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REVIEWS IN Aquaculture

REVIEW

Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps

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Abstract

Aquaculture can have negative environmental impacts, adding to the suite of anthropogenic stressors that challenge coastal ecosystems. However, a growing body of scientific evidence indicates that the commercial cultivation of bivalve shellfish and seaweed can deliver valuable ecosystem goods and services, including provision of new habitats for fish and mobile invertebrate species. We completed a systematic literature review of studies focused on understanding habitat-related interactions associated with bivalve and seaweed aquaculture, and a brief meta-analysis of 65 studies to evaluate fish and mobile macroinvertebrate populations at farms and reference sites. Bivalve and seaweed aquaculture were associated with higher abundance (n = 59, range: 0.05× to 473×, median $lnRR$ = 0.67) and species richness (n = 29, range: 0.68× to 4.3×, median $lnRR$ = 0.13) of wild, mobile macrofauna. Suspended or elevated mussel and oyster culture yielded the largest increases in wild macrofaunal abundance and species richness. We describe the major mechanisms and pathways by which bivalve and seaweed aquaculture may positively influence the structure and function of faunal communities—including provision of structured habitat, provision of food resources and enhanced reproduction and recruitment—and identify the role of the species cultivated and cultivation gear in affecting habitat value. Given the continued deterioration of coastal habitats and increasing investments into their restoration, understanding how industry activities such as aquaculture can be designed to deliver food within ecological limits and have positive influences on ecosystem goods and services is essential in ensuring ecological, social and economic objectives can be achieved.

KEYWORDS
ecosystem services, food systems, marine aquaculture, marine ecology, restoration

1 | INTRODUCTION

Anthropogenic stressors such as eutrophication, habitat degradation, overfishing and climate change are increasingly challenging coastal ecosystems and communities reliant on their productivity.[1] These threats have left coastal communities searching for new solutions to sustain livelihoods and support the needs of nutritionally vulnerable nations,[2,3] all while keeping food production for a growing population within planetary ecological limits.[4] Aquaculture, which is the farming of finfish, shellfish and seaweed in fresh and saltwater environments, is amongst the fastest growing forms of food production on the planet.[5] Aquaculture's rapid rise has coincided in many cases with negative impacts on surrounding ecosystems.[6] Increasingly, however, evidence indicates that appropriately located and managed aquaculture operations can provide a broad and positive range of interactions with local environments including ecosystem services.[7–10] Bivalve shellfish (hereafter bivalve) and seaweed aquaculture in particular have the potential to provide wide-ranging ecosystem services, such as water quality regulation and wildlife habitat, and may provide opportunities to complement commercial production with positive effects on coastal habitat conservation and restoration efforts.

Although aquaculture is viewed as a food industry, aquaculture activities align with a much broader spectrum of ecological concepts, ecosystem dynamics and research and management-based themes, such as conservation, global change, habitat restoration and sustainability (Table 1). For example, aquaculture activities can support restoration of bivalve ecosystems for species recovery or stock replenishment and various forms of cultivation for seaweed forest enhancement.[11,12] There could be much to learn from a broader and more cross-disciplinary evaluation of the ways in which aquaculture can deliver outcomes for people and nature. Understanding the role of bivalves and seaweed used in aquaculture through central tenets in ecology, conservation or fisheries science, as well as aquaculture research, could enable a more holistic and nuanced understanding—across the full spectrum of aquaculture activities—of the opportunity that exists to design aquaculture for intentional delivery of ecological, economic and social values.

An important source of knowledge on the ecosystem benefits of bivalves in engineered environments has been the extensive research conducted on oyster reef restoration.[11] But there has been comparatively little research on potential ecological benefits associated with bivalve and seaweed aquaculture practised for food production,[7] despite some aspects of these activities being comparable, including the use of artificial or supplemented substrate. Any environmental values associated with aquaculture have largely been 'pigeonholed' as nominal and non-market benefits rarely linked to market applications and products.[10] Increasing our understanding of how and when aquaculture systems could deliver ecosystem services and promote market-based opportunities could incentivize industry to seek greater positive impact on local environments through their activities and governments to achieve multiple, often competing, sustainability targets through proactive policy.[13]

Increased understanding of how commercial aquaculture can operate in step with natural ecosystem process and provide positive environmental effects (referred to as 'restorative aquaculture') will support the long-term sustainable use of natural resources (eg United Nations Sustainable Development Goal [SDG],[14] 'Conserve and sustainably use the oceans, seas and marine resources'). Importantly, it will also provide opportunities for communities in both developed and developing nations to realize greater food, economic and social security (eg SDG 2, 'Zero hunger') and could avoid trade-offs between achieving one target over another.[14] Over the past decade, multiple reviews have examined the state of knowledge surrounding the wildlife impacts of aquaculture (eg refs 15,16). It is clear that aquaculture can have a wide range of negative, neutral or positive impacts on ecosystems and that the direction and magnitude of the impact(s) are dependent on the interaction of multiple factors (eg physical conditions at the site, cultivation gear utilized on the farm).[17] Given the growth trajectory of aquaculture, it is timely to make an intentional shift towards better understanding what benefits we might expect from aquaculture and the requisite conditions—the enabling

TABLE 1 The spectrum of 'aquaculture' includes activities ranging from habitat restoration to commercial aquaculture, with distinct environmental or economic drivers and unique purpose or beneficiaries influencing each activity

	Environmental drivers	⟷	Economic drivers
Activity	Habitat restoration	'Restorative aquaculture' (commercial aquaculture with positive ecological value)	Commercial aquaculture
Perceived ecological value	Positive	⟷	Low to negative
Target or beneficiary	Conservation, community, indirect commerce (co-benefits, eg water quality, fish and invertebrate habitat)	Food production, indirect commerce (co-benefits, eg water quality, fish and invertebrate habitat)	Global trade/markets
Key research disciplines	Ecology, restoration ecology	Food and sustainability, aquaculture, ecology	Aquaculture, food sciences, husbandry, animal health
Central habitat principles	Habitat provision, bottom-up and top-down processes	Farming and ecosystem productivity	Farming

conditions and mechanisms through which aquaculture can provide those benefits—that could ensure aquaculture practices generate substantial, consistent benefits to nature, as well as people. Here, we provide a review of these considerations as they relate to the habitat value of bivalve and seaweed aquaculture for fish and mobile macroinvertebrate species, derived from a systematic literature review. We draw on examples provided by identified studies that addressed habitat-related considerations associated with bivalve and seaweed aquaculture and provide measured analysis of 65 studies that evaluated fish and mobile macroinvertebrate populations at farms and reference sites. We describe the alignment of aquaculture activities with ecological drivers of habitat value, including provision of structured habitat, provision of food resources and enhanced reproduction and recruitment, consider the policy and operational ramifications of these findings and identify major research needs to advance the capacity of bivalve and seaweed aquaculture to support ecosystem functions and deliver ecosystem services in marine and coastal environments.

2 | MECHANISMS AND PATHWAYS FOR BIVALVE SHELLFISH AND SEAWEED AQUACULTURE TO AFFECT HABITAT VALUE FOR FISH AND MOBILE INVERTEBRATES

Bivalve and seaweed species are typically cultivated within an open environment and therefore interact with a range of ecological processes.[7,18,19] These processes can create habitats for marine life alongside the cultivated species, but they can also, for example, have an effect on benthic-pelagic coupling through biodeposition and introduction of shell or other detritus. All types of bivalve and seaweed aquaculture involve the introduction of cultivated organisms and, in many cases, production gear into the coastal environment for 'farming'. The introduction of gear associated with aquaculture activities can generate novel interactions within the coastal environment, such as the provision of additional surface area for settlement by fouling communities, structured habitat and alteration of local hydrodynamics.[20,21] These represent important and complex ecological processes in natural habitats and should also be considered when assessing the ecological role of bivalve and seaweed aquaculture.

It is well established that aquaculture—including forms of bivalve and seaweed aquaculture—can in some cases yield negative impacts on ecosystems and wildlife, particularly at larger scales of aquaculture (eg total footprint or intensity of culture).[18,22,23] For example, aquaculture may increase disease transmission risk for wild taxa,[24] the introduction of farming infrastructure can disadvantage species such as wading birds that forage on soft sediments,[25] and farming operations can negatively impact the density and productivity of submerged aquatic vegetation that provide habitat for many marine species.[26] Consequently, to understand the role of bivalve and seaweed aquaculture in driving habitat effects and value in coastal ecosystems, it is important to evaluate a broad range of factors and circumstances associated with the operating environment created by aquaculture, from local environmental conditions, intensity and scale of culture, cultivation gear and species cultivated, through to farm management practices as well as the policy and management setting (Figure 1).

