Thanks to scientists at the Milford Lab, following is an annotated bibliography of papers supporting the fact that shellfish farming provides ecosystem services.

The primary services documented here are nutrient removal and fish habitat provision, but also include erosion prevention, benthic stabilization, job creation, and production of sustainable seafood.

Annotated Bibliography of Wild Fish Interactions With Shellfish Aquaculture Gear and Nutrient Removal Benefits Provided by Shellfish Farms

<u>Relevant review articles</u>

Alleway, H. K., C. L Gillies, M. J. Bishop, R. R. Gentry, Seth. J. Theuerkauf, R. Jones. 2019. The ecosystem services of marine aquaculture: Valuing benefits to people and nature, BioScience, 69 (1): 59–68, https://doi.org/10.1093/biosci/biy137
Aquaculture is crucial to the future supply of seafood, but challenges associated with negative impacts could impede increased production, especially production that is efficient and safe for the environment. Using the typology established by The Economics of Ecosystems and Biodiversity Initiative, we describe how marine aquaculture could be influential in supporting ecosystem services beyond solely the production of goods, through provisioning services, regulating services, habitat or supporting services, and cultural services. The provision of these services will vary, depending on functional traits of culture species, biotic and abiotic characteristics of the surrounding environment, farm design, and operational standards. Increasing recognition, understanding, and accounting of ecosystem service provision by mariculture activities, through innovative policies, financing, and certification schemes may incentivize active delivery of benefits and may enable effects at a greater scale.

Dumbauld, B. R., J. L. Ruesink, and S. S. Rumill. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: a review with application to oyster and clam culture in West Coast (USA) estuaries. Aquaculture 290:196–223.
This literature review explores the ecological role of bivalve shellfish aquaculture within West Coast (USA) estuaries which has an >100-year history of practice and describes direct and indirect ecological effects of shellfish cultivation. Effects of bivalve aquaculture on modifying estuarine habitat (e.g., provision of additional structured habitat from cultivated organisms and gear) at both local- and landscape-levels are identified. Structure provided by aquaculture appeared functionally similar to eelgrass for small benthic infauna and mobile epibenthic fauna, while use of aquaculture as habitat by larger more mobile invertebrates and fish depended on mobility and varied with life-history stage and taxon being evaluated.

Forest, B.M., N. B. Keeley, G. A. Hopkins, S. C. Webb, and D. M. Clement. 2009. Bivalve aquaculture in estuaries: Review and synthesis of oyster cultivation effects. Aquaculture 298: 1-15. doi: 10.1016/j.aquaculture.2009.09.032.
This literature review describes benefits and ecological impacts of oyster cultivation. Previous studies suggest that live oysters, shell valves and farm materials provide novel habitats for colonizing organisms and mobile biota, such as fish, shown to occur at higher densities than in

the absence of farming. Increases in provision of fish habitat have been associated with aquaculture gear. Studies suggest oyster cultivation may increase food supply, or reduce predation, and may enhance wild fish populations. Authors conclude: "Together with creation of novel habitat...changes [from aquaculture] may benefit some fish...species and provide a range of other beneficial ecosystem services such as local enhancement of biodiversity."

<u>Meta-analyses</u>

Barrett, L. T., Theuerkauf, S. J., Rose, J. M., Alleway, H. K., Bricker, S. B., Parker, M., Petrolia, D. R., & Jones, R. C. (2022). Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. Ecosystem Services, 53, 101396.
https://doi.org/https://doi.org/10.1016/j.ecoser.2021.101396
The authors reviewed literature on nitrogen removal and habitat provisioning services by shellfish and seaweed farms globally. Across all species and locations, a typical farm removed 275-581 kg N per hectare and supported 348 - 1110 kg additional wild fish production annually. The value of the nitrogen removal service was calculated to be 84 - 505 USD per ton of harvest, 972-2504 USD per hectare to commercial fishers or 1087 - 2848 USD per hectare to recreational fishers annually.

Clements, J. C., & Comeau, L. A. (2019). Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. Aquaculture Reports, 13, 100183. https://doi.org/https://doi.org/10.1016/j.aqrep.2019.100183
This meta-analysis used available literature to calculate and compare the nitrogen removal potential of blue mussels (Mytilus edulis) and eastern oysters (Crassostrea virginica). Authors documented low variability in shellfish tissue and shell nitrogen concentration. Oysters and mussels had similar tissue nitrogen concentration but mussel shells had significantly higher nitrogen than oyster shells. Based on publicly available harvest records, mean total shellfish harvest in New Brunswick removed an estimated 99088 kg N and in Prince Edward Island removed 204571 kg annually.

