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Synergies on the coast: Challenges facing shellfish aquaculture development on the central and north coast of British Columbia

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ABSTRACT

The rise in global demand for seafood has led many people to view shellfish aquaculture as an economically and ecologically viable source of seafood. However, interactions with the environment, existing industry, and societal values must be considered to ensure sustainability of this industry. Shellfish aquaculture in British Columbia (BC), Canada, showcases many of these issues. This review explores key socio-economic and ecological considerations for future growth of shellfish aquaculture on the central and north coast of BC, with implications for the continuing global expansion of the industry. Interactions among shellfish aquaculture, coastal groups, existing industries, and First Nations, as well as considerations under changing oceanic conditions are investigated. Expansion of shellfish aquaculture on the central and north coast of BC will need to be socially, environmentally, and economically sustainable. The results of this review strongly indicate that shellfish aquaculture should be incorporated in marine planning initiatives and developed in consideration of local ecological, environmental, economic, and social context.

1. Introduction

As the global demand for seafood increases, shellfish aquaculture may provide an economically and ecologically viable substitute for wild stocks [1–3]. Many wild capture fisheries are already exploited at, or beyond, sustainable capacity [4], and face the demand of an exponentially growing human population [5]. Shellfish aquaculture has the potential to address shortfalls in capture fisheries, while providing jobs and economic benefits for coastal communities [1–3]. The clean and productive waters of coastal British Columbia (BC), Canada, make this region well-suited for shellfish aquaculture. Despite favourable biophysical conditions, the shellfish aquaculture sector has not met growth expectations over the past two decades. In 1998, the Province of BC set a goal for the provincial shellfish aquaculture industry to be worth CAD $100 million by 2010. In 2013, however, the wholesale value of the BC industry was worth only CAD $21.9 million [6]. This review explores the socio-economic and environmental factors which may limit expansion of the shellfish aquaculture industry and the potential for increased synergy amongst these elements as part of marine planning initiatives.

The central and north coast of BC remains relatively underdeveloped for shellfish aquaculture [7]. In 2010, for example, only 27 of the 480 tenured shellfish aquaculture sites in BC (approximately six %) were located on the Pacific north coast; all others were along the southern BC coast or Vancouver Island [8]. Remote coastal communities along the north and central coast, which over the last decade have experienced a declining population and higher rates of unemployment than the provincial average [9,10], stand to benefit substantially from the economic opportunities associated with shellfish aquaculture. Given their long-standing cultural and social connection to shellfish culture, it has been suggested that First Nations communities are particularly well positioned to take a lead in the expansion of the industry [18–20]. Industry development in these regions, however, may conflict with existing commercial activities, traditional use, and the values of First Nations and other Canadians (Fig. 1).

This review focuses on the interactions between shellfish

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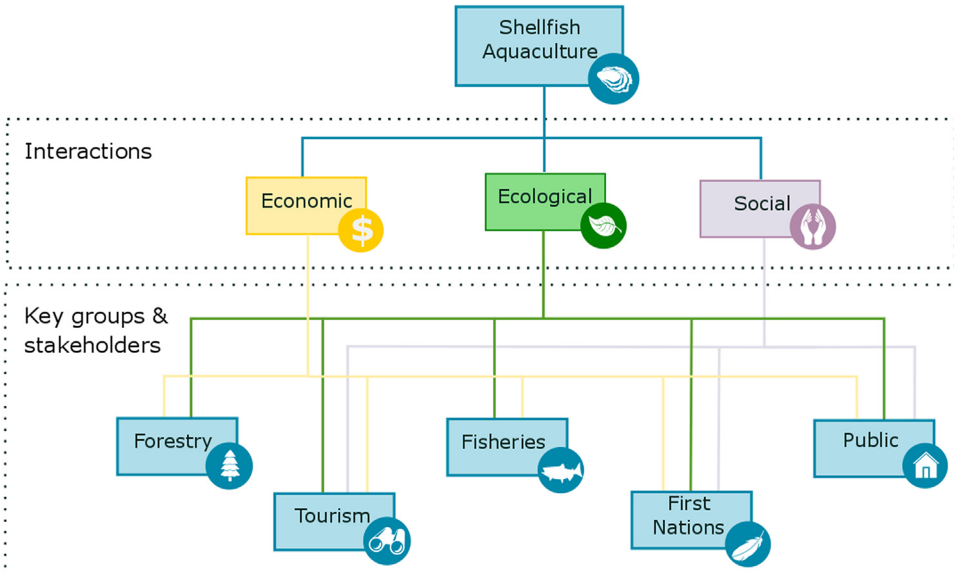

Fig. 1. Interactions between shellfish aquaculture, existing industries, First Nations, and the general public arising from economic, ecological, and social considerations associated with industry development.

aquaculture and three major existing industries on BC's central and north coast: forestry, fisheries (finfish and wild shellfish), and tourism and recreation. This article explores key social considerations, including Indigenous sovereignty and public perceptions. Finally, the logistic, economic, and environmental challenges unique to the remote central and north coast of BC are considered, as well as current and future risks associated with changing oceanic conditions. In the synthesis of these topics, this review included primary, secondary, and available grey literature. While the focus of this research was specific to BC, this review draws on international sources where there were knowledge gaps pertaining to this geographical region. Broadly applicable to other marine planning initiatives, this synthesis highlights the relationships and interactions among coastal industries as well as stakeholder values.