For organisms in aquatic and marine environments, 'habitat' can include provision of physical structure, food or substrate resources, or favourable hydrodynamics and hydrology.[27] The 'value' of a habitat depends on the ability of individuals to survive and reproduce within it, and in aquatic environments, habitat value is often viewed in relation to its ability to support a fishery resource (eg finfish, crustaceans, molluscs) and is generally quantified in terms of biomass or abundance data. Increasingly, evidence indicates that bivalve and seaweed aquaculture could provide valuable habitat for wild fish and mobile invertebrates and potentially improve their production by increasing forage, breeding and/or predator refuge habitats (Figure 2), as measured by density or abundance of these species associated with these types of aquaculture.[15,16] While it is possible that the presence of greater abundances of wild fish and mobile invertebrates at farms could simply represent increased concentrations of these organisms and not additional production,[16] we posit that the mechanisms described in detail below could—in certain circumstances—support enhanced productivity for wild fish and mobile invertebrates. For a given species, the potential for increased productivity arising from elevated abundance at farms will depend on the individual experience and characteristic behaviour of the species. If farms bring lower risk of mortality or higher reproductive success, for example due to high-quality shelter, that is sufficient to outweigh risks due to displacement or capture during harvesting and maintenance, then the farms may play a role in increasing productivity. However, if a high risk of mortality or lower reproductive success occurs due to low-quality shelter or frequent disturbance from farm maintenance and harvesting (eg ref. 28), then farms may act as 'ecological traps' that drain surrounding wild populations.[29] Populations of structure-reliant, habitat-limited or demersal fish species may have the most to gain from farm structures, but also may be the most vulnerable to impacts from farm harvesting or maintenance. Transient species that feed opportunistically at farms and are less affected by displacement during harvesting may also experience higher productivity.

At the farm scale, aquaculture gear (eg ropes, cages) can provide settlement substrates for recruitment and establishment of sessile invertebrate (fouling) communities that can increase habitat complexity and provide novel forage opportunities. Additionally, the physical structure associated with some types of gears (eg floating cages with open meshes) can provide refuge for small juvenile fish and invertebrate species and restrict larger predator species.[21] At the bay or ecosystem scale, water filtration by bivalves and nutrient removal by seaweed could result in water clarity improvements that can increase the overall distribution of submerged aquatic vegetation.[30] Additionally, reproduction of cultivated organisms—particularly of species that have been locally extirpated (eg oysters)—could provide important subsidies to benefit wild populations and ecosystems in certain circumstances.[31]

FIGURE 1 The direction (negative, neutral or positive) and magnitude of the impact of aquaculture on ecosystems is dependent on multiple interacting drivers. Note that the relative importance of each driver varies

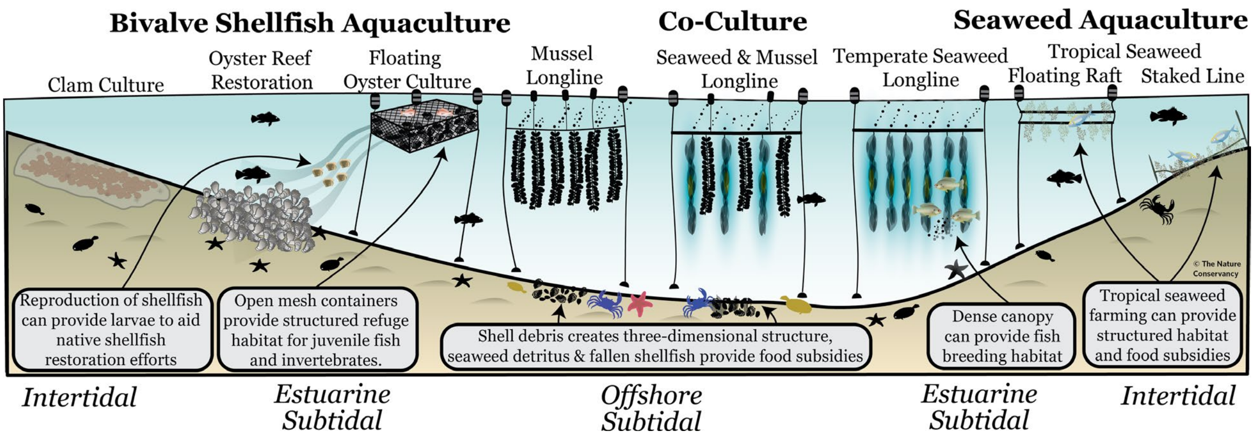

FIGURE 2 Bivalve and seaweed aquaculture production methods and mechanisms and pathways associated with habitat value

2.1 | Bivalve shellfish aquaculture habitat interactions

2.1.1 | Bivalve aquaculture production methods

Bivalve aquaculture in the coastal zone involves outplanting of cultured organisms directly on the seafloor ('on-bottom' culture) or in suspension within the water column ('off-bottom' culture) using associated production gear.[32] Scallops, mussels, oysters and clams can be produced via on-bottom culture, with outplanting of these organisms involving direct planting of juvenile bivalves on or within the seafloor without the use of in situ gear (Figure 2). In some cases, such as with on-bottom culture of clams, outplanted organisms are covered via protective plastic mesh netting to limit predation.[33] Off-bottom culture of bivalves can involve a variety of methods, but generally involves use of container-, raft- or longline-based systems where cultured bivalves are suspended above the seafloor. Container-based systems include 'rack and bag' or 'tray' culture, where containers (eg vinyl mesh bags) or trays are suspended above the seafloor within the intertidal zone via a rack or tray system. Cage culture typically involves use of large containers that are positioned on the seafloor in the subtidal zone. Surface or floating culture includes use of anchored floating containers at the surface of the water column, and suspended culture involves use of anchored longline systems that can be used to suspend containers (eg mussel 'socks', pearl or lantern nets) or used directly for grow-out of cultured organisms.

Sources of bivalve seed can be either collected from the wild or produced through hatchery operations. Wild seed collection typically involves use of settlement substrate (eg oyster shells, mussel spat collector ropes) placed in areas of high wild larval recruitment. Grow-out of seed may take place in the same location that spat was collected, or they may be moved to other locations and affixed to grow-out gear (eg 'bouchot' poles, longlines). Where wild larval recruitment is insufficient, hatcheries are often utilized to produce seed. For example, in oyster culture operations, spawned larvae is sometimes 'set' on oyster shell prior to deployment (often referred to as a 'spat-on-shell' method), or on small grains of oyster shell (referred to as 'microcultch') for use in off-bottom culture.

2.1.2 | Structured habitats

Cultivated bivalves and associated gear can provide structured habitat that benefits juvenile fish and mobile invertebrate species. Complex, structured habitats have been found to generally host higher densities of fish and invertebrates relative to adjacent unstructured habitats.[34] Further, degradation of natural habitats (eg seagrass, mangroves, coral reefs) has been increasingly implicated in fishery recruitment failures and the inability of management efforts to recover certain fish stocks.[35] Structure associated with bivalve aquaculture could (a) increase forage habitat for adult, juvenile and or/newly recruited fish (Figure 3A); (b) increase breeding habitat (Figure 3B); and (c) increase predator refuge or resting habitat (Figure 3C,D). Outplanting of live bivalves and/or shell or other substrate material for wild recruitment creates novel three-dimensional structure with interstitial space in otherwise unstructured, soft-sediment systems and can mimic natural bivalve beds.[28] This can facilitate reef-associated community development—including sessile fouling communities and larger mobile species.