Cornwell, J., Rose, J., Kellogg, L., Luckenbach, M., Bricker, S., Paynter, K., Moore, C., Parker, M., Sanford, L., Wolinski, B., Lacatell, A., Fegley, L., & Hudson, K. (2016). Panel Recommendations on the Oyster BMP Nutrient and Suspended Sediment Reduction Effectiveness Determination Decision Framework and Nitrogen and Phosphorus Assimilation in Oyster Tissue Reduction Effectiveness for Oyster Aquaculture Practices. Available online at http://www.chesapeakebay.net/documents/Oyster_BMP_1st_Report_Final_Approved_2016-12-19.pdf
The Chesapeake Bay Program convened an expert panel to review the literature and provide recommendations on the nitrogen and phosphorus reduction effectiveness of oyster practices, including oyster aquaculture. The panel recommended adoption of oyster aquaculture as a nutrient reduction best management practice and provided a calculation of harvested oyster nitrogen content (in pounds of N) that could be applied Baywide. Analysis of available data indicated that harvest-based nitrogen removal did not vary seasonally or by location in the Bay, enabling broad application of the results.

Rose, J. M., Morse, R., & Schillaci, C. (2024). Development and application of an online tool to quantify nitrogen removal associated with harvest of cultivated eastern oysters. PLoS One, 19(9), e0310062. https://doi.org/10.1371/journal.pone.0310062
This study adapted the methodology employed by the Chesapeake Bay Oyster Expert Panel (see above) and expanded the analysis to the regional scale, aggregating nitrogen concentration and morphological data from oyster farms from North Carolina to Maine. Authors documented low variability in nitrogen concentration of oyster tissue and shell by geography, ploidy, and cultivation practices, and gathered sufficient data to provide a robust calculation of total animal nitrogen weight based on shell length at harvest. They built a publicly-available tool that takes simple inputs to generate an infographic and report customized to an individual oyster farm.

Theuerkauf, SJ, Barrett, LT, Alleway, HK, Costa-Pierce, BA, St. Gelais, A, Jones, RC. 2021. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Rev Aquac*. 00: 1– 19. https://doi.org/10.1111/raq.12584
This study 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, which was posited to 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). The authors found these observations to be relatively consistent across a range of environments and regions.The study further describes 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.

<u>Nutrient primary literature (* = Northeast region; ** = Massachusetts)</u>

*Bayer, S. R., Cubillo, A. M., Rose, J. M., Ferreira, J. G., Dixon, M., Alvarado, A., Barr, J., Bernatchez, G., Meseck, S., Poach, M., Pousse, E., Wikfors, G. H., & Bricker, S. (2024). Refining the Farm Aquaculture Resource Management Model for Shellfish Nitrogen Removal at the Local Scale. Estuaries and Coasts. https://doi.org/10.1007/s12237-024-01354-7
Authors collected primary data on Connecticut farmed oysters and the local environment, to calibrate a transferable farm-scale model that can predict nitrogen removal by cultivated eastern oysters. Model outputs were within the range of previously-reported studies in the US Northeast. Oyster nitrogen removal at harvest ranged from 159 - 274 kg per hectare annually.

*Higgins, C. B., Stephenson, K., & Brown, B. L. (2011). Nutrient bioassimilation capacity of aquacultured oysters: quantification of an ecosystem service. Journal of Environmental Quality, 40, 271-277. https://doi.org/10.2134/jeq2010.0203
This study collected eastern oyster carbon, nitrogen, and phosphorus data from hatchery-produced eastern oysters grown using common farming practices in two Chesapeake Bay tributaries (Maryland and Virginia). Authors developed regression equations that accurately predicted oyster nutrient content (g N and P per individual) based on oyster shell length. Based on these equations, 1 million harvest-sized eastern oysters (76 mm) on average will remove 132 kg nitrogen, 19 kg phosphorus, and 3823 kg carbon.

*Poach, M., Morse, R., Meseck, S. L., Alvarado, A., Reichert-Nguyen, J., McFarland, K., Elliott, H., Kellogg, M. L., Luckenbach, M. W., & Rose, J. M. (2024). Nutrient reduction by eastern oysters exhibits low variability associated with reproduction, ploidy, and farm location. Marine Pollution Bulletin, 202, 116286. https://doi.org/https://doi.org/10.1016/j.marpolbul.2024.116286
This study sought to address data gaps identified by the Chesapeake Bay Oyster Expert Panel (see Cornwell et al. above) involving variation in nutrient concentration (N and P) related to ploidy and reproductive development, as well as provide expanded baseline information about phosphorus concentration in farmed oysters. Authors analyzed oysters from two farms (Virginia, Maryland), validated nitrogen and phosphorus calculations used by the Chesapeake Bay Program, and observed only minor differences in nutrient removal associated with ploidy and reproductive cycle timing.