2. Shellfish aquaculture in BC

There are two main species of shellfish cultured in BC: the Pacific oyster (*Magallana gigas*) and the Manila clam (*Tapes philippinarim*). The Pacific oyster was first introduced from Japan in the 1900s. It does not breed regularly in most BC waters due to generally cooler temperatures compared to the species' natural breeding range [7]. Pacific oyster "seed" is typically acquired as larvae and set or nursed in floating upwellers prior to transferring to final grow-out techniques. Seed is typically purchased from hatcheries located in Washington state, Hawaii, or other places in the United States and internationally. Some shellfish farmers purchase seed from the south coast of BC, and a limited number of aquaculture producers, such as Coastal Shellfish in Prince Rupert, have on-site hatcheries, used to rear their own seed. The oldest and simplest method for growing out Pacific oysters is to spread oyster seed on the beach and wait for them to reach a marketable size of 10–15 cm (typically two to five years or more). Much of the industry now uses deep-water or off-bottom culture techniques which substantially reduce the grow-out time, whereby oysters are grown out on strings or tubes hung vertically from longlines or rafts. Once they reach market-size, deep-water cultured oysters are commonly transferred to a beach to harden their shells before sale, increasing their meat content and ability to survive transport. The Manila clam has become well established in BC since its accidental introduction in the mid-1930s. Hatchery-produced clam seed is typically purchased from nurseries and spread directly onto mud-gravel grow-out beaches. Due to high predation by birds, fish and crabs, panels of lightweight plastic anti-predator netting are often laid down and secured across grow-out plots to protect the young clams. Clams are harvested after 2–4 years, during low tides, using rakes or scrapers to turn them out of the substrate and collect the clams by hand.

Some of the relatively new cold-water species for culture, such as scallops, mussels (*Mytilus* spp.), geoduck (*Panopea generosa*), and abalone (*Haliotis* spp.), are anticipated to promote the expansion of aquaculture beyond the traditional oyster-growing areas of southern BC [7]. The Japanese weathervane scallop (*Patinopecten yessoensis*), marketed as the "Pacific scallop", was intentionally introduced to BC during the 1980s and is the most commonly farmed species of scallop in BC. This fast-growing species can reach harvestable sizes within two years of being transferred from hatcheries to aquaculture sites. Local aquaculture producers primarily use traditional Japanese techniques for cultivation, including the use of specialized "lantern" or "pearl" nets, as well as a technique known as "ear-hanging" for off-bottom grow-out. Mussels are also farmed using off-bottom techniques, typically grown out in mussel "socks" suspended from longline systems or rafts. Geoducks, on the other hand, are planted or seeded inside PVC tubes that are placed into soft substrate within the subtidal zone. These tubes are often covered with a mesh net to protect the geoducks from predation. Cultured geoducks are harvested by first using a high-pressured water hose to loosen the substrate and are then collected by hand. Abalone are not yet cultured in BC, but in other parts of the world they are grown in suspended cages or in land-based flow-through tanks.

An expanding shellfish aquaculture industry may create many new jobs and support the economic development of communities on the central and north coast of BC. Data collected by the Province of BC indicate large potential for expansion of the industry beyond its current bounds based on biophysical capability assessments of the growing conditions for Pacific oysters, Japanese scallops, and Manila clams (Fig. 2). But growing the shellfish aquaculture industry will have to consider impacts on existing industries. This will require identifying industry interactions, establishing clear thresholds, spatial separation, as well as ongoing monitoring and enforcement. To be sustainable, the shellfish aquaculture industry will need to address social considerations, such as Indigenous sovereignty and public perceptions, as well as economic and environmental challenges specific to this region.