Beyond cultivated organisms themselves, bivalve aquaculture gear can also provide habitat. For example, mesh material or interstitial space associated with the gear can restrict larger predators, allowing cages to become refugia for many juvenile fish (Figure 3C).[21,36] This is consistent with other studies that have examined aquatic habitats and have identified that increasing complexity yields higher abundances of organisms due to increased protection from predation.[37] Moreover, bivalve aquaculture gear provides additional settlement substrate for organisms that can increase the associated habitat complexity, such as the sessile fouling community.[38,39] The structure, combining the collective of cultivated organisms and farming gear, provided by bivalve aquaculture can contribute to physical stress reduction (ie reducing the impact of waves and currents)[40] and can also reduce physiological stress. For example, Helmuth[41] found that mussels living within a biogenic matrix in the

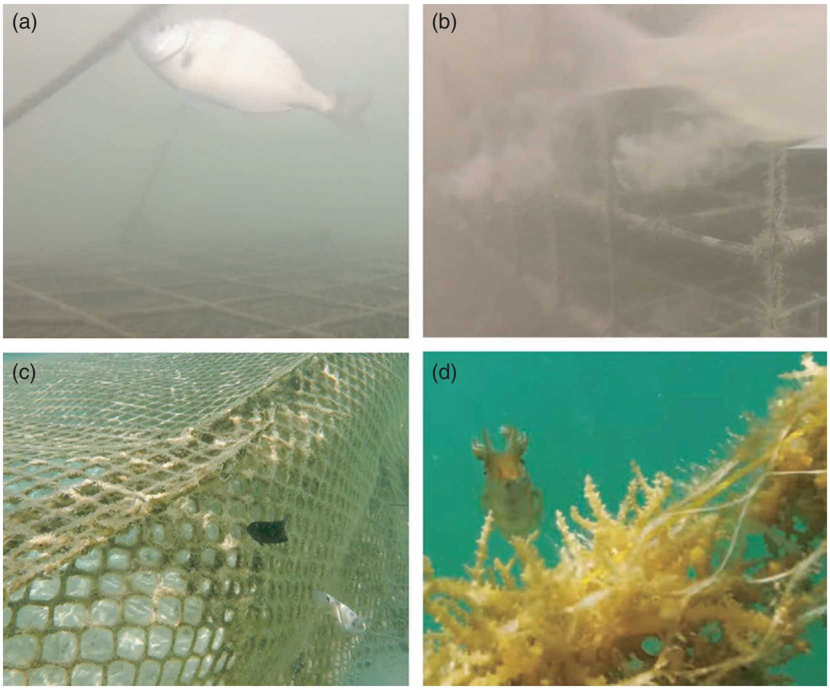

FIGURE 3 Reported examples of habitat value provided by bivalve and seaweed aquaculture, including (A) gear providing substrate for fouling organisms that provide forage resources for fish (subtidal oyster cage within Long Island Sound, USA), (B) structured habitat for fish reproduction (subtidal oyster cage within Long Island Sound, USA), (C) refuge habitat for juvenile fish (giant clam grow-out cage within Nikko Bay, Palau) and (D) resting habitat for fish and invertebrates (subtidal raft culture for seaweed in Turneffe Atoll, Belize). Images (A) and (B) were taken by NOAA Fisheries, and (C) and (D) by The Nature Conservancy

rocky intertidal environment could reduce thermal stress through the presence of mussel biomass that could modulate temperatures relative to external environments.

Off-bottom cultivation of bivalves can also result in 'fall-off' of live bivalves and/or shell debris that can alter benthic communities through creation of structured benthic habitat that can increase habitat complexity and heterogeneity.[18] However, these mechanisms by which bivalve aquaculture can provide structured habitat can unevenly benefit or negatively impact certain species (eg infaunal communities) and can in some cases affect other related processes such as trophic dynamics. For example, in some cases, aquaculture structures have been found to have no effect on the diversity and abundance of mobile species (eg refs 42,43) and, in other cases, have been found to displace and alter movement patterns of predator species (eg 44). The additional substrate can also be colonized by and/or serve as 'stepping stones' for invasive species, and the introduction of cultivated bivalves can transfer disease and hitchhiking species, some of which may be invasive (ie unintended introduction of novel species alongside the cultivated species).[26,45,46]

2.1.3 | Food resources

Bivalve aquaculture can create a trophic subsidy for wild fauna, potentially increasing productivity of various ecologically and/or commercially important species. Sessile fouling communities form the basis of the food web for many artificial reef communities,[38] and comparisons have previously been drawn between bivalve aquaculture and artificial reefs.[21,36] The presence of bivalves and associated gear used in their production increases the amount of surface area available for settlement by sessile epibiotic organisms, such as macroalgae, barnacles, hydroids, tunicate ascidians and mussel spat.[45,47] These organisms have been found to provide important food subsidies for artificial reef-associated fish species[48] and are well established as key contributors to bivalve reef communities that can enhance fish and mobile invertebrate production.[49,50]

Cultivated bivalves themselves can provide an additional food subsidy. Many invertebrate species groups have been known to prey on cultivated bivalve species, particularly gastropods, starfish, crabs and flatworms.[51] Cownose stingrays (*Rhinoptera bonasus*), which are distributed along the eastern seaboard of the Americas from southern New England to Brazil, have been associated with substantial consumption of cultivated oysters and clam species.[52] Further, fall-off of live mussels from aquaculture activities provided substantial food subsidies (~46% of the diet) to a commercially important lobster species (*Homarus americanus*).[53]

2.1.4 | Reproduction

Many bivalve species are broadcast spawners that produce planktonic larvae that can be distributed by local hydrodynamics throughout waterbodies (Figure 2). Reproduction of cultivated bivalves can contribute to the larval pool and to wild recruitment, thereby potentially contributing to the creation of additional habitat by increasing the abundance of bivalves. This contribution could be particularly valuable where 'wild' populations of cultivated species have been extirpated. For example, in the Damariscotta River, Maine, USA—a system where native Eastern oyster (*Crassostrea virginica*) populations had previously been extirpated—a 'wild' population of eastern oyster (*C. virginica)* has recently emerged as a result of spawning of diploid farmed oysters, resulting in a 'new' fishery.[31,54] However, in cases where non-native species are cultivated (eg the Pacific oyster, *Crassostrea gigas*, in the Wadden Sea), there have been documented instances of reproduction and establishment of these cultivated organisms yielding negative ecosystem impacts (eg outcompetition of native species).[55] Reproduction of cultivated bivalves could also impact the genetic structure of wild populations.

2.2 | Seaweed aquaculture habitat interactions

2.2.1 | Seaweed aquaculture production methods

Seaweed aquaculture typically occurs via 'off-bottom' culture, involving floating or staked lines, longline systems or use of floating rafts or racks (Figure 2).[32,56] Floating systems are typically utilized in deeper subtidal waters and are designed to keep cultivated seaweeds near surface waters. Staked systems are used in intertidal environments and consist of longlines attached to stakes driven into the intertidal seafloor. In the case of tropical seaweeds, seaweed is generally fragmented into 'seeds' that are tied to lines. Temperate kelp aquaculture typically involves hatchery-based reproductive production of sporelings in a hatchery setting that are set on thin twine lines and subsequently outplanted to larger longlines in the marine environment for grow-out.[19]

2.2.2 | Structured habitat

Seaweeds and the gear used in their cultivation can provide complex structured habitat (Figure 2).[57] The dense canopy and structure associated with seaweeds— within both natural and aquaculture settings—can provide habitat for diverse fish and invertebrate species. Tall, branching kelps have been found to serve as preferred shelter by macroalgae-associated fish species whether native or not.[58,59] Further, the complex habitat created by kelp holdfasts can host a high diversity of macroinvertebrates. Walls et al.[60] documented higher species richness in the holdfasts of suspended culture Horsetail kelp (*Laminaria digitata*) in Ireland as compared to wild benthic counterparts. Lumpfish (*Cylopterus lumpus*) have been reported associating with suspended culture of temperate kelps.[61] These fish are valued for their roe and as biological control agents in salmon aquaculture.[62] Recent research in coastal Belize—where a seaweed aquaculture sector is emerging—has identified increased fish abundance associated with seaweed farms relative to nearby adjacent structured reference sites.[63] de Carvalho et al.[56] compared the abundance, diversity and richness of fish species within experimental seaweed farm sites relative to nearby reference control sites of similar environmental characteristics and identified no significant differences across any of the parameters measured, highlighting the importance of local environmental characteristics, farming practices and other related considerations in determining the directionality of seaweed aquaculture's benefit or impact on habitat provision. Poorly located tropical seaweed farms can also negatively affect natural seagrass habitats through shading and trampling associated with farming activities, yielding impacts to associated macrofaunal communities (eg ref. 64).

2.2.3 | Food resources

Cultivated seaweeds can provide a direct food subsidy to herbivorous fish species. For example, Anyango et al.[65] examined the abundance, diversity and trophic status of wild fish around seaweed farms in Kibuyuni, Kenya, and identified farmed seaweeds (*Kappaphycus alvarezii*) within the stomachs of fish captured at sites adjacent to seaweed farms. Hehre[66] utilized gut content and stable isotope analysis to determine the contribution of farmed seaweeds to herbivorous rabbitfish diets and found farmed seaweed contributions of up to 50% of the total diet. At national scales, Hehre and Meeuwig[67] examined the relationship between national-level seaweed production and herbivorous reef fish catch and reported a positive correlation between farmed seaweed and herbivorous reef fish catch in Southeast Asia—where there are continuous high volumes of seaweed production—but not in east Africa or the western Pacific where production is smaller and more sporadic.

