *marina* (the greatest abundance) and mud habitats. Ferraro and Cole (2007) also studied habitat associations for infauna in Willapa Bay (4 habitats in 1996 and 7 in 1998) with multiple sites for each habitat type. The study found that community diversity, richness, biomass and abundance as well as the abundance of each of 3 functional groups (deposit, facultative, and suspension feeders) was similar in bottom oyster aquaculture and *Z*. *marina* sites and generally greater than that of other habitat types. Erbland and Ozbay (2008) studied modified stacked cage on-bottom oyster culture and its influence on underlying infaunal communities in Delaware by comparing these to macrofaunal communities from a near-by sand/mud reference area. Although temporally variable, abundance and richness of infauna was generally greater in the reference area than under cage structures. Castel (1989) examined 2 sites with on-bottom oyster culture, each pared with a similar site with the native eelgrass (*Zostera noltii*) and, in one location, a site with a bare sandy bottom, in Arcachon Bay, France. Oysters were shown to increase the abundance of benthic meiofauna but decrease the abundance of benthic macrofauna relative to the sandy site but all sites with eelgrass had the greatest abundance of both types of organisms. However, it is not clear what factor led to increased abundances in oyster sites and the authors suggest it was due to biodeposition by farmed oysters. Indeed, most studies examining the influence of oyster culture or reefs on infaunal and macrofaunal communities cannot separate the impact of the biodeposition from these structures and their physical structure which may directly or indirectly modify many physical (e.g., currents, sediment biogeochemistry, seston supply, etc.) and biological parameters (e.g., recruitment, food supply). A study by Trianni (1995) goes some way towards overcoming this issue by studying infaunal communities from upper and lower regions of Arcata Bay (Humboldt Bay, California), within which 3 habitat types were sampled: on-bottom oyster culture, bottoms where oyster shell had been deposited, and either a muddy area or one with *Z*. *marina* in each of 2 seasons. Although temporally variable, the study found the greatest diversity, abundance, and biomass in the eelgrass site. Diversity seemed to be greater in culture sites than paired shell deposition sites, both of which were greater than in the muddy site. In the upper Bay, abundance was greatest in mudflat, followed by oyster culture and then by the shell site; biomass was greatest in the shell site and lowest in the mudflat; and diversity was greatest in the oyster site and least in the mudflat. In the lower bay, abundance was least in the shell site and biomass did not differ between habitats. In all cases, increased diversity in sites with oyster or oyster shell was due to the addition of epifaunal species, suggesting the direct contribution of shell structure. Bouchet et al. (2008) examined various biotic and biogeochemical indices from sediments in a number of on-bottom and off-bottom oyster culture and control sites in intertidal mudflats in the Pertuis Charentais (France) over a number of seasons. Although quite variable among indices of ecological quality status (i.e., using the biotic indices H', AMBI, BENTIX, BOPA, and M-AMBI), off-bottom oyster culture was found to have a greater effect (positive or negative) than on-bottom oyster culture and it was suggested that hydrodynamics may interact with culture practices to mediate effects from biodeposition.

Further cascading effects arising from the addition of physical structure associated with on-bottom oyster aquaculture, such as the impact of filter-feeding by associated species on planktonic communities and the resulting impact of pelagic and benthic communities and processes or of the structure provided by epibiota growing on oyster valves have not been evaluated.

The structural complexity of oyster reefs will modify hydrodynamics (Breitburg 1999, Kennedy and Sanford 1999) with cascading effects on a variety of processes (e.g., food and recruit delivery) that may indirectly influence the ecosystem (Jumars and Nowell 1984, Sebens 1991, Breitburg et al. 1995, Eggleston et al. 1999). For example, Breitburg et al. (1995) studied the settlement of the Naked goby (*Gobiosoma bosc*) larvae within oyster reefs in Chesapeake Bay and found that larvae accumulated downstream and in the wake of large sources of heterogeneity in the reefs by swimming actively against the currents and that settlement patterns reflected this. Hydrodynamic changes due to reef structures may also influence sediments locally with various cascading effects on the ecosystem (see section 2.2.1). It is not clear how on-bottom oyster aquaculture, where oysters are mostly individuals spaced out on the bottom, will influence such cascading effects and such effects have not been studied.

Indirect effects on benthic fauna due to harvesting (by hand or mechanical dredge) and crop maintenance have been suggested in a number of studies although these have rarely been evaluated for on-bottom oyster culture (but see section 3.3 for off-bottom oyster culture where studies have been done). (Note that the effects of historic practices as outlined by Simenstad and Fresh (1995) are mostly irrelevant today given the great changes to practices used in on-bottom culture.) Given that these husbandry activities involve considerable movement in culture areas, often by walking or with boats in shallow waters, the potential for impacts is considerable. Lenihan and Peterson (2004) compared the impacts of harvesting oysters using a dredge, tongs, and commercial divers on oyster reef size (height and diameter), oyster mortality, and harvest efficiency. Dredge and tongs removed significantly more structure than did scuba collection (which did not differ from a control site) and there was greater mortality of oysters left on the bottom in the sites harvested by dredge or tongs than in the site harvested by divers or the control site. Moreover, yields were greater using the diver-harvested methods. This review identified no studies that have evaluated the impact of oyster “hardening off” (where oysters grown subtidally are placed directly or in bags on the bottom or on racks in intertidal areas to make them more resistant to desiccation and thus increase their shelf life and/or remove fouling) or of oysters grown in bags directly on beach bottoms.

A number of studies have shown that on-bottom culture of bivalves may have a number of direct effects on bird populations (by the cultured bivalves acting as a food source) as well as indirect effects by the associated organisms acting as a food source or by the physical structure of the cultured bivalves disrupting feeding or other behaviours in the rest of the ecosystem (see review in McKindsey et al. 2006a). Given the potential grazing pressure of shorebirds and sea birds in some areas, this may have a variety of cascading effects on the rest of the ecosystem. In contrast, on-bottom oysters that have become invasive in New Zealand have displaced some bird populations that forage in soft-bottom sediments and that cannot forage for organisms associated with oysters on the bottom (B. Forrest, pers. comm.).

**3.2.1.iv. Magnitude of effects.** Given the historic size of on-bottom culture sites, potential effects may have been great. However, the oyster industry in Canada is moving towards off-bottom and suspended techniques on both temperate coasts and thus, although potentially of local importance, cumulative cascading effects due to on-bottom oyster culture are probably not great at this time.

**3.2.1.v. Modifiers of effects.** Effects are likely affected by local hydrodynamics and related properties (sediment type, depth, etc.). Husbandry practices are also likely important. Potential effects have not been examined to date.

**3.2.1.vi. Available evidence.** There is little field evidence for most plausible effects resulting from the addition of bottom structure for on-bottom oyster aquaculture. Most potential effects are extrapolations from studies from natural and artificial reefs but these differ fundamentally different from on-bottom oyster aquaculture in a number of ways.

**3.2.1.vii. Uncertainties and knowledge gaps.** Basic work on associations between oysters in bottom culture and other organisms are needed. Data from this type of study could then be used to make better predictions of the role of this practice in the environment. The impact of on-bottom bag culture for oysters, either for grow-out or for hardening off, also needs to be addressed.

**3.2.1. Activity-specific links.** The most important activity for on-bottom oyster culture is the movement of people and/or machinery across the bottom during seeding, maintenance, and harvest. Different methods vary in their effects and intensity (Simenstad and Fresh 1995).

### 3.2.2 Stressors on Habitat Structure, Cover, and Vegetation

**3.2.2.i. Effects profile.** The addition of benthic structure in on-bottom oyster aquaculture may impact habitat structure directly as cultured oysters themselves create such structure (see section 3.2.1) and husbandry practices may have great indirect impacts on vegetation in culture sites.

The influence of modifications of benthic structure related to on-bottom oyster culture on habitat structure, cover and vegetation and the indirect influence of this on other populations/communities are largely unstudied in the context of aquaculture.

**3.2.2.ii. State of knowledge of direct effects.** Effects related to the structure provided by the oysters being cultured are covered in section 3.2.1.

Several studies have examined the relationship between the presence of on-bottom oyster culture and vegetation. Generally, activities related to husbandry (seeding, maintenance, harvest) seem to have the greatest direct impact (see Simenstad and Fresh 1995 for an historic account of culture practices and impacts). Tallis et al. (2009) measured the growth, density, and biomass of eelgrass in multiple sites subjected to three types of oyster culture (on-bottom with harvesting by hand – H, on-bottom with harvesting by dredge – D, and off-bottom longline – L) and control (C) sites in Willapa Bay, Washington, over 3 years. Results for eelgrass density were $C \geq L \approx H > D$ suggesting that harvesting by dredging had the greatest impact of eelgrass whereas the limited disturbance from hand harvesting and off-bottom longline systems had limited effects on the eelgrass. The authors also point out that physical pre-emption of space and cutting or otherwise damaging the eelgrass by oysters may also decrease eelgrass density. Biomass of individual eelgrass shoots was greatest in control sites and differed little among grow-out treatments. Eelgrass growth was greatest in dredged and hand-picked sites. Overall eelgrass production among treatments was ca. $C > H \geq L \geq D$. Within culture method treatments, eelgrass density was not a function of oyster density. Wisehart et al. (2007) did observational and manipulative studies to examine factors related to the recovery of eelgrass disturbed by oyster culture in the same area and showed that the greatest abundance of eelgrass seedlings was in on-bottom sites harvested by dredging, intermediate numbers in control sites and the lowest number in sites with off-bottom longline culture (note that on-bottom sites harvested by hand were not evaluated in the study). Eelgrass seed production was greatest in dredged sites and least in off-bottom longline sites. Within dredged sites, the number of eelgrass seedlings was negatively correlated with the abundance of oysters on the bottom whereas the cover of macroalgae was greatest in sites with on-bottom oyster culture (Wisehart et al. 2007). Waddell (1964) reported that oyster culture leases in Humboldt Bay, California, that were harvested by dredging displayed decreased shoot density, shoot length, and biomass compared to reference plots. Biomass was reduced 30% after one year and 96% after 4 years with effects persisting up to two years post-treatment (Waddell 1964). As such, it is clear that these harvesting practices cause substantial alterations to primary productivity in culture areas and these alterations can persist many years after cessation of disturbance due to the time required for macrophytes (especially seagrasses) to recolonize disturbed areas.

No studies have examined the impacts of on-bottom bag culture for oysters on habitat structure, cover, and vegetation.

**3.2.2.iii. Cascading effects and biological implications for ecosystem.** Little work has examined the cascading effects of on-bottom oyster culture on the ecosystem. On-bottom oyster culture may alter the abundance of macrophytes, including macroalgae and eelgrass, in an area (Wisehart et al. 2007, Tallis et al. 2009). The presence of such structural species is commonly correlated with increased diversity, abundance, and productivity, often as great as that observed in eelgrass (e.g., Bertness et al. 2000, Heck et al. 2003). Thus the presence of on-bottom oyster culture may thus lead to considerable changes in communities locally with a variety of cascading effects on the ecosystem (Waycott et al. 2009).

No studies have examined the indirect or cascading effects of on-bottom bag culture of oysters.

**3.2.2.iv. Magnitude of effects.** Given the extent of areas within sites that may be impacted by the addition of benthic structure and the importance of macrophyte communities to ecological processes, effects may be considerable.

**3.2.2.v. Modifiers of effects.** Effects are likely affected by local hydrodynamics and related properties (sediment type, depth, etc.). Husbandry practices have been shown to be important. Cascading effects remain speculative.

**3.2.2.vi. Available evidence.** There is some evidence that on-bottom oyster culture impacts structural grass and algal communities. There is a strong theoretical basis developed through observational and manipulative studies to support the idea that modified macrophytes communities will impact various aspects of the environment.

**3.2.2.vii. Uncertainties and knowledge gaps.** Cascading effects due to aquaculture-related effects are unstudied.

**3.2.2.viii. Activity-specific links.** All aspects of husbandry may impact habitat structure, cover, and vegetation. The most important impact seems to be due to harvesting although impacts are related to harvest methods.

### 3.2.3 Stressors on Substrate Composition

**3.2.3.i. Effects profile.** Benthic substrate composition may be modified directly by the addition of 3-D physical structure used in aquaculture to the bottom (the oysters themselves) and by harvest methods and indirectly via modification of current regimes and by biological modification of the underlying substrate.

These effects have been little studied in the context of aquaculture. See also section 3.2.1.

**3.2.3.ii. State of knowledge of direct effects.** This literature review found no studies on the direct effects of structure related to on-bottom oyster culture on sediment composition (other than of the oysters themselves being part of the "substrate"). The presence of oysters on the bottom has been shown to directly modify current regimes in natural and restored oyster reefs (e.g., Breitburg et al. 1995) or else indirectly via modification of physical structure due to associated fauna (see section 3.2.1) or of macrophytes either fouling the oysters or living in the general area (see section 3.2.2). This may, in turn, modify sedimentation, accretion, and erosion. Biodeposition by associated species may also enrich sediments locally as has been shown for suspended and off-bottom culture of oysters and for on-bottom culture of other bivalve species.

Wisehart et al. (2007) evaluated sediment characteristics in eelgrass sites, off-bottom oyster longline sites, and dredged on-bottom oyster sites in Willapa Bay, Washington. They found that redox potentials were lowest in longline sites and greatest in eelgrass sites and that sediment silt content and accretion were lower in dredged sites relative to longline and eelgrass sites. It was suggested that lower structural heterogeneity due to lower eelgrass abundance or lack of longline structures in on-bottom dredged sites may have accounted for these effects. The study by Bouchet et al. (2008), which included variation in biogeochemical indices from sediments in a number of on-bottom and off-bottom oyster culture and control sites in intertidal mudflats in the Pertuis Charentais (France), found that redox potentials were lower (hypoxic conditions) within off-bottom oyster culture sites as compared to on-bottom (intermediate levels) and control sites (positive redox potentials). Mean grain size was smaller in culture sites relative to controls and organic matter was greatest in off-bottom oyster culture sites, intermediate in on-bottom oyster culture sites, and least in control sites. Erbland and Ozbay (2008) studied modified stacked cage culture and found median grain size of sediments directly under cage structures to be similar to that from a nearby sand/mud reference site whereas the silt/clay fraction was greater in the reference site. It was suggested that the bi-weekly cleaning of cages (which were lifted up to be cleaned) gave this result that is largely contradictory to known effects of bivalve culture.

In all of these examples, the relative contribution of biodeposition from cultured, modified physical structure, and other factors to the modification of benthic substrate is unclear. Although this review found no evidence of biodeposition by fouling organisms in on-bottom oyster culture impacting sediments, this is likely to occur if fouling is great.

**3.2.3.iii. Cascading effects and biological implications for ecosystem.** Physical modification of sediments has been shown to impact benthic communities in a large number of studies (Hargrave et al. 2008, Gray and Elliott 2009). Thus changes in sediment biogeochemistry due to on-bottom oyster culture will likely impact benthic communities with cascading effects on the rest of the ecosystem. Indeed, a number of studies have identified on-bottom oyster culture impacts on benthic communities (see section 3.2.1). Similarly, changes in sediment biogeochemistry will also modify nutrient fluxes and oxygen consumption which may also have a variety of cascading effects on the environment. No studies have linked such changes specifically to altered sediment biogeochemistry due to on-bottom oyster culture.

**3.2.3.iv. Magnitude of effects.** Effects are likely somewhat limited given that none have been suggested in the scientific literature which, overall, suggests that current methods of on-bottom oyster culture are fairly benign relative to other forms of bivalve culture.

**3.2.3.v. Modifiers of effects.** The magnitude of effects is likely mostly a function of husbandry practices, including stocking density and harvest method. Proposed effects will be affected by bottom, depth, current regimes, season, etc.

**3.2.3.vi. Available evidence.** This review found little published evidence of the influence of benthic structure in on-bottom oyster culture bivalve culture impacting benthic sediments or the influence of this on the ecosystem. Suggested impacts are based on extrapolations from the ecological literature or from literature regarding interactions from other types of bivalve culture and the environment.

**3.2.3.vii. Uncertainties and knowledge gaps.** Basic descriptive work is lacking. The impact of on-bottom bag culture for oysters, either for grow-out or for hardening off is poorly known.

**3.2.3.viii. Activity-specific links.** Husbandry practices likely have a great importance, including harvest method and maintenance throughout the grow-out cycle.

### 3.2.4 Stressors on Primary Productivity

**3.2.4.i. Effects profile.** Modification of benthic communities by the addition of benthic 3-D structure for on-bottom oyster culture may influence various benthic processes that may alter nutrient fluxes/recycling and thus impact primary productivity in the water column. These effects have not been examined in the aquaculture context.

**3.2.4.ii. State of knowledge of direct effects.** Direct effects of the addition of benthic structure on primary productivity in the water column seem unlikely. This review found no suggested effects.

**3.2.4.iii. Cascading effects and biological implications for ecosystem.** Modified benthic structure may influence benthic communities and sediments (see sections 2.2.1, 3.2.2, and 3.2.3). A number of studies have shown that variation in these parameters may modify nutrient fluxes and oxygen consumption (Reay et al. 1995, Cowan and Boynton 1996) which may alter the composition and primary productivity of plankton communities with cascading effects on the rest of the ecosystem. Although studies have shown the importance of suspended bivalve culture on benthic nutrient fluxes here in Canada (Richard et al. 2007a, Richard et al. 2007b) and internationally (e.g., Baudinet et al. 1990, Hatcher et al. 1994, Stenton-Dozey et al. 2001, Christensen et al. 2003, Giles et al. 2006, Nizzoli et al. 2006), this is usually assumed to be due to organic loading from the cultured product and associated organisms and not to effects arising from the addition of benthic structure. Filtration by associated species may also impact primary production locally but this has not been studied with respect to on-bottom oyster culture.

Resuspension or modification of sediments during harvesting and other husbandry practices could potentially influence primary production in the water column. That being said, on-bottom oyster culture is usually done in areas that experience considerable resuspension of sediments naturally and so any additional effects due to harvesting of on-bottom culture of oysters would likely be minor. This has not been evaluated.

**3.2.4.iv. Magnitude of effects.** The magnitude of any potential effects due to the modification of benthic physical structure on primary productivity in the water column is likely to be small.

**3.2.4.v. Modifiers of effects.** Proposed effects will be affected by bottom type, depth, current regimes, season, configuration of added benthic structure, the extent of oyster farms, the timing of the addition and removal of harvesting, seeding, maintenance, other husbandry variables, etc.

**3.2.4.vi. Available evidence.** No direct evidence is available to support the suggested links due to the modification of on-bottom oyster culture. All links are predicted based on ecological principles with solid theoretical and empirical foundations.

**3.2.4.vii. Uncertainties and knowledge gaps.** Although suggested pathways are based on a wealth of solid ecological work, none of the proposed effects have been evaluated for on-bottom oyster culture.

**3.2.4.viii. Activity-specific links.** The longer benthic structure is left in place, the greater effects will be until some sort of equilibrium is reached.

## 3.3 ADDITION/REMOVAL OF VERTICAL SITE INFRASTRUCTURE

Increasingly, oyster culture in near-coastal areas is moving from on-bottom to off-bottom methods as growth and husbandry efforts seem to be maximized using these methods and, in western Canada, on-bottom sites are increasingly being used for clam culture. Off-bottom oyster culture involves the use of trays, nets, cages, etc. that either float and are moored in place or else are supported by racks that sit on the bottom. Other methods include the use of on-bottom longline systems and stakes on which oysters are grown directly on the structures (see Mackenzie et al. 1997a, Mackenzie et al. 1997b, c, Boghen 2000 and Appendix I for reviews). In all cases, both the infrastructure used and the product itself constitute a considerable addition of 3-D structure in the near-shore environment, an environment that is often characterized by very little (in the case of mud flats) or considerable (in the case of eelgrass beds) benthic heterogeneity and structure. Although variable regionally, culture areas may range in size from a hectare or less to many hectares. Thus, substantial physical structure may be added to the near-shore environment which adds to or differs fundamentally from that which occurs naturally.

As for suspended bivalve culture, many of the potential and documented effects of off-bottom oyster culture are due to filtration and biodeposition by the cultured bivalves. However, many organisms grow associated with the water column structure added in off-bottom oyster culture, including many other filter feeding organisms which likely also have an effect similar to that of the bivalves being cultured with respect to grazing on plankton (Petersen 2007), providing structure (Paine and Suchanek 1983), contributing larvae to the meroplankton community (Broekhuizen et al. 2002), and biodeposition (Mallet et al. 2009). Given that the effects of grazing, larval production, and biodeposition were presented at the CSAS Pathway of Effects ,eeting, limited reference is made to related effects in the present document. In addition, a considerable amount of work has examined (or discussed) hydrodynamic modifications due to the added structure and its effect on benthic sediments as well as the general effects of the practice on eelgrass. An overview of the main pathways of effects for this stressor class is given in Figure 11. Figure 12 shows general effects relating to the addition of anchors for suspended bivalve culture.

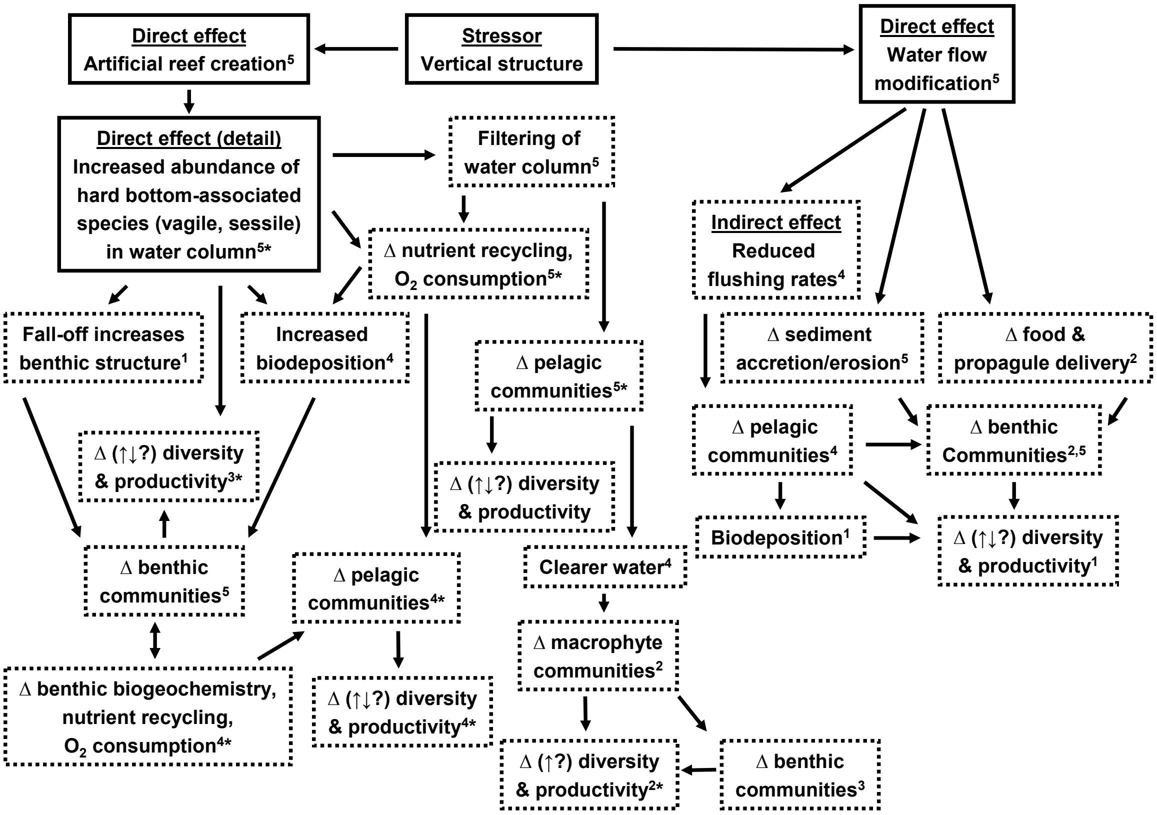

*Figure 11. Main pathways of effects for adjustments due to the addition/removal of vertical structure relating to off-bottom oyster culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

## 3.3.1 Stressors on Wild Fish Populations/Communities*

**3.3.1.i. Effects profile.** Off-bottom oyster culture adds considerable 3-D hard physical structure close to the bottom in near-shore areas and thus directly and indirectly increases the abundance of “benthic” organisms in this milieu. This may have cascading effects on the functioning of the rest of the surrounding ecosystem, including altering the abundance and/or productivity of a number of species/communities. A large number of other effects have also been proposed.