**Reitsma, J., Murphy, D. C., Archer, A. F., & York, R. H. (2017). Nitrogen extraction potential of wild and cultured bivalves harvested from nearshore waters of Cape Cod, USA. Marine Pollution Bulletin, 116(1), 175-181.
https://doi.org/https://doi.org/10.1016/j.marpolbul.2016.12.072
This study analyzed nitrogen contained in eastern oysters and hard clams from a variety of locations around Cape Cod, Massachusetts. Local oysters averaged 0.28 g nitrogen per individual at harvest. Minor variation in total nitrogen was observed related to location and season. Analysis of stable isotopes indicated that nitrogen removed by shellfish farms was from land-based sources that are the target of nutrient management programs.

*Sebastiano, D., Levinton, J. S., Doall, M., & Kamath, S. (2015). Using a Shellfish Harvest Strategy to Extract High Nitrogen Inputs in Urban and Suburban Coastal Bays: Practical and Economic Implications. Journal of Shellfish Research, 34(2), 573-583, 511.
https://doi.org/10.2983/035.034.0242
Authors compared nitrogen removal by eastern oysters in a high nutrient location (Jamaica Bay, NY) to a moderate nutrient location (Great South Bay, NY). Oysters were grown using common farming techniques. There were no differences in oyster tissue nitrogen concentration (%) among sites, and results were consistent with oyster nitrogen concentration measured in other locations across the US Northeast region. Authors calculated that 3000 acres of oyster farms in Great South Bay would remove 90% of nitrogen inputs from that watershed.

<u>Habitat primary literature (* = Northeast region)</u>

Ambrose, A., and D. Munroe. 2025. Habitat usage on an oyster aquaculture farm: Impacts of farm activities and biological fouling on marine communities. Journal of Shellfish Research 43(3): 389-397. https://doi.org/10.2983/035.043.0310

To assess how farm tending activities and the presence of biological fouling on farming gear impact habitat usage by fish, underwater video was collected in and around oyster cages, floating bags, and a natural marsh habitat on an oyster farm in the Little Egg Harbor, Barnegat Bay, NJ in 2019. A total of 27 species from 4 phyla were observed with five species; Atlantic silverside Menidia menidia, mummichog Fundulus heteroclitus, grass shrimp Palaemonetes spp., blue crab Callinectes sapidus, and feather blenny Hypsoblennius hentz; accounting for 98% of the total observations. Significantly more individuals were observed in the floating bags than in the other habitat types. Farm tending activities had an overall neutral impact on the number of individuals observed on the farm, with Atlantic silverside the only species observed more during tending activities. The median time it took for a fish to return after a human disturbance was 1.07 min. The two gear types were colonized by different biological fouling communities, which provided species-specific benefits. Heavy fouling attracted more individuals to the floating bags, whereas fouling had little impact on the number of individuals observed in the oyster cages. Authors note that "these data support how shellfish farms and their attributes can provide habitat provisioning for local species"

*Armbruster A. D., R. Mercaldo-Allen, J. M. Rose, K. Seda, P. Clark, G. Phillips, D. Redman, and C. W. Conroy. 2024. Territorial and occupancy behavior of black sea bass on oyster aquaculture gear and boulder habitat. Front. Mar. Sci. 11:1380484. doi: 10.3389/fmars.2024.1380484

This study used underwater action cameras to record video of black sea bass to assess territorial (agonistic, ambush, displacement) and occupancy (station-keeping) behaviors on shelf and bag style oyster cages at a shellfish farm, and on boulders at a natural rock reef near Milford, CT in Long Island Sound. Black sea bass at a variety of life stages were highly associated with cages, including young-of-the-year, and age 1+ fish. The high abundance of black sea bass observed on cages relative to boulders suggests this species has an affinity for the vertical structure created by aquaculture gear. When behaviors were normalized to the total fish sightings, black sea bass showed no significant difference in frequency of behaviors between habitats, indicating that per-fish rates of behavior were similar on cages and boulders. Demonstration of territorial and occupancy behaviors by black sea bass on, and around cages suggests that aquaculture gear provides structured habitat and ecosystem services for this species similar to natural reefs. Authors note "results suggest that essential fish habitat descriptions of manmade structures used by black sea bass could be broadened to include aquaculture gear."