2.2.4 | Reproduction

Seaweed farming techniques show potential for applications to restore or re-establish kelp forests and other macroalgae species, which could contribute to the creation of additional habitat by increasing the abundance of seaweeds. When settlement from wild reproduction is insufficient, direct transplantation of hatchery-produced kelp seedlings as a restoration method was suggested as many as four decades ago to support wild reproduction when insufficient in a natural setting.[12] Several academic and NGO efforts are underway to develop restoration methods to rebuild kelp forests in the eastern Pacific, the North Sea and eastern Atlantic. However, the authors are unaware of field studies that have identified farm-derived reproductive restoration of wild populations. With established and emerging seaweed farming sectors, in situ reproduction of farmed (native) seaweeds could also be considered a source of restoration. For example, seaweeds can be farmed in areas where oceanographic conditions are suitable, but where seascape structure precludes establishment of wild populations. Farming in these areas, if hydrodynamically linked with impacted habitat areas, may help serve as reproductive 'exporters' to downstream impacted habitats where natural recruitment is unlikely due to geographical distance between isolated extant populations.[68] As aquaculture technologies continue to develop—such as advanced genetics and breeding technologies that permit enhanced growth rates and disease tolerances for cultured species—novel interactions between farmed organisms and wild populations (eg genetic interactions) are an increasingly important consideration, as well as the potential for reproduction of non-native species.[69,70]

3 | ESTIMATING THE RANGE OF HABITAT VALUE OF BIVALVE SHELLFISH AND SEAWEED AQUACULTURE FOR FISH AND MOBILE MACROINVERTEBRATES

The effects of aquaculture activities on wildlife are likely to depend on a range of site-specific conditions, such as the type of gear used, the organism farmed and the nature of the surrounding environment. This review builds upon Barrett et al.[16] who reviewed the effect of marine and freshwater aquaculture broadly (including fin- and shellfish) on wildlife (ie fish, birds, mammals, amphibians). That review did not consider invertebrates, nor did it distinguish between the diverse farming methods and taxa used in bivalve and seaweed aquaculture. The present study—through extending this systematic review of the literature specific to bivalve shellfish and seaweed—sought to further identify broad patterns in the habitat role of these forms of aquaculture for fish and mobile macroinvertebrate populations.

3.1 | Methods for analysis

We limited the scope of analysis to abundance and richness of fish and mobile macroinvertebrate species as maintenance of populations of these organisms is a commonly stated objective of coastal marine and estuarine habitat conservation and restoration efforts (eg ref. 11). We considered studies of birds, mammals, sessile organisms or infauna to be outside the scope of this review. Relevant peer-reviewed primary publications up to May 2020 were discovered by searching ISI Web of Science and Google Scholar with the search string: (aquaculture OR mariculture OR shellfish farm* OR mussel farm* OR oyster farm* OR seaweed farm* OR macroalgal farm* OR algal farm*) AND (abund* OR density OR communit* OR attract* OR displace*) AND (wildlife OR animal* OR fauna* OR fish* OR shark* OR invertebra*) NOT (bacteria* OR pathog* OR bird* OR mammal*). This search string was selected to capture the full range of relevant literature, including terms (eg attract, displace) intended to identify studies that may have focused more on positive or negative effects. Grey literature not indexed at the above sources were discovered using OpenGray, Scopus and Open Access Theses and Dissertations archives, specialized Google NGO and IGO searches and a standard Google search including the first 10 pages of returns. Finally, studies missed by the search protocol were identified by reading the reference lists of relevant studies and seeking feedback from contacts associated with these studies.

Our searches returned >4000 hits, of which we limited our review to studies that addressed habitat-related considerations for fish or invertebrates relative to bivalve or seaweed aquaculture from which we draw examples. We further narrowed studies to be included in the quantitative analysis to include those that assessed a relevant farm habitat (either a commercial bivalve or seaweed farm, or faithful experimental simulation thereof) and compared fish or mobile macroinvertebrate populations using a control-impact or before-after experimental design (ie farm vs. reference site). If an article or report included data on both fish and invertebrates, multiple survey methods, or at multiple farm types, it was split into multiple studies accordingly. We identified 65 studies within 44 articles that met the criteria for the systematic review (Appendix S1). To summarize the effects of aquaculture on wildlife, we calculated a standardized metric from each study, the natural log response ratio: *lnRR* = *ln(F/R)*, where *F* is either mean abundance or mean species richness at farm sites and *R* is the same at reference sites.[71] Positive values for *lnRR* indicate a positive effect of farms.

To assess the evidence for publication bias (due to the ‘file drawer’ effect) within this data set, we generated funnel plots of reported effect sizes in relation to study sample sizes for those studies that provided total abundance and/or species richness (Figure 4). The expected pattern is that studies with larger sample sizes and/or lower variance will tend towards effect sizes closer to the overall mean effect.[72] In the absence of publication bias, this distribution should typically be mirrored either side of the mean effect, while in this case, visual examination of the funnel plot indicated that studies with small sample sizes ($n < 60$) that find strong negative effects of farms on wildlife abundance (*lnRR* < −1) are perhaps less likely to be published than those that find neutral or positive effects (Fig. 4). Such a result can reflect differences in the populations sampled by small and large studies rather than systematic publication bias, but to partly mitigate any potential bias, we weighted all median values, models and plots to increase the relative influence of studies with large sample sizes.

To test for an overall effect of aquaculture on fish and mobile macroinvertebrate abundance and species richness, we first fitted intercept-only (null) linear models using R,[73] weighted according to study sample size, to test whether the overall mean effect for each response (abundance and species richness) was significantly different from zero. Second, to test for factors that were significantly correlated with habitat effects, we fitted 4 factors to the previously intercept-only linear models. These factors represented the cultured taxa (5 levels: Clam, Mussel, Oyster, Seaweed or Co-Culture), the wild taxa (3 levels: Fish, Invertebrates or Both), the type of reference habitat (3 levels: Structured, Non-Structured or Both) and the tidal elevation (3 levels: Subtidal, Intertidal or Both). Model outputs and marginal effect plots are available in Appendix S2.

3.2 | Distribution of research effort

Of the 65 identified studies, publication dates spanned 1979 to 2019 (median = 2011). North America received the most research activity, followed by approximately equal contributions from Africa, Asia, Europe and Oceania (Figures 5A and 6). Most studies concerned the effect of bivalve aquaculture, especially mussels and oysters, with only 8 studies on the effects of seaweed aquaculture (Figure 5B). Longline or on-bottom aquaculture was most common, with on-bottom sites often employing some form of gear (eg protective netting over clam beds; Figure 5C). Data were available from farms placed in intertidal, mixed and subtidal zones, and a variety of structured (eg reef, seagrass), mixed or unstructured (ie soft sediment) reference habitats (Figure 5D,E). Estimates of production area or

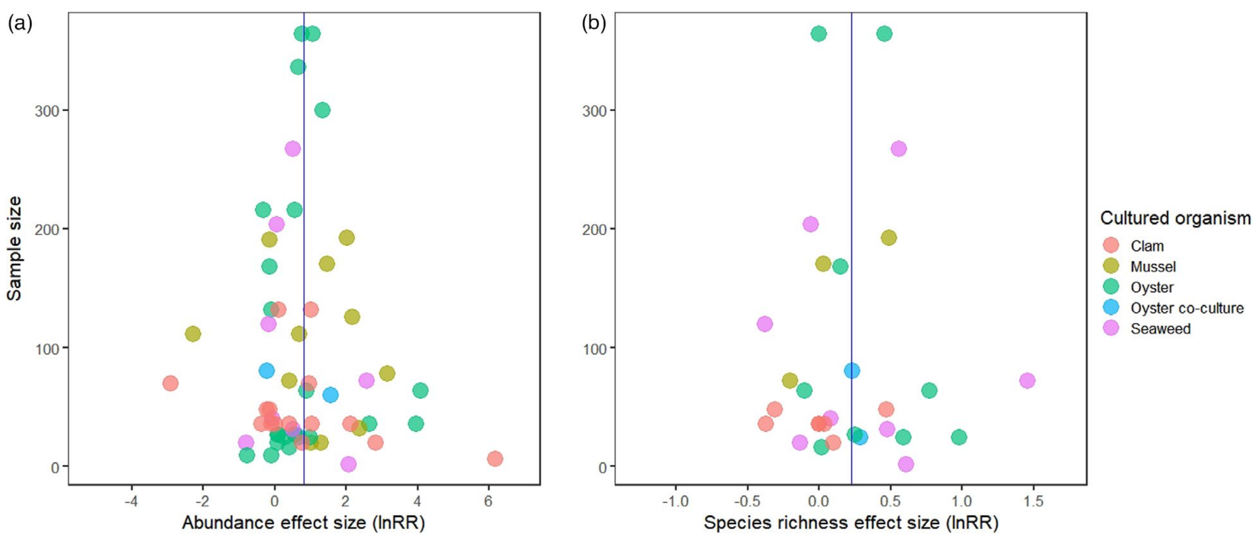

FIGURE 4 Funnel plot of reported effect sizes in relation to study sample size, for studies that provided (A) total abundance and/or (B) species richness. The blue vertical line indicates the overall mean effect size