Direct effects due to the addition of physical structure in the water column have been fairly well studied. In contrast, indirect and cascading effects on wild fish populations/communities have not been studied and are largely conjecture. It is suggested that modelling would be best able to address these gaps.

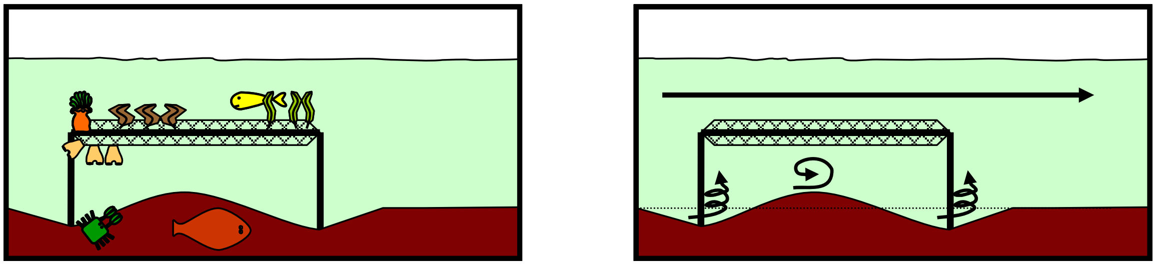

*Figure 12. General potential effects resulting from the addition of off-bottom physical structures for oyster culture (oyster tables) to the benthic environment. Left: creation of habitat for a variety of benthic organisms directly on the structures and under the structures. Right: current modifications lead to accretion and scouring and modify sediments around structures. Floating bag culture is usually done in less hydrodynamically energetic areas and likely has less of a hydrodynamic effect.*

**3.3.1.ii. State of knowledge of direct effects.** The bivalves and structures associated with off-bottom oyster culture create favourable habitats for other invertebrates by providing refuges from predation and adverse environmental conditions and a direct source of food for other invertebrates. A study of the assemblages associated with *C. virginica* floating bag culture in Virginia found a total of 45 (mean = 29) taxa on 50 oysters in each bag with annelids and molluscs being the most abundant groups (O'Beirn et al. 2004). The same study also noted that the portunid crab (*Cronius ruber*) was considered rare in Virginia but that 5 individuals were found in the sampled cages and that the numerous fish species sampled highlight the importance of oysters as habitat, suggesting that not only is the interstitial space among the oysters important but so too is the space arising from dead articulated shells for the blennies and gobies (Breitburg 1999). Similarly, in Australia the space between valves of dead Sydney Rock Oysters in table culture create favorable habitat for a variety of organisms that would not otherwise be present, such as the Blue Rring Octopus (Pieter Honkoop, personal communications). A manipulative experiment examining the epifaunal communities that develop associated with different proportions of live and dead Sydney Rock Oysters with shells together or disarticulated found that different types of communities develop in the different treatments, showing that the type of structure provided will impact the type of community that develops (Summerhayes et al. 2009). Likewise, Harwell et al. (2010) examined the communities associated with experimental grow-out trays with various combinations of *Crassostrea virginica* and *C. ariakensis* oysters and shell only controls and found site-specific differences between treatments in Chesapeake Bay. Cognie et al. (2006) examined the distribution of “wild” oyster (*Crassostrea gigas*) set in Bourgneuf Bay, France, and noted that such oysters accounted for 21% and up to 55 kg m$^{-2}$ of the biomass of oysters on oyster grow-out gear (racks). Mallet et al. (2009) examined the recruitment of various fouling organisms to floating bag culture over a 4 month period in 2 sites in New Brunswick and the influence of maintenance (turning the floating bags over to expose previously submerged sides of the bags to the air and sunlight to eliminate fouling organisms) on fouling levels and oyster growth. Bags (0.529 m$^{2}$) that were never turned had substantial fouling communities (mostly barnacles and mussels) develop on them (ca. 150 or 250 g dw bag$^{-1}$). In contrast, bags that were turned just once decreased fouling intensity by greater than 80%.

At a larger scale, Pinnix et al. (2005) examined fish communities throughout a year in eelgrass, mud flats, and off-bottom longline oyster culture in eelgrass or mud flats in Arcata Bay, Humboldt Bay, California (Figure 13). There was great temporal variation in catch rates and no clear trends were observed with respect to any of the parameters measured among habitat types. Dubois et al. (2007) examined the influence of off-bottom oyster culture in the Bay of Veys, France, on the trophic structure of *Lanice conchilega* tubeworm communities of the surrounding mudflats. They found that the biomass of benthic fauna within culture sites was dominated (almost 90% of the total biomass) by the European Green Crab (*Carcinus maenas*), but was absent in the surrounding mudflats. Given that this species is generally associated hard bottom or some type of physical structure (Behrens Yamada 2001), it is likely that this species was abundant due to the physical structure provided by the culture tables.

A multi-year observational study of Harbour seals in California by Becker et al. (2009) shows that this population changed the location of haul-out sites used coincident with the establishment of off-bottom oyster culture in certain areas. The authors suggest that this may be due, in part, to simple displacement of the seals by the oyster-growing equipment.

*Figure 13. Typical off-bottom longline oyster culture in Humboldt Bay, California (Photo: Bill Pinnix)*

As for most aspects related to “structure” per se, the influence of “structure” on the ecosystem is confounded by other factors. For example, it is not clear whether it is the physical structure of the equipment used, the oysters themselves, or both that lead to generally increased abundances of benthic-related organisms in the near-shore area. This review found few studies that attempted to separate these factors or to separate the importance of physical aspects of the cultured oysters (i.e., physical structure) from biological ones (e.g., filtration, biodeposition, prey source, etc.). That being said, that O’Beirn et al. (2004) found no correlation between the number of oysters in floating bag culture and the abundance and richness of the associated organisms suggests that the physical structure of the bag structure is largely responsible for the communities associated with the culture structures. This could be easily tested through a series of manipulative experiments. One such study was done by Laffargue et al. (2006) in the Bay of Biscay, although at a larger spatial scale, to evaluate the potential effect of off-bottom (trestle) oyster culture on the swimming activity of the sole (*Solea solea*). In a 600 $m^2$ mesocosm with 3 habitat types (zones - trestles with bags of live oysters, trestles with bags of oyster shell, and no aquaculture infrastructure, or free zone – note that the study was not replicated with respect to habitat type within the mesocosm), nine juvenile sole were followed using acoustic telemetry over 3, 2-week periods. Six of the nine sole examined remained largely (78 to 98% of the time) in the oyster zone during daylight whereas 2 others preferred the shell zone and the other the free zone. At night, sole moved much more and visited all zones although the oyster zone remained the preferred habitat for 6 sole. It was suggested that increased sedimentation in the oyster site due to the oysters themselves likely modified sediments to make it easier for the sole to burry themselves in the day. Thus, the physical structure itself was likely not that important for this species.

As pointed out above, many studies have shown that suspended bivalve culture sites act as a focus for a large number of invasive species and perpetuate infestations once they are established (see review in McKindsey et al. 2007) and it is likely that this is also true for off-bottom oyster culture. This point was further stressed by Forrest et al. (2009) who suggest that is the introduction and spread of invasive species is likely the single most important effect associated with oyster culture.

Forrest et al. (2009) suggest that the structure provided by off-bottom oyster culture may increase the abundance of jellyfish in an area by providing enhanced recruitment opportunities for the sessile medusa-producing stage. This could have a series of cascading effects (see Richardson et al. 2009) and reflects the observations made for suspended bivalve culture (see section 2.3.1.ii).

For some taxa, such as mussels, oysters, and scallops, spat are typically collected from the wild for growout in eastern Canada (see McKindsey et al. 2006a). This harvest of individuals from wild populations may be considerable but its impact unknown.

**3.3.1.iii. Cascading effects and biological implications for ecosystem.** According to Forrest et al. (2009), the accumulation of live oysters, shell litter and farm debris, and fouling or epibenthic organisms beneath growing structures can be the most visible effects of oyster farms. The extent of drop-off to the seabed is likely a function of grow-out method (e.g., stake or longline culture is likely to deposit more debris than floating bag or cage and rack culture). The degree of fouling accumulation will depend on local fouling levels and patterns of natural and husbandry-induced (cleaning and harvesting) drop-off. Although known to be of importance in suspended bivalve culture (see section 2.3.1), this review found no studies that have examined the importance of this structure on benthic or other communities.

Excessive deposition due to fouling organisms and decay of fouling biomass may also exacerbate organic enrichment due to biodeposition by cultured bivalves. Mallet et al. (2009) recently examined the importance of various management approaches (cleaning) to reducing fouling and biodeposition related to oysters and fouling for floating bag culture in New Brunswick. Greater maintenance reduced the fouling by some species but had no effect on biodeposition rates.

Indirect effects due to structure related to off-bottom oyster culture are difficult to separate from the indirect effects due to biodeposition from the cultured oysters themselves. Given that a considerable biomass of organisms may be associated with off-bottom oyster culture structure (see section 3.3.1.ii), biodeposition from this fraction of the culture-related biomass may be considerable. Further, a number of studies have suggested that off-bottom oyster culture structures modify hydrodynamics (section 3.3.7) and sedimentary processes (section 3.3.4), both of which may also influence benthic communities. For example, Nugues et al. (1996) examined the environmental effects associated with off-bottom (trestle) oyster culture in the River Exe estuary, England. In the study, they examined benthic infaunal communities, variation in current speed, sedimentation rates, and sediment biogeochemical measures (redox potential, organic content, chlorophyll content) in 2 culture plots and control plots. Infaunal abundance and diversity were lower under trestles than in control plots, sedimentation rates were greater, sediment organic content was greater under one trestle than the paired control but there was no difference in organic content between the other trestle and its paired control, currents were reduced in trestle sites relative to the controls, phaeopigment content was greater under trestles, and the redox discontinuity was much shallower under trestles relative to adjacent control areas. The authors suggest that the increased organic, silt and phaeopigment content under trestles relative to control plots was due to decreased current velocity due to the physical structure of the trestles. Forrest and Creese (2006) evaluated the impacts of off-bottom oyster culture in New Zealand and found that, although sedimentation and silt/clay and organic content were increased below culture racks, seabed elevation was lower, again suggesting that hydrodynamics due to culture equipment are important to modifying the benthic environment. Species dominance was as would be predicted by the disturbance gradient and sediment sheer strength was the best predictor of macrofauna distribution. De Grave et al. (1998) examined benthic attributes below oyster trestles, between them in access lanes, and in control sites in Dungarvan Bay, Ireland. They found little evidence of organic enrichment in the site and attribute this to the highly dissipative nature of the site. Similarly, Bouchet et al. (2008) suggest that the effects of off-bottom oyster culture in the Pertuis Charentais (France) are influenced by hydrodynamics such that they mediate effects from biodeposition.

As pointed out previously, organisms growing on farmed bivalves in suspension may filter great quantities of water to feed, consuming a variety of seston, phyto- mero- and zooplankton (e.g., Duarte et al. 2008, Grant et al. 2008). This may have great impacts on the pelagic ecosystem with concomitant impacts on fish, macrophytes, benthic organisms, etc. (Prins et al. 1998, Gibbs 2004, Newell 2004). For example, work by Decottignies et al. (2007) on the interactions between *C. gigas* grown in off-bottom oyster culture in Bourgneuf Bay, France, and the invasive gastropod (*Crepidula fornicata*), growing associated with it suggests that the two species are likely trophic competitors at some times of the year. This is also likely true for other species as well. Disruption of the benthic environment may also be mediated indirectly by augmenting the abundance of ecologically important species. For example, oyster table culture in Bay de Veys, France, has been shown to augment the abundance of the European Green Crab (*Carcinus maenas*), within culture areas (Dubois et al. 2007). The authors of this work suggest that this may influence the abundance of large bivalves within the culture sites as few were present but they were abundant outside of culture sites in the surrounding area. Modeling efforts to understand broader implications of off-bottom oyster culture on the ecosystem have, to date, not included the organisms associated with the structural complexity of the structure associated with off-bottom oyster culture (for example, Leguerrier et al. 2004, Lin et al. 2009). This topic is not covered further here.

Abandonment of off-bottom oyster culture equipment in Arcachon Bay, France, has led to the development of “wild” reefs of Pacific Oysters that settle on this equipment. This represents at greater biomass of oysters in the site than that represented by farmed oysters (Salvo submitted). This increase in the biodiversity of hard-bottom associated species and alters benthic infaunal and planktonic communities, even to a greater extent than do the farmed oysters.

Physical disturbance due to equipment and personnel during husbandry (maintenance and harvesting) activities have been reported to impact benthic communities at off-bottom (trestle) *C. gigas* culture sites in Ireland (De Grave et al. 1998). Heightened abundances of decapods, reduced numbers of small crustaceans and fragile, shallow-burying bivalves in access lanes relative to control locations combined with no significant organic matter increases led the authors to conclude these results were caused by physical disturbance from vehicle and foot traffic.

**3.3.1.iv. Magnitude of effects.** Given the considerable structure that is added in off-bottom oyster culture, effects may be similarly great. The direct impacts of added structure may greatly augment diversity locally and indirect effects may influence both benthic and pelagic ecosystems. These cascading effects have been poorly studied.

**3.3.1.v. Modifiers of effects.** The most important potential modifiers are likely depth (e.g., subtidal vs intertidal), current regimes, and husbandry practices. Other modifiers include season, larval supply, substrate type, etc. These factors have been little examined to date.

**3.3.1.vi. Available evidence.** A limited number of observational studies have documented the influence of off-bottom oyster culture on associated communities. Most of these have been done at a single or limited number of dates and so data is limited to a series of snapshots of what is present at a given time. Cascading effects from direct effects are less well studied although most proposed pathways are based on solid ecological foundations. Very little experimental or theoretical (modelling) work has tried to establish dose-dependent relationships for impacts from the practice.

**3.3.1.vii. Uncertainties and knowledge gaps.** Basic data on the association between off-bottom oyster culture structures and fouling and other associated communities are lacking from Canada. These are needed to make predictions of ecosystem-level influences. Bags kept at the surface in floating bag culture are typically placed on the bottom to avoid ice-scour over the winter (Mallet et al. 2006). It is unknown what impacts this may have on wild fish populations. In all cases, relationships between the number/size of structures and oysters within them and the influence of this on the associated assemblages is unknown.

**3.3.1.viii. Activity-specific links.** Effects occur throughout the culture period and effects likely increase with time. Husbandry practices, especially harvesting and cleaning, likely greatly impact community development and related effects due to fall-off and foot or vehicular movement across the bottom in culture sites.

### 3.3.2 Stressors on Habitat Structure, Cover, and Vegetation

**3.3.2.i. Effects profile.** Benthic habitat structure, cover, and vegetation may be impacted directly by off-bottom oyster culture via mechanical disturbance associated with husbandry activities. Indirect effects due to filtration leading to decreased turbidity and nutrient release may stimulate growth of algae and seagrasses.

Direct effects due to husbandry practices on eelgrass have been fairly well studied but indirect effects have not.

**3.3.2.ii. State of knowledge of direct effects.** Off-bottom oyster culture has been shown to modify eelgrass communities in a number of extensive studies. Everett et al. (1995) examined the impact of off-bottom stake and rack oyster culture methods in Coos Bay, Oregon, on eelgrass (*Z. marina*) cover, density and growth (and of physicochemical parameters and the vertical profile of bottom sediments) using a manipulative experiment where they established multiple culture sites (plots) and compared these to control plots without such treatments. Eelgrass density was reduced by both off-bottom methods although the density within stake plots seemed to start off that way and the effect did not increase over time, unlike the rack treatment which showed an increasing effect over time. Shoot density was also lower in stake culture than in control plots and remained so even after stakes were removed during the commercial harvest. No recruitment was observed in one stake experiment but was in a second, when recruitment was greater in control plots. In general, shoot density was almost nil directly under racks which were surrounded by a halo of low density eelgrass. Eelgrass growth was not affected by the presence of off-bottom oyster culture although it is not clear where samples for this were taken for the rack culture (i.e., under or adjacent to racks). It was suggested that differences in the architecture of culture structures modified current regimes locally to alter benthic sedimentation/scouring and sediment structure. Algal biomass was greater in stake plots (often growing on the stakes themselves) than the paired control sites whereas the opposite was true for the rack treatment. The authors suggest that increased abundance of algae may occur through 3 mechanisms: passive trapping of algae, the addition of stable substratum, and the reduced currents within stake sites.

Tallis et al. (2009) compared eelgrass (*Z. marina*) density, growth and biomass in multiple sites for each of 4 treatments: off-bottom longline, on-bottom harvested by hand, on-bottom harvested by dredge, and reference (no oyster culture) in Willapa Bay, Washington (see section 3.2.2.ii). In short, eelgrass density was least affected by longline culture methods and overall productivity was slightly less in all culture sites relative to controls. They suggest that limited impacts due to this practice (relative to using a dredge to harvest on-bottom oysters) are due to the more benign method of harvesting: limited foot traffic. Wisehart et al. (2007) looked more specifically at the response of early life stages of eelgrass to oyster culture in the same area and found that seed production by the plant was lowest in areas with longline culture. A manipulative study done within this work showed that seedling growth, germination, and survival did not differ among treatments initially but were lower in longline areas thereafter.

Vaudrey et al. (2009) examined short-term effects of off-bottom oyster culture on eelgrass (*Z. marina*) in Long Island Sound, near the Mystic River, Connecticut, where the practice is used as a depuration technique. In this system, 0.9 × 0.9 m cages on 15 cm legs are placed within eelgrass beds for 2 to 3 week periods. The presence of the structures had no effect on the growth of eelgrass adjacent to the cages and little or no effect on the eelgrass directly under the cages as evaluated immediately following cage removal after 2 weeks deployment.

Rumrill and Poulton (2004) compared the impact of line spacing of off-bottom longline culture on eelgrass in experimental plots in Humboldt Bay, California. Experimental oyster plots (30 m X 30 m) had 1 of 7 treatments: line spacing distances of 1.5 ft (narrow), 2.5 ft (standard), 5 ft (wide), 10 ft (very wide), a longline control (no lines, only stakes to support them), an on-bottom commercial plot, and 5 control plots. Eelgrass density was followed throughout the culture period and harvesting was done by hand. Eelgrass spatial cover and shoot density were consistently greatest within the control plot and least in the 1.5 ft spacing plot. Eelgrass metrics generally scaled directly with oyster density and the spatial cover and density of eelgrass in control plots was only observed in the 10 ft spacing plot.

**3.3.2.iii. Cascading effects and biological implications for ecosystem.** Impacts on eelgrass, which is considered to be an “ecologically significant species” (DFO 2009), may have a number of cascading effects on the surrounding ecosystem. The importance of this habitat has been described in many reviews (e.g., Chambers et al. 1999, Jackson et al. 2001, Heck et al. 2003, Williams 2007) and is not elaborated upon here. See section 2.3.2.iii for a brief overview.

**3.3.2.iv. Magnitude of effects.** Given the vast areas over which this type of culture may occur, impacts on eelgrass and cascading effect from this may be great.

**3.3.2.v. Modifiers of effects.** The most important modifiers are likely husbandry practices, especially harvesting and cleaning. Other modifiers include stocking density, depth and turbidity, current regimes, season, substrate type, etc. These latter factors have been little examined to date.

**3.3.2.vi. Available evidence.** Several observational studies and limited manipulative studies have addressed these effects.

**3.3.2.vii. Uncertainties and knowledge gaps.** Cascading effects are poorly known but of potential great importance to the functioning of the ecosystem. These should be better studied empirically and through modelling. Bags kept at the surface in floating bag culture are typically placed on the bottom to avoid ice-scour over the winter (Mallet et al. 2006). It is unknown what impacts this may have on eelgrass another structural species.

**3.3.2.viii. Activity-specific links.** The activities with the greatest impact on eelgrass are likely related to harvest methods, maintenance, and stocking density.

### 3.3.3 Stressors on Access to Habitat/Migration Routes

**3.3.3.i. Effects profile.** The vertical infrastructure added in off-bottom oyster culture provides shelter for some species, creating habitat that may not otherwise exist in some coastal areas.

Such direct effects may be confounded with a variety of other factors. Indirect effects have not been evaluated.

**3.3.3.ii. State of knowledge of direct effects.** A number of studies have shown that large vagile animals may be associated with the structure provided by off-bottom oyster culture, using it as a base from which it may migrate some distance to forage, etc. For example, Laffargue et al. (2006) evaluated the potential effect of off-bottom (trestle) oyster culture on the swimming activity of the sole (*Solea solea*). In a 600 $m^2$ mesocosm with 3 habitat types (zones - trestles with bags of live mussels, trestles with bags of oyster shell, and no aquaculture infrastructure, or free zone) in the Bay of Biscay, France. The majority of fish studied stayed associated with off-bottom structures in the day but foraged in all habitats at night time. Work in the Bay de Veys, France, has shown that the abundance of the European Green Crab, *Carcinus maenas*, is augmented within culture areas relative to nearby control areas (Dubois et al. 2007). It is likely that this species uses this shelter as a base from which it may forage on the surrounding habitats. Greater influences on migration routes have not been described or proposed. As pointed out earlier (section 3.3.1.ii), Becker et al. (2009) found that use of haul out sites by Harbour seals was negatively correlated to off-bottom oyster production (harvest rates) and suggest that this was due to disturbance by culture activities, either passive (presence of culture equipment) or active (husbandry activities).

**3.3.3.iii. Cascading effects and biological implications for ecosystem.** Given the limited effects of off-bottom oyster culture on migration routes and habitat access, cascading effects are likely very slight.

**3.3.3.iv. Magnitude of effects.** Given the limited effects of off-bottom oyster culture on migration routes and habitat access, the magnitude of effects is likely slight.

**3.3.3.v. Modifiers of effects.** Effects are likely modified by the abundance of structure related to off-bottom oyster culture in an area. Effects are likely variable seasonally and among areas.

**3.3.3.vi. Available evidence.** There is limited evidence that vertical structure used in off-bottom oyster culture impacts access to habitat and migration routes. This comes from various research observations conducted throughout the world. Experimental evidence is mostly lacking.

**3.3.3.vii. Uncertainties and knowledge gaps.** Given the paucity of data on this effect, its overall importance is largely uncertain.

**3.3.3.viii. Activity-specific links.** Effects likely vary with harvesting and maintenance schedules.

### 3.3.4 Stressors on Substrate Composition

**3.3.4.i. Effects profile.** Substrate composition may be influenced by biodeposition in the form of faeces (from farmed bivalves and associated organisms) and drop-off of farmed bivalves and associated organisms, by activities related to husbandry, and by modification of current regimes due to the structure associated with off-bottom oyster culture.

Impacts from biodeposition have been largely studied (see section 3.3.1, Keeley et al. 2009. McKindsey et al. 2011); most of such studies for off-bottom oyster culture are confounded with other factors. Little work has focused on the importance of drop-off. Impacts on substrate composition due to currents are complex and are discussed in sections 3.3.1.iii and 3.3.7.

**3.3.4.ii. State of knowledge of direct effects.** The most direct way that off-bottom oyster culture may impact substrate composition is via the accumulation of live oysters, shell litter and farm debris, and fouling or epibenthic organisms beneath growing structures (Forrest et al. 2009). The extent of drop-off to the seabed is likely a function of grow-out method (e.g., stake or longline culture is likely to deposit more debris than floating bag or cage and rack culture). The degree of fouling accumulation will depend on local fouling levels and patterns of natural and husbandry-induced (cleaning and harvesting) drop-off. Fouling in suspended bivalve culture has been shown to greatly increase sedimentation rates locally (see section 2.3.1.iii) and it is likely that this occurs in off-bottom oyster culture as well, given the heavy fouling often associated with this practice. The only study this review found to have evaluated this was that by Mallet et al. (2009), who looked at variation in sedimentation loads associated with different maintenance strategies for oyster floating bag culture in New Brunswick. Bag maintenance (= fouling intensity) did not influence sedimentation rates (including drop-off) under the bags.

The structures associated with off-bottom oyster culture have been shown or suggested to modify current regimes in a number of studies (see sections 3.3.7 and 3.3.1.iii). In short, current modifications have been shown to impact accretion and erosion rates with impacts on sediment structure, organic content, and other related physicochemical indices.