*****DeAlteris, J. T., B. D. Kilpatrick, and R. B. Rheault. 2004. A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. Journal of Shellfish Research 23:867–874. Available at: https://www.researchgate.net/publication/279569781_A_comparative_evaluation_of_the_habitat_value_of_shellfish_aquaculture_gear_submerged_aquatic_vegetation_and_a_non-vegetated_seabed

This study compared the habitat value of modified rack and bag oyster aquaculture gear (SAG) to submerged aquatic vegetation (Zostera marina) (SAV) and shallow nonvegetated seabed

(NVSB) in Point Judith Pond estuary, Rhode Island. Enclosure gear was used to sample habitats. The SAG habitat provided more surface area than the other habitats, which may serve to protect juvenile fish from predation and provide substrate for sessile organisms, a food source for fish. Species abundance and richness were higher on the SAG habitat versus the SAV and NVSB habitats. The SAG showed higher species diversity than the NVSB but did not differ significantly from the SAV. Authors note "that shellfish aquaculture gear provides habitat for many organisms…and is especially beneficial to ecosystems that support native species of recreationally and commercially important fish and invertebrates in their early life stages" and conclude that " SAG has substantially greater habitat value than NCSB and has habitat value equal or superior to SAV."

*Erbland, P. J., and G. Ozbay. 2008. A comparison of macrofaunal communities inhabiting a Crassostrea virginica oyster reef and oyster aquaculture gear in Indian River Bay, Delaware. Journal of Shellfish Research 27:757–768. https://doi.org/10.2983/0730-8000(2008)27[757:ACOTMC]2.0.CO;2
Macrofaunal communities associated with restored oyster reefs were compared to subtidal oyster bottom cages using lift nets. Greater species abundance and richness was observed on aquaculture gear, greater species evenness on the oyster reef, and no difference in diversity was observed. Authors conclude "because there exists a broad range of variables contributing to the quality of these two types of habitats this study shows that cultured oysters and cages can impart benefits to other species and the ecosystem as a whole. Even if oyster culture is not 'better' than oyster reef creation, the habitat created is comparable and both have a beneficial effect on populations of other important macrofauna".

Ferriss, B., K. Veggerby, M. Bogeberg, L. Conway-Cranos, L. Hoberecht, P. Kiffney, K. Litle, J., Toft, and B. Sanderson. 2021. Characterizing the habitat function of bivalve aquaculture using underwater video. Aquacult Environ Interact 13. 10.3354/aei00418
Underwater video was used to document associations of fish and crab species with cultured Pacific oyster and Manila clam aquaculture sites in comparison to uncultured reference sediment and eelgrass habitat at 9 locations across 3 regions of Puget Sound, Washington, in summer 2017 and 2018. Of the 3038 fish and crabs observed, 98% were represented by Embiotocidae (surfperch), crabs, three-spined stickleback Gasterosteus aculeatus, Cottidae (sculpins), and Pleuronectiformes (flatfish). Overall, the affiliations of fish and crabs with bivalve aquaculture varied by species groups, culture type, and regional environmental and habitat conditions. Interactions varied on a scale of ~ 150 km, highlighting variation of aquaculture−ecological interactions at a scale not previously recorded in Puget Sound. Species composition varied between aquaculture and non-aquaculture habitats in 2 of the 3 regions studied. Species diversity and richness in aquaculture habitats varied regionally, relative to reference habitats. Pelagic species were more abundant in aquaculture and reference sites that

had vertical structure, but abundances of demersal and benthic species on aquaculture habitat relative to reference sites varied regionally. Authors note “that availability of habitats within intertidal regions, including varying types of aquaculture, may determine community structure for marine organisms such as fish and crab of fish and crab species, affecting their refuge, movement, and feeding.”

Kawai, K., H. Fujita, G. Sanchez, and T. Umino. 2021. Oyster farms are the main spawning grounds of the black sea bream *Acanthopagrus schlegelii* in Hiroshima Bay, Japan. PeerJ. doi: 10.7717/peerj.11475.
Black sea bream Acanthopagrus schlegelii are abundant in oyster farming areas of Hiroshima Bay, Japan. A survey of 14 stations in the bay was conducted to sample sea bream egg density on oyster farms and at historical spawning sites. Overall, oyster farms contained higher egg densities than historical spawning areas. Three of the 4 stations with the highest egg densities were oyster farms. Results suggest that oyster farms may provide habitat and resources for adult black sea bream that supports successful spawning. Authors note “our study revealed the important role in the coastal ecosystems of oyster farm areas as a new spawning ground for black sea bream”.