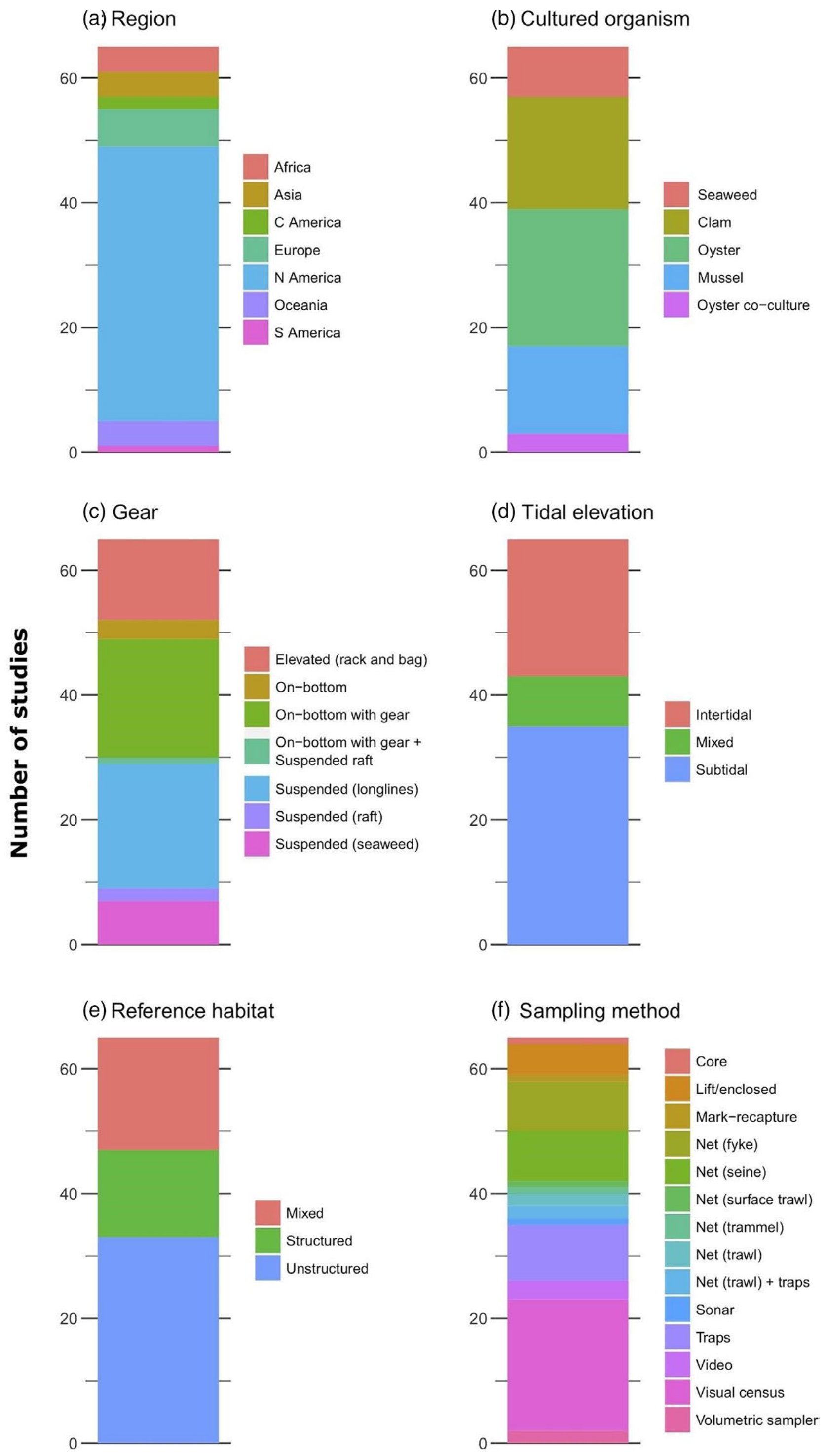

FIGURE 5 Distribution of research effort on effects of bivalve and seaweed aquaculture on wild fish and mobile macroinvertebrates by: (A) region, (B) cultured organism, (C) cultivation gear, (D) tidal elevation, (E) reference habitat type and (F) sampling method

intensity were not always provided, but those that were generally reflected commercial practices. Manila and hard clams were seeded at ~500–750 m^{-2} and geoduck seeded at 30–50 m^{-2}. Mussels were generally suspended under parallel longlines 10–50 m apart, with droppers or socks hung every ~0.5 m. Oyster grow-out bags were usually placed 2–6 m apart, whether on-bottom or on racks. Studies took place at locations with a wide range of farming area, from small scale or experimental farms (<1 ha) to extensive aquaculture (eg 6 km^2 of relatively continuous clam farming[74]). Data on intensity or area were rarely provided for seaweed farming, although de Carvalho et al.[56] noted that Brazilian *Kappaphycus alvarezii* farms had a standing biomass of 3000 kg per 4000 m^2 site. Visual census was

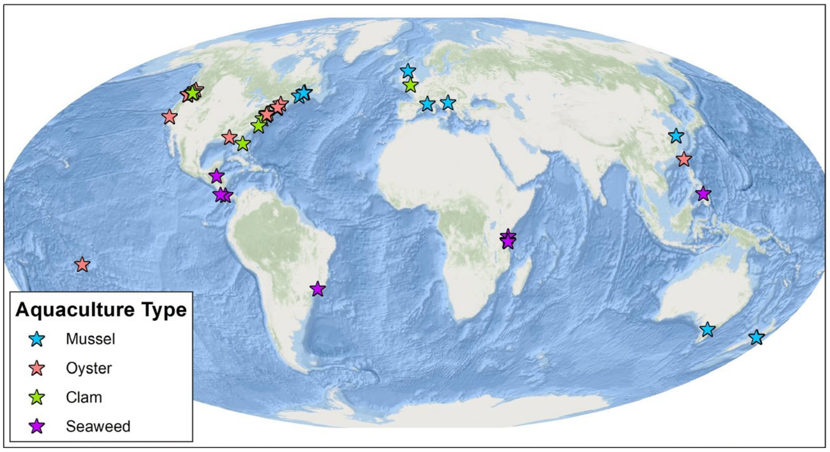

FIGURE 6 Map indicating the 46 unique locations worldwide associated with studies that examined fish and mobile macroinvertebrate populations at farm and reference sites that were identified within this study's systematic literature review

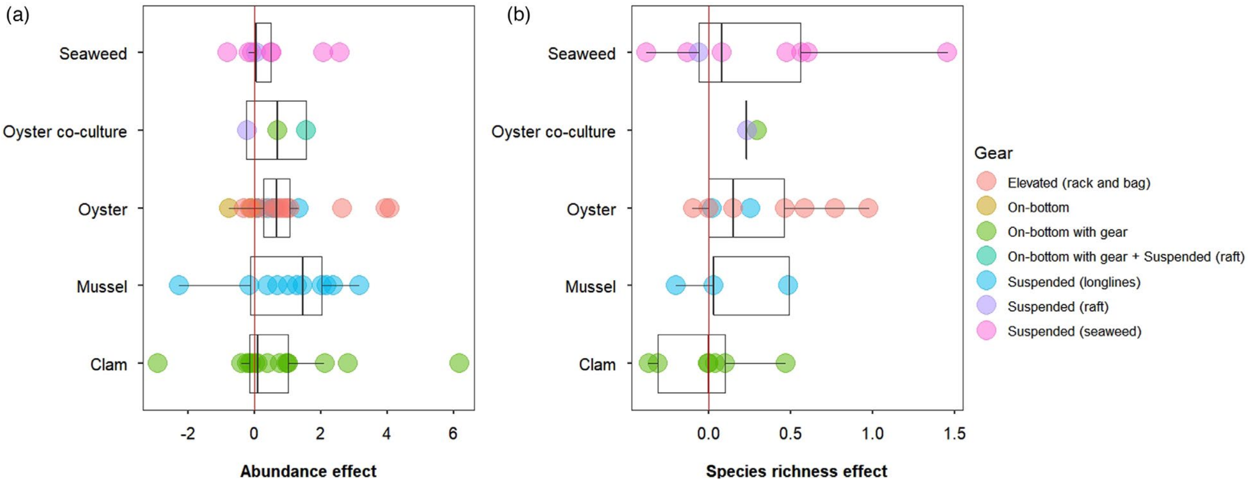

FIGURE 7 Effect of bivalve and seaweed aquaculture on abundance (A) and species richness (B) of wild fish and mobile macroinvertebrates relative to reference sites. Effects are standardized using the natural log response ratio *ln(F/R)*, where *F* is the mean abundance or species richness at farm sites and *R* is the same at reference sites. The vertical red line at zero indicates no difference between farm and reference sites, with higher values indicating a positive effect of farms. Studies (dots) are grouped by the cultured organism (mussel, oyster, clam, seaweed) and coloured according to the type of gear used. Boxes indicate the median effect and interquartile range, while the whiskers are 1.5× the interquartile range. Boxplots are weighted to increase the relative influence of studies with large sample sizes in determining the median effect and interquartile range

the most common sampling method, followed by trapping and seine or fyke netting (Figure 5F).