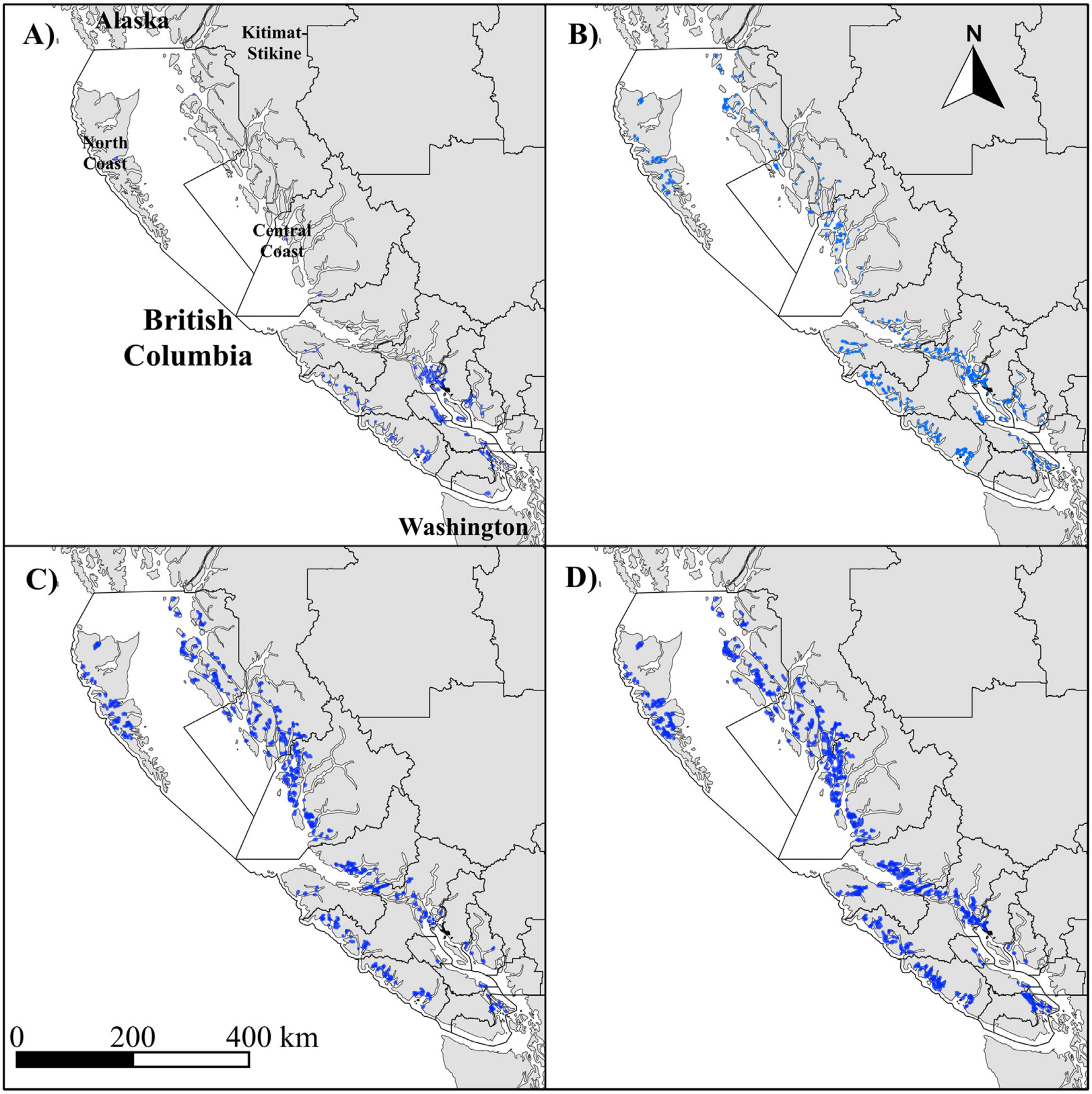

Fig. 2. Maps of western British Columbia showing the location of the north and central coasts, and A) current beach and deep water shellfish aquaculture tenures, B) locations rated good for the potential beach culture of Pacific oysters and Manila clams, C) locations rated good for the potential deep water culture of Japanese scallops, and D) locations rated good for the potential deep water culture of Pacific oysters. Data for All ratings are based on biophysical capability appraisals as determined by studies conducted from 1993 to 2004. All data downloaded from the British Columbia Data Catalogue (https://catalogue.data.gov.bc.ca/dataset).

3. Forestry

Forestry represents a substantial industry and important source of income on the central and north coast of BC. Considerable declines in this sector have led to a reduction in forestry employment, as well as associated infrastructure and transportation [14]. These declines may be particularly hard-felt in rural and remote communities, which account for 81% of employment in this sector [15]. Since forestry can have an array of short-and long-term consequences for shellfish aquaculture productivity (e.g., increased sedimentation, leachates, and log movement on land and by sea), many ecological considerations must be addressed for the two industries to co-exist.

Terrestrial-based logging practices may have far-reaching effects on environments downstream of logged tributaries. The construction and maintenance of roads, tree-felling activity, and the transportation of logs, for example, disturb the soil surface which contributes to increased sedimentation in nearby creeks, rivers, and nearshore environments [16]. As suspension feeders, bivalves are particularly susceptible to increased sediment, which can obstruct feeding, decrease efficient particle selection, and increase an individual's energetic expenditures [17]. Given that harmful sedimentation thresholds vary among species and environmental conditions [18], further studies will be necessary to quantify such limits for specific species and areas of interest on the central and north coast of BC. Once identified, these thresholds can contribute to natural resource planning and the establishment of best management practices for forestry activity in synergy with aquaculture expansion.

Water-based transportation of harvested logs through shallow aquatic environments is another source of habitat degradation which could impede the productivity of shellfish aquaculture tenures in northern BC. As there are few roads on the north and central coast, log transport is primarily water-based. Most commonly, logs are dumped into the water via skidways or slides [19]. Lost logs can disturb shallow intertidal habitats, crushing suspension feeders such as clams [19], and/or become entangled in ropes and rafts and damage aquaculture infrastructure. Furthermore, bundled log booms or loaded barges can re-suspend sediments during transport and increase turbidity, potentially scouring shallow substrates [19].

In the aquatic environment, accumulation of forestry debris such as bark and wood residue can occur at all stages of log harvest, handling, and transport. High concentrations of woody debris can cause significant oxygen depletion and smother habitats [20]. For example, accumulations of wood waste and bark debris decrease the survival and condition of the Pacific littleneck clam (*Leukoma staminea*) and blue mussel (*Mytilus edulis*), both native to the Pacific Northwest [22]. Leachates from these woody debris deposits can also be toxic to shellfish [23] and other aquatic organisms [24]. Leachate toxicity can be long-lasting: some sites show less than a 10% reduction of leachable material in aspen logs after two years of exposure [24]. Such findings emphasize the need for long-term planning and management practices and further examination of nearshore ecological consequences associated with all stages of forestry.