Although off-bottom oyster culture is usually associated with considerable movement of personnel in and around culture structures, this review found only one study (De Grave et al. 1998) that explicitly compared sediment conditions in access lanes to those in other areas of a farm site and general area. The study found significantly lower levels of coarse and medium sand and higher levels of fine sand in access lanes and under trestles than in adjacent control areas but that organic matter did not vary among areas. Together, this suggests that some factor other than biodeposition (foot or vehicular traffic or current regimes) likely modified sediment composition.

**3.3.4.iii. Cascading effects and biological implications for ecosystem.** Indirect effects related to biodeposition from bivalve culture have been well documented with respect to changes to sediment biogeochemistry (e.g., Cranford et al. 2006, Hargrave et al. 2008) and the creation of benthic reef-like hard bottom structure (see section 3.3.1.ii). See sections 3.3.1.iii and 3.3.7 for impacts from hydrodynamic-mediated effects.

**3.3.4.iv. Magnitude of effects.** Given the large scale of off-bottom oyster culture operations in some regions, local effects may be substantial. Altered sediment structure will have a large variety of cascading effects throughout the ecosystem.

**3.3.4.v. Modifiers of effects.** Potential modifiers include depth, season, background current regimes, substrate type, degree of fouling and fall-off, husbandry practices, etc. See section 3.3.1 for further details.

**3.3.4.vi. Available evidence.** There is a wealth of observational studies examining the link between suspended bivalve culture and benthic communities. No manipulative studies were found in this review.

**3.3.4.vii. Uncertainties and knowledge gaps.** There has been very limited experimental work to try to establish dose-dependent relationships between farming intensity/extent and influence on sediments and cascading effects from this.

**3.3.4.viii. Activity-specific links.** Tables, racks, etc., are semi-permanent structures and so their impacts likely reach an equilibrium in the environment once they have been installed for a period. Harvesting will likely greatly change benthic sediment structure due to fall-off and on-site cleaning and compaction and resuspension of sediments.

### 3.3.5 Stressors on Food Availability/Supply

**3.3.5.i. Effects profile.** The vertical structure associated with off-bottom oyster culture serves as a structure for the growth of bivalves and the organisms associated with them. These provide a direct resource to pelagic and benthic organisms, modify benthic structure that alter benthic communities, and compete directly with, prey on, and contribute to pelagic communities.

These effects have been fairly well established although dose-dependent effects are needed to advance modelling efforts to better predict impacts and carrying capacity.

**3.3.5.ii. State of knowledge of direct effects.** A fair bit of information is available about the influence of vertical structure used in suspended bivalve culture on the availability of food in the water column and on the bottom. This has been covered in section 3.3.1.

**3.3.5.iii. Cascading effects and biological implications for ecosystem.** Alterations in food supply related to the addition of vertical structure have been shown to alter benthic and pelagic components of the ecosystem. This has been covered in section 3.3.1

**3.3.5.iv. Magnitude of effects.** Given the size and number of farm sites in some areas, effects are potentially great.

**3.3.5.v. Modifiers of effects.** Potential modifiers include depth and turbidity, current regimes, season, larval supply, substrate type, etc. Husbandry practices (such as seeding, maintenance, and harvesting) are likely of importance but have been little studied to date.

**3.3.5.vi. Available evidence.** Direct effects have been examined using observational studies but indirect or cascading effects have been much less well studied. Most predicted pathways remain supposition based on ecological principles.

**3.3.5.vii. Uncertainties and knowledge gaps.** Dose-dependent responses of benthic and pelagic communities to the level of off-bottom oyster culture are needed to develop models to predict impacts and determine ecological carrying capacities of areas for off-bottom oyster culture.

**3.3.5.viii. Activity-specific links.** Effects occur throughout the culture period and likely increase with time (increased fouling, etc.).

### 3.3.6 Stressors on Primary Productivity*

**3.3.6.i. Effects profile.** Vertical structure used in off-bottom oyster culture allows for the growth of many associated filter-feeding and other species that may prey directly on phytoplankton or alter nutrient fluxes and oxygen consumption/generation and thereby alter plankton community composition.

Grazing by species associated with the structure associated with off-bottom oyster culture structures has been poorly studied.

**3.3.6.ii. State of knowledge of direct effects.** Direct effects of the provision of vertical structure in suspended bivalve culture on primary productivity are largely unknown.

Modified benthic structure may influence benthic communities and sediments (see sections 2.2.1, 3.2.2, and 3.2.3). A number of studies have shown that variation in these parameters may modify nutrient fluxes and oxygen consumption (Reay et al. 1995, Cowan and Boynton 1996) which may alter the composition and primary productivity of planktonic communities with cascading effects on the rest of the ecosystem. Although a number of studies have shown the importance of suspended bivalve culture on nutrient fluxes here in Canada (Richard et al. 2007a, Richard et al. 2007b) and internationally (e.g., Baudinet et al. 1990, Hatcher et al. 1994, Stenton-Dozey et al. 2001, Christensen et al. 2003, Giles et al. 2006, Nizzoli et al. 2006), this is usually assumed to be due to organic loading from the cultured product and associated organisms and not to effects arising from the addition of benthic structure. That being said, Richard et al. (2007b) suggest that entrapment of organic matter by scallop culture equipment (pearl nets) increases and alters nutrient fluxes in the water column, an effect that could, in principle, also arise with off-bottom oyster culture, given that the oysters are commonly in netting that may similarly trap organic matter. Filtration by associated species may also impact primary production locally but this has been little studied and will be a function of fouling intensity. Souchu et al. (2001) studied the influence of bivalve culture (mostly oysters and a mix of off-bottom and suspended methods) in the Thau Lagoon in southern France on nutrient and oxygen trends as well as primary production and the composition of planktonic communities. Unlike most studies, they explicitly consider the contribution of epifaunal filter-feeders to the observed trends. Although temporally and spatially variable, oxygen concentration, chlorophyll a, and primary production were decreased by the presence of filter-feeders. Nutrient concentrations were also modified by the presence of oyster culture in the sites. Together, these modifications shifted the phytoplanktonic community to one dominated by picophytoplankton. In sum, they suggested that filter feeders were able to alter the dominant biogeochemical process in the water column by stimulating nitrification. Estimates of the clearance rate by fouling tunicates associated with oyster culture in Thau Lagoon (off-bottom and suspended) suggest that the former take about 2 to 3 times as long to filter the water than do the oysters in culture that they grow associated with (2.4 days for oysters vs. 10.5 days for tunicates, Gangnery 2003). Given the greater retention efficiency and ability of tunicates to filter smaller particles than the bivalves they grow associated with (Petersen 2007), Gagnery (2003) suggests that the fouling component may have and important effect on the functioning of the ecosystem of the lagoon.

Abandoned culture equipment used in off-bottom oyster culture may act as a substrate on which oysters and other organisms may develop, transforming eventually into reef-like structures. This has been shown in Arcachon Bay, France. A recent study by Salvo (submitted) found that oysters and related associated organisms growing on these structures filter a greater proportion of the water in the bay than do the oysters being cultured within it and also have a greater influence on nutrient recycling and release, all of which may impact primary production within the bay.

**3.3.6.iii. Cascading effects and biological implications for ecosystem.** Cascading effects of the provision of vertical structure in off-bottom oyster culture on primary productivity are related to the development of filter-feeding communities associated with the structure provided by off-bottom oyster culture. This review found no research on this subject that focuses specifically on oysters in off-bottom oyster culture; most focus on suspended bivalve culture or oyster reefs.

**3.3.6.iv. Magnitude of effects.** The magnitude of any potential effects due to the addition of vertical physical structure on primary productivity may be great given the scale of culture sites and the fundamental ecological importance of grazing and nutrient regeneration in coastal areas.

**3.3.6.v. Modifiers of effects.** Effects are greatly modified by hydrodynamics (flushing due to winds, tides, rivers, etc.), bottom type, depth, season, configuration of added vertical structure, the extent of oyster farms, etc.

**3.3.6.vi. Available evidence.** There is only limited evidence for proposed effects. Most studies on such interaction concentrate on suspended bivalve culture. Extrapolation to off-bottom oyster culture is likely possible but proposed effects must be evaluated based on this uncertainty.

**3.3.6.vii. Uncertainties and knowledge gaps.** Better quantification of associations between the structure added in off-bottom oyster culture and fouling communities is needed to better predict filter-feeding and respiration effects due to this component.

**3.3.6.viii. Activity-specific links.** It is assumed that effects on primary productivity are ongoing throughout the grow-out period. Harvesting and cleaning/maintenance will reduce pelagic fluxes and oxygen consumption from off-bottom culture units and the benthic environment.

### 3.3.7 Stressors on Water Flow

**3.3.7.i. Effects profile.** The physical vertical structure placed in the water column for off-bottom oyster culture influences current regimes within sites, slowing currents at a large scale but increasing turbulence and accretion and sedimentation at smaller scales.

The effect of this on benthic sediments and communities is evident but the indirect effects arising from this are not.

**3.3.7.ii. State of knowledge of direct effects.** A large number of studies have suggested that the addition of structure associated with off-bottom oyster culture in physically dynamic intertidal and shallow subtidal environments could obstruct current flow patterns, increasing sedimentation rates and decreasing mechanical erosion (e.g., Ottman and Sornin 1985, Castel et al. 1989, Martin et al. 1991, Kirby 1994, Everett et al. 1995, Nugues et al. 1996, Bertin et al. 2005, Bertin and Chaumillon 2006, Forrest and Creese 2006, Mallet et al. 2006, Cayocca et al. 2008, Kervella et al. 2010). However, few studies have actually measured these effects and simply attribute observed differences in sediment accumulation, benthic communities, etc., to this effect (see section 3.3.1.iii for examples). There are also some notable exceptions.

In a large manipulative study (Everett et al. 1995), rack culture was shown to induce considerable erosion at the edge of the racks (up to 25 cm deep) whereas stake methods encouraged deposition. There were trends for an increased clay/silt fraction and organic content in stake sites whereas the opposite was true for rack sites. Ottman and Sornin (1985) report similar effects for table and Bouchot (blue mussel, *Mytilus edulis*) culture in France, suggesting the importance of physical modification of local hydrodynamics due to culture structures on the benthic environment. Kervella et al. (2010) did a series of flume studies to better understand the impacts of arrays of oyster tables on small-scale hydrodynamics and thus sediment dynamics. An array of tables was set up perpendicular to flow and currents examined under various hydrodynamic regimes; results are described for 3 boundary areas around the tables: one immediately above, one immediately below, and one next to the bottom. Currents above tables are decreased by up to ca. 50% after about 3.6 m along the array, the thickness of the boundary area depending on the roughness of the culture structures (bags). Currents are deflected to the side and then converge at the trailing edge of the table. Merging of below-table and bottom boundary areas greatly decreases flow velocities. In contrast, increased structure under the tables (i.e., table legs) increases bottom sheer stress and turbulence. The impact of these effects together will determine whether sedimentation will be increased or decreased.

At a larger scale, Kervella et al. (personal communications) showed that oyster tables in the Baie du Mont-Saint-Michel, France, reduce tidal flow by up to 40 and 50% and deflect it by 15 to 20º (ebb and flow tides, respectively) and attenuate waves with a long period by up to 40% but have little impact on waves with a short period. Sornin (1981) showed that tidal currents are slowed by almost 50% by oyster tables in the Marennes-Oléron Bay, France, and Bertin et al. (2005) have suggested that the presence of oyster tables in the same area increases the frictional properties of the bay to the extent that flushing rates have been modified. This has also been suggested for areas of Mont Saint Michel Bay, France (Cayocca et al. 2008). Ultimately, it is suggested that these modified currents will lead to increased infilling of the embayment. Based on the work described above, Kervella et al. (2010) suggest that oyster tables reduce tidal flow and wave propagation and that hydrodynamic models for coastal circulation should modify coefficients for current dissipation by a factor of √10 when there are oyster culture structures. However, they also point out that this reduction does not consider the heterogeneity of the added structure, which includes alleys between table rows, and so this value is likely too high (they cite values of 1.4 to 2.5 for *bouchot* farms).

**3.3.7.iii. Cascading effects and biological implications for ecosystem.** Change in currents may influence flushing and thus the provision/replenishment of planktonic food/communities in sites, nutrient exchange with more oceanic waters, oxygen concentrations in the water column, etc.

**3.3.7.iv. Magnitude of effects.** Effects may be quite great, especially in areas where culture sites are large/abundant.

**3.3.7.v. Modifiers of effects.** Impacts on flow are largely determined by husbandry practices, including stocking density and farm configurations. This includes the density and form of culture structures (size, height from substrates, orientation to flow, etc.). Flow may be further reduced via the accumulation of fouling organisms on culture structures.

**3.3.7.vi. Available evidence.** Much empirical work has shown water flow to be impacted by the presence of vertical structure used in off-bottom oyster culture. In contrast, little work has evaluated how modifications at different spatial scales interact or what effect they have on the organisms in the surrounding environment.

**3.3.7.vii. Uncertainties and knowledge gaps.** Interactions between the effects on flow at different spatial scales and their effects on the surrounding ecosystem are mostly unknown. Interactions between husbandry practices (stocking density and cleaning) and flow have not been evaluated but are likely important in determining site carrying capacities.

**3.3.7.viii. Activity-specific links.** Effects occur throughout the culture period but likely vary with respect to the timing of stocking, harvesting, and maintenance/cleaning.

## 3.4 RESUSPENSION/ENTRAINMENT OF SEDIMENTS

Once added, equipment used in off-bottom oyster culture is often a more or less permanent fixture of the benthic environment. Modification of current regimes around off-bottom oyster culture infrastructure (cages on racks, etc.) may lead to very specific erosion and accretion patterns for sediments around culture fixtures. Other factors that may influence sediments have been discussed in the preceding sections (3.2 and 3.3) and are not discussed further here. All sections requested are addressed below but simply as references to the appropriate preceding sections.

### 3.4.1 Stressors on Wild Fish Populations/Communities

See sections 3.2.1 and 3.3.1

### 3.4.2 Stressors on Substrate Composition

See sections 3.2.3 and 3.3.4

### 3.4.3 Stressors on Oxygen (Water Column and Benthos)

See sections 3.2.4 and 3.3.6

### 3.4.4 Stressors on Contaminant Concentrations

**3.4.4.i. Effects profile.** Increased biodeposition linked to the presence of bivalves and their associated fauna may lead to the accumulation of contaminants in benthic sediments. Modified sedimentation and erosion around culture structures may alter contaminant concentrations in sediments.

Direct effects due to the addition of physical structure in the water column have been observed, although only rarely. Indirect effects are unknown but likely.

**3.4.4.ii. State of knowledge of direct effects.** Much of the epifauna associated with off-bottom oyster culture, in addition to the cultured oysters themselves, are filter feeders. As such, they may filter great quantities of water and concentrate contaminants in the seston and plankton in faeces and pseudofaeces, thus increasing the concentration of these contaminants in benthic sediments. This has been suggested to occur for off-bottom oyster culture by Kirby (1994). Martin et al. (1991) have shown experimentally that in-sediment contaminant loads were correlated with sedimentation rates related to biodeposition by off-bottom oyster culture. The effect was greatest in sandy sediments where increased contaminant levels were observed to a depth of 25 cm. Sediment contamination was mitigated by the removal of cultured oysters within 2 months. It is not clear if only oysters were removed or if oysters and culture structures were removed and so it is not clear if effects were due to increased biodeposition from the oysters or from culture structure hydrodynamic-mediated increases in sedimentation.

**3.4.4.iii. Cascading effects and biological implications for ecosystem.** There are many impacts of contaminants in sediments (Reynoldson 1987, Gray and Elliott 2009).

**3.4.4.iv. Magnitude of effects.** Effects will be cumulative over time but may be reversible. Given the restrictions on site licensing in Canada, it is expected that these will be limited.

**3.4.4.v. Modifiers of effects.** The most important modifiers are background contaminant levels, stocking density, age of culture sites, and site hydrodynamics.

**3.4.4.vi. Available evidence.** There is much literature showing the importance of filter-feeders on the bioconcentration of contaminants in sediments. Few have examined these effects with respect to suspended bivalve culture.

**3.4.4.vii. Uncertainties and knowledge gaps.** The importance of these effects is generally poorly studied and thus not well-known.

**3.4.4.viii. Activity-specific links.** The process will occur throughout the culture period with effects becoming more important through time.

### 3.4.5 Stressors on Suspended Sediment Concentration

See sections 3.2.1, 3.3.1, and 3.3.2.

# 4. IN-BOTTOM CLAM MARINE AQUACULTURE

In-bottom clam culture in Canada is concentrated mostly on the Pacific coast where the Manila Clam (*Tapes philippinarum*) is the main species cultured. Culture of the Geoduck Clam (*Panopea abrupta*) is in its infancy (Hand and Marcus 2004) although commercial trials are underway. Considerable portions of some areas may be devoted to the practice. For example, Carswell et al. (2006) states that shellfish tenures (exact type is not stated and may include oyster and clam culture) occupy 20.3% and clam netting 2.9% of the intertidal area of Baynes Sound. Although a maximum of 6% of major habitat types in Baynes Sound is covered, up to 22% of optimal clam habitat in 3 regions in BC may be covered with anti-predator netting (Carswell et al. 2006). The B.C. Ministry of Sustainable Resource Management (2002) suggests that 32% of beach area in Baynes Sound is under tenure for shellfish culture (again, no distinction is made between oyster and clam leases but most of this was for oyster culture originally but many leases are being switched to Manila clam culture). On the Atlantic coast, clam culture is in its infancy and the main species being investigated are the Soft-Shell Clam (*Mya arenaria*) and Quahog (*Mercenaria mercenaria*). The availability and quality of the evidence supporting the various linkages between stressors and ecosystem components is given in Table 3.

## 4.1 SHADING ADJUSTMENTS

Considerable areas may be covered with car mats or other types of anti-predator netting in in-bottom clam culture. This will clearly negatively impact the amount of light that reaches the bottom. In turn, this will logically impact wild fish populations/communities, habitat structure, including SAV, and have a cascading influence on a variety of other communities. This review found no discussion of these issues with respect to in-bottom clam culture. It is suggested that any such effects will likely be similar to those outlined in sections 2.1 and 3.1, except for the scale of any impacts, and these sections should be consulted for a general understanding of the issues. Any effects due to shading adjustments will likely be confounded with other effects (altered hydrodynamics, sedimentation, organic loading, etc.).

## 4.2 ADDITION/REMOVAL OF SHORELINE/BOTTOM STRUCTURE

Structural modifications associated with in-bottom clam culture are mostly limited to the addition of anti-predator covering over clam beds. Other structural modifications include the placement of tubes to protect juvenile clams in the case of Geoduck (*Panopea abrupta*) culture. Bottom structure may also be modified by the addition of the cultured bivalves and, at times, sediment (gravel) of a size that encourages good growth of the cultured bivalves and stabilizes the sediments. Moreover, culture sites are also subject to physical disruption of substrates during harvesting and thus all clam culture will have at least some impact via this physical disturbance (Vandermeulen et al. 2006).

Most studies on physical modifications of sites due to in-bottom clam culture are observational and confounded with other factors (e.g., increased biodeposition due to the presence of cultured clams, the addition of clams themselves). Ecosystem-level effects have not been well studied. It seems apparent that community responses to disturbance are habitat-specific insomuch as benthic communities impacted by in-bottom clam culture disturbances in more unstructured areas (simple soft-sediment bottoms) are quite resilient, returning to normal conditions quite rapidly, whereas benthic communities in habitats dominated by structure-providing species (eelgrass or polychaetes) require longer to return to normal conditions. The rapid recovery is likely due to the dynamic nature of the unstructured habitats whereas the habitats dominated by structural species are dependent on the prior development of populations of longer-lived species. An overview of the main pathways of effects for this stressor class covered in this review is given in Figure 14 and Figure 15 shows general effects relating to the addition of protective netting for in-bottom clam culture.

### 4.2.1 Stressors on Wild Fish Populations/Communities

**4.2.1.i. Effects profile.** Addition of netting on the bottom or placement of tubes in the bottom allows for many organisms to become established directly on the netting and increases recruitment or establishment of other species and alters sedimentation rates (Spencer et al. 1996). Modification of sediments by adding gravel and removing large rocks and woody debris modifies benthic communities and related parameters. Modification/disturbance of the bottom via harvesting impacts benthic communities directly. Such direct effects may have various cascading effects on the ecosystem.

*Table 3. Availability and quality of information supporting the linkages between 4 stressor types and various ecosystem components for in-bottom clam culture. Note that the table does not recognize the direction or severity of the stressor-effect linkage; the table must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Labels refer to the various sections in document. For example, Section 4.2.1 concerns the effects of in-bottom clam culture on shoreline/bottom structure on wild fish populations/communities.*

| **In-bottom clam** | **Ecosystem components** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Stressor type** | **Wild fish populations / communities** | **Habitat structure, cover, vegetation** | **Access to habitat / migration routes** | **Substrate composition** | **Food availability / supply** | **Primary productivity** | **Water flow** | **Oxygen (water column/benthos)** | **Contaminant concentrations** | **Suspended sediment concentration** |
| **Shading adjustments** | **1, mostly not relevant** | | | | | | | | | |
| **Shoreline/bottom structure** | **4** | **4** | **5*** | **4** | | **→0** | | | | |
| **Vertical structure** | **1, mostly not relevant** | | | | | | | | | |
| **Resuspension/ entrainment** | **1, mostly not relevant** | | | | | | | | | |

Key to table: 5 – Substantial peer-reviewed evidence from aquaculture setting. 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature. 3 – Substantial peer-reviewed evidence from non-aquaculture literature. 2 – Limited peer-reviewed evidence from non-aquaculture literature. 1 – Best guess. →0 – Effect not supported by literature. Empty cells indicate that the pathway was not considered. Asterisk indicates that this is the purpose of adding the structure (i.e., to control organisms from consuming farmed bivalves).

Some direct effects have been studied to good degree whereas others have not. Very few studies have examined the cascading effects resulting from in-bottom clam culture. Further basic descriptive work is needed to address such knowledge gaps. Modelling is needed to address cascading effects.

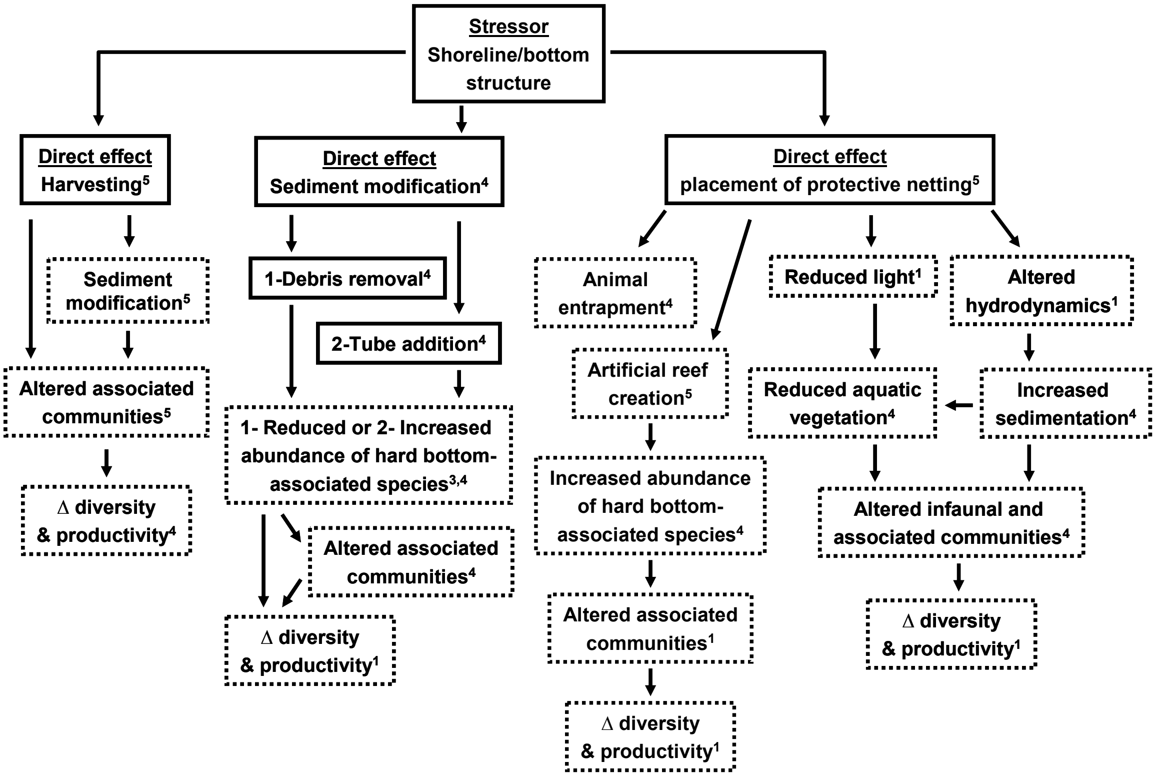

*Figure 14. Main pathways of effects for adjustments due to the addition/removal of shoreline/bottom structure relating to in-bottom clam culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**4.2.1.ii. State of knowledge of direct effects.** In-bottom clam culture practices involve a number of activities that modify the physical environment. This includes clearing the beach of large rocks, woody debris, and competing species. In British Columbia, these species may include Littleneck clam (*Protothaca stamenia*) and surface species such as mussels (*Mytilus trossulus)* and barnacles (*Balanus glandula*) as well as predatory species such as Moon Snails (*Euspira lewisii*) and starfish (*Pisaster* spp.) (Bendell, personal communication; Jamieson et al. 2001). These predatory organisms may be removed from the systems altogether and disposed of above the high water line (Bendell, personal communications). Historically, gravel of the appropriate size to encourage good growth and stabilize sediments was added to some beaches and berms or vexar fencing may have been constructed to attenuate wave exposure in British Columbia (Jamieson et al. 2001) but these practices are not common now. After seeding, sites in British Columbia and elsewhere around the world are often covered with anti-predator netting that may be of plastic with 1.25 cm apertures or woven rope with apertures up to 3.5 cm.