3.3 | Effects of shellfish and seaweed aquaculture

Overall, bivalve and seaweed aquaculture was associated with both higher relative abundance (n = 59, range: 0.05× to 473×, median *lnRR* = 0.67, $p < 0.0001$) and species richness ($n = 29$, range: 0.68× to 4.3×, median *lnRR* = 0.13, $p = 0.003$) of wild mobile macrofauna (Figure 7). The cultured organism did not significantly predict abundance increases ($p = 0.53$), but did predict the increase in species richness (highest at oyster farms: $n = 9$, range: 0.90× to 2.7×, median *lnRR* = 0.18, $p = 0.011$; Figure 7). The single largest increase in abundance was periwinkles living on protective netting at an on-bottom Manila clam farm (473× higher population density relative to soft bottom reference habitats[75]). The type of gear used is closely correlated with the cultured species (mussels and seaweed on longlines, clams on-bottom with protective netting) and so could not be statistically tested. Oysters are farmed with a variety of gear, but most studies assessed rack-and-bag systems or similar (Figure 7).

The density of wild fauna supported by aquaculture habitats varies widely. One study found remarkably high fish densities at an oyster rack-and-bag farm, with 136 individuals m^{-2} at the farm and 103 m^{-2} on natural oyster reef reference sites.[76] Otherwise, the highest fish densities at aquaculture sites occurred at a hard clam farm with protective netting (7.9 m^{-2} *cf.* 2.9 m^{-2} at reference sites[39]). Tropical seaweed farms also had a high density of relatively large and mobile fish species within farm boundaries (0.3–1.15 m^{-2}), but densities were generally similar or higher at reference sites (0.37–1.4 m^{-2}).[56,77,78] Bivalve farming generally supported the highest density of mobile macroinvertebrates, including 868 m^{-2} on oyster bags *cf.* 322 m^{-2} at reference habitat[76] and 51 m^{-2} on longline-suspended oyster bags *cf.* 13 m^{-2} at reference habitats.[79] Biomass was rarely assessed, but the highest estimates for both fish (758 g m^{-2}) and mobile macroinvertebrates (1002 g m^{-2}) occurred during volumetric sampling of elevated oyster farm habitat.[80]

Quantification of wildlife abundance and biomass across the whole farm environment remains a challenge, with different taxa and settings requiring a range of survey methods. For example, invertebrates and small benthic fish living on the farm structure may be best sampled by methods that enclose the structure (ie lift-netting or bagging of oyster rack-and-bag gear, eg ref. 76), while peripheral epibenthic communities are most effectively sampled by survey transects (eg ref. 81). Visual census counts of large or highly mobile species can be biased by fish behaviour or high turbidity, and catch-per-unit-effort data from trapping, angling or fyke netting do not translate easily to per-area density estimates. Appropriate use of methods such as seine or trawl netting in combination with towed video or visual census may offer the best density and biomass data for such species. Such data, replicated across a range of regions, environments and farming practices, would greatly improve our ability to predict the effects of new aquaculture sites on abundance of local fauna. The systematic literature review further revealed multiple knowledge gaps in our understanding of the habitat role of bivalve and seaweed aquaculture for fish and mobile invertebrates that should be addressed through future research. We provide an overview of knowledge gaps, future research needs and recommendations within Table 2.

4 | DRIVERS OF HABITAT VALUE AND OPERATIONAL CONSIDERATIONS

The positive, neutral or negative impacts of bivalve and seaweed aquaculture on habitat value depend upon local environmental conditions, intensity and scale of culture, cultivation gear utilized, species cultivated, farm management practices and interactions between these factors (Figure 1).[17] Our quantitative analysis, derived from data in the literature identified during the systematic review, provides insights into the role of cultivated species and cultivation gear in determining directionality of aquaculture's habitat value. However, given the wide variation in reporting of local environmental characteristics, intensity and scale of culture, and farm management practices, we were unable to quantitatively evaluate the effects of these factors on fish and mobile invertebrate abundance and species richness. While further research is needed to explicitly quantify conditions (eg optimal local environmental conditions or farm management practices) and associated habitat value metrics (eg abundance, species richness, production) across multiple scales (eg local, regional, and biogeographical; Table 2), we draw upon findings from our quantitative analysis and examples drawn from prior studies to describe below drivers of habitat value.

4.1 | Species cultivated

Differences in cultivated species groups, habitat preferences (eg infaunal or epifaunal), morphology and life history (eg gregarious, reef-building species) amongst other considerations (eg native or foreign species status), can yield differential habitat value of bivalve and seaweed aquaculture for fish and mobile invertebrate species.

TABLE 2 Identified knowledge gaps, research needs and testable hypotheses that could immediately advance our understanding and the application of habitat values from bivalve and seaweed aquaculture

Knowledge gap	Approach
Contribution of seaweed and bivalve aquaculture to production and standing biomass of wild fauna	Evaluate effects of aquaculture on recruitment and survival of wild fauna (ie compare abundance, growth, and mortality over time) relative to reference sites (sensu[50,113])
Role and relative importance of individual drivers (eg production intensity, local environmental characteristics, farm management practices) on habitat value for wild fauna	Replication of studies across a range of species cultivated, gear utilized, environmental conditions, intensity and scale of culture, and farm management practices—manipulating one condition singularly while holding all others constant (eg evaluating faunal abundance associated with identical rack-and-bag oyster culture across a range of production intensities)
Influence of surrounding habitat type on habitat value of bivalve and seaweed aquaculture for wild fauna	Evaluation of the relative habitat value of aquaculture in systems along a gradient of natural habitat status (healthy to degraded, structured to unstructured) using an experimental design similar to that described above
Scale of existing and potential habitat value of bivalve and seaweed aquaculture	Quantification of the amount of habitat value provided by existing bivalve and seaweed aquaculture, and expectations for various systems under aquaculture development scenarios
Ecological role of wildlife at bivalve and seaweed farms	Evaluation of the ecological functional group and trophic level of species associated with bivalve and seaweed farms (eg niche creation or removal)

In general, we identified that aquaculture of bivalve species appears to offer the greatest benefits for abundance and species richness of wild fish and mobile macroinvertebrates (Figure 7). Mussel and oyster farms, and particularly those that were suspended or elevated, yielded the largest increases in species abundance and richness, respectively. This may be a function of the habitat complexity and trophic subsidy provided by off-bottom bivalve aquaculture (in the form of farm structures such as racks, bags and longlines, or fallen stock and other detritus). These observations appear to be relatively consistent across a range of environments and regions. Clam aquaculture resulted in comparatively lower increases in species abundance and richness than oyster or mussel culture, likely due to the within-sediment nature of farming these organisms and comparatively less three-dimensional structure associated with these farming systems. Some studies have identified higher species abundance or richness of wildlife associated with seaweed aquaculture—for example, Radulovich et al.[82] identified a strong positive effect of a longline seaweed farm (13× abundance, 4.3× species richness, mean of fish across timepoints) compared to sandy habitats 50 m away. However, we identified seaweed farming as associated with the smallest increase in wild fish and mobile invertebrate abundance and the largest and most variable increase in species richness (Figure 7). Because the majority of studies evaluated seaweed farm sites in comparison to seagrass-dominated reference sites, this finding may be due in part to comparability in fish or mobile invertebrates' preference for, and association with, these highly productive vegetated habitats (eg ref. 64).