4. Finfish fisheries

Intertidal shellfish aquaculture may overlap extensively with critical fish habitat, having implications for important commercial and subsistence finfish harvests. When juvenile Pacific salmon (*Onchorhynchus* sp.) leave their natal streams, they use nearshore areas to feed, grow, and acclimate to marine conditions before moving into the open ocean. This period is critical for growth and determining survivorship to adulthood [25]. Pacific herring (*Clupea pallasii*) also use intertidal zones for spawning and juvenile rearing. These spawning sites are critical locations for commercial and subsistence roe-on-kelp and roe-on-cedar harvests. In 2013, BC's wild Pacific salmon and herring commercial fisheries were worth a combined wholesale value of CAD $220.5 million – approximately 15% of the total fisheries and aquaculture wholesale value for that year [6]. Salmon and herring harvests are also culturally important to coastal First Nations, who have used and holistically managed these fish stocks for millennia [11,26].

By modifying important intertidal and nearshore environments, shellfish aquaculture can have an array of implications for the productivity of wild fish stocks. On one hand, high densities of filter feeding bivalves can enhance habitat complexity, water clarity, and the growth of aquatic vegetation [27], which attracts and supports a diverse abundance of fish and invertebrate species [28–30]. On the other hand, pulse disturbances from harvesting practices can negatively impact local vegetation, which provides key spawning and rearing habitat for fish and their prey [31]. Geoduck harvesting, for example, typically uses pressurized water jets to dislodge sediment surrounding the animals, disturbing the benthic environment and suspending sediments. These effects, however, appear to be spatially limited and similar to sediment mixing caused by storms and high winds [32]. Another primary concern associated with shellfish aquaculture is the production of large volumes of faeces and pseudofaeces [33], leading to an influx of organic matter and the creation of anoxic conditions that may negatively impact benthic communities, including fish [34–37,41,42]. In clam and geoduck culture, this accumulation of organic matter and sedimentation can be further exacerbated by anti-predator netting [38–40]. Research has shown, however, that increases in sedimentation and organic matter associated with shellfish aquaculture are highly localized [42] or insignificant [43–45].

Whether the cumulative effects of shellfish aquaculture on fish stocks are positive or negative may depend on a suite of site-specific factors, such as bivalve species and density, culture techniques, local environmental parameters, as well as the spatial and temporal extent of aquaculture activity. Avoiding known fish nurseries (e.g., eelgrass beds) when establishing new shellfish aquaculture facilities will help to mitigate potential impacts on fish stocks and their associated fisheries. Coarse-scale marine planning for the central north coast of BC has broadly zoned shellfish management in locations expected to have lower environmental impact [14,46]; however, specific siting will require more detailed examination, e.g., where industry-related activities have a neutral or minimal effect on juvenile fish habitat and herring spawning grounds to promote the sustainable continuation of finfish fisheries that are relevant to the area.

5. Wild shellfish fisheries

Overlapping both geographically and in niche space, there is substantial potential for interactions between shellfish aquaculture and wild shellfish harvests on the central and north coast of BC. Wild geoduck harvests accounted for nearly 20% of the CAD $245.7 million wholesale value of BC shellfish harvests in 2013, with a wholesale value of CAD $48.2 million [6], while wild clam and scallop harvests contributed an additional 2.5%. Traditional harvests of wild shellfish are also culturally important for coastal First Nations, who have been cultivating clam gardens for thousands of years [12]. Commonly harvested species include the Pacific littleneck clam (*Leukoma staminea*), butter clam (*Saxidomus gigantea*), Nuttall's cockle (*Clinocardium nuttallii*), horse clam (*Tresus capax, T. nuttallii*), and various mussels (*Mytilus californianus, M. edulis/trossolus/galloprovincialis* species complex) [47]. Given this historical and ongoing connection to shellfish, it has been suggested that Indigenous-led shellfish aquaculture development would greatly benefit these communities [48]. Such expansion, however, requires a deeper understanding of the barriers created by the tenure system, as well as interactions between cultured and wild shellfish.

Expansion of the shellfish aquaculture industry has the potential to displace commercial and traditional wild shellfish harvests from preferred harvesting sites. Shellfish aquaculture tenures are selectively placed in areas identified as prime shellfish habitat [49]. Under the current tenure system, individuals other than the tenure-holder are prevented from harvesting within the allotment, leading to the exclusion of wild harvests from these productive habitats. While native shellfish species collected by wild harvests occupy the mid-intertidal zone, and do not directly compete for space with commonly cultured species, tenure of intertidal areas for farming-related activities can still exclude intertidal wild harvests. If productive shellfish sites are preferentially allocated to wild harvests, on the other hand, shellfish aquaculture may experience decreased operating efficiency resulting in an increase in cost per unit harvest. Remote northern communities may suffer under such circumstances, given existing challenges associated with access and shorter growing season, relative to their southern counterparts [54]. The expansion of cold-water off-bottom or subtidal culture species, such as scallops and geoducks, and seeded or hatchery grown oysters, may therefore minimize potential conflicts with wild shellfish harvests on the central and north coast of BC. The tenure of any intertidal areas which are currently or have historically been used for wild or traditional harvest should be limited or excluded to mitigate competition for space between the fisheries. It is critical that wild fishery harvesters and coastal First Nations are engaged in the process of identifying appropriate tenure areas.