Harvesting in British Columbia is done exclusively by hand raking (Jamieson et al. 2001) although trials of mechanized methods are ongoing (Stirling and Cross 2009).

Perhaps the most evident physical modification of the environment in in-bottom clam culture is the addition of anti-predator netting. Many species have been reported growing associated with such netting, including mussels and other filter feeders and various types of algae. Many of these species would not find suitable substrate in what may otherwise be a coastal area with fine sediments. For example, Powers et al. (2007) sampled "biogenic structure" (mostly algae but also some erect epifauna) associated with Quahog (*Mercenaria mercenaria*) culture with polypropylene mesh bags as well as with seagrass (*Zostera* marina and *Holdule wrightii*) and a sand flat. This biogenic structure biomass in culture sites was consistently greater on aquaculture mesh than sand flats but did not differ from that associated with seagrass on most sample dates. A number of other articles also discuss the abundance of such fouling organisms on protective netting (Simenstad et al. 1993, Spencer et al. 1996, 1997, Whiteley and Bendell-Young 2007) but this has not typically been quantified. Although growth of such species has also been suggested to occur with PVC tubes inserted into bottom sediments for geoduck culture (Vadopalas et al. 2005, Fisher et al. 2008, Straus et al. 2008), this review found no quantitative data on the subject.

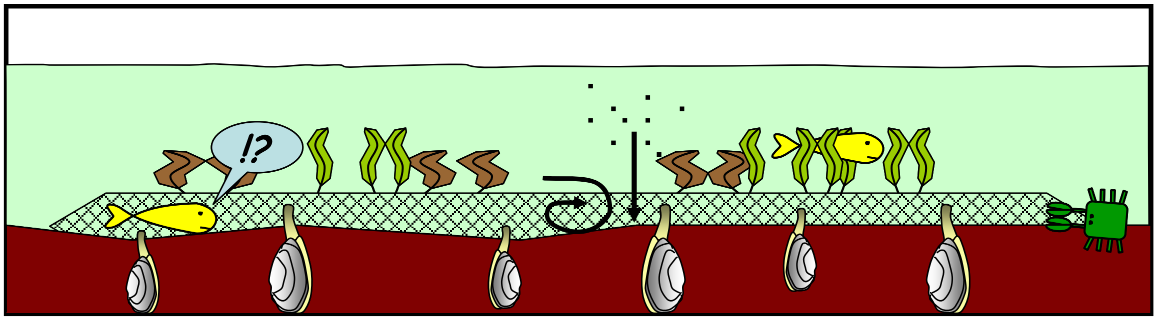

*Figure 15. General potential effects resulting from the addition of protective anti-predator netting for in-bottom clam culture to the benthic environment. Creation of habitat for a variety of benthic organisms directly on the structures. Currents are modified and increases sedimentation under the netting. Netting may also trap fish and other species.*

Anti-predator netting may also entrap a variety of organisms and lead to their death (e.g., entrapment of fish at low tide and entanglement of birds caught while foraging at high tide). This review found no quantitative data on this subject. Similarly, anti-predator netting may end up as refuse in the ecosystem (subtidal and intertidal), as has been shown for netting used in Quahaug farms in eastern North America (Ayers 2006). The impact of such derelict equipment has drawn much interest (e.g., Good et al. 2010) but this review found no references addressing this issue specifically for clam culture.

Anti-predator netting has also been suggested to increase sedimentation rates (Spencer et al. 1996) and recruitment of some species to the underlying sediments (Beal and Kraus 2002). One of the few studies to attempt to separate the factors of anti-predator netting and the presence of seeded and farmed bivalves was that of Spencer et al. (Spencer et al. 1996, 1997, 1998). In this long-term study in the River Exe, England, they followed the benthic communities and related parameters associated with Manila Clam farming over the complete grow-out cycle through harvesting and recovery. They had 3 main treatments: clams and netting, netting only, and no net or clams. Nets alone were shown to reduce flow and increase sedimentation, modifying substrate conditions (smaller grain size, increased organic content), thus showing that increased sedimentation is due to the nets and not only the presence of the cultured Manila clams. In contrast, a study on sedimentation rates and benthic-pelagic particle flux related to the culture of Manila clams found a significant correlation between Manila Clam biomass and density and biodeposition rates in China (Jie et al. 2001). Thus, it is likely that modification of biodeposition rates is modified by both biological and physical processes.

However, netting does not always alter benthic substrates. For example, Munroe and McKinley (2007) examined the influence of predator netting on four farms and paired control sites in British Columbia and found that predator netting did not influence grain size or organic content. Similarly, PVC tubes added to the bottom for Geoduck culture would be predicted to alter hydrodynamics and thus sediment characteristics and recruitment rates. However, Pearse et al. (submitted) found no evidence that such an effect occurred in an experimental installation in British Columbia as infaunal community and sediment characteristics were not affected by the addition of PVC tubes over a period of 1 year. In contrast, sulphide levels decreased immediately after adding the tubes to the sediments, possibly due to mixing anoxic sediments by the physical insertion (i.e., disturbance) of the tubes into the sediments.

Whitely and Bendell-Young (2007) examined the influence of Manila clam culture and predator netting on bivalve communities in 3 regions of British Columbia. Overall, richness, diversity, abundance and evenness did not vary between farmed (anti-predator netting) and adjacent non-farmed areas. Although bivalve community composition did not differ between farmed and reference sites, variation among farmed sites was much less than variation within and among reference sites, suggesting that some characteristic of Manila Clam farming (nets or the clams themselves) is forcing in-bottom clam culture sites to converge on a similar community type, thereby losing regional distinctness.

Clearing of rocks and other hard substrates will have the opposite effect insomuch as they often represent the only natural attachment sites for algae, mussels, barnacles, and other hard-bottom associated species in areas characterized by soft sediments, such as those used for in-bottom clam culture (Bendell, personal communications). Clearing beaches of large predators, such as starfish and snails, will obviously reduce the abundance of these species locally.

The addition of gravel has been shown to increase the density of bivalves and cover by macroalgae, primarily *Ulva* sp., in both a sandy and a mud/sand area in Puget Sound, Washington (Thom et al. 1994). Thompson (1995) found that plots to which gravel was added had greater abundances of nemerteans and amphipods as well as shore crabs, which were not present in control plots, but the abundance of polychaetes was reduced. Mussels were observed in dense patches and bound the gravel together with byssal threads. Community changes were consistent with the textural changes brought about by the addition of gravel. Simenstad et al. (1991) examined the influence of gravel addition on the abundance of 9 epibenthic invertebrate taxa that are used to sustain fishes, including juvenile salmon, in 2 sites in Puget Sound. Species associated with algae seem to increase in abundance when gravel is added whereas gammarid amphipods (i.e., *Corophium* spp.) and cumaceans (*Cumella vulgaris*) respond differently, depending on the initial substrate (increase in abundance if initial substrate is mud but decrease if initial substrate was sand).

Harvesting of bivalves farmed in in-bottom clam culture has a number of direct effects on benthic communities and sediments. Although harvesting of Manila Clams is now conducted solely by hand using rakes (Jamieson et al. 2001), trials are ongoing on both the west (Stirling and Cross 2009) and east (Provencher, personal communications) coasts to evaluate the efficacy and impacts of mechanized methods to harvest clams in aquaculture. To date, past trials on the impact of harvest methods have shown that mechanized methods have a greater impact on the bottom than do hand harvesting methods although both have impacts (Peterson et al. 1987). Much work has been done on "fishery" impacts from harvesting and less on "in-bottom clam culture-related harvesting impacts.

Harvest of Geoducks uses partially mechanized systems whereby high volumes of pressurised sea water is injected into sediments (using "stingers", see Dumbauld et al. 2009) to liquefy them, lifting the clams to the surface. The principle is similar to that being evaluated by Provencher (unpublished results) whereby a hydraulic rake does the same for soft-shell clams. In both cases, there are little peer-reviewed results although loss of some associated fauna would be expected, at least in the short term. Provencher et al. (unpublished data) evaluated the impact of a hydraulic rake to harvest Softshell clams by sampling 3 experimental and 3 reference sites immediately prior to and following harvest and at 1, 4, 12, and 52 weeks after harvesting in both the spring and fall. In short, the abundance, biomass and richness of organisms > 1mm were decreased by harvesting operations in the fall (but not the spring) but recovered within 1 year. The abundance of large organisms (other than Softshell clams) was not affected by harvesting. A recent study, presented at a Pacific CSAS Invertebrate SubCommittee Meeting: Pink and Spiny Scallop, Sea Cucumber, Central Coast Manila Clam, Geoduck Clam Aquaculture, evaluated the effect of outseeding and harvesting Geoducks by sampling infauna (> 1 mm) before seeding through 6 months post-harvest (of 1-year old clams) within an experimental culture plot and at a reference site 10 m from it along a transect sampled for many indices running parallel to the shore. Outplanting seemed to have no effect but harvesting negated increased richness and abundance observed in the paired reference location. This effect disappeared following 6 months.

Kaiser et al. (2001) examined the impact of harvesting cockles (*Cerastoderma edule*) using hand raking on non-target species and under-sized cockles associated with intertidal cockle beds and the effects of size of disturbed sediment patch size on subsequent recolonisation. Harvesting increased damage rates of undersized cockles three-fold relative to control plots. Infaunal communities were altered by harvesting but small plots recovered within 56 days whereas large plots did not. Commercial digging for soft-shell clams in Maine was found to reduce species richness and the abundance of species of polychaetes (Brown and Wilson 1997). Westhead (2005) recorded similar findings where commercial harvesting of bloodworms (by hand raking) and soft-shell clams (by digging) in the Minas Basin, Nova Scotia, reduced the biomass and abundance of intertidal benthic macro- and meiofaunal communities and community dominance shifted from sessile, tube-dwelling polychaetes to mobile opportunists such as harpacticoid copepods, nematodes, capitellids, and mud shrimp, causing overall increased abundance in harvested areas relative to non-harvested areas.

While significant effects are often observed immediately following bottom culture harvesting in unvegetated, soft-sediment habitat, quick recovery of invertebrate communities appears quite common (Kaiser et al. 1998). Ferns et al. (2000) examined the impact of cockle (*Cerastoderma edule*) harvesting in muddy sand and sandy habitats in Wales. Harvesting in both habitats greatly reduced the abundance of the most common species and some remained that way for at least 100 days post-harvest. Invertebrate populations in clean sand with relatively few cockles recovered more quickly than those in muddy sand with a more structured community, which included several tube-dwelling polychaetes such as *Pygospio elegans* and *Lanice conchilega*. Cockle harvesting by suction and tractor dredges greatly reduced the abundance of non-target benthic fauna but the communities recovered rapidly as the study sites were indistinguishable from controls within 56 days (Hall and Harding 1997). Dolmer et al. (2001) noted that infaunal abundance and diversity decreased immediately following suction dredge harvesting of Manila clams from an area of muddy-sand bottom in Northern Europe (Spencer et al. 1998). That said, the infaunal community returned to reference conditions after only 1 year. Toupoint et al. (2008) examined the impact of Manila clam farming on benthic communities in an area with strong tidal currents in the Chausey Archipelago, France. Harvesting greatly reduced the abundance of the structure-providing polychaete, *Lanice conchilega,* and the abundance, richness and diversity of other infaunal species with these indices tending towards that of control sites as the communities developed over the 3-yr grow-out cycle. Peterson et al. (1987) compared the impacts of harvesting Quahog (*Mercenaria mercenaria*) by hand and two intensities of mechanized harvesting ("clam kicking", where a modified boat engine directs the propeller wash downwards to suspend bottom sediments and clams into a plume in the water column; the clams are collected in a trawl net towed behind the boat) in two habitats (sandy bottom and one with eelgrass) in North Carolina. Clam harvest type did not affect the density or species composition of small infauna (but see section 4.2.2). A study using a similar method to harvest Manila clams in the Lagoon of Venice showed that this harvest method reduced the abundance of macrofauna but did not impact infaunal communities (Pranovi et al. 2004).

Kaiser et al. (1996) showed that harvesting by suction dredge altered sediments by removing the larger sand fractions down to the clay substratum. Pranovi and Gionavardi (1994) showed that hydraulic dredging for short-necked clams (*Tapes* spp.) left 8 to10 cm deep furrows but did not modify the size structure of the benthic sediments. Pearce et al. (submitted) evaluated the effect of outseeding and harvesting Geoducks on sediment characteristics by sampling benthic sediments before seeding through 6 months post-harvest (of 1-year old clams) within an experimental culture plot and at distances of 5, 10, 25, and 50 m from it by sampling along transects running on-shore, off-shore, and parallel to the shore. In short, of all the sediment characteristics evaluated, only the proportion of silt and clay seemed to be impacted by culture activities and this was only brought on by harvesting and the effect disappeared within 4 months. It was suggested that the sediment plume resulting from harvesting, sedimented close to or within the culture site, thereby increasing the proportion of fine sediments there.

Depending on how clams are harvested, much sediment may be raised in suspension by the method used. For example, Pranovi et al. (2004) measured the impact of Manila clam harvest using a "rusca" (modified propeller system that produces a downward jet of water that resuspends target species and sediments, the target species being caught in a net towed by the harvest boat). They reported that this practice creates furrows in the bottom about 60 cm wide and 7 cm deep, the bottom sediments ending up in suspension and increasing suspended particulate loads by greater than 2 orders of magnitude and augmenting the total and organic carbon, total nitrogen, and sulphide loads in the water column. It is very likely that this is a general effect related to this type of harvesting as well as suction methods. It is reasonable to assume that harvesting by hand in the intertidal zone would have a much lesser impacted on SPM loads although this review found no studies on this effect.

One possible mechanism by which bivalves may influence the structure of benthic communities is the displacement of other infaunal species by their physical structure. However, even in commercial leases in British Columbia, the physical space occupied by the cultured bivalves averages about 2% (range: < 0.01% to 13.2%, Whiteley and Bendell-Young 2007) and so this is not the likely mechanism.

**4.2.1.iii. Cascading effects and biological implications for ecosystem.** Despite the good number of studies on the effects of in-bottom clam culture on various communities, few consider the cascading effects of the practice on the greater environment. Thom et al. (1994) report that amphipods and isopods were abundant and used the habitat created by mussels that bound gravel together by byssal threads. Spencer et al. (1996, 1997) suggest that increased abundances of algae associated with predator netting likely increased the abundance of the gastropod, *Littorina littorea*. They also suggested that the algae grew more abundantly because of increased nutrient fluxes due to increased sedimentation, the algae consequently slowing currents locally and further increasing sedimentation rates, showing the complexity of the addition of structure, such as netting. Thom et al. (1994) showed that addition of gravel for clam culture in Puget Sound, Washington, increased benthic respiration rates and increased the flux of all nutrients measured (silicate, phosphate, nitrate, nitrite, ammonia, and total inorganic nitrogen). A number of other studies have shown that clam farming increases benthic respiration and nutrient fluxes (Bartoli et al. 2001, Nizzoli et al. 2006, Nizzoli et al. 2007) although these latter studies have not discussed the importance of modified habitat structure in bringing about these effects. Given that much of the primary productivity in coastal areas is supported by nutrient recycling, (Nixon 1981), modification of nutrient fluxes may have a wide variety of ecosystem-level effects, as have been discussed in previous sections. Such effects are scale-dependent but their importance has not been evaluated in the context of in-bottom clam culture (but see Marinov et al. 2007).

Toupoint et al. (2008) describe a situation whereby modification of the physical environment brought on by farming Manila Clams (a completely mechanized system starting with beach preparation, seeding with juvenile clams, covering with anti-predator netting which is cleaned monthly, grow-out over 2 to 3 years, and then harvest) reduces the abundance of the structure-forming polychaete, *Lanice conchilega,* which when present, promotes a diverse associated assemblage which itself promotes secondary consumers, such as fish and birds. They further question the impact of this on the trophic structure of the greater ecosystem.

A study by Powers et al. (2007) suggested that the increased abundance of structural species growing on quahog grow-out bags in North Carolina (mostly macroalgae, but also some erect epifauna) increased the abundance and diversity of associated macrofauna (fish and macroinvertebrates) from base-line levels observed in sandy habitats to those found in near-by seagrass beds. However, it is not clear if this increased density of associated fauna was due to the presence of structural species, such as algae, or the structure provided by the bags used in that culture method (i.e., bags used in the study resemble 3-D cages more than layers of netting on the bottom.

Thompson (1995) suggests that the removal of large benthic structure such as boulders and woody debris removes the structure that creates small-scale eddies and other hydrodynamic turbulence that enhances recruitment of some species locally and modifies food delivery and other related processes. These types of effects are discussed in the context of the addition of benthic structure in the section on suspended bivalve culture (see section 2.3).

Ferns et al. (2000) noted that bird feeding activity increased following mechanical harvesting for cockles in Wales, with gulls and waders consuming the invertebrates that were made available by harvesting. Kaiser et al. (1996) showed that harvesting by suction dredge that removed the larger sand fractions of bottom sediments down to the clay substratum reduced the abundance and taxonomic richness of the harvested areas. These communities were re-established within 7 months in the dynamic study region, highlighting the importance of hydrodynamic processes. Similarly, work by Spencer showed that physical structure in the form of anti-predator netting rather than farmed Manila clams increased sedimentation and thus the abundance of small opportunistic worms, changing benthic community structure and functioning below the nets. Pranovi and Gionavardi (1994) showed that hydraulic dredging for clams in Italy removed much of the abundance and biomass of infauna associated with benthic sediments. Again, many of the lost organisms returned to levels comparable to those in reference sites within 2 months.

Removal of large predators from culture sites may alter predator-prey dynamics with various cascading effects on the rest of the ecosystem, including increasing the abundance of infauna locally. Jamieson et al. (2001) suggest that the absence of such predators from culture sites may account for unpredictable differences between culture and control sites rather than other explanatory factors, such as the use of anti-predator netting.

**4.2.1.iv. Magnitude of effects.** Although many effects have been shown to arise from the modification of physical structure related to in-bottom clam culture, few discuss or predict many larger-scale effects on the ecosystem. However, given the increasing number and size of in-bottom clam culture sites, potential effects may become of importance locally.

**4.2.1.v. Modifiers of effects.** Effects are likely modified greatly by husbandry practices, such as cleaning frequency, and harvest method. Natural modifiers include substrate type and current regimes, wave exposure, depth, etc.

**4.2.1.vi. Available evidence.** Most evidence for direct impacts due to altered physical structure are observational in nature and are often confounded by other factors. That being said, effects observed are often as would be predicted based on ecological principles and are thus most likely valid.

**4.2.1.vii. Uncertainties and knowledge gaps.** Studies on indirect effects are lacking. In particular, given the apparent importance of algal development in some situations and the importance of this as habitat in near-shore areas, basic research on associations such as the work by Powers et al. (2007) are needed.

**4.2.1.viii. Activity-specific links.** Many activities in in-bottom clam culture may modify the physical structure of the sea bottom in culture sites. These include removal of large natural structure from sites, channelisation of streams, addition of anti-predator netting and gravel, and harvesting as well as on-going maintenance and foot/vehicular traffic in culture zones.

### 4.2.2 Stressors on Habitat Structure, Cover, and Vegetation

**4.2.2.i. Effects profile.** The modification of benthic structure due to in-bottom clam culture may impact habitat structure directly as many associated activities/practices may negatively impact vegetation and faunal bioherms in culture sites.

The influence of modifications of benthic structure related to in-bottom clam culture on habitat structure, cover and vegetation and the indirect influence of this on other populations and communities are largely unstudied in the context of aquaculture.

**4.2.2.ii. State of knowledge of direct effects.** Removal of large rocks and woody structure in the preparation of in-bottom clam culture sites may also remove the only benthic structure in near-shore areas that may support large algae and hard bottom-associated invertebrates, such as mussels and barnacles, thus potentially reducing the abundance of these important foundation species in near-shore areas. This review found no studies that address this point directly. In contrast, addition of anti-predator netting or gravel may increase the abundance of algae locally (see section 4.2.1)

A study by Peterson et al. (1987) compared the impacts of harvesting quahog (*Mercenaria mercenaria*) by hand and two intensities of mechanized harvesting. Raking and light clam-kicking treatments decreased seagrass biomass by ca. 25% below controls but full recovery occurred within a year. Seagrass biomass was decreased by ca. 65% by the intense clam-kicking treatment and recovery did not begin until after 2 years passed and remained 35% lower than predicted 4 years later. Alexandre et al. (2005) studied the effect of harvesting clams in wild and private concessions for clam culture and paired control sites on seagrass (*Zostera noltii*) density and reproductive output in Portugal. In short, seagrass densities in harvested meadows were significantly less than in control sites. In contrast, reproductive output (seed production and reproductive season length) by the plant was significantly greater in harvested areas. Experimental harvesting mirrored these results. Interestingly, seagrass densities did not differ one month post harvest (roots cut or damaged but plants not removed by hydrodynamic forces) but did in subsequent months, although it returned to baseline conditions within one year. Boese (2002) did an experimental study on the impact of recreational clam harvesting on eelgrass (*Zostera marina*) in Yaquina Bay, Oregon, and found similar results; experimental harvesting had no immediate effect but eelgrass cover and above- and below-ground biomass was reduced 1 month following simulated harvesting. Statistical differences between treatment and control plots were not evident 10 months post-manipulation. The author also points out that the site in which the study was conducted has been harvested intensively for decades and that eelgrass is still present.

**4.2.2.iii. Cascading effects and biological implications for ecosystem.** Little work has examined the cascading effects of in-bottom clam culture on the ecosystem. Boese (2002) examined effects of clam harvesting on eelgrass and also sampled benthic infauna. Despite effects on eelgrass, no effects were observed on infauna. However, manipulated plots were only 1 × 1 m and thus are not representative of commercial harvesting of culture sites, border effects make rapid migration by fauna into the sites likely, and impacts may or may not be related to eelgrass loss. Given that in-bottom clam culture has been shown to reduce eelgrass abundance and that presence of this plant is commonly correlated with increased diversity, abundance, and productivity (e.g., Bertness et al. 2000, Heck et al. 2003), such loss may have a number of cascading effects on the environment (Waycott et al. 2009). These have not been addressed in the context of in-bottom clam culture. Likewise, the cascading effects from the loss of the habitat-forming polychaete *Lanice conchilega* due to the culture of Manila Clams in France are poorly known but likely impact not only the associated invertebrates but also secondary consumers such as fish and birds (Toupoint et al. 2008).

Few studies have examined the cascading effects of in-bottom clam culture increasing the abundance of algae and other habitat-forming species on anti-predator netting or gravel. The few that have are discussed in section 4.2.1.iii.

**4.2.2.iv. Magnitude of effects.** Given the extent of areas within sites that may be impacted by the modification of benthic structure in in-bottom clam culture and the importance of macrophytes and other habitat-forming taxa to ecological processes, effects may be locally important.

**4.2.2.v. Modifiers of effects.** The variety of possible effects may be modified by substrate type, hydrodynamics, depth/intertidal height, and husbandry practices.