4.2 | Cultivation gear utilized

The gear utilized in cultivation of bivalves or seaweed can promote or inhibit habitat value for fish and mobile invertebrate species. For example, bivalve aquaculture gear can include mesh bags or containers with small openings that allow juvenile organisms to enter and provide refuge from predators.[21,36] We identified that elevated or suspended bivalve gear (particularly oyster rack-and-bag systems) was typically associated with the largest increases in abundance and species richness rather than on-bottom or longline gear (Figure 7). The enhanced three-dimensional structure and habitat complexity provided by off-bottom bivalve aquaculture gear likely provides greater forage, breeding or predator refuge opportunities relative to the other forms of aquaculture evaluated. Various aspects of cultivation gear could be evaluated and modified to improve habitat value, such as material, size or location within the water column. Certain materials promote or inhibit settlement of fouling organisms that provide food resources for fish and mobile invertebrates and specific sizes of openings within gear can optimize refuge benefits, while the location of gear within the water column could affect species utilization. Importantly, the characteristics of gear needed to provide optimal habitat value likely vary depending on local environmental setting, wild species utilization preferences, amongst other factors. Furthermore, in some cases, gear utilized in cultivation will provide clear negative habitat impacts. Fences or other structures used to restrict wildlife access to cultured organisms—such as the use of gillnet fencing around tropical seaweed farms—can create entanglement risks and result in injury or mortality of fish, mobile invertebrates and other wildlife.[83]

4.3 | Local environmental characteristics

The environmental setting of a farm—inclusive of physical (eg hydrodynamics, depth), biological (eg presence and status of existing communities, such as coral reef or benthic infaunal) and geographical (eg location within nearshore estuarine vs. offshore waters) components—may be an important determinant of its habitat value for fish and mobile invertebrate species. For example, bivalve farms located within shallow estuarine waters with low current velocities can result in accumulation of biodeposits, shell material and live bivalves below farms that can bury infaunal or epibenthic communities (eg ref. 84). Some fish and mobile invertebrate species may benefit from the enhanced benthic structure and food resources (eg lobster[53]), while others dependent upon infaunal food resources could be impacted. Further, the presence and status of existing habitat-forming communities could also be an important determinant of habitat value. For example, if seaweed farms are situated atop seagrass beds within the intertidal zone, algal shading and mechanical abrasion can negatively affect seagrass biomass and density thereby reducing the value of natural habitats.[64] At broader environmental scales, such as at the scale of a bay or estuary, the status of existing habitat-forming communities could be a determinant of the relative habitat value of farms. Within degraded systems where natural habitats such as kelp forests or mussel beds are limited, bivalve or seaweed aquaculture could provide important contributions of structure and habitat complexity. Farms located in the intertidal or subtidal zones of nearshore estuarine waters or further offshore within coastal ocean waters will benefit or impact different species given variation in these species across environments. Importantly, improved siting of aquaculture operations (eg siting farms in areas with appropriate current velocities, not atop sensitive habitats) could mitigate potential habitat impacts and potentially improve benefits (eg siting farms within waterbodies where natural habitats are degraded).

4.4 | Intensity and scale of culture

The intensity and scale at which bivalves and seaweed are cultivated within a waterbody is an important determinant of habitat value or impact for fish and mobile invertebrates. Large-scale cultivation of bivalves and seaweed can affect habitat value indirectly and directly. For example, large-scale bivalve aquaculture can result in increased bay-scale water retention time which can increase sedimentation and increase eutrophication risk, both of which could indirectly negatively impact natural habitats (eg burial of oyster reefs or mortality due to exposure to low dissolved oxygen[85]). As habitat complexity can be a mediator of predator-prey relationships,[37] high levels of habitat complexity—such as that associated with large amounts of aquaculture gear within a waterbody—could reduce feeding efficiency of predators and provide opportunities for expansion of, and competition amongst, prey species.[86] Low levels of habitat complexity are associated with lower prey abundances and limited trophic breadth of predators, while at intermediate levels of habitat complexity, predator feeding rates are maximized, dynamically balancing these processes.[37] Importantly, within estuaries and waterbodies where natural habitats are degraded, increased habitat complexity associated with moderate levels of bivalve and seaweed aquaculture may be more likely to improve trophic dynamics, although further research into trophodynamics across a range of operating environments is needed.

4.5 | Farm management practices

Activities associated with the establishment and operation of bivalve and seaweed farms could affect habitat value for fish and mobile invertebrates. For example, when establishing a new farm operation, use of high-quality materials for gear, careful construction and timing of development, and appropriate spatial configurations of gear could improve habitat value and reduce impacts. Use of high-quality materials (eg high-density polyethylene mesh) in place of lower quality materials (eg polystyrene foam or low-quality plastics) can minimize farm-related marine debris. Planning the construction of the farm to ensure that mooring installation does not excessively disturb seafloor communities and the timing does not coincide with critical life-history stages of wild fish or invertebrates can minimize negative impacts.[87] Similarly, appropriate spatial configuration of gear within farms can minimize potential entanglement impacts, avoid crowding of cultured organisms and could improve accessibility and utility for fish and mobile invertebrates.

Access, maintenance and harvest activities associated with regular operation of bivalve and seaweed farms represent disturbances that could affect habitat value. For example, as multiple forms of bivalve and seaweed farming involve use of intertidal areas which can correspond with areas of seagrass beds and/or foraging habitat for seabirds and other wildlife, access to farm sites can result in trampling and impacts to these coastal habitats. Ferris et al.[88] identified substantial negative impacts to existing coastal habitats, such as seagrasses, from the combined effects of trampling and shading associated with high-intensity intertidal production of bivalve aquaculture. Certain farm management practices may help ensure that farms provide habitat value and reduce any negative potential wildlife impacts. For example, when removing gear from the water for maintenance or harvest, ensuring adjacent gear is available for fish and mobile invertebrates to access may ensure habitat value is sustained. Cycling production to ensure a certain amount of gear is retained within the water throughout the year, dragging gear through the water during harvest or maintenance to allow organisms to escape prior to removal (ie minimizing bycatch) and optimizing the length of time between cleaning gear and removing fouling organisms could improve habitat value. Luckenbach et al.[89] partially attributed enhanced blue crab (*Callinectes sapidus*) biomass associated with clam aquaculture sites to differences in farm management practices across the two locations they studied. In New Jersey, USA, dense macroalgae atop nets used in on-bottom clam aquaculture were removed less frequently than those in Virginia, USA, potentially enhancing availability of structured habitat for blue crabs. Further studies should be undertaken to determine the effect that certain farm management practices may have on sustaining and enhancing habitat value or reducing impacts.

Optimal practices associated with each of these considerations likely varies depending on specific characteristics of the farm and local environment (eg cultivation gear utilized, target species for wildlife habitat benefits) and should be a focus of future research. Certain improvements in practices that can maximize habitat value may represent trade-offs amongst economic and ecosystem objectives. While many ‘Best Management Practices’ (BMP) guides and certification schemes have been developed by farmers, government agencies, academic institutions and/or collaborations amongst these groups to improve bivalve and seaweed aquaculture practices (eg refs 90,91), the intent of these guides has been primarily environmental or social impact reduction. Guiding principles and recommendations for practices that improve habitat value or ecosystem services could be considered in the development of future bivalve and seaweed aquaculture BMPs.

5 | POLICY, MARKET AND MANAGEMENT CONSIDERATIONS

Assessing the current state of aquaculture around the world, including where it has been well and poorly managed, can provide insights into how the sector should be managed going forward. Policy can provide control for the way aquaculture is practised at a local scale, and the positive effects it can have on the surrounding ecosystem. At regional and global scales, the values of aquaculture in providing food and employment can also shape policy, particularly policy that supports food and economic security as well as social equity. As a result, deepening our understanding and appreciation of local-scale management to support the delivery of positive habitat effects, and the capacity to ‘scale-up’ these effects to achieve broader ecosystem outcomes, could enable aquaculture to play a pivotal role in food security as well as conservation or restoration objectives. To realize this degree of (positive) effect at successive scales of influence, attention is needed to both technical and policy components of managing aquaculture and the importance of each with respect to market and non-market drivers.

5.1 | Local scale

Improving the environmental performance of individual aquaculture facilities has been a principal focus for managers and industry over the last several decades.[92] Reducing negative impacts to achieve greater sustainability is a recurring challenge, but also an opportunity for innovation. Direct environmental impacts of bivalve and seaweed aquaculture as non-fed aquaculture species primarily relate to the use of built infrastructure and its associated effects such as clearance of habitat for farm construction, shading and biofouling,[93] but can also include effects related to the cultivated organisms themselves (eg genetic interactions, reproduction of non-native species[69,70]). These effects are often managed through licensing and approval processes where the proposed activity is assessed with conditions stipulated to ensure control of ongoing effects.[94] Management of potential impacts becomes the responsibility of a licence or permit holder with governance structures often seeking to maintain compliance programmes to ensure limited impact. Although there is substantial opportunity to build novel applications to mitigating risks,[95] current risk assessment approaches typically view these interactions as 'hazards' requiring treatment (ie risk analysis and control[96]).