In addition to limiting harvester access to preferred sites, shellfish aquaculture has the potential to reduce the productivity of nearby wild shellfish stocks through competition for resources. Beyond a certain shellfish density, inter- and intra-specific competition may result in a net loss in wild populations [32,51,52]. This bivalve carrying capacity will be influenced by site-specific parameters including: water turnover, rate of primary production, and the biomass and filtration rate of bivalves [50]. For example, in certain areas where Pacific oysters are intensely cultured (250 g/m^2 shucked wet weight), filter feeders are estimated to be near carrying capacity, suggesting that if filtering capacity (i.e., bivalve density) were increased, food intake per individual would decrease [53]. Reduced productivity for wild or subsistence shellfish fisheries could decrease catch per unit effort and increase harvesting expenses [54]. When evaluating such trade-offs an analysis of benthic filter feeder population distribution, densities, feeding rates, and primary productivity in the area, may be used to predict the level of shellfish aquaculture that an area can support before the growth and survival of shellfish will be affected [52]. Due to spatial variation in ecological carrying capacity, it will likely be most effective to make such management decisions based on regional assessments, for example, within a single bay or estuary [32].

In addition to competition for space and resources, shellfish aquaculture has the potential to impact wild shellfish productivity through the transfer of genes and diseases. Genes from genetically bottlenecked cultured bivalves bred in a hatchery may be disadvantageous for wild populations that rely on genetic diversity to thrive in a variable environment. BC geoducks from different areas, for example, are genetically distinct [55]. Although the consequences of gene transfer for the fitness and survival of wild stocks remain largely unknown, to some degree the risk can be reduced by industry protocols and procedures. Limited shellfish transfer between regions, for example, has been implemented through regional management and regulation systems for shellfish transfers through Fisheries and Oceans Canada. Other mitigation measures for limiting gene transfer and encouraging the maintenance of genetic diversity include: replicating genetic diversity and selective pressures found in local environments; harvesting cultured shellfish before reproductive age; and the use of sterile, triploid shellfish for aquaculture [55,56]. Disease and parasite transfer, associated with high stocking density on aquaculture farms, presents another threat to the fitness of wild and cultured shellfish populations alike [57]. The risk of disease and parasite transfer is increase by factors such as: the transfer of shellfish between areas, high aquaculture stocking densities, and the culture non-native species that are not adapted to withstand local disease and parasites [58]. New aquaculture facilities in remote areas will need to carefully monitor their stock and follow regulations to minimize the risk of disease and parasite transfer between cultured and wild shellfish.

Shellfish aquaculture in BC predominantly cultures non-native species, which could have a variety of implications for the productivity of native shellfish stocks and the wild harvests dependent upon them. While established non-native shellfish populations could become a source of competition for native species, many cultured species, such as the Japanese scallop (*Patinopecten yessoensis*), do not naturally reproduce in BC waters and are highly predated [59]. Other non-native species like Manila clams (*Venerupis philippinarum*) and Pacific oysters (*Magallana gigas*) are temperature limited and unlikely to expand their populations in BC beyond currently established areas, including the central and south coasts of BC. However, as the shellfish aquaculture industry begins to use native/non-native hybrid shellfish, such as the Japanese/Weathervane scallop, careful monitoring will be required to determine if these species can interbreed with native populations and/or become established on the central and north coast [60]. Cultured non-native shellfish can also have profound impacts on wild stocks as a vector for other non-native species which predate or parasitize native shellfish [60,61]. The European green crab (*Carcinus maenas*), for example, is a voracious predator species that was accidentally introduced to BC by the shellfish aquaculture industry [62,63]. Although strict regional management and regulation systems for shellfish transfers implemented by Fisheries and Oceans Canada provide some degree of protection, more research will be required to identify potential species introduction risks and effective mitigation measures.

6. Tourism and recreation

Shellfish aquaculture shares or competes for space with a multitude of recreational and nature-based tourism activities in BC, including bear-viewing, bird-watching and boating. Tourism is an important economic sector in BC, generating CAD $13.9 billion in revenue annually and employing 132,200 people [64]. While the contribution of marine tourism specifically is not well documented, a study by Tourism BC in 2006 found that seven of the top ten tourist choices involved the marine environment [65].

Shellfish aquaculture may disrupt recreational use of coastlines by restricting access and decreasing the aesthetic or experiential appeal of these locations. For example, long line culture requires the use of various floating structures or rafts in deep water and may physically block these areas from recreational boating. In a study evaluating marine protected areas in BC, Murray and D'Anna [66] surveyed 543 recreational boaters and found that 39% experienced negative feelings towards shellfish aquaculture, while 56% believed it had no effect on their boating experience. Only 5% of boaters believed that shellfish aquaculture enhanced their experience [66]. Conflict appeared to stem from direct contact situations, such as the inability to anchor boats in areas occupied by active shellfish tenures. In addition, anti-predator nets may pose entanglement hazards for boaters if they detach from the beach [67]. Tour guides have also reported negative client reactions to salmon farming on the basis that these operations conflict with the values of ecotourists and their reasons for visiting BC [68]. Though finfish aquaculture is generally more controversial, a low tolerance for industrial development may also be germane to shellfish farming [69,70].