**4.2.2.vi. Available evidence.** There is considerable evidence from observational and manipulative studies (as well as basic ecological principles) that in-bottom clam culture operations may directly influence habitat structure, cover, and vegetation. Cascading effects from this have been little studied in the context of in-bottom clam culture.

**4.2.2.vii. Uncertainties and knowledge gaps.** Cascading effects due to in-bottom clam culture-related effects are largely unstudied.

**4.2.2.viii. Activity-specific links.** All aspects of husbandry may impact habitat structure, cover, and vegetation. The most important impact seems to be due to harvesting method and the use of anti-predator netting.

### 4.2.3 Stressors on Substrate Composition

**4.2.3.i. Effects profile.** Benthic substrate composition may be greatly impacted by a large variety of mechanisms. Direct effects include modification of benthic communities, including a variety of foundation species. Indirect effects are not well known.

Many direct effects resulting from these activities have been evaluated through observational studies; some have been through manipulative studies. Very few studies have considered cascading effects from such substrate composition modifications. See also section 2.1C.17B.

**4.2.3.ii. State of knowledge of direct effects.** Mechanisms of substrate modification include the addition of bivalves being cultured, the addition of gravel to ameliorate growing conditions for cultured bivalves, the use of anti-predator netting, addition of PVC tubes for geoduck farming, the removal of large rocks and woody and other debris from culture sites, maintenance activities such as net cleaning and vehicular use and trampling in and around culture sites, and harvesting. These are discussed in section 4.2.1 and are not reiterated here.

Direct effects due to substrate modification are consistent with shifting benthic communities towards a structure that is more typical of the new substrate structure brought about by modification of the physical environment by practices associated with in-bottom clam culture. These are discussed in section 4.2.1 and are not reiterated here.

**4.2.3.iii. Cascading effects and biological implications for ecosystem.** Physical modification of sediments has been shown to impact benthic communities in a large number of studies (Hargrave et al. 2008, Gray and Elliott 2009). Thus changes in sediment structure and biogeochemistry due to in-bottom clam culture likely impact benthic communities and nutrient fluxes and oxygen consumption with cascading effects on the rest of the ecosystem. Very few studies have evaluated or discussed these implications (see section 4.2.1). No studies have linked such changes specifically to altered substrate composition due to in-bottom clam culture.

**4.2.3.iv. Magnitude of effects.** It seems apparent that community responses to disturbance are habitat-specific. Benthic communities impacted by in-bottom clam culture disturbances in unstructured areas (simple soft-sediment bottoms) are quite resilient, returning to normal conditions quite rapidly, whereas benthic communities in habitats dominated by structure-providing species (eelgrass or polychaetes) require longer to return to normal conditions. The rapid recovery is likely due to the dynamic nature of the unstructured habitats whereas the habitats dominated by foundation species are dependent on the prior development of populations of longer-lived species.

**4.2.3.v. Modifiers of effects.** The magnitude of effects is likely mostly a function of husbandry practices, including the area under culture, site preparation (structure and predator removal, addition of gravel), anti-predator net use, harvest method, and traffic within and around sites. Effects will be affected by bottom type, depth, current regimes, season, etc.

**4.2.3.vi. Available evidence.** There is considerable evidence to support some proposed effects. However, most studies on effects have been confounded (e.g., addition of predator netting or gravel as well as the cultured clam). Thus, separation of individual factors is very difficult.

**4.2.3.vii. Uncertainties and knowledge gaps.** Basic descriptive work is lacking. The direct impact of the addition of physical structure on associated fouling species and the cascading effects of this are lacking. Studies separating various potential causative factors for effects are lacking.

**4.2.3.viii. Activity-specific links.** All husbandry-related practices are likely of great importance.

### 4.2.4 Stressors on Primary Productivity

**4.2.4.i. Effects profile.** Modification of benthic communities by the addition or modification of benthic structure for in-bottom clam culture may influence various benthic processes that may alter nutrient fluxes/recycling and grazing rates on phytoplankton and thus impact primary productivity in the water column. These effects have not been examined in the context of in-bottom clam culture.

**4.2.4.ii. State of knowledge of direct effects.** Direct effects of the addition or modification of benthic structure on primary productivity in the water column seem unlikely. This review found no suggested effects.

**4.2.4.iii. Cascading effects and biological implications for ecosystem.** Marinov et al. (2007, 2008) have modelled hydrodynamic-biogeochemical interactions for Manila Clam farming in the Sacca di Goro Lagoon and shown the importance of the practice in controlling primary productivity. Spillman et al. (2008, 2009) also modeled Manila clam culture-nutrient-phytoplankton dynamics for aquaculture in Italy (Barbamarco Lagoon) and also showed the link between these three factors. Although benthic communities may be modified via in-bottom clam culture (see section 4.2.1) and species associated with infaunal clams are of potential importance in controlling grazing rates on phytoplankton and primary productivity (Riisgård et al. 2007), these parameters were not included in these modelling efforts.

Resuspension or modification of sediments through the various husbandry-related activities may also potentially influence primary production in the water column. That being said, in-bottom clam culture is often done in areas that experience considerable resuspension of sediments naturally and thus any additional effects due to clam culture are likely minor. This has not been evaluated.

**4.2.4.iv. Magnitude of effects.** The magnitude of any potential effects due to the modification of benthic physical structure on primary productivity in the water column is likely to be small.

**4.2.4.v. Modifiers of effects.** Proposed effects will be affected by bottom type, depth, current regimes, season, configuration of added benthic structure, the extent of clam farms and all husbandry-related activities.

**4.2.4.vi. Available evidence.** No direct evidence is available to support the suggested links due to the modification of in-bottom clam culture. All links are predicted based on ecological principles with solid theoretical and empirical foundations.

**4.2.4.vii. Uncertainties and knowledge gaps.** Although suggested pathways are based on a wealth of solid ecological work, none of the proposed effects have been evaluated for in-bottom clam culture.

**4.2.4.viii. Activity-specific links.** All husbandry-related activities may influence primary productivity through a variety of pathways.

# 5. FINFISH CAGE AQUACULTURE

Finfish culture in Canada is based largely on net pen or cage culture of salmonids (salmon and trout) and mostly in the marine environment. Salmon culture alone accounts for almost 100 thousand tonnes of the total Canadian aquaculture production of 150 thousand tonnes. A typical salmon farm operates 6 to 24 net cages, each with between 35,000 and 50,000 fish per cage with farms varying in size from 2.8 to 4.6 hectares in size. Net cages can be circular or square. Circular cages typically have a circumference of between 23 and 32 metres and square cages are roughly 30 by 30 metres. Nets are typically attached to flexible support structures of steel and/or plastic and a walkway. Weights are used to keep the proper tension on the net to maintain its proper shape. Several cages in a site are typically grouped together with heavy moorings. Nets have various mesh sizes and are usually increased in size throughout the growing cycle and additional nets may be used on the outside to keep out seals and other predators. Depth varies considerably by location. The submerged substrate of a typical salmon farm in Puget Sound, Washington, was estimated at ca. 18 000, 1 000, and 120 $m^2$ for nets (1 side only), floats, and lines, respectively (Rensel and Forster 2007). Most salmon culture is centred in British Columbia and New Brunswick whereas most freshwater trout cage culture is in Ontario. Current trends for cage culture are towards intensification and proliferation of cage production. Taken together, it is clear that cage farming of salmonids in Canada contributes much physical structure to the nearshore environment.

To date, most research on the influence of cage culture for salmonids has focussed on nutrient loading, genetic effects, and disease. Little work has addressed the importance of the physical structure added in fish cage aquaculture. Yet cage structures are known to modify the physical environment at the farm location by modifying light penetration, currents, and wave action as well as providing surfaces for the development of rich assemblages that may further increase the complexity of the habitat (Davenport et al. 2003). In fact, major recent reviews on aquaculture-environment interactions (e.g., Black 2001, Pillay 2004, Hargrave 2005, Podemski and Blanchfield 2006, Holmer et al. 2008) do not discuss the implications of these structures or do so only in a very limited way. Only Johannes (2006), Davenport et al. (2003), and Costa-Pierce and Bridger (in Stickney and McVey 2002) treat this issue explicitly. The issue of physical structure related to fish cage aquaculture is also mentioned in Tlusty et al. (2001) but discussions are largely limited to threats due to entanglement and loss of structures to the bottom. Dürr and Watson (2010) discuss the impact of fouling on the cost to the industry and means to address the problem. Further, comparatively little work has been done in freshwater systems. As such, this review covers marine and freshwater finfish cage culture together with an emphasis on marine systems. An overriding issue in all discussions is the fact that most proposed effects due to the addition of structure related to fish cage aquaculture are confounded by the addition of large quantities of feed to the environment and any observable impacts may be due, at least in part, to this factor. Effects due to closed containment systems would likely resemble those of net cage structures although they may differ in predictable ways (e.g., greater shade, modification of currents altered fouling communities. These have not been evaluated and are not considered further. The availability and quality of the evidence supporting the various linkages between stressors and ecosystem components is given in Table 4.

## 5.1 SHADING ADJUSTMENTS

Considerable infrastructure is added in finfish cage aquaculture. This includes the mooring and support systems as well as the nets that contain the fish and keep out predators. Mesh size varies throughout the production cycle and nets and other structures become increasingly fouled with time. All of these factors act to create shading in the water column and bottom in the immediate vicinity of farms. Further, turbidity may be increased immediately around the farm areas due to excess feed and fish faeces being advected away from farm sites. This review does not consider the impact of increased shading in the form of epiphytes that grow on SAV due to increased organic loading from fish farm culture, an effect that has been reported in a number of studies (Cancemi et al. 2003, Vandermeulen 2005).

This review found several studies that evaluated the reduction in light (shading and increased turbidity) due to finfish cage aquaculture. Ruiz et al. (2001) measured light levels (PPFD) in 2 areas (one 40 m from a fish farm and another in a control area at the same depth) on 30 random days over almost 1 year. They found that light levels in the farm area were, on average, lower than those measured in the control location (ca. 30% and 39% of the surface irradiance, respectively) and suggest that, as this is still above the minimal estimated light requirements for the species, that this could not explain differences in the condition of seagrass between the 2 areas. That being said, this effect would also be present at times when light levels would be close to limiting and may have an impact at those times. Mendez et al. (1997) and Pergent et al. (1999) measured the light directly below a finfish (*Dicentrarchus labrax* and *Sparus aurata*) cage culture site, at a reference site 20 m distant, and at a depth near the lower limit of the seagrass (*Posidonia oceanica*) in an area of the Mediterranean Sea. Light levels were consistently lower under the cage site than the reference site throughout the day but were also always greater than that recorded at the deepest limit of the seagrass bed, suggesting that it was not the reduced light alone that accounted for decreased seagrass under the cage farm site. These latter authors suggest that reduced light was due to increased turbidity in the vicinity of the fish cage site as well as shading from the culture structure at some times. Verneau et al. (1995) did earlier studies in *P. oceanica* meadows in the Corsica and found that light under a cage farm was reduced by 38% relative to that outside of the shadow created by the structure of the farm (light levels were determined along a transect starting under the cage to 30 m outside of the cage structure shadow). An overview of the main pathways of effects for this stressor class is given in Figure 16.

*Table 4. Availability and quality of information supporting the linkages between 4 stressor types and various ecosystem components for finfish cage culture. Note that the table does not recognize the direction or severity of the stressor-effect linkage; the table must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Labels refer to the various sections in document. For example, Section 5.1.1 concerns the effects of finfish cage culture on shading adjustments on wild fish populations/communities.*

| Finfish cage | Ecosystem components | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Stressor type** | **Wild fish populations / communities** | **Habitat structure, cover, vegetation** | **Access to habitat / migration routes** | **Substrate composition** | **Food availability / supply** | **Primary productivity** | **Water flow** | **Oxygen (water column/benthos)** | **Contaminant concentrations** | **Suspended sediment concentration** |
| **Shading adjustments** | **4** | **4** | | | **1** | **1** | | | | |
| **Shoreline/bottom structure** | **4** | **4** | | **4** | | **→0** | | | | |
| **Vertical structure** | **5** | **5** | **1** | **5** | **3** | **3** | **5** | | | |
| **Resuspension/ entrainment** | **→0** | | | **5** | | | | **→0** | **1** | **→0** |

Key to table: 5 – Substantial peer-reviewed evidence from aquaculture setting. 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature. 3 – Substantial peer-reviewed evidence from non-aquaculture literature. 2 – Limited peer-reviewed evidence from non-aquaculture literature. 1 – Best guess. →0 – Effect not supported by literature. Empty cells indicate that the pathway was not considered.

### 5.1.1 Stressors on Wild Fish Populations/Communities*

**5.1.1.i. Effects profile.** Finfish cage aquaculture adds physical structure to the environment in the form of infrastructure but also in the form of physical wastes that emanate from any cage operation in the form of uneaten feed and fish waste. This will create shadows and increase turbidity, both of which will modify light regimes locally.

The direct effects of these shading adjustments have been poorly studied and are mostly confounded with organic loading and other effects. The cascading effects from this have been even less-well studied. Some predictions may be made based on ecological principles but these remain conjecture in the context of aquaculture-environment interactions.

**5.1.1.ii. State of knowledge of direct effects.** All else being equal, given that the structure associated with finfish cage culture logically reduce the quantity of light that reaches the sea bottom, this should increase the abundance of sciaphilic (shade-loving) species while decreasing the abundance of phytophyllic (light-loving) species. That being said, it is difficult to separate the influence of physical structure and shading effects as many benthic species are both thigmophilic and sciaphilic, such as lobster (Cobb 1971). Thus, sections 5.2.1 and 5.3.1 should also be consulted. Moreover, shading adjustments may also be confounded by deposition of organic matter, which may have a greater effect than that of the shading effect per se.

Shading by physical structures has been shown to impact a variety of biological communities, particularly of macrophytes (see section 5.1.2), but also of sessile and mobile benthic and epibenthic species, either directly or indirectly through loss of structural macrophytes. Examples include increased abundances of sponges, spirorbid polychaetes, and other colonial sessile forms (see review in Glasby 1999b). Shade produced by finfish cage culture structures may also influence the abundance of more mobiles species, including crabs, lobster and some fishes. This has been suggested to by Bayer (1989), who captured a greater abundance of lobster beneath a salmon cage site in Maine than 100 m distant from it. In contrast, Lawton reports a shift in the distribution of lobster away from a nearly installed salmon farm site in New Brunswick but that the historical pattern of distribution was restablished following the cessation of farming activities. Shade has also been suggested as one of the mechanisms (Beveridge 1984) (see Table 5) by which finfish cage aquaculture sites attract mobile organisms, although at a more proximate distance (i.e., cage-associated, not on the sea or lake bottom under cages). A second mechanism suggested by Beveridge (1984) is that the shadows created by finfish cage aquaculture structures make zooplankton more visible to predators, thereby attracting predators to such structures. In contrast, increased turbidity brought about by the addtion of waste feed and fish excrements may have the opposite effect, whereby some organisms may seek out the the “cover” created by increased turbidity. This review found no instance of this in the aquaculture litterature. However, the influence of turbidity on foraging strategies and success is well documented in the ecological litterature for both freshwater and marine environments (Cuker 1993, Utne-Palm 2002, De Robertis et al. 2003, Rowe et al. 2003, Utne-Palm 2004, Meager et al. 2005, Meager and Batty 2007, Nilsson et al. 2009, Reichert et al. 2010).

**5.1.1.iii. Cascading effects and biological implications for ecosystem.** Cascading effects from shading modifications have not been evaluated in the context of finfish cage aquaculture. A brief review of possible outcomes is given in sections 3.1.2.iii and 2.1.2.iii.

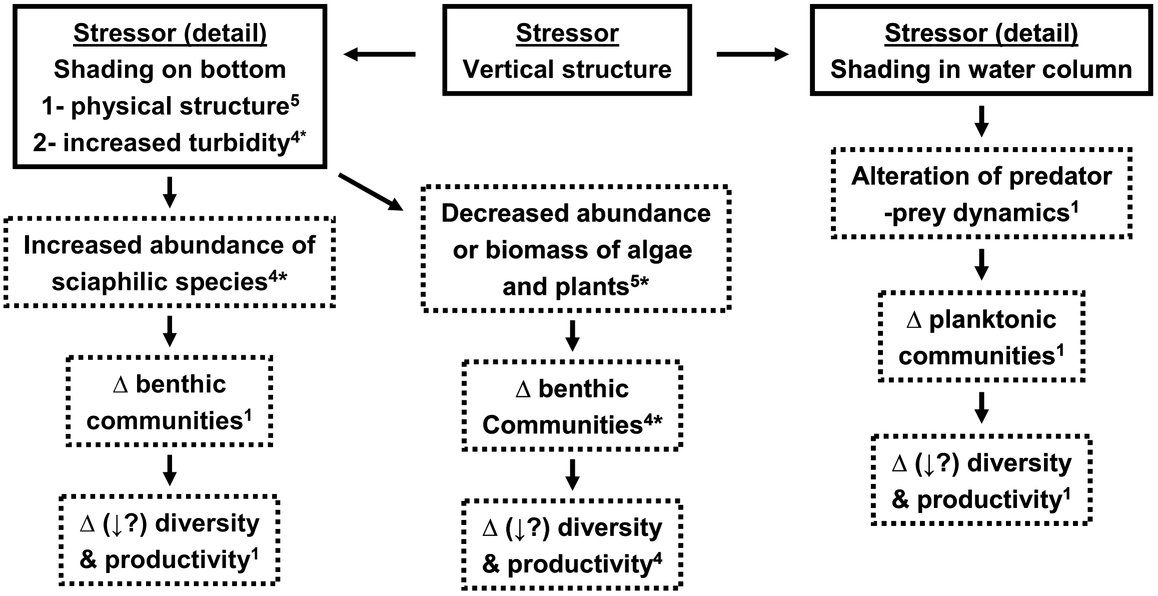

*Figure 16. Main pathways of effects for shading adjustments due finfish cage culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess; asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks*

**5.1.1.iv. Magnitude of effects.** Given the restrained physical size of finfish cage aquaculture sites, their direct impact on the bottom due to shading created by the associated physical structure will be restrained. Multiple cage sites within a single area will obviously have a greater effect. Likewise, it is unlikely that differential prey capture rates due to shading in the water column will have a great effect on planktonic communities, given that these should only be impacted during their brief voyage through the shadows produced by cage structures. Depending on the increase in turbidity due to the addition of wastes from the culture sites, this factor will have a lesser or greater effect on planktonic communities. Increases in turbidity are likely punctual (related to feeding regimes) and finfish cage aquaculture sites are usually situated in areas with good flushing so this effect is, overall, expected to be limited.

**5.1.1.v. Modifiers of effects.** Potential modifiers of the shadows produced by the physical structure of finfish cage aquaculture include intensity of production, spacing of culture structures (cages, walkways, etc.), fouling intensity on nets, the size of mesh used for the nets used at different stages of the production cycle, and water depth. These factors have not been well identified or studied. Modifiers of turbidity associated with finfish cage aquaculture include intensity of production, frequency of feeding, and hydrodynamics and depth of the site. In all cases, effects are also a function of the number and proximity of sites in any region.

**5.1.1.vi. Available evidence.** There is very little information (3 studies) on the degree of light attenuation due to finfish cage aquaculture and it is never clear whether the effect is due to shading from the physical cage structure itself or from increased turbidity due to waste emanating from the cage site.

**5.1.1.vii. Uncertainties and knowledge gaps.** This subject is essentially unstudied – from shading levels to direct and indirect and cascading effects.

**5.1.1.viii. Activity-specific links.** Effects occur throughout the culture period and likely vary over time with net changes and cleaning. The physical structure of the net site remains fairly constant over time but feeding rates may vary, although rotation of crops may homogenize this effect.

### 5.1.2 Stressors on Habitat Structure, Cover, and Vegetation

**5.1.2.i. Effects profile.** The physical structure used in finfish cage aquaculture creates a shading effect on the bottom in the area directly under and surrounding the farm site and increased turbidity due to waste feed and excrement from farmed fish may increase turbidity and thus impact shading over a larger spatial scale. Reduced light will impact benthic macrophytes (algae and seagrass: submerged aquatic vegetation - SAV) with consequent impacts on the functioning of the rest of the surrounding ecosystem.

Although many authors have suggested that shading adjustments due to finfish cage aquaculture may impact SAV, the studies on the subject have been ambiguous in their conclusions with respect to shading adjustments as no attempts have been made to separate shadow and turbidity effects and biodeposition from farmed fish and fouling organisms and excess feed loading to the bottom, all of which may create the observed effects. Although indirect and cascading effects on wild fish populations/communities may be predicted, these have not been well studied.

**5.1.2.ii. State of knowledge of direct effects.** Direct effects of shading adjustments due to finfish cage aquaculture may arise from shading from the physical structure of finfish cage aquaculture installations and from increased turbidity resulting from wastes emanating from farm sites. Both of these factors may impact the health of SAV, as outlined by Pergent-Martini et al. (2006) in a review for the seagrass (*P. oceanica*) and suggested by a number of authors in a number of studies (e.g., Dimech et al. 2002).

Seagrasses in general are very sensitive to impacts from finfish cage aquaculture (Boudouresque et al. 2009). A fairly recent review of the impact of finfish cage aquaculture on *P. oceanica* meadows (Pergent-Martini et al. 2006) highlighted the impact of shading adjustment effects and made suggestions to limit the development of the industry to areas that are not directly above seagrass meadows and that the buffer zone around meadows (in which sites may not be established) be increased as deeper sites will be more sensitive to turbidity. Similarly, Holmer et al. (2003) have stressed the need to consider the importance of SAV in the Mediterranean ecosystem and to manage human activities, with an emphasis on finfish cage aquaculture, to that end.

Ruiz et al. (2001) examined the influence of a fish farm on seagrass (*P. oceanica*) in the Mediterranean Sea and evaluated the cover of lost and degraded meadows and grass performance (photosynthesis, size, and growth) in different areas under and around the farm. They found degradation of seagrass metrics under and surrounding the farm (as compared to historical data and through experiments). Although turbidity resulting from fish farms apparently reduced light levels on the bottom, they determined that light levels remained high enough to maintain seagrass health, and thus sought other mechanisms to explain seagrass decline. They thus attributed effects to nutrient loading and, indirectly, through increased grazing from mobile epifauna (apparently attracted by more palatable seagrass due to organic loading) rather than to shading adjustments. This latter effect has also been reported in other studies from the Mediterranean (Delgado et al. 1997, Pergent et al. 1999) and was evaluated experimentally by Ruíz et al. (2009). It is unknown if these grazers may have been attracted via shading adjustments but at least one of the grazers that had increased abundance, the sea urchin *Paracentrotus lividus*, is affected by light and seeks to limit its exposure to it (Verling et al. 2002) and may migrate to avoid it (Barnes and Crook 2001).

Delgado et al. (1997) examined the impact of small scale (1 to 1.6 tonnes of production over 2 years) Sea bream (*Sparus auratus*) finfish cage aquaculture farms in the Mediterranean Sea on seagrass (*P. oceanica* and *Cymodocea nodosa*). In general, impacts ranged from complete elimination of *P. oceanica* under one site to reduced density and shoot length elsewhere. *C. nodosa* showed similar effects, although where coexisting, the impact on *P. oceanica* was greatest. They suggest that shading reductions may have played a role but refer mostly to reduced light due to enhanced epiphyte cover due to organic loading. The waste stream from the farm was likely considerable given that that they added 99 tonnes of meal to produce 1.6 tonnes of fish in one of the farms studied. Delgado et al. (1999) examined the recovery of these sites following the cessation of farming activities and noted a continuing decline in seagrass condition even though the shading adjustments in the water column had ceased. Epiphyte growth continued to be great and sediments remained very organically enriched, suggesting that the continued decline was due to these other factors and not reduced light levels in the water column. Verneau et al. (1995) noted a marked decline in *P. oceanica* cover and density under a farm site in Corsica and suggested that this was mostly due to shading. In contrast, they also noted a much greater density of fish under the cage sites, suggesting, given other work on the subject, that they were there because of wasted feed.