Martínez-Baena, F., B. S. Lanham, I. McLeod, M. D. Taylor, S. McOrrie, and M. J. Bishop. 2022. De novo reefs: Fish habitat provision by oyster aquaculture varies with farming method. Aquacult Environ Interact 14:71-84. https://doi.org/10.3354/aei00431
This study in south-eastern Australia assessed how the fish communities associated with oyster farms vary with production method, how fish communities utilize oyster infrastructure relative to nearby natural habitats and whether oyster infrastructure can serve as de facto oyster reefs by supporting similar fish communities. Underwater video surveys conducted in summer and winter during 2 study years found higher fish observations and species richness on rack and rail aquaculture structures (rack) versus longline and basket cultivation (basket). Both types of oyster farms supported at least as many species of fish as adjacent natural habitats (oyster reef, seagrass, mangrove and bare sediment). Generally, fish communities were most similar between racks and baskets and most dissimilar between racks and bare sediments. Oyster farms supported species of fish otherwise limited to habitats with wild oysters, and unique harvested fish species were observed more frequently at racks. Fish use of oyster-growing infrastructure for foraging and shelter mirrored use of natural biogenic habitats. This study suggests that the oyster aquaculture infrastructure can support fish communities with species composition similar to those of natural biogenic habitats, although this service is dependent on the farming method.

*Mercaldo-Allen, R., A. J., Auster, P. Clark, M. S. Dixon, E. Estela, Y. Liu, L. Milke, G. Phillips, D. Redman, B. C. Smith, A. Verkade, and J. M Rose. 2023. Oyster aquaculture cages provide fish habitat similar to natural structure with minimal differences based on farm location. Front. Mar. Sci., Sec. Marine Fisheries, Aquaculture and Living Resources 10. doi: 10.3389/fmars.2023.105870
This study used underwater video to assess fish abundance and community composition on shelf and bag style off-bottom cages and rock reef habitat in Long Island Sound. In 2018, action

cameras were mounted on four study cages at a dense shellfish farm (40-100 commercial cages (dense cage farm), on four single cages on low relief seafloor (sparse cage farm), and amongst four boulders on a rock reef (rock reef) in Milford, CT. In 2019, cameras were similarly deployed on two study cages per farm at each of three farms off Milford, Norwalk and Westport, CT. Abundance of black sea bass, scup, and tautog was significantly higher on cages than boulders, regardless of cage number. Cunner was significantly more abundant on boulders than cages when cage sites were grouped. However pairwise comparisons indicated that cunner were significantly higher at the sparse cage farm versus the rock reef but cunner abundance did not differ between the dense cage farm and rock reef sites. Abundance of black sea bass, scup, tautog, and cunner were not significantly different across 2019 farm locations. Young-of-the-year fish occurred episodically at all sites during both years, with black sea bass and scup most abundant. Fish abundance corresponded to seasonal changes in seawater temperature and was highest at the warmest temperatures. Authors note "these results suggest that multi-tiered oyster aquaculture cages provide habitat for temperate reef fish similar to natural rock reefs".

*Mercaldo-Allen, R., P. Clark, Y. Liu, G. Phillips, D. Redman, P.J. Auster, E. Estela, L. Milke, A. Verkade, J.M. Rose. 2021. Exploring video and eDNA metabarcoding methods to assess oyster aquaculture cages as fish habitat. Aquaculture Environment Interactions doi:10.3354/aei00408
Underwater video and environmental DNA (eDNA) metabarcoding methods were developed to assess fish assemblages associated with oyster aquaculture bottom cages and natural rock reef habitat in Long Island Sound, CT. Results from field tests indicated that fish were consistently associated with aquaculture gear across multiple summer deployments. The four most commonly observed fish species occurred on both types of structured habitats. Preliminary results from a single deployment suggested that cunner occurred at higher abundance on the rock reef while black sea bass, tautog, and scup occurred at higher abundance on the aquaculture gear.