In addition to direct effects on access and aesthetic appeal, shellfish aquaculture has the potential to interact with ecotourism industries by influencing wildlife behaviour. Although the interactions between shellfish aquaculture and the bear-viewing tourism industry have yet to be studied directly, potential effects can be inferred by examining changes in bear behaviour in response to components of the aquaculture industry. Fortin et al. [71], for example, combined results from published studies and expert knowledge to describe population level impacts of recreational activities, such as hiking, angling, camping, and hunting, among others, on grizzly bears (*Ursus arctos*). Across the 46 studies examined, results indicated spatial and temporal avoidance, also referred to as displacement, of brown bears in response to human activities. Increased human presence associated with shellfish aquaculture could therefore decrease bear viewing opportunities as a result of displacement. Elmeligi and Shultis [72], on the other hand, found that grizzly bear responses to boat-based wildlife viewing in BC varied greatly among individuals. Most notably, no male grizzly bears were observed in viewing areas after the mating season [72]. This finding is further supported by Nevin and Gilbert [73], who also reported a displacement of male grizzly bears from coastal habitats after mating season in response to human activity. They proposed that this behavioural response could provide a temporal refuge for female grizzly bears and their cubs, allowing for greater feeding opportunities, higher mean female mass, a larger litter size, and an overall increase in population productivity [73,74]. These findings suggest that the development of shellfish aquaculture, and associated increases in human presence, could benefit feeding opportunities and fitness for female bears, depending on placement and the cumulative amount of human activity. Higher shellfish densities, as a result of aquaculture farming practices, may benefit both male and female bears by providing a reliable food source. Smith and Partridge [75] found that intertidal foraging provided a significant nutritional resource for grizzly bears, especially during spring months when salmon and berries are largely absent. Although their study focused on clams, other shellfish types (e.g., mussels) may provide similar foraging opportunities. While this interaction could be economically beneficial to tourism by increasing bear-viewing opportunities, it would likely be unfavourable for the shellfish aquaculture industry, due to increased safety risk for workers and damages or a loss of product.

Although not as lucrative as bear-viewing, birding represents another important and growing ecotourism attraction along the central and north coast of BC which may interact with the shellfish aquaculture industry. As well recognized and charismatic coastal foragers, bird interactions with shellfish aquaculture have been better studied than those with bears. Current research, focused on deep water longline oyster and mussel culture, suggests that interactions between birds and shellfish aquaculture are neutral or positive [76–81], however, it is worth noting that modifications to behaviour have not been studied. Because bivalves make up a portion of the diet of many species of coastal birds, shellfish aquaculture beds become attractive foraging areas [79]. In addition to cultured shellfish, high concentrations of wild mussels also settle and grow on, or in the vicinity of shellfish aquaculture infrastructure, providing further nutritional benefits for birds [79]. While some shellfish farmers welcome birds for their assistance in removing fouled organisms from their shellfish infrastructure [80], others consider birds to be a nuisance consuming their product. Shellfish farmers may employ deterrents, such as noise, lights, predator models, or fencing to reduce bird predation at aquaculture facilities [82]. Studies focused on varying types of birds and aquaculture indicate there may be species-specific responses [79]. While the literature suggests that shellfish aquaculture and bird-watching tourism could be sustainable, more research is required to understand the interactions between these two industries.

As tourism and shellfish aquaculture continue to expand on BC's north and central coast, these industries must work to minimize conflicts with one another. For example, zoning and siting of new shellfish farms should consider the cumulative effects of industry expansion on the various recreational activities, wildlife species, and tourism industries which share this space. Such considerations would allow these economically important activities to thrive, while maintaining and protecting the natural environment of the central and north coast.

7. Indigenous sovereignty

Loss of access to traditional coastal territories and preferred harvest sites due to tenure privatization for shellfish aquaculture is a major concern among First Nations in BC [49,83]. Coastal First Nations have a long history of traditional marine resource use, including the culture and harvesting of wild shellfish [47]. There is substantial risk of conflict between traditional use of coastal marine areas and the government tenure system, which limits access to foreshore and ocean space [13]. Many First Nations view shellfish aquaculture as a threat to their culture and territorial sovereignty [84]. As a result, some First Nations have purchased aquaculture leases to preclude non-First Nations investors from securing exclusive access to traditional harvest sites [49]. However, many First Nations members believe they should not be required to pay leasing fees to access shellfish beaches within their traditional territories [49].

Relationships between the shellfish aquaculture industry and coastal First Nations in BC may benefit from developing and implementing improved community-led management practices. The involvement of First Nations in management decisions can improve government-to-government relationships, promoting the social and ecological sustainability of shellfish aquaculture. First Nations' participation in geoduck fishery management on the central coast, for example, is anticipated to promote long-term sustainable management of geoduck [86]. Many years of negotiations among First Nations, Fisheries and Oceans Canada (DFO), and the Province of BC on the west coast of Vancouver Island highlight the importance of incorporating Indigenous rights and priorities in shellfish aquaculture development [85].