A number of other studies have also evaluated seagrass (*P. oceanica*) health metrics and found that most have typically increased with increasing distance from farm sites, citing shading adjustments as possible contributing factor to seagrass decline. Dimech et al. (2000a, 2002) evaluated seagrass metrics (shoot density and biomass, leaf number per shoot, leaf area and length) along a transect (330 m long) leading away from a fish (*S. aurata*, ca. 15 tonnes yr$^{-1}$) cage farm in Malta and found that all metrics increased with distance from the farm. In contrast to most studies, epiphyte load decreased with distance from the farms, lending support to the notion that other types of shading or indirect impacts from organic loading were more important in causing reductions in seagrass metrics. Pergent et al. (1999) evaluated the impact of fish farms in 3 sites in the Mediterranean Sea (between Corsica and Sardinia) by measuring sediment and seagrass metrics (density, leaf age, leaf production and rhizome growth and production) along transects (300 m long) leading from the sites. Annual production at the farms was 16, 15, and ca. 200 tonnes with feed use of 40, 38, and ca. 700 tonnes. In short, most metrics of seagrass "health" increased with distance from the farms although there was some variation among sites and metrics. Again, although changes in seagrass condition were consistent with shading effects, epiphyte loads also increased with proximity to farm sites.

A study by Marbà et al. (2006) evaluated seagrass vertical rhizome growth as an indicator of finfish cage aquaculture-related stress at four sites in the Mediterranean Sea (Cyprus, Greece, Italy, and Spain). Production at these sites was greater than the above-mentioned studies (260 to 1150 tonnes yr$^{-1}$). They too used a gradient approach and evaluated seagrass along 800-

1000 m transects leading away from farm (*S. aurata* and Sea bass, *Dicentrachus labrax*) sites. Use of this method allows an historical retrospective (i.e., they could compare growth rates in sites over the past 19 to 25 years) and they found reduced growth coincident with the onset of farming activities in each site and that the effect increased with proximity to the farm sites.

This review found no evidence of impacts of shading from finfish cage aquaculture on kelp or other macroalgae although Vandermeulen (2005) reports kelp die back under a finfish cage sites in Newfoundland. According to Vandermeulen (2005), kelp seems to be less sensitive than eelgrass. That being said, a recent analysis of historical data (Kavanaugh et al. 2009) has shown a negative relationship between kelp abundance and phytoplankton density (= turbidity), suggesting that turbidity from farming operations may also impact kelp.

**5.1.2.iii. Cascading effects and biological implications for ecosystem.** Given the importance of SAV in the functioning of the ecosystem (e.g., Bertness et al. 2000), impacts to this component may be substantial. The few studies that have evaluated the impact on benthic communities associated with seagrass (Dimech et al. 2000b, Dimech et al. 2002, Apostolaki et al. 2007) have found decreased abundances and richness under or immediately adjacent to farm sites and increased abundances and richness at intermediate distances from the farm sites. Although this may be due to shading adjustments, it is also consistent with patterns expected from organic loading (but see discussion on grazers in section 5.1.2.ii).

**5.1.2.iv. Magnitude of effects.** Given that effects are likely localized (limited to the physical shading of culture structures and dispersal of wastes in the farm area), it is suggested that the magnitude of this issue for finfish cage aquaculture is not of great importance.

**5.1.2.v. Modifiers of effects.** Potential modifiers of the shadows produced by finfish cage aquaculture structures include intensity of production, spacing of culture structures (cages, walkways, etc.), fouling intensity on nets, the size of mesh used for the nets used in the different stages of the production cycle, and water depth. These factors have not been well identified or studied. Modifiers of turbidity associated with finfish cage aquaculture include intensity of production, frequency of feeding, and hydrodynamics and depth of the site. In all cases, effects are also a function of the number and proximity of sites in any region. Obviously, presence or absence of SAV in culture areas (or beyond – if far-field effects) will determine potential effects.

**5.1.2.vi. Available evidence.** Although shading adjustments have been implied to have an influence in numerous studies on seagrass, this factor was never separated from other confounding factors. Direct effects of shading adjustments due to finfish cage aquaculture are confounded with organic loading from farm sites (Leoni et al. 2008) and epiphytes were often referred to as one of the mechanisms by which light was reduced in addition to increased turbidity and shadows from the farm structures. Evidence of impacts on seagrass due to light reduction are most often attributed to increased epiphyte growth due to organic enrichment rather than to shading adjustments due to increased turbidity or shadows from the physical structure of cage sites.

Most work done on this subject have concentrated on seagrass species present in the Mediterranean Sea, mostly *P. oceanica*, which is a much longer lived species than those found in Canada and grows to much greater depths because of the clarity of the water there. It is not clear how evidence from the Mediterranean may be extrapolated to the Canadian situation where we have seagrass that typically grows only in the littoral fringe because of generally turbid (relative to the Mediterranean) coastal waters. Most work on this subject has also been done on farm sites with a very low production. It is not clear how the scale of operations may impact shading adjustment effects. Cascading effects from shading adjustments on SAV have not been studied. There is no work on the effect of shading adjustments on other types of habitat structures or cover.

**5.1.2.vii. Uncertainties and knowledge gaps.** Basic contemporary information on reduction of incident light due to finfish cage aquaculture in the Canadian context (species, hydrodynamics, turbidity, scale of operations and depth) is lacking. No work has evaluated shading adjustments or their impacts in deeper sites dominated by kelps or other macroalgae.

**5.1.2.viii. Activity-specific links.** Effects occur throughout the culture period and likely vary over time. The physical structure of net sites remains fairly constant over time but feeding rates may vary; rotation of crops may homogenize this effect.

### 5.1.3 Stressors on Food Availability/Supply

Effects of shading adjustments on food availability and supply for finfish cage aquaculture are basically unknown and unstudied but are likely to be similar to those outlined in section 2.1.3 and this section should be consulted to this end.

### 5.1.4 Stressors on Primary Productivity

Effects of shading adjustments on primary productivity for finfish cage aquaculture are largely unknown and unstudied but are likely to be similar to those outlined in section 2.1.4 and this section should be consulted to this end. It is suggested, given the limited physical reach of fish farms (in terms of shadows produced by the physical structure of the farm and the area in which turbulence may be increased over background levels), that impacts will not be great.

## 5.2 ADDITION/REMOVAL OF SHORELINE/BOTTOM STRUCTURE

There is a general paucity of information related to the addition of physical structure related to fish cage aquaculture to the bottom. Even studies that consider benthic impacts from fish cage aquaculture have not explicitly addressed this issue. In a related field of study, research is ongoing to understand how physical structures may be added to benthic environments under and around fish cage aquaculture sites to mitigate increased organic flux related to feeding the farmed fish (Angel et al. 2002, Angel and Spanier 2002, Hughes et al. 2005). This latter aspect is not covered further. Pathways of effects for this stressor class are expected to be similar to those for suspended bivalve culture for the same stressor class (see Figure 3), although scaled differently relative to the physical size of the two culture types.

### 5.2.1 Stressors on Wild Fish Populations/Communities

**5.2.1.i. Effects profile.** The addition of physical structure to the benthic environment directly alters the abundance/productivity and composition of benthic communities under blocks and the abundance/productivity of some benthic species (mobile and sessile) associated with the provision of hard substrate. This may in turn alter the abundance/productivity of other populations/communities in the ecosystem.

The influence of the addition of benthic structure related to fish cage aquaculture has not been evaluated and all discussed effects are merely predictions based on ecological principles.

**5.2.1.ii. State of knowledge of direct effects.** The addition of benthic structure is largely limited to the addition of anchoring systems used to keep cage structures in place. These quite likely crush/smother any underlying organisms but they may also act as artificial reefs and augment the abundance and diversity of a number of organisms including algae, fouling and mobile invertebrates, and fishes. These issues are discussed in section 2.2.1.ii in the context of suspended bivalve culture but the mechanisms will be similar, if not the scale.

This review found no literature on the subject of derelict benthic structure used in finfish cage aquaculture. It is assumed that this would simply act as hard structure in the benthic environment (see also section 5.3.1.ii).

**5.2.1.iii. Cascading effects and biological implications for ecosystem.** The addition of physical structure to the bottom typically increases the abundance and diversity of organisms locally although whether this represents simple attraction or increased productivity is a point of great debate (Bortone 1998). These points have been discussed at some length in section 2.2.1.iii in the context of the addition of anchorage for suspended bivalve culture but the mechanisms will be similar, if not the scale.

**5.2.1.iv. Magnitude of effects.** Given the limited number of anchorage structures used in fish cage aquaculture sites, effects are likely limited.

**5.2.1.v. Modifiers of effects.** Effects are likely affected by local hydrodynamics and related properties (sediment type, depth, etc.). Potential effects have not been examined to date.

**5.2.1.vi. Available evidence.** This review identified no field evidence for most plausible effects resulting from the addition of bottom structure for fish cage aquaculture. All suggestions are based on well-established ecological principles.

**5.2.1.vii. Uncertainties and knowledge gaps.** Basic research on the associations between benthic structures related to fish cage aquaculture and benthic communities are lacking. Separation of potential causative factors (e.g., structure vs. nutrient loading) is needed.

**5.2.1.viii. Activity-specific links.** The most important activity for fish cage aquaculture is the initial placement of benthic structures and any displacement thereafter.

### 5.2.2 Stressors on Habitat Structure, Cover, and Vegetation

**5.2.2.i. Effects profile.** The addition of benthic structure may directly impact biogenic species by crushing or otherwise smothering them. In contrast, added structures (e.g., blocks) may also serve as a new substrate for biogenic structural species (see section 5.2.1).

Effects of the addition of benthic structure on habitat structure, cover and vegetation and the indirect influence of this on other populations/communities remain unstudied in the context of the addition of benthic structure for fish cage aquaculture. Many of the arguments developed in Section 2.2.1 may be extended to the current section as they result from cascading effects from the addition of biogenic species.

**5.2.2.ii. State of knowledge of direct effects.** Effects related to the structure associated with fish cage aquaculture are covered in section 5.2.1.

No information was found in this review with respect to the destruction of benthic habitat structure, cover, and vegetation due to the addition of benthic structure. It is assumed that the addition of such structure will have a direct negative impact on underlying biogenic structural species. Both vegetation and animal species may be directly affected by the addition of structure although different types of structural species and vegetation will clearly profit from this provision of physical structure to varying degrees (e.g., *Zostera marina* and other structural species that do not rely on hard sediments will not profit from the addition of cement blocks whereas kelp and sponges may).

**5.2.2.iii. Cascading effects and biological implications for ecosystem.** No work has examined the cascading effects resulting from the addition of benthic physical structure related to fish cage aquaculture. Organisms associated with lost habitat will also be lost or displaced whereas those associated with biogenic species growing on added benthic structures will benefit.

**5.2.2.iv. Magnitude of effects.** Given the limited number of anchorage structures used in fish cage aquaculture sites, effects are likely limited.

**5.2.2.v. Modifiers of effects.** Effects are likely affected by local hydrodynamics and related properties (sediment type, depth, etc.).

**5.2.2.vi. Available evidence.** This review found no published evidence on the importance of benthic structure added to the environment for fish cage aquaculture. If there are direct effects on benthic foundation species, there is a strong theoretical basis developed through observational and manipulative studies to support the prediction that this will impact various aspects of the environment.

**5.2.2.vii. Uncertainties and knowledge gaps.** Direct and cascading effects due to aquaculture-related effects have not been studied. As a first step, simple observational studies are needed.

**5.2.2.viii. Activity-specific links.** Impacts are brought about by the initial placement (and displacement) of anchoring structures.

### 5.2.3 Stressors on Substrate Composition

**5.2.3.i. Effects profile.** Benthic substrate composition is modified directly by the addition of 3-D physical structure used in aquaculture to the bottom and indirectly via modification of current regimes and by biological modification of the underlying substrate.

These effects have not been studied in the context of fish cage aquaculture. See also section 2.2.1.

**5.2.3.ii. State of knowledge of direct effects.** There is no published information on the direct impacts of the addition of benthic structure used in fish cage aquaculture on substrate composition. The most obvious direct impact is the addition of 3-D hard substrate to benthic environments which may have more or less natural benthic structure (as compared by soft-sediment and rocky hard-bottom communities). These structures may also compress underlying sediments which will likely remain somewhat so for an unknown period of time after the removal/displacement of the structures. Modifications due to hydrodynamic processes (i.e., altered currents around benthic structures) have not been examined in the context of finfish cage aquaculture.

**5.2.3.iii. Cascading effects and biological implications for ecosystem.** There is no information with respect to the indirect and cascading impacts due to the addition of benthic structure used in fish cage aquaculture on substrate composition. However, some predictions may be made based on the findings from various ecological studies (see section 2.2.3.iii).

**5.2.3.iv. Magnitude of effects.** Given the limited amount of structure added to the benthic environment, effects are likely very limited and of only small-scale importance.

**5.2.3.v. Modifiers of effects.** Effects will be a function of timing and the number of structures added to the bottom, bottom type, depth, current regimes, season, etc.

**5.2.3.vi. Available evidence.** This review found no published evidence of the influence of benthic structure associated with fish cage aquaculture impacting benthic sediments or the influence of this on the ecosystem. Suggested impacts are based on extrapolations from the ecological literature.

**5.2.3.vii. Uncertainties and knowledge gaps.** Basic descriptive work is lacking.

**5.2.3.viii. Activity-specific links.** Anchor placement and displacement will have the greatest impact.

### 5.2.4 Stressors on Primary Productivity

This review found no studies that have addressed the importance of anthropogenic benthic structure related to fish cage aquaculture on primary productivity. Possible effects are outlined in the context of suspended bivalve culture in section 2.2.4 and may be similar for fish cage aquaculture.

## 5.3 ADDITION/REMOVAL OF VERTICAL SITE INFRASTRUCTURE

Considerable vertical infrastructure is added in fish cage aquaculture (see Boghen 2000, Costa-Pierce and Bridger 2002, Davenport et al. 2003, and preamble to section 2.2). The netting makes up the bulk of the physical structure associated with the vertical portion of fish cage aquaculture-related structure. The net mesh is dependent of fish size, target species, desired water flow, and cleaning protocols used on a specific farm site (Costa-Pierce and Bridger 2002).

Many of the potential and documented effects from fish cage aquaculture are due to enrichment of the surrounding environment from added feed. Few studies have been done to separate this factor from those related to the addition of vertical structure related to fish cage aquaculture in the water column. Many proposed effects result from fouling, much as they do in suspended bivalve culture. As such, extensive reference is made to the section that addresses this (see section 2.3) to avoid reiterating the same information. An overview of the main pathways of effects for this stressor class is given in Figure 17.

### 5.3.1 Stressors on Wild Fish Populations/Communities*

**5.3.1.i. Effects profile.** Fish cage aquaculture adds considerable 3-D hard physical structure into the water column and thus directly and indirectly increases the abundance of “benthic” organisms in this milieu. Fish cages are also well known as fish attraction/aggregation devices (FADs), augmenting the local density and diversity of fishes. Fall-off of and biodeposition from fouling organisms on cages may also greatly influence benthic communities. These effects may have cascading effects on the functioning of the rest of the surrounding ecosystem, including altering the abundance and/or productivity of a number of species and communities. Culture equipment may entrap seals and other large organisms. Lost equipment, particularly nets, may have impacts on various communities.

Some direct effects due to the addition of physical structure in the water column have been fairly well studied. In contrast, indirect and cascading effects on wild fish populations and communities have not been studied and are largely conjecture. It is suggested that modelling would be best able to address these gaps.

**5.3.1.ii. State of knowledge of direct effects.** Much work has shown that the netting used in fish cage aquaculture structures is a suitable substrate for the development of rich and abundant fouling communities (see review in Braithwaite and McEvoy 2004). For example, Hargrave (2003) suggests that the biomass of macroalgal communities on net cages in southwest New Brunswick may amount to > 1 kg $m^{-2}$. However, despite the wealth of studies that have reported fouling on net pens, much of the evidence is anecdotal and there are few quantitative studies, especially in the freshwater environment (Braithwaite and McEvoy 2004).

One good exception to this is an experimental study on the seasonal (monthly) succession on netting material at an offshore cage site in Maine (Greene and Grizzle 2007). The study showed that the biomass of fouling organisms may reach up to 30 kg $m^{-2}$, most of which was mussels (seastars, caprellids, and anemones were also abundant seasonally but accounted for much less biomass). It was suggested that differential predation pressure between coastal and offshore sites (greater in offshore sites) accounted for differences in community composition between fouling communities observed at the site and the multitude of studies on fouling communities that have been done in neighbouring coastal areas. They also suggest that the

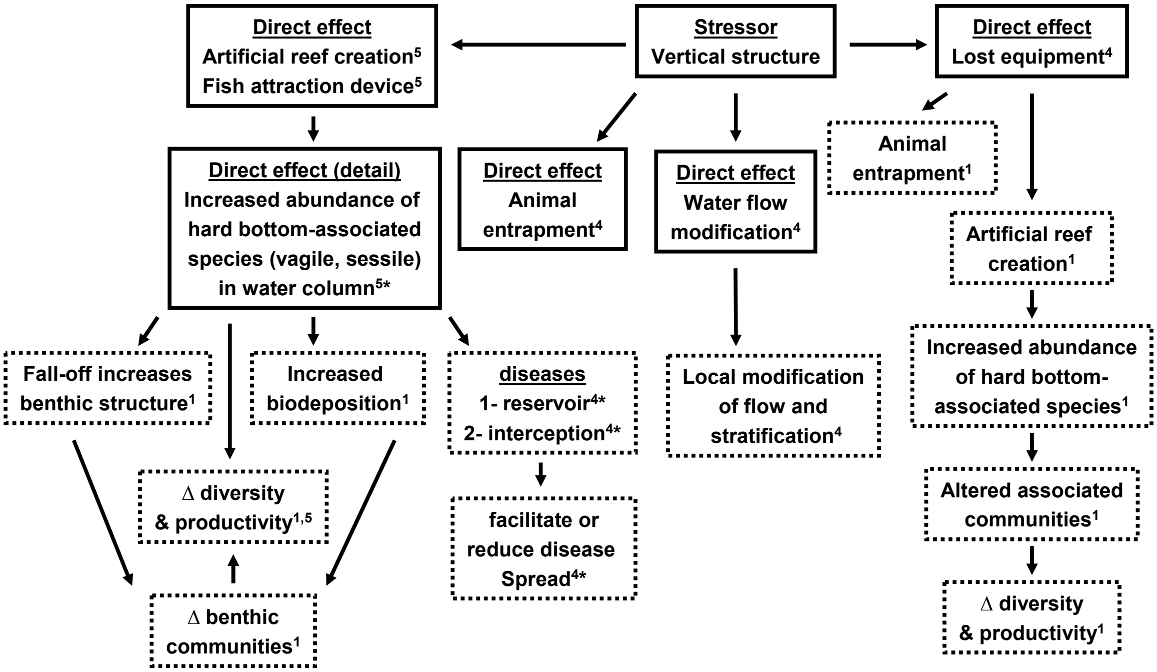

*Figure 17. Main pathways of effects for adjustments due to the addition/removal of vertical structure relating to finfish cage culture on various ecosystem components. Direct effects are in boxes with solid borders; indirect effects are in boxes with hatched borders. Superscripts indicate the availability and quality of the information supporting the proposed linkages: 5 – Substantial peer-reviewed evidence from aquaculture setting; 4 – Limited peer-reviewed evidence from aquaculture setting or personal observations or grey and/or ecological literature; 3 – Substantial peer-reviewed evidence from non-aquaculture literature; 2 – Limited peer-reviewed evidence from non-aquaculture literature; 1 – Best guess. Note that the figure does not recognize the direction or severity of the stressor-effect linkage; the figure must be considered together with the supporting text in the relevant sections to understand the complexity and magnitude of the various potential feedbacks. Asterisk indicates that some effects have been shown but that results are very variable or that mechanisms are unclear.*

relatively rough substrate of the nets encourages settlement of fouling species. In Australia, a study on tuna farms (Cronin et al. 1999) found that biofouling on nets adds an additional 2.2 kg $m^{-2}$ net or a total fouling community of 6.5 tonnes, and Hodson et al. (2000) found biofouling of 8.5 kg $m^{-2}$ (mostly ascidians and the green macroalga, *Ulva rigida*) on nets in a salmon farm. Zongguo et al. (1999) examined the fouling communities associated with 5 fish farms in Hong Kong and found between 33 and 55 fouling species per site with a biomass between ca. 4.9 and 11.0 kg $m^{-2}$. Fouling in freshwater systems may also be substantial. Dubost et al. (1996) measured fouling experimentally on mesh of different sizes in 2 freshwater sites in France. Fouling levels differed between sites and mesh sizes (intermediate mesh sizes of 4 and 6 mm were most heavily fouled) and reached up to ca. 1.4 kg $m^{-2}$ after only 21 days in the water. Madin et al. (2010) measured the fouling of mesh panels in a fish cage culture site in Malaysia and found the biomass of sessile and mobile organisms to reach ca. 2.2 and 0.27 kg $m^{-2}$, respectively, after only 8 weeks immersion. Many other examples are given in Braithwaite and McEvoy (2005) and Dürr and Watson (2010).

A large number of recent studies have shown the importance of fish cage aquaculture structures as fish attraction/aggregation devices (FADs) (Boyra et al. 2004, see recent review in

Johannes 2006, but also Tuya et al. 2006, Valle et al. 2007, Fernandez-Jover et al. 2008, Dempster et al. 2009, Oakes and Pondella 2009, Sudirman et al. 2009, Dempster et al. 2010). It is not simply that fish migrate onto cage sites. A recent study of two fish cage farm sites in the Mediterranean (Fernandez-Jover et al. 2009) showed that, over a 22 month period, a total of 22 species of fish recruited directly to farm structures. The near absence of these same fish species in the open areas between cages suggests that the fish use the cage structure as refuges from predation. Beveridge (1984) lists a number of features that explain how fish cage aquaculture sites act as FADs; these are given in Table 5. In addition, fish may also be attracted to cage sites because of altered benthic communities or organic loading (see section 5.3.1.iii), the typical reason why fish are believed to be most attracted to fish cage aquaculture sites (Johannes 2006). Oakes and Pondella (2009) found that not only was the abundance and diversity of fishes increased by the presence of cage structures in California, but also that the trophic structure of those fish communities differed from those from near-by kelp beds at 3 positions in the water column. In short, there was a shift towards crushers and pickers at cage sites, suggesting the importance of the fouling community on the cage structures to the shift in fish community composition and abundance. This suggests that the physical structure attracts a certain suite of fish. However, it is also likely that a large proportion of the wild fish associated with a site are present because of the abundance of excess feed added to the surrounding environment. To separate these two possibilities, Tuya et al. (2006) studied the fish associated with a net cage in the Canary Islands by doing surveys on 4 dates prior to and four dates following the removal of fish and feeding (but leaving the cage structure in place). The abundance of most species declined markedly following removal of fish and feeding but the abundance of several groups remained the same (herbivores, benthic macro- and meso-carnivores), including one (benthic macro-carnivores) that remained in greater abundances than in control locations, suggesting that they were present because of the structure provided.

Despite the large number of studies that have documented increased abundances and biomasses of fishes at finfish cage culture sites relative to reference locations and that fishes are generally larger at fish cages sites relative to those in reference locations around the world, little effort has been made to identify the mechanisms that account for this and to determine if such associations serve to augment the productivity of fishes within culture sites (Oakes and Pondella 2009). The quantity of fish in culture sites may be considerable. In a study of 9 salmon cage culture sites in Norway, Dempster et al. (2009) observed a total of 13 associated species and conservatively estimated that the average biomass of wild fish associated with a single farm was 10.2 tonnes. When extrapolated to all farms in Norway, this suggests that greater than 12,000 tonnes of wild fish may be associated with the 750 ha of fish cage sites in Norway at any one time during the summer (when the study was done, Dempster et al. 2009). What's more, using acoustic transmitters fitted on 24 fish, Uglem et al. (2009) show that at least one species of the dominant associated species, Saithe (*Pollachius virens*), is quite closely associated with cage farms, with 63% of each spending at least some time each day on one of the three farms monitored over the course of 3 months. Similar studies done in Mediterranean Spain (Dempster et al. 2002, Dempster et al. 2004, Valle et al. 2007, Fernandez-Jover et al. 2008) showed a similar but seasonally variable biomass as the studies done in Norway, suggesting that this may be a general effect of fish cage sites.

This review found a single study that examined the distribution of wild fish relative to fish cage culture sites in Canada. Johnston et al. (2010) examined the distribution of wild fish with gill nets and minnow traps around 5 active cage sites and near and distant control sites near Manitoulin Island, Lake Huron. Although the authors suggest that the results may under-represent the degree of attraction by cage sites due to the non-visual methods used (fish are typically very closely associated and the gill nets may not have well sampled the fish immediately adjacent to cages), catch per unit effort was typically greater near cage sites than corresponding control sites. Overall, analysis of community composition and food webs suggested that the physical structure of the cage sites was more likely the cause of the increased abundance of fishes around cage sites rather than fish being attracted by farm wastes.