Viewing marine resource activities as purely extractive and anthropocentric can marginalize research and social opinion about the scope of possibility for benefits and values.[97] Consequently, risk assessment and licensing approaches that view aquaculture interactions as only negative (ie risk events requiring treatment) might provide management for environmental impacts but will overlook broader, positive interactions of this activity with or 'as' habitat. The evidence provided here illustrates the value of local management approaches to be broader in scope around the role of aquaculture within the ecosystem.

If aquaculture operators are supporting ecosystem services and positive environmental effects, there may be a cause to reward these operators through novel policy or market approaches (see below). Validated activities that show continued provision of habitat values could be the basis for market incentives, such as monetary offsets for licensing fees. More ambitious policy options might include payment for commercial or recreational fisheries production outcomes, which could be approached as local benefits to operators but also an influential macropolicy.[98] Testing of management options that (1) could support the development of novel and shared policy approaches, (2) guide the use of effective gear to provide habitat value, (3) improve farming practices and siting of aquaculture or (4) perhaps support their use as quasi-sanctuary areas or artificial reefs is essential to building the case for validated and rewarded habitat value of bivalve and seaweed aquaculture.

5.2 | Regional scale

Management of individual and collective aquaculture activities by a statutory authority is the primary mechanism through which ecological and social impacts are measured and controlled. But state-formed governance is not the sole mechanism, and models of hybrid governance can play an important part in environmental stewardship, corporate social responsibility and associated market value, and increased community confidence in the industry. Hybrid governance is a combination of social mechanisms (community, market and the statutory authority) whereby collaboration is reached between these actors for benefits such as increased efficiency, flexibility and innovation amongst state and non-state actors.[99] Non-state actors traditionally include industry associations, conservation organizations and formal supporting mechanisms such as certification programmes, although there is an increasing trend towards greater influence of larger environmental and financial non-government organizations, philanthropic groups and private investment (including impact investors) in driving the development of ecosystem-centred aquaculture approaches.[100] To build a shared understanding of the regional-scale habitat effects of bivalve and seaweed aquaculture, state and national authorities, in collaboration with non-state actors, could play a greater role in communicating potential habitat values to engender broader support for environmentally valuable practices. The model of hybrid governance might be particularly effective where there is an obvious 'people-policy' gap,[101] a lack of adoption of supporting policy, a lack of innovation in policy to enable new approaches, or competition in marine areas for shared resources or space. For example, aquaculture is typically excluded from conservation objectives and marine protected areas where the provision or maintenance of biodiversity is a primary objective, merely because of its industry status,[102] yet biodiversity enhancement associated with aquaculture habitat has been documented (see Section 3).

A valuable concept supporting the scaling up of positive habitat effects has been the development of an Ecosystem Approach to Aquaculture (EAA).[103,104] Spheres of interactions within an EAA enable a clear depiction of the role of aquaculture sites within the broader water body and/or associated aquaculture zone, as well as relevant markets and trade and the social and ecological benefits that arise from these interactions as well as the economic.[103] Hence, it is an approach to policy that is well placed to support operational outcomes that can increase the ecological sustainability of aquaculture. However, a review of EAA 10 years after its presentation found the uptake of ecosystem-centric approaches to be limited, largely due to regulatory impediments, management constraints and ambiguity in value.[105] Where trust, legitimacy and (we believe) credibility through repeatable and transparent evidence can be built, a model of hybrid governance[99] could be effective to further enact policy, management and social and corporate recognition that can accelerate active delivery of positive habitat effects.

A recent survey of aquaculture-producing countries found that nearly all jurisdictions now have a permit-based system in place to authorize activity; 83% require some level of environmental impact assessment prior to the activity beginning, and within regulation, 78% require monitoring of operations for pollution effects.[106] This same paper identified that a large portion of countries currently practising aquaculture and having low governance scores have high potential for growth in lower impact bivalve aquaculture. Many of these are not currently producing bivalves (59 of 69).

5.3 | Global scale

Though habitat values may be relevant to cumulative and 'at scale' positive effects, recognition of a global-scale impact (eg the contribution of aquaculture towards global biodiversity goals) is diminished by the currently narrow focus on aquaculture for the primary purpose of providing food. The need to provide for a growing population can result in trade-offs between a jurisdictions efforts or desire to meet conservation objectives alongside, for example the need to also ensure food security,[14] for example UN SDG 2 and SDG 14. Unfortunately, these challenges will be increasingly challenged by climate change.[107] At a global level, hybrid governance approaches might similarly play an important role in broader and sustained delivery of habitat effects. Certification schemes that provide a framework for validating environmental stewardship of operators and sectors are an important development for the reduction in negative impacts. These instruments can, however, have significant limitations in their capacity to measure ecosystem-scale and cumulative interactions because of their narrow definitions of sustainability.[108] They also have a prevailing focus on assessment of negative effects, largely in response to consumer and societal expectations for environmentally sustainable and socially responsible seafood (eg Global Aquaculture Alliance, Marine Stewardship Council. Seafood Watch of the Monterey Bay Aquarium, WWF),[109] while schemes that recognize broader positive effects of aquaculture in the surrounding environment are rare. Because certification schemes play an important role in addressing and building sustainable products, support from community for the industry and the social licence to operate, and corporate social responsibility, the triangulation of state and non-state actors alongside community and market values may present a way to balance objectives and overcome the challenges of meeting multiple, sometimes competing, industry, community and environmental needs.[14,99] A key next step to this approach is for actors in policy and certification globally to lead the development of industry-facing policies that validate and support the delivery of positive environmental effects from aquaculture.

5.4 | Non-market versus market effects

At a local, regional and global scales, it is important to recognize the differences and similarities in non-market and market effects. Non-market values, through habitat effects, typically reflect a broader set of ecosystem services that are often linked to conservation and restoration objectives, and social and cultural values.[7,10] Non-monetary approaches are essential to examine and weight the relevance of preferences, values and demands of people towards nature and can provide a pluralistic outlook whereby monetary worth is only one type of value (eg ref. 110).

Market values associated with habitat interactions, as mentioned above, are currently limited in application but provide an important pathway for scaling up positive effects. Market drivers are a pathway for affecting sustainable activities in commercial industry. For example, building the market value of environmental stewardship is a basis of certification schemes, but the use and administration of macropolicies form an important part of enabling a 'business friendly' environment.[98] As a result, 'activating' the delivery of ecosystem services associated with the provision of habitat could be an important mechanism for (1) rewarding industry for sustainable and novel approaches thereby encouraging further innovation and (2) monetizing the effectiveness of the industry in supporting broader ecosystem function and repair through a market value that has the opportunity for continued growth. Market-based approaches that monetize values associated with bivalve and seaweed aquaculture, such as the removal of nitrogen through water filtration and denitrification, could provide a valuable extension to nutrient trading schemes.[95,111]

6 | CONCLUDING REMARKS

Providing food for a growing global population within planetary ecological limits is a major challenge for humanity.[4] Global objectives attest to the complexity of realizing multiple goals for sustainable development; goals that have inherent and often unavoidable trade-offs, such as realizing effective security in seafood production and biodiversity outcomes.[14] In recent years, a major trend within food systems research has been to advance methods of food production that not only reduce negative environmental impacts but simultaneously provide ecological value (eg ecosystem service provision, regenerative approaches to agriculture[10,112]). The projected rapid growth of aquaculture presents an opportunity to focus on developing the positive influence of this sector, guiding it towards being one that produces food alongside a wide range of ecological values for marine and coastal environments. A deeper understanding of the role of existing bivalve and seaweed aquaculture practices within ecosystems and the farming practices, markets and management options that create and enhance ecological value are necessary to achieve this objective.

We identify that higher abundance and species richness of wild mobile macrofauna are generally associated with bivalve and seaweed aquaculture (than reference sites) and that certain species groups (ie oysters and mussels) and cultivation methods (ie off-bottom) provide measurable enhancements. Future research should seek to understand how aquaculture can best function in step with local environmental characteristics, under appropriate culture intensities and scales, and with farm management practices that drive consistent, potentially widespread, delivery of habitat values. If repeatable operational circumstances for habitat benefits can be identified and acknowledged or rewarded through proactive policy or market-based incentives, it would become possible to expand local effects to generate regional and national ecosystem outcomes. As our understanding of the ecological role of bivalve and seaweed aquaculture within coastal ecosystems deepens, corresponding changes in existing management of the industry could serve to reinforce practices that improve aquaculture's delivery of habitat values and ecosystem services and potentially achieve impact at a global scale.

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CONFLICT OF INTEREST

Robert C. Jones serves as a Director of the Global Aquaculture Alliance.

ETHICS APPROVAL

No ethical issues have been identified by the authors.

DATA AVAILABILITY STATEMENT

Data will be made available at Dryad upon acceptance.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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