When government policy does not facilitate First Nations' participation in aquaculture, it may represent a substantial hindrance to the expansion of BC's shellfish industry in remote areas of the central and north coast. Based on comparisons with shellfish aquaculture in New Zealand, for example, Tollefson and Scott [87] concluded that a lack of First Nations engagement in the BC shellfish aquaculture industry is the primary factor inhibiting its growth. DFO's 2014 Pacific Region Shellfish Integrated Management of Aquaculture Plan [61] included the support of First Nations participation in shellfish aquaculture as a priority and suggested that First Nations' capacity and engagement with aquaculture was encouraged through programs like the Aboriginal Aquatic Resource and Oceans Management and the Pacific Integrated Commercial Fisheries Initiative. The report also states that DFO works closely with the First Nations Fisheries Council. The development of guidelines and policy in support of First Nations participation will also need to consider risks associated with shellfish aquaculture in remote communities, where small-scale operations may not be preferable to wild harvest [49,84]. Successful implementation of shellfish aquaculture in First Nations' territories will need to ensure that their access to the ecosystem services provided by both shellfish aquaculture and traditional wild harvest are maintained [88].

8. Social perceptions

Social perceptions of shellfish aquaculture have a strong influence on local decisions, and may limit industry expansion regardless of the physical, production, or ecological carrying capacities of the environment [89]. Sheltered inlets ideal for shellfish aquaculture are often used by multiple groups and stakeholders for a variety of aesthetic and recreational purposes [90,91]. This can create competition for space with recreational boaters, visiting tourists, coastal residents, and other resource users [67,92]. As a result, public perception of aquaculture-associated risks can be a more important indicator of the potential for industry growth than ecological capacity or economic cost-benefit analyses [84]. Long-term solutions to this conflict require that shellfish aquaculture practices in BC be perceived as socially, environmentally, and economically sustainable [93]. Understanding the perceptions and concerns of local stakeholders is of considerable importance to the success of shellfish aquaculture expansion on the central and north coast.

Perceived shellfish aquaculture-associated risks in BC span three dimensions: experiential, environmental, and economic. Experiential concerns are those that affect the stakeholder's way of life, and include detrimental effects on aesthetic value, the creation of noise pollution, and limited accessibility to the foreshore or coastal waters [67,69,92]. Environmental concerns, such as pollution, changes to local biodiversity, and negative impacts on water quality, are of high priority among stakeholders [69,92,94]. However, the actual effects of shellfish aquaculture on the environment, as perceived by stakeholders, are shrouded in a great deal of uncertainty [69,94]. In some cases, limited access to information has fostered a sense of distrust for the industry [69]. While most stakeholders have positive perceptions of shellfish aquaculture's economic effects and sustainable job creation [67,92,94], some have expressed concern that the wealth generated does not return to adjacent communities and that expansion of the aquaculture industry could alienate other economic uses [69].

Despite their importance, social science studies of shellfish aquaculture in BC are few and have been limited in both scope of farming practices and regional coverage, yielding significant knowledge gaps for future development on the central and north coast. For species such as the geoduck, cockle, abalone, sea urchin, and sea cucumber, stakeholder perceptions remain largely unknown. Studies have focused almost exclusively on southern BC, in areas such as Baynes Sound [67,69,93] and the Gulf Islands [92], where commercial shellfish aquaculture has been most intense. Remote communities and First Nations on the central and north coast likely have concerns which are poorly represented in these studies. It should therefore be with caution that these findings are evaluated as a representation of the social considerations of shellfish aquaculture for industry expansion in central and northern BC.

9. Logistic and economic considerations

Despite its success in southern BC, some industry stakeholders have questioned the logistics and economic viability of shellfish aquaculture on the central and north coast of BC. Colder water temperatures are expected to yield lower growth rates and slow the delivery of mature shellfish to the market [95]. Geoduck grown in colder water, for example, can take five to seven years longer to reach marketable size. Though many experts anticipate that these farms would remain economically viable, this could make central and north coast aquaculture operations less productive overall than their southern counterparts [95]. Higher labor and transportation costs at remote sites present another disadvantage for central and north coast aquaculture businesses [96]. A lack of infrastructure, including dock access and accommodation, poses a further challenge in remote regions. Furthermore, most hatcheries and processing plants in the province are located on the south coast of BC, requiring central and north coast farmers to build their own or ship their product further. Due to their distance from major aquaculture centers, remote growers have also expressed concern over limited networking opportunities and a lack of communication with the rest of the industry [96]. This disconnect has led to worries among growers that they have little access to new research, technology, and market information important to the success and economic viability of their aquaculture operations [96].

10. Changing oceanic conditions

Ocean acidification and associated changes to marine conditions present an array of challenges for the expansion of the shellfish aquaculture industry in BC. With the absorption of atmospheric carbon dioxide, acidification (decreasing pH) of the marine environment reduces the availability of aragonite and calcite, which are essential for bivalve shell formation [97]. Biological effects on shell-forming organisms, including cultured shellfish, range from minor physiological changes to mortality, and broad-scale shifts in distribution [98]. Findings by Haigh et al. [99], for example, indicate that the growth and physiology of farmed oysters, clams, and scallops, as well as wild abalone, geoduck, and sea cucumbers will be negatively affected by ocean acidification. The productivity of shellfish aquaculture operations is particularly sensitive to pH conditions during early shellfish embryo and larval life stages [100]. Consequences of this susceptibility have been observed during strong upwelling events, which transport acidified water to hatchery inflows, resulting in high rates of mortality in larval shellfish [100]. Oceanic currents on BC's coastline cause upwelling events that can drastically reduce pH at shallow depths (< 125 m) [101,102]. Occurring primarily in the spring and summer months, these upwelling events coincide with critical periods of high productivity for planktonic, shell-forming invertebrate larvae [103,104]. These regional conditions have the potential to exacerbate the negative effects of decreased oceanic pH on the growth and survival of cultured shellfish.