*Table 5. Theories proposed to explain floating and stationary Fish Attraction Devices (FAD's), and their applicability to inland water cage and pen structures (from Beveridge 1984). Note that only water column effects are considered; benthic effects (including feed pellet and other organic loading, benthic community modifications) are not. -, *, and ** indicate the mechanism has little, some, and considerable probable importance.*

| Theory | Applicability |
|---|---|
| 1. Use as cleaning stations where external parasites of pelagic fishes can be removed by other fishes | - |
| 2. Shade | * |
| 3. Creates shadow areas in which zooplankton become more visible | * |
| 4. Provides substrate for egg laying | - |
| 5. Drifting object serves as schooling companion | - |
| 6. Provides spatial reference around which fishes could orient in an otherwise unstructured environment | * |
| 7. Provides shelter from predators for small fishes | ** |
| 8. Attracts larger fishes because of presence of smaller fishes | ** |
| 9. Acts as substrate for plant and animal growth, thus attracting grazing fishes | ** |

Finfish culture farms offer predators a very tempting source of potential food (both farmed and associated fish) and many take advantage of this. Thus many farms use anti-predator netting to reduce the impacts of these animals on their stock. Given that such predators may easily become entangled in the vast array of nets and other hardware in the water column in fish farms, a number of authors have also highlighted the importance of potential entanglement of seals and other marine mammals, birds, and sharks by the physical structure associated with fish cage aquaculture (e.g., Kemper and Gibbs 2001, Tlusty et al. 2001, Würsig and Gailey 2002, Forrest et al. 2007, Ribeiro et al. 2007). Data on this are rarely quantitative and the extent of the problem is poorly known. In one rare exception, in a 15 month survey in Italy, Díaz López and Bernal Shuria (2007) observed an average entanglement rate of 0.2 dolphins month$^{-1}$ for cages (1 dolphin per month for cages with loose anti-predator netting and 0 for those with taught anti-predator netting). As visitations by dolphins to fish cage sites in the area where this study was done seem to be increasing with the number of farms (Bearzi et al. 2009), such encounters may become more common. Historic California sea lion deaths due to finfish cage aquaculture entanglements in British Columbia increased from 1994 (the first year with data) and then declined over the period 2000 through 2004 (the last year with data, see Table 6) (Anonymous 2000, 2003, 2007), largely due to better weighting practices attain proper net tension. Similarly, minimum estimates (i.e., from self-reporting) of harbour seal entanglements in Washington over the period 1997 through 2001 declined from 15 in 1997, to 5 in 1998, and to zero thereafter (Carretta et al. 2009). Unpublished data (G. Perry, pers. comm.) suggests that 60 to 70 and ca. 30 sharks and tuna were trapped by Newfoundland finfish cage aquaculture installations in 2008 and 2009, respectively.

Some of the equipment used in finfish cage aquaculture will ultimately become lost, abandoned, or derelict and Keller et al. (2010) consider derelict equipment from aquaculture as a major source of marine debris. Hinojosa and Thiel (2009) studied floating debris in Chile and found that feed bags from salmon farms were the second most common type of debris encountered in the northern part of the country, following styrofoam, presumably mostly from mussel aquaculture buoys. Cho (2005) reports that almost 40 thousand tonnes of gear is lost from coastal aquaculture activities in South Korea annually (compared to 24 thousand tonnes in the fishing industry). Historically, nets used in salmon cage culture in Maine had been left on the bottom to be cleaned of fouling organisms. However, some of these seemed to be become buried in sediments or even more completely fouled, suggesting that they would be even more difficult to remove than when they were lowered to that position (Heinig 2000). In a review of the derelict nets recovered from the bottom of Puget Sound and US side of the Strait of Juan de Fuca (State of Washington), Good et al. (2009, 2010) report that only one of 876 or 902 (depending of the reference) nets recovered were from aquaculture. Silvert (2001) discusses the importance of the loss of culture equipment, such as netting, to the bottom and suggests that although these structures may provide habitat for various fouling and benthic species (Watters et al. 2010), they also have a variety of negative impacts (entanglement, consumption, etc.). Entanglement by or consumption of these or similar materials by marine organisms, including birds and marine mammals, may have serious effects, ranging from sublethal physiological ones to death (Moore 2008, Raum-Suryan et al. 2009, Jacobsen et al. 2010, Boerger et al. 2010). As an example of the potential impacts lost nets may have, Gilardi et al. (2010) suggested that a single 137 $m^2$ gill net catches about 1.2 Dungeness crabs per day. Good et al. (2009) suggests that lost fishing nets have a major impact on seabirds in the Salish Sea, with over 15 species being recovered from nets pulled from the area. This review found no literature on this subject in an aquaculture context; no literature quantified this effect.

**5.3.1.iii. Cascading effects and biological implications for ecosystem.** Fouling organisms associated with fish cage aquaculture may fall from nets and related structures and accumulate on the bottom, potentially influencing organic loading and/or altering benthic community characteristics. This is particularly true when nets are cleaned *in situ* (Hodson et al. 1997, Braithwaite and McEvoy 2004), which encourages great drop-off. Further, although fouling organisms may intercept part of the particulate matter emanating from cage farms (one of the basic tenets of IMTA systems), they also feed on naturally occurring particulate matter and may contribute substantially to benthic loading through biodeposition. The influence of such fall-off and biodeposition may be great and is discussed in the context of suspended bivalve culture in section 2.3.1.iii and is not further elaborated upon. Similarly, the impacts of grazing by filter-feeding fouling organisms associated with fish cage aquaculture structures on the pelagic community are also discussed in the context of suspended bivalve culture in section 2.3.1.iii. Fouling organisms may also greatly influence respiration rates and nutrient fluxes, at times threatening the health of the farmed fish within the nets (Cronin et al. 1999). Altered nutrient fluxes may also have a variety of cascading effects on the ecosystem. Again, these issues are covered in section 2.3.1.iii and are not further elaborated upon.

*Table 6. Marine mammal mortalities due to entanglement with gear used in finfish (salmon) cage aquaculture in western North America, 1994-2004. All data is from NOAA (Anonymous 2000, 2003, 2007, Carretta et al. 2009). Double numbers for 2000 sea lion counts represents discrepancies between published reports. "-" indicates that data is not available.*

| Year | California sea lions | | Harbour seals |
|---|---|---|---|
| | British Columbia (observed) | Washington (estimated) | Washington (estimated) |
| 1994 | 13 | - | - |
| 1995 | 23 | - | - |
| 1996 | 54 | 4 | - |
| 1997 | 52 | 9 | 10 |
| 1998 | 88 | 9 | 5 |
| 1999 | 134 | - | 0 |
| 2000 | 217 / 225 | - | 0 |
| 2001 | 88 | - | 0 |
| 2002 | 19 | - | - |
| 2003 | 14 | - | - |
| 2004 | 6 | - | - |

As mentioned previously, interpretation of observational studies to identify a single causative factor is usually confounded by the possibility that other factors may explain, in part, the observed patterns (such as structure and the addition of feed). An interesting study by Felsing et al. (2005) separated the impact of "fish" in "fish cages" from "cages" on sedimentation rates and the impact of wild fishes on mitigating effects on benthic communities due to rainbow trout culture in Australia. They had 4 replicated treatments: reference sites (no cages or trout – the natural condition), sites with farmed trout in cages, sites with farmed trout in cages but excluding wild fish (by using a net around the fish cages), and sites without farmed trout in cages and excluding wild fish (control sites). Sedimentation at cage only and reference sites did not differ and were significantly greater at cage sites with trout, showing the importance of direct aquaculture-related biodeposition and feed loss. Benthos under cages with fences was more impacted than the benthos under cages without the fences, highlighting the importance of scavenging fishes to limiting benthic impacts due to fish cage aquaculture. The benthos under cages without trout resembled that at reference sites showing that the cage structure had little influence on its own. However, this experiment was done over a very short time period (62 days) and in the winter and thus fouling was likely not a significant issue at the site studied.

In a study using fatty acid tracers, Fernandez-Jover et al. (2009) show that cage-associated copepods eat fish feed which are in turn eaten by associated juvenile fish which find both food resources and shelter on cage sites. Although Wood (2009) suggests that caprellid amphipods may be an important food resource for farmed fish and Hay et al. (2004) found this to be the main wild feed in the stomachs of farmed Atlantic Salmon in 2 BC cage sites, this latter study noted that little such food was actually taken by farmed fish, as did another study on the gut contents of Chinook salmon in an experimental cage site in Puget Sound, Washington (Moring and Moring 1975), and Fernandez-Jover et al. (2009) suggest that caprellids and other associated amphipods may be too large for wild juvenile fish to eat in the farm sites they studied in Spain.

Larger fish are then attracted to these smaller ones, including some commercially important species (Valle et al. 2007) as well as birds and marine mammals (see section 5.3.1.ii). For example, a series of studies headed by Díaz López (Díaz López et al. 2005, Díaz López 2006, Díaz López and Bernal Shirai 2007, Díaz López et al. 2008) have shown that dolphins *Tursiops truncatus* are attracted to fish cages in Italy because of the large number of fishes, on which they feed, that are attracted to the net structures. These same authors have shown that the dolphins have also changed their social structure, switching from hunting mostly cooperatively to hunting individually and opportunistically, to take advantage of the aggregation of fishes around the fish cages. They are also apparently able to modify hunting tactics to respond to prey densities around fish farms (Díaz López 2009). Bearzi et al. (2009) discuss these studies at length. Elsewhere, Ribeiro et al. (2007) suggest that the spatial distribution and habitat use by Chilean Dolphins *Cephalorhynchus eutropia* is not influenced by the presence of salmon cage farms in Chiloé Island, Chile. At the other end of the food web, it has also been recently suggested that the great density of fishes associated with fish cages may impact local plankton communities through predation and thus food web dynamics (Fernandez-Jover et al. 2009).

Fouling associated with nets and other structure has also been shown to act as a potential reservoir for fish diseases. For example, Tan et al. (2002) examined the prevalence of the causative agent for amoebic gill disease in Atlantic Salmon, the amoeba (*Neoparameoba pemaquidensis*) in fouling organisms associated with a salmon farm in Tasmania, Australia, and found that the parasite was prevalent in a number of fouling organisms, particularly the bryozoan, *Scrupocellaria bertholetti*, and the tunicate, *Ciona intestinalis*. They suggest that this may account for the observed negative relationship (Clark and Nowak 1999) between net changing rate and AMG prevalence. In contrast, this is not always so and some fouling species may destroy certain disease agents that may emanate from farm sites (e.g., Paclibare et al. 1994).

Recently, a number of authors have suggested the possible importance of the attraction of wild fish to cage farms to bi-directional transfer of disease between farmed and wild fish and, via movement of wild fish between farm sites, among farm sites (Dempster et al. 2009, Uglem et al. 2009). Aggregation of wild fish around fish farms may also render them more susceptible to exploitation (Dempster et al. 2006, Dempster et al. 2009) or, conversely, less susceptible to fishing effort if "no take" zones are established around cage sites. This latter option may effectively establish MPAs around fish farms with the potential benefit of increasing coastal fish stocks.

**5.3.1.iv. Magnitude of effects.** Given the considerable structure that is added in fish cage aquaculture, effects may be similarly great. The direct impacts of added structure may greatly augment diversity locally and indirect effects may influence both benthic and pelagic ecosystems. These cascading effects have been poorly studied.

**5.3.1.v. Modifiers of effects.** The most important potential modifiers are likely depth, current regimes, and husbandry (cleaning) practices. Other modifiers include season, substrate type, etc. These factors have been little examined to date.

**5.3.1.vi. Available evidence.** A good number of observational studies have documented the influence of fish cage aquaculture on fouling communities although much of the available data is not quantitative. Observational studies on the influence of fish cages on the distribution of wild fishes can not elucidate what factor(s) are most responsible for such effects. This review found no experimental or theoretical (modelling) work that has evaluated dose-dependent relationships for the cascading impacts from the practice (i.e., how a given level of fouling influences the surrounding ecosystem).

**5.3.1.vii. Uncertainties and knowledge gaps.** Factors that account for most variation in fish communities have not been elucidated and experimental work is needed to this end. The influence of fouling communities on local biodeposition, filtration, and cascading effects from this remain largely unstudied. Modelling based on targeted observational studies is needed to better understand the influence of fish cage aquaculture-structure on the environment.

**5.3.1.viii. Activity-specific links.** Effects occur throughout the culture period and effects likely increase with time. Husbandry practices, especially harvesting and cleaning, likely greatly impact community development and related effects due to fall-off from net structures.

### 5.3.2 Stressors on Habitat Structure, Cover, and Vegetation

**5.3.2.i. Effects profile.** Biodeposition from (or of) fouling organisms on nets may enrich the benthic environment, potentially smothering or otherwise covering biogenic structure. However, fall-off of product and associated organisms may directly increase benthic biogenic structure. Indirect effects due to filtration may lead to decreased turbidity and nutrient release may stimulate growth of algae and seagrasses. See also section 5.1 for shading effects.

Both proposed direct and indirect effects are poorly studied and largely unknown.

**5.3.2.ii. State of knowledge of direct effects.** Finfish aquaculture-macrophyte community interactions in Canadian waters have been poorly studied. In the Mediterranean and Adriatic regions, seagrass beds (*P. oceanica*) are naturally found up to depths of 40 m due to high light penetration resulting from low turbidity (Holmer et al. 2003) and finfish aquaculture operations have been linked to massive seagrass bed declines (Katavic and Antolic 1999, Ruiz et al. 2001, Cancemi et al. 2003). In the majority of areas where farms have been situated over seagrass meadows, the substrate has eventually become completely defoliated within the farm perimeter with effects still apparent within a 200-300 m radius (Ruiz et al. 2001, Holmer et al. 2003). Initial hypotheses on the cause of these declines focused on shading effects of fish cages but significant differences in light irradiance among farms and reference locations are not always observed (see section 5.1) but increased sedimentation, nutrient concentrations, and organic loading have since been linked to these effects and others (Ruiz et al. 2001, Cancemi et al. 2003). Further effects observed include: increased nitrophilic macroalgae coverage (such as invasive *Caulerpa racemosa*) along shorelines adjacent to farms (Argyrou et al. 1999) as well in defoliated patches in seagrass meadows (Katavic and Antolic 1999, Holmer et al. 2003), decreased growth of rhizomes, leaves, and shoots (Ruiz et al. 2001); decreased shoot density (Ruiz et al. 2001, Cancemi et al. 2003); increased concentrations of phosphorous and nitrogen in plant tissues (Ruiz et al. 2001); and increased epiphyte abundance leading to leaf fragility (Cancemi et al. 2003). Conversely, Ruiz et al. (2001) recorded decreased epiphyte abundances at farms but also increased abundances of the herbivorous sea urchin, *Paracentrotus lividus,* relative to reference stations and published literature from similar habitats. *P. lividus* is generally believe to be herbivorous and Ruiz et al. (2001) suggest that these organisms were attracted to the vicinity of farms due to the increased palatability of seagrass tissues (from incorporating increased concentrations of fish farm-derived phosphorous and nitrogen) and this accounted for lower epiphyte abundance and declines in shoot density and cover. However, this urchin may also grow associated with mussels (Cook and Kelly 2009) and may be more abundant near farms due to fall-off from the net structure which are typically dominated by mussels (Braithwaite and McEvoy 2004).

Fall-off from culture structures from natural causes and during cleaning operations may add to benthic habitat structure and/or smother what is already present on the bottom. This review found no published study that quantifies this effect on benthic habitat structure, cover, or vegetation.

**5.3.2.iii. Cascading effects and biological implications for ecosystem.** Impacts on eelgrass, which is considered to be an "ecologically significant species" (DFO 2009), may have a number of cascading effects on the surrounding ecosystem. The importance of this habitat has been described in many reviews (e.g., Chambers et al. 1999, Jackson et al. 2001, Heck et al. 2003, Williams 2007) and is not elaborated upon here. See section 2.3.2.iii for a brief overview.

**5.3.2.iv. Magnitude of effects.** Effects related to structure in fish cage aquaculture are likely slight.

**5.3.2.v. Modifiers of effects.** The most important modifiers are likely husbandry practices, especially cleaning. Other modifiers include depth and turbidity, current regimes, season, substrate type, etc. These latter factors have been little examined to date.

**5.3.2.vi. Available evidence.** This review found no published literature (other than shading) on potential effects arising from structure in fish cage aquaculture on benthic habitat structure, cover, and vegetation.

**5.3.2.vii. Uncertainties and knowledge gaps.** Direct and indirect effects, if there are any, are poorly known.

**5.3.2.viii. Activity-specific links.** The activities with the greatest impact on eelgrass and other benthic structural species are likely related to maintenance of biofouling levels.

### 5.3.3 Stressors on Access to Habitat/Migration Routes

Although habitat fragmentation may limit migration for some species, other than direct impacts of entanglement on birds, marine mammals, and sharks (see section 5.3.1), this review found no evidence of the impact of physical structure in fish cage aquaculture on access to habitat/migration routes and this issue is not considered further.

### 5.3.4 Stressors on Substrate Composition

Substrate composition may be influenced by biodeposition in the form of faeces (from fouling organisms on nets), and the fouling organisms themselves, and by modification of current regimes due to the structure associated with fish cage aquaculture.

Impacts from biodeposition due to fouling organisms have not been studied separately from that resulting from cultured fishes (see section 5.3.1); most such studies for fish cage aquaculture are confounded. No work has focused on the importance of drop-off. Impacts on substrate composition due to currents are complex and impacts from this are discussed in section 5.3.7. General notions about modification of substrate composition due to such factors are discussed in the context of suspended bivalve culture in section 2.3.4 and are not discussed further.

### 5.3.5 Stressors on Food Availability/Supply

The vertical structure associated with fish cage aquaculture serves as a structure for the growth of a large variety and abundance of fouling organisms. These provide a direct resource to pelagic and benthic organisms, modify benthic structure that alter benthic communities, and compete directly with, prey on, and contribute to pelagic communities. Effects of cleaning schedules are probably of great importance

These effects have been described with respect to suspended bivalve culture in section 2.3.5 and are not discussed further.

### 5.3.6 Stressors on Primary Productivity

Vertical structure used in fish cage aquaculture allows for the growth of many filter-feeding species, both on that structure and on the bottom, that may prey directly on phytoplankton or alter nutrient fluxes and oxygen consumption/generation and thereby alter plankton community composition. These effects have been covered in the context of suspended bivalve culture in section 2.3.6 and with respect to fish cage aquaculture in section 5.3.1 and are not considered further.

### 5.3.7 Stressors on Water Flow

**5.3.7.i. Effects profile.** The physical vertical structure placed in the water column for fish cage aquaculture influences current regimes within sites, slowing currents at various scales. Net pen arrangement, mesh size and fouling intensity likely greatly impact effects by modifying turbulence, accretion and sedimentation.

Effects on the environment from such modifications are poorly known.

**5.3.7.ii. State of knowledge of direct effects.** A great amount of research effort has been invested into understanding the hydrodynamics of cage structures used in fish cage aquaculture (e.g., Fredriksson et al. 2005, Lader and Enerhaug 2005, Huang et al. 2006, Lader et al. 2008, Balash et al. 2009). Considerably less effort has examined how cage structures modify local hydrodynamics and the importance of this on ecological processes (but see Helsley and Kim 2005).

The large physical structure of fish cages has a considerable effect on local hydrodynamic as it creates considerable drag that alters flow velocity and turbulence as water flows around cage structures and through the cage netting. Reid and Moccia (2007) summarize the factors that influence the drag created by net cages as the ratio of net thread to space (referred to as solidity or porosity), the roughness of individual net threads, number of net pen crossings, cage flexibility, angle of attack, lift, space between cages, and current velocity. It appears that the influence of fish within cages on flow is largely unknown (Reid and Moccia 2007). As water viscosity is a function of its temperature, water temperature will also influence drag. As for suspended bivalve culture, hydrodynamic modifications are evident at a number of spatial scales, ranging from individual net threads to the scale of the farm and down-stream vortical flow variations and to the local area. Water flowing through a fish farm will be deflected around and below the cage structures with this deflection becoming greater as the water moves through the farm (i.e., less water will pass through the last cage in a series of cages than does through the first cage as each cage deflects a proportion of the water that it intercepts) (Løland 1993).

This will produce a large wake with reduced flow and increased turbulence downstream of cage sites with the potential to increase sedimentation. In contrast, scouring may occur directly below cages as current speeds are likely increased due to deflection of part of the water mass by the cage structures. Swift (2006) examined the interactions between fouling and drag associated with nets in fish cage aquaculture and found that fouling may increase drag by up to 240% relative to that of clean nets. Guenther et al. (2010) suggest that, even with cleaning, some species may be able to regrow sufficiently from remaining portions of colonial organisms to basically occlude net openings within a matter of a few days. Thus the presence of fouling species in fish cage aquaculture may greatly augment down-stream hydrodynamic effects, such as increasing turbulence. Thus problems associated with modelling dispersion of organic matter from finfish farms due to post-cage turbulence (Chamberlain 2002) are likely accentuated due to biofouling.

Direct effects of this include potential mixing of the water column including localized breakdown of stratification. At a larger scale, flushing times of areas may be increased by attenuation of currents due to the presence of net cages (Forrest et al. 2007).

**5.3.7.iii. Cascading effects and biological implications for ecosystem.** Breakdown in stratification and altered flushing may have concomitant influences on oxygen and nutrient concentrations locally as well as altered planktonic communities and lead to build-up of wastes and propagules of associated species, including undesirable fouling species with short larval stages, within culture sites. Altered currents may also lead to the accumulation of contaminants and therapeutants emanating from cage farms. Effects from this are beyond the scope of this review.

**5.3.7.iv. Magnitude of effects.** Effects may be quite great locally, especially in areas where culture sites are large/abundant or flushing is not great.

**5.3.7.v. Modifiers of effects.** Effects are likely modified by fouling levels, farm configuration, local bathymetry, local hydrodynamics - which varies at a number of time scales, and stocking density.

**5.3.7.vi. Available evidence.** Theoretical work has shown that water flow is impacted by the presence of vertical structure used in fish cage aquaculture. In contrast, little work has evaluated the importance of this on the receiving biological and physical environment.

**5.3.7.vii. Uncertainties and knowledge gaps.** The effects on flow modifications due to structure associated with fish cage aquaculture are mostly unknown. Intermediate to large (bay) scale effects may be of importance for carrying capacity studies but research on this is needed.

**5.3.7.viii. Activity-specific links.** Effects occur throughout the culture period but likely vary with respect to the timing of stocking, harvesting, and maintenance/cleaning.

## 5.4 RESUSPENSION/ENTRAINMENT OF SEDIMENTS

The physical structure associated with fish cage aquaculture may lead to erosion and accretion of sediments around culture fixtures. Other factors that may influence sediments have been discussed in the preceding sections (see sections 5.2 and 5.3) and are not discussed further.

### 5.4.1 Stressors on Wild Fish Populations/Communities

See sections 5.2.1 and 5.3.1

### 5.4.2 Stressors on Substrate Composition

See sections 5.2.3 and 5.3.4

### 5.4.3 Stressors on Oxygen (Water Column and Benthos)

See sections 5.2.4 and 5.3.6, and 5.3.7

### 5.4.4 Stressors on Contaminant Concentrations

Contaminant concentrations may be influenced directly from feed and faeces emanating from culture sites as well as leech-out from materials used in the netting for fish culture cages. This subject is beyond the scope of the current review. Associated fouling organisms may also increase loadings via filter-feeding and excretion. This review found no published works that discuss this latter effect in the context of fish cage aquaculture. See also section 2.4.4. This subject is not discussed further.

### 5.4.5 Stressors on Suspended Sediment Concentration

See sections 5.2.1, 5.3.1, and 5.3.2.

# 6. OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Prior to outlining general conclusions and recommendations for future research, it is important to reflect on a basic question: “What are we and/or should we be managing for?” (Dumbauld et al. 2009: p 215). Coastal areas provide a multitude of functions and these must be considered in a holistic ecosystem context. For example, does increased diversity associated with net pens offset loss on the sea bottom? These are more sociological-type questions (aesthetics, economic, etc.) than ecological (McKindsey et al. 2006b). Recent work on ecological modelling for aquaculture (e.g., Sequeira et al. 2008, Ferreira et al. 2009) has started to incorporate such questions into analyses, basically accepting that there are trade-offs to be made and that all acts by humans in coastal zones likely have some impact.