Increasing oceanic temperatures present a second consequence of climate change with implications for shellfish aquaculture productivity. Global temperature models indicate that the planet warmed by 0.6 °C throughout the twentieth century, while the Pacific Northwest has warmed by 0.8 °C during the same period [105,106]. Warming is predicted to continue throughout the century and increases could reach 1.2 °C globally and 2.0 °C within the Pacific Northwest by 2030–2059 [106]. Globally, increases in mean water temperatures are associated with extensions and shifts in marine species ranges [107,108]. More extreme warming events are often followed by mass mortality events for shellfish and other benthic species [109,110]. Although this may allow certain species to be cultivated further north than their current ranges, cold-adapted northern species will likely suffer dire consequences, particularly because higher latitudes are warming more rapidly than their equatorial counterparts [105]. Expansion of the shellfish aquaculture industry must therefore consider localized changes in oceanic temperatures as well as the physiological constraints of cultured species.

To counter the negative effects of warming ocean temperatures and acidification, shellfish farmers have developed adaptive strategies to increase shellfish survivorship. Hatchery managers, for example, can adjust pH levels by adding sodium carbonate during upwelling events [97]. This strategy increases shellfish survival and maximizes hatchery production [97]. Moving aquaculture production to cooler, deeper offshore waters, may allow growers to avoid extreme warming events that occur in shallow coastal waters, particularly in the summer [111]. Climate mitigation strategies to combat changing sea levels, oceanographic conditions, and carbonate chemistry, are also being incorporated into the design, construction, and restoration of shellfish facilities [112]. Furthering current understanding of how ocean acidification and warming waters impact shellfish growth, survival, and productivity will be crucial for identifying future mitigation strategies to safeguard hatcheries and shellfish farms. All life stages, hatchery processes, and local oceanic conditions will need to be considered when determining how vulnerable shellfish aquaculture operations may be to the effects of climate change.

11. Conclusions

Clean and productive waters make the central and north coast of BC prime candidates for the expansion of shellfish aquaculture to meet growing global demand for seafood. With careful planning, implementation, and monitoring, this industry has the potential to provide jobs and economic benefits for coastal communities, while having a relatively small environmental footprint. Such expansion of the shellfish aquaculture industry on the central and north coast of BC will need to address several challenges.

Although the direct interactions between shellfish aquaculture and existing industries, such as forestry, commercial fisheries, and ecotourism are largely unstudied, these operations could be mutually sustainable if developed in consideration of regional management goals. Shellfish aquaculture could be an attractive economic subsidy in communities impacted by declines in the forestry and wild fishery sectors [2,3]. Care must be taken, however, in the selection of shellfish aquaculture sites to mitigate negative impacts, such as habitat alteration within important fish spawning and rearing habitats. Similarly, marine planning for the benefit of both wild and cultured shellfish industries will need to consider ecological carrying capacities and local economic trade-offs. Predicting the effects of shellfish aquaculture expansion on tourism and recreation will require a better understanding of local access requirements, tourist perceptions, and the industry's influence on wildlife ecology and behaviour.

Given the multitude of stakeholders, groups, and governments that share these shorelines, there will likely be conflicts of interest among shellfish growers, residents, and First Nations. The physical exclusion of land use imposed by the tenure system will be a significant challenge to the social acceptance of shellfish aquaculture development. Mitigating aesthetic impacts and noise, however, are ways that growers can substantially improve public perceptions of the industry. Though the ecological impacts of shellfish aquaculture are a primary concern among stakeholders, there are some important knowledge gaps regarding the industry's interactions with native biota, including wild shellfish, commercial finfish, shorebirds and even charismatic megafauna such as bears. Research furthering our understanding of these interactions and better disseminating information to the public would not only inform management practices, but potentially improve the relationship between local stakeholders and the shellfish industry.

In the face of a changing marine environment, the shellfish aquaculture industry will need to adapt to the challenges posed by increasing ocean acidity, water temperatures, and rising sea levels. These conditions have implications for all life history stages, influencing shellfish physiology, growth, size and survival. While there are still significant knowledge gaps regarding how shellfish species will respond, it is certain that the aquaculture industry will be affected. Research on these topics has helped inform innovative industry practices designed to circumvent associated impacts.

Expansion of shellfish aquaculture on the central and north coast of BC will need to be socially, environmentally, and economically sustainable. The results of this review strongly indicate that shellfish aquaculture should be incorporated in marine planning initiatives and developed in consideration of local ecological, environmental, economic, and social context. While numerous, the challenges posed to the future development of this industry are not insurmountable. With continued research on the interactions between shellfish aquaculture and socio-ecological communities, filled knowledge gaps will contribute to the informed management of industry development.

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Declarations of interest

None.

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