It is crucial that the factors deemed to be of importance be identified through an open process and then evaluated against established relationships. Unfortunately, dose-dependent relationships between cause and effects (such as benthic loading rates and infaunal community structure) are very poorly studied and rarely known under varying environmental conditions (e.g., enclosed eutrophic embayments vs. off-shore and/or well-flushed oligotrophic areas). Use of various indices of impacts of effects may lead to biased interpretation due to non-calibrated thresholds or difficulties in detecting additional impacts due to farming activities (i.e., in addition to those caused by other factors) (Bouchet and Sauriau 2008).

In general, very little work has been directed at separating the different factors that lead to habitat modifications due to the physical alteration of the environment due to aquaculture in Canada or around the world. Separation of direct physical factors from confounding ones, such as the physical structure of cultured bivalves and the increased biodeposition due to them or their associated fouling communities, is a difficult task. Further, although of interest academically, separating possible confounding factors is likely less important for the management of the practice, and diminishes the importance of the sum of all interactions between aquaculture and the environment. Because of the scales and complexity of the systems involved in bivalve culture, it is anticipated that indirect (cascading) effects may only be evaluated through the use of modelling (Gibbs 2004, McKindsey et al. 2006b, Sequeira et al. 2008).

Keeping this in mind, a reduced list of needed research to address knowledge gaps identified in this review includes the following:

1. Basic descriptions of the relationships between physical structures and the associated assemblages are needed. Most studies on this are not quantitative. This type of data is needed to feed quantitative models of carrying capacity. For example, given that fouling communities may contribute substantially to filtering and biodeposition in bivalve culture, these effects must be quantified. It is also important to evaluate the importance of the culture organisms themselves as “habitat” and how this changes with management/husbandry practices. This information is needed so that it may be included within carrying capacity studies (see below).

2. For bivalve culture, production and environmental carrying capacity modelling that consider physical structure more explicitly is needed. For example, variation in mussel sock diameter (= socking density), length, and spacing, longline spacing, etc., will all have important effects on food delivery, grazing, biodeposition, nutrient fluxes (benthic and pelagic), and the related cascading effects. Currently, most carrying capacity modelling is based on extrapolations from limited (unrealistic?) lab studies and scaled up to bay-scale effects.

3. Modelling (energy and nutrient budgets within mass-balance models) needs to be developed to evaluate larger-scale effects and also include other anthropogenic effects. This will likely require experiments to better understand nutrient budgets at realistic scales (i.e., culture units as opposed to individuals). This is particularly true for bivalve culture.

4. Dose-dependent relationships need to be better studied so that effects may be predicted. For example, at what rate of benthic loading does a community switch from oxic to hypoxic conditions and under what circumstances (i.e., condition-specific responses).

5. In all cases, effective indices must be developed to identify significant effects.

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# 9. APPENDIX - OVERVIEW OF BIVALVE AQUACULTURE IN CANADA[1]

There are many steps involved in most types of bivalve aquaculture and these vary greatly among the species, among regions, and among individual producers. Much of this information is already readily available in the pertinent literature and is only summarized here. Because of broad differences between the regions, methods used on the east and west coasts are treated separately.

## 9.1 OVERVIEW OF BIVALVES IN AQUACULTURE (EAST COAST)

The bivalve culture industry on Canada's east coast is dominated by the blue mussel (*Mytilus edulis* and varying amounts of *M. trossulus*), followed by oysters and then scallops with lesser numbers of other species also being raised. On the whole, most species being cultured are indigenous and spat are obtained through natural set, the juveniles usually being transferred to grow-out sites distant from areas in which they were collected. General information about culture methods for both of these two species may be obtained from DFO websites (Fisheries and Oceans Canada 2003b, a) and information about these operations is only summarized below.

### 9.1.1 Mussels

Mussel aquaculture is practiced around the world using two main approaches: bottom culture, which accounts for approximately 15% of the overall production, and suspended culture, which accounts for about 85%. Although bottom culture is presently used in the US, it is mainly practiced in Europe, particularly in the Netherlands, Germany, Ireland and the UK. In short, the technique consists of transferring juvenile mussels from natural, high density beds, to sheltered beds where the stocking density is managed to improve productivity and market value (Spencer 2002). There are no mussel bottom leases in Atlantic Canada.

Mussel seed are mainly collected in the same bays or water system where the grow-out takes place, but generally on specialized leases in separate section of the bay. For the most part, wild seed is collected on ropes that are attached to longline systems (see below). The ropes are usually 2-6 m in length and are attached at short distances apart (30-50 cm) on a longline that can average 100 m in length (Mallet and Myrand 1995). They are usually deployed in late spring and are retrieved or harvested approximately 5 months later, in late fall for socking activities. A small proportion of the mussel seed used in mussel farming is harvested directly from wild beds. Harvesting in this instance is mainly done using tongs or rakes, in late fall.

Seed collection on artificial collectors has not been linked changes in the recruitment success on wild beds occurring in the same system. The main concern with the deployment of seed collectors is their effect on the recruitment of non-target species. There is also some concern about the high biomass of these filtering animals, certainly as it reaches its highest level, just prior to the recovery of the seed. For instance, in Tracadie Bay PEI, the average seed density (km/m$^2$) on seed collection leases in the month of October can exceed the mussel densities on grow-out leases (Landry personal communications).

Suspended culture is conducted using three main approaches. In Spain, Scotland and South Africa mussel culture is mainly conducted on rafts (Boyd and Heasman 1998, Okumus and Stirling 1998, Fuentes et al. 2000). This culture technique involves suspending mussels

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[1] This appendix is copied mostly verbatim from McKindsey et al. (2006a).

attached on ropes or in socks, typically 8-10 m in length, from a moored raft with cylindrical floats. The bouchots (poles) technique was developed in France (Garen et al. 2004). This technique involves the uses of poles or stakes driven into the ground in regions with high tidal regime. This method is only used in France and is located in shallow water where access is possible at low tide. The third type of suspended culture is the longline system, which is used around the world. It can be used in a wide variety of environment, from the open sea to enclosed areas. Mussel aquaculture was first introduced in Atlantic Canada, on PEI in the late 1970's. From it's beginning, the off-bottom longline was the preferred technique and is now sole method of culture on the island. It consists of a series of lines anchored at both ends and floated in the water by buoys with a series of "legs" with weights at their ends, usually cement blocks, as counter balance (see Figure A1). The number of each is varied throughout the year and their length adjusted to maintain the growing bivalves at the appropriate level in the water column to maximize growth and minimize impacts from fouling, ice, etc. Mussels are hung along the line in mesh socks typically around 3 m in length. The longline can vary in length from < 100 m up to 200 m. (Mallet and Myrand 1995). During the winter period, the longlines are sunk deeper in the water column to avoid ice damage. The system is similar in the Magdalen Islands except for the fact that continuous socking methods are used. In Newfoundland, culture sites are typically deeper and both methods are used.

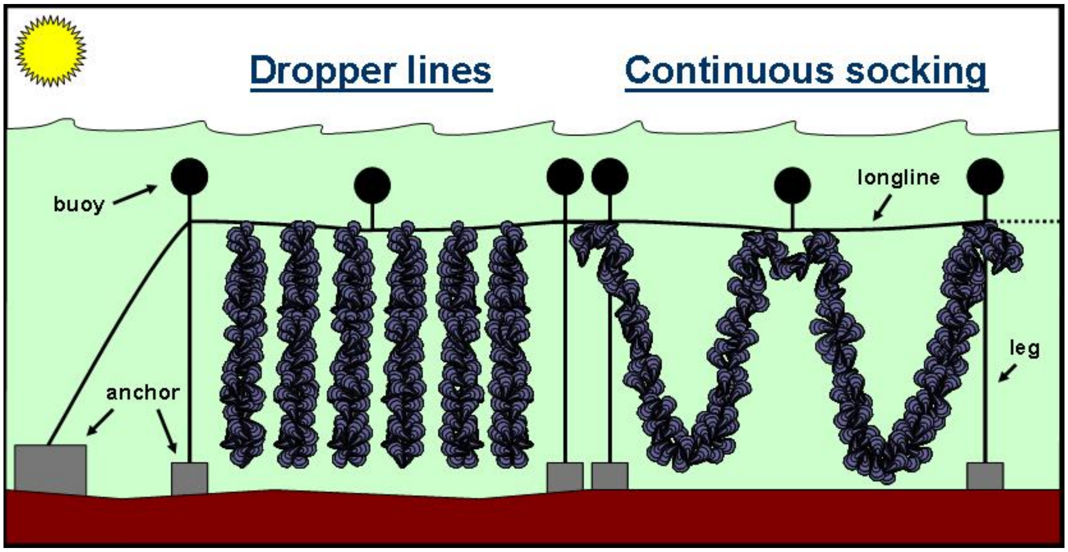

*Figure A1. Schematic of a basic mussel longline system. The two most common systems used in Canada are shown. Longline systems may also be used for the culture of other species in nets, trays, etc..*

### 9.1.2 The American Oyster

The American Oyster, *Crassostrea virginica*, is naturally found along the Atlantic coast of North America. Along the Atlantic coast, this species is common from Cape Cod, Massachusetts to the Gulf of Mexico with large populations found at the northernmost portion of its distribution in the southwestern Gulf of St. Lawrence (Lavoie 1995). In the Maritimes, oysters have traditionally been cultured to market size (76 mm in length) seeding and growing oysters directly on the substrate (bottom culture) or by growing oyster seed in plastic mesh bags on tables or trestles approximately 30 cm above the substrate (off-bottom culture).

Bottom culture in the Maritimes is predominantly conducted in low intertidal and subtidal areas (up to 5-8 m in depth) with moderately soft substrates. Such areas are generally regarded as the best locations for bottom seeding as the substrate provides adequate shell support which results in oysters growing strong, round shells that have high market appeal. Once seeded in an area suitable for growth as well as protection from winter ice exposure, bottom culturing requires little care other than monitoring growth and survival and presence of predators or fouling organisms. Upon reaching market size (approximately 4-7 years in the southern Gulf of St. Lawrence), oysters are most commonly harvested by small boat using tongs or drags. In some areas, large boats with high-powered engines towing heavy drags are used for harvesting which can result in severe bottom damage and losses of product (Lavoie 1995). Less destructive alternatives such as diver harvesting are used, but are the exception as it is generally cost-prohibitive to harvest in this manner.

With off-bottom culture, oysters are contained in plastic mesh bags which are then attached to metal or wooden tables or trestles in the low intertidal or shallow subtidal zones. The combination of raising oysters above the substrate and placing them in bags acts to decrease predation while exposing the oysters to increased water circulation, improving growth and elevating the organisms above areas of substrate where anoxic events may occur. In the Maritimes, harvesting of sub-tidal leases is generally done from barges with trestles or racks mechanically lifted on to the barge resulting in little bottom disturbance. Alternatively, intertidal harvesting from racks or trestles involves increased vehicular and foot traffic in the intertidal zone.

Early attempts at suspension culture involved many different techniques. Spat were traditionally collected on scallop shells suspended through the water column on strings from wooden racks. Some growers would leave spat to develop on these shells where they were capable of reaching market size within two years by taking advantage of warmer water temperatures and higher primary productivity of the upper water column (Lavoie 1995). Similar methods included the suspension of wooden or stacked plastic trays. Drawbacks of these early attempts were related to the increased cost of suspension infrastructure materials and product quality. Much effort and cost are required to construct suspension structures which can withstand Maritime weather events. Further, increased labour costs generally result from efforts to keep suspended structures free of algal and other biological fouling which reduce water circulation and impair oyster growth. In terms of product quality, the increased growth rates of suspended oysters resulted in thin shells which often could not withstand shipping rigors or were difficult to open without breaking. To counteract this dilemma, growers were forced to spread oysters on the bottom for a period to increase shell strength, raising labour costs. All of these factors combine to decrease the marketability of a competitive product and led to cessation of this culture approach in the mid-1990’s (Lavoie 1995).

Today, seed supply for oyster aquaculture in Atlantic Canada comes from two main sources. The first is through the collection of pre-commercial oysters from wild contaminated beds for relaying operations on private leases (Lavoie 1995). Collection of these pre-commercial oysters is mainly done with the use of thongs. This form of aquaculture is still active, but represents a decreasing proportion of oyster production in Atlantic Canada, particularly in N.B. The second source of oysters for aquaculture operations is though the collection of seed, which is solely collected on artificial collectors. Harvesting of oyster seed on wild beds is not permitted. These artificial collectors usually consist of a wide variety of plastic surfaces covered with a thin coat of cement. Oyster and other bivalve shells held in mesh bags are also used for collecting seed in some areas. These collectors are deployed in the water column either on a longline system (see above) or on a wooden fence system. Deployment occurs in early summer and the collectors are usually retrieved in the fall for thrashing (removal of individual seeds for the plastic collectors) or they are directly deposit on the bottom, in water safe from ice damage, for the winter month and thrashing in the spring.

New developments in culture technology and market demand, however, have led to the adoption a new suspension technique used for rapidly growing smaller, cocktail-sized (approx. 50 mm) oysters: floating bag culture. While still extremely rare in Prince Edward Island and moderately rare Nova Scotia, over 85% of active New Brunswick oyster leases have abandoned bottom and off-bottom culture and adopted this new technique (R. Dupuis, New Brunswick Department of Agriculture, Fisheries, and Aquaculture, *pers. comm. to Marc Skinner*). Using this method – floating bag culture, lines of plastic mesh bags (similar to those used by off-bottom growers) are suspended at or just below the waters' surface in the shallow subtidal zone using styrofoam or plastic floats attached to the bags. The ends of these lines are anchored to the substrate and measure approximately100 ft. In general, bags measure approximately 2-3 feet long by 1 foot wide and are 3-4 inches deep and may be floated in single or double rows (A. Levi, Elsipogtog First Nation, *pers. comm. to Marc Skinner.*). In certain regions, growers float multiple bags (two across by two deep) in metal cages to increase the number of oysters cultured per unit area (M. Skinner, *pers. obs.)*. Lease sizes in the Maritimes range from 3.51-15.71 ha with an average of 4.01 ha (Fisheries and Oceans Canada 2003a). With this method, oysters grow to cocktail size in 3-4 years. Oysters grown to cocktail size in this manner are generally kept at lower densities than oysters grown using other techniques. Lower densities and the movement of oysters back and forth in bags due to wave action contribute to the production of thick, round shells which high meat quality (Fisheries and Oceans Canada 2003a). After reaching a desired size, the bags are removed from the longlines by workers using boats resulting in little or no physical disturbance of habitat.

### 9.1.3 Scallops

Two species are involved, the "giant" or "sea" scallop, *Placopecten magellanicus, and the* Iceland Scallop, *Chlamys islandica*. Scallop spat are obtained using collectors (nylon sacs stuffed with some filamentous material such as nylon mesh to which the recruiting scallops attach with byssal threads). Once the scallops grow to a sufficient size to live a free-living existence, they detach themselves from the recruiting material only to be trapped by the mesh of the collector bag in which the filamentous collecting material was placed. The juvenile scallops are then placed in some type of cage (often pearl nets, several strung together and placed in a longline grow-out system, but experiments are also being done to evaluate the use of trays, tables, etc.). These are then grown to "princess" size for consumption on the half-shell or then released into the environment for sea ranching or else to full market size. There is also limited culture of the introduced Bay Scallop, *Argopecten irradians*, in Prince Edward Island.

### 9.1.4 Others

Clam culture in Atlantic Canada is not fully developed. The main species that are being considered for aquaculture are the Northern Quahog (*Mercenaria mercenaria*) and the Soft Shell Clam (*Mya arenaria*). For both species, nursery systems such Vexar bags or field upwellers (see below) are used for the first spring and summer months of the growout cycle. In the fall, juvenile calms are either seeded directly on intertidal to subtidal bottom leases for the remainder of the grow-out cycle or can be overwintered in Vexar® bags for planting in the following spring. Predator nets may be used for the first year. Small *M. arenaria* may also be relayed to grow-out sites to improve growing conditions and shorten grow-out times.

## 9.2 OVERVIEW OF BIVALVES IN AQUACULTURE (WEST COAST)

The bivalve culture industry in western Canada is very diverse with a number of species being cultured in a number of ways. The state of the industry there is very well described in Jamieson et al. (2001) and Kingzett et al. (2002) as well as on the industry website (http://www.bcsga.ca). The following is largely a summary of what is presented in these sources.

The most important bivalve species being cultured in British Columbia are a suite of non-indigenous species, the Pacific Oyster (*Crassostrea gigas*), the Japanese Weathervane Scallop (*Patinopecten yessoensis*), and the Manila Clam (*Venerupis philippinarum*), the former two having been introduced intentionally and the latter arriving as a hitchhiker with *C. gigas*. (See McKindsey et al. 2007 for a general discussion of the implications of exotic species in bivalve aquaculture) Other species being cultured include both the Blue and Mediterranean Mussels (*M. edulis* and *M. galloprovicialis*, respectively, also both exotic species), Geoduck Clams (*Panope generosa*), the Heart Cockle (*Clinocardium nuttallii*) and the European Flat Oyster (*Ostrea edulis*), a further exotic species. Most of this industry is based on hatchery-reared seed although a variety of methods are used by farmers to enhance natural set and survival. Below, we briefly outline the methods used for culturing each of these species.

### 9.2.1 Pacific Oysters

As in most of the world, *C. gigas* is the most important cultured bivalve species in British Columbia. It is grown using a variety of methods but the trend is towards more deep-water (suspended longline and raft culture) ones because of the ease of mechanised methods and greater growth rates 2-5 years for beach culture vs 1-3 years for suspended culture). Because of unreliable set, most of the industry is based on hatchery-raised larvae or seed. Eyed larvae are set (undergoes metamorphosis into juveniles and, in the case of oysters, adheres to a substrate where they will grow-out) onto culch (a substrate to which the larvae will accept to settle, often old oyster shells or tubes used for grow-out) either directly at the hatchery or elsewhere (i.e., remote setting at the farm site). “Single” seed is produced by setting onto ground shell fragments in downwellers at the hatchery or setting facilities. Nursery rearing of single seed (over 2 mm) is often done in floating upwelling systems (FLUPSY-a floating structure with bins with screened bottoms and tops, through which natural seawater flows and keeps the bivalve within them more or less suspended). Such seed may also be bought commercially, as can larger seed that is suitable for being transferred directly to tray systems for grow-out. Oysters on shell culch or tubes may also be transferred to deep-water systems for grow-out or else upgraded to “singles” for the half-shell market. Single shells may also be placed in bags or cages that may also be suspended in suspended systems or placed on beaches or tables grow-out.

Grow-out may be done in a number of ways, based on the type of seed acquired and individual farmer preference. The least involved system is simply spreading out culch oysters on a beach for grow-out. This may involve a number of possible modifications of the beach area, including setting up fences, creating berms (breakwaters) removing large rocks and debris, and possibly tilling. Depending on the type of substrate on a given beach, oysters may also be grown-out in Vexar® (rigid plastic mesh) bags or Aquamesh® (wire mesh with PVC coating) cages directly on the beach or on racks, on stakes, or longline systems. The mesh size used is the largest possible to avoid losing the bivalves and to ensure maximal water flow. Bags and cages placed directly on the bottom must be staked in place and turned over from time to time to prevent excessive fouling. In areas with softer sediments, bags and cages are typically placed on trays made of rebar. Although large individuals may be placed directly into bags or cages, smaller seed may first be placed in bags with smaller mesh inside of bags and cages with larger mesh size and then split and sorted as they grow. Many of the beaches historically used for oyster culture are now being used for clam culture as the oyster industry moves more off-shore.

In deep-water systems, racks may be constructed that hold several layers of bags or cages. These are most often suspended from rafts or longlines. A good discussion of the different tray types is presented on the industry website. Individual shell culch with the associated growing oysters may also be inserted into the strands of ropes and used in suspended culture. Tube culture uses 2 m corrugated plastic tubes with a 25 mm diameter that oysters accept as appropriate material to settle on. New tubes must be conditioned, usually in the intertidal area, for up to one year to leach out chemicals and allow the development of an appropriate (for spat settlement) microbial community. The tubes are placed in a tank to allow the larvae to set and then transferred to nursery rearing system and then to a grow-out site after a couple of months. Grow-out is either on longlines or rafts, with 2-3 tubes often connected together.

### 9.2.2 Manila Clam

The Manila Clam is another widely farmed bivalve and has recently become the second-most important bivalve species being cultured in British Columbia. Although now fairly widely distributed in southern BC, unreliable recruitment means that the industry relies on hatchery-raised spat or seed. Either larger seed are or else eyed spat are purchased from commercial sources, the latter being raised for a brief period by the growers in FLUPSY systems until large enough to de seeded into grow-out sites. All clams beyond 20 mm are grown intertidally on beaches with specific types of sediments (stable, loosely packed mixture of gravel, sand, mud and shell). Modification of lease sites to enhance clam growth and survival may be considerable. For example, low boulder berms may be established seaward of the sites to reduce waves, gravel and/or crushed oyster shell may be added to make the substrate better for the clams (Jamieson et al. 2001). Prior to seeding, lease sites are first dug to remove any clams present. Seed is planted at size of 5-8 mm at a rate of about 200-600 $m^{-2}$. The seed is often covered with plastic netting (car cover) to protect it from predation and from being advected away by currents. This netting may become fouled and measures taken to address this problem. Predator removal is also a common practice with clam culture. Beaches may also be tilled throughout the production cycle during transplantation, thinning and redistribution and harvesting. Harvest at present is exclusively by hand digging although mechanised harvesters have been tested.

### 9.2.3 Japanese Weathervane Scallop

As with mussels, the scallop culture industry is fairly recent and entirely based on hatchery-raised spat which are ready to set at about 3-4 weeks under hatchery conditions. The scallops are commonly set in the hatchery on appropriate settlement material (e.g., kinran) inside of mesh bags. These “seed bags” are then transferred to nursery ponds or grow-out sites for nursery rearing. The bags are set to down lines at a rate of about 1 bag $m^{-1}$ and left to grow until they measure about 1.5cm and detach from the settlement material, becoming trapped within the bags (mid-summer). At this time, the scallops are then sorted and placed in pearl nets that may be stacked to about 15 deep, until they reach about 3 cm (September). Following this, they are graded once more and either placed in lantern nets (staked to about 10 deep) or else ear hung (hung from the corner of their shells). Grow-out is in about 1.5-2 years.

### 9.2.4 Mussels

The mussel industry in BC is fairly new, and is based on hatchery-raised spat. Seed is usually purchased at a size of 1mm or at a larger size after being raised on screens. Alternately, some growers are also experimenting with raising their own seed which is set directly on twine that is then wrapped around ropes for grow-out. Purchased seed is placed in framed screens and, once hard set, put in mesh bags and suspended on longlines for 2-3 months. The seed is then loaded into cotton tubing and this is wound around ropes for either continuous socking or else on dropper socks, usually in the fall. Both rafts and longline systems are being used at this time and grow-out is usually accomplished within about 1-1.5 yrs following socking.

### 9.2.5 Geoduck Clam

This is one of the indigenous species being cultured in British Columbia. The Geoduck is the largest bivalve in British Columbia with a high market value and thus has a good potential as an aquaculture species. However, subtidal culture of this species is still in transition from the experimental to the commercial phase. All seed being used is from commercial hatcheries and is usually supplied at about 3-6 mm for outgrowing. Nursery areas are subtidal (tables), floating (tables), or land-based (concrete raceways filled with sand) and the clams stay there for the following 9-11 months until they reach a size of 12-20 mm. This seed is then planted mechanically subtidally where it grows to market size (0.7-1 kg) over the following 5-7 years. As with manila clams, geoduck clams are often covered with netting to avoid predation. Harvest is by scuba or hooka diving with divers using pressurized water jets to remove the clams. Intertidal culture of geoduck is well-established in Washington State but is currently done only on a small-scale in BC.

### 9.2.6 Others

The heart cockle is a further indigenous species with prospects of being cultured in British Columbia. Grow-out techniques for manila clams may be used for cockles. However, the species is not being cultured commercially at this time. There is also limited culture of both the European Flat (or Belon) Oyster (*Ostrea edulis*) as well as increasing interest in culturing the native Olympia Oyster (*Ostrea conchaphila*). However, the culture of these is limited and is not discussed further.