*Mercaldo-Allen R, Clark P, Liu Y, Meseck S, Milke L, Redman D (2020) Macrofaunal assemblages on oyster aquaculture and rock reef habitat in Long Island Sound. North Amer J Aquacult 82:92–100. https://doi.org/10.1002/naaq.10127
Trap sampling was used to survey the relative abundance of juvenile fish and invertebrates near an off-bottom oyster cage farm, a traditional on-bottom oyster culture area, and a natural cobble and boulder reef in central Long Island Sound,CT. The assemblages of juvenile finfish appeared to be similar on the cage farm and rock reef. Authors note "these preliminary observations suggest that oyster cage farms may provide functional habitat that is populated by structure-oriented finfish communities similar to those that are found on natural rock reefs."

Muething, K.A., F. Tomas, G. Waldbusser, and B.R. Dumbauld. 2020. On the edge: assessing fish habitat use across the boundary between Pacific oyster aquaculture and eelgrass in Willapa Bay, Washington, USA. Aquaculture Environment Interactions 12: 541-557. doi: 10.3354/aei00381
Underwater video camera, fish trapping, predation tethering units, and eelgrass survey methods were combined to compare fish habitat use of oyster aquaculture gear (longlines and bottom cages) and eelgrass beds in Willapa Bay, WA. No differences in total catch of fish and crab, or

species richness, were observed between aquaculture and eelgrass sites, although more fish were observed associated with longlines than bottom cages. The two most commonly observed species (shiner perch, Pacific staghorn sculpin) occurred in all three habitat types, although sculpin were observed more frequently in aquaculture habitats, and shiner perch were more frequently associated with longlines than bottom cages. Greater levels of predation were observed in longline than bottom cage habitats. Authors note that overall fish use of longlines was greater than bottom cages, and "the type of aquaculture and structure it provides influences its functional value as estuarine habitat and that it is comparable to eelgrass for some resources".

Powers, M.J., C.H. Peterson, H.C. Summerson, and S.P. Powers. 2007. Macroalgal growth on bivalve aquaculture netting enhances nursery habitat for mobile invertebrates and juvenile fishes. Marine Ecology Progress Series 339: 109-122.
Mobile invertebrates and juvenile fish associated with clam aquaculture, seagrass, and sandflat habitats were quantified by seining in Westmouth Bay, NC. Both structured habitats supported elevated abundance of mobile invertebrates and juvenile fish over unstructured seafloor. Associated invertebrate and fish communities were more similar between the structured habitats than the unstructured seafloor. Authors note "this ecological role for structural habitat rising above clam aquaculture leases is consistent with a broader recognition that artificial reefs, plastic seagrass, oyster shell mounds, and other emergent bottom structures provide habitat services"

*****Shinn, J.P., D.M. Munroe, J.M.Rose. 2021. A fish's-eye-view: accessible tools to document shellfish farms as marine habitat in New Jersey, USA. Aquaculture Environment Interactions doi: 10.3354/aei00407
Nekton abundance and community composition was quantified using underwater cameras deployed on oyster bottom cages, floating oyster bags, and natural marsh edge habitat in Barnegat Bay, NJ. Significantly greater numbers of individuals were observed on the bottom cages than the other two habitats, but no differences in species richness or diversity were observed across habitats. Authors noted that data and video footage "provide evidence of habitat provisioning for both finfish and invertebrates by intertidal oyster farms that could operate similarly to a naturally structured habitat".

*****Tallman, J.C., and G.E. Forrester. 2007. Oyster Grow-Out Cages Function as Artificial Reefs for Temperate Fishes. Transactions of the American Fisheries Society 136: 790-799. doi: 10.1577/T06-119.1
Trap surveys and a mark-recapture study were used to compare fish density, growth, and disappearance on oyster aquaculture bottom cages as well as natural and artificial rock reefs in Narragansett Bay, RI. The four most commonly observed species (black sea bass, cunner, scup, tautog) were present at all three structured habitat types. Black sea bass were present at similar abundance across habitat types, cunner had higher abundance on reefs, scup and tautog had higher abundance on aquaculture gear. Fish grew faster on natural rock reefs, but had lower disappearance from aquaculture gear. Authors note "because only a few cages are

hauled up at one time and they are returned to the water quickly, displaced finfish and invertebrates are likely to be able to seek refuge in other nearby cages" and "the oyster grow-out cages provide good-quality habitat for fishes typically associated with hard-bottom habitats".

Tsuyuki, A. and T. Umino. 2017. Spatial movement of black sea bream *Acanthopagrus schlegelii* around the oyster farming area in Hiroshima Bay, Japan. Fish. Sci. 83: 235-244. doi: 1007/s12562-016-1058-9)
Movements of black sea bream in an oyster farming area in Hiroshima Bay, Japan were tracked using depth transmitters. Six out of 7 fish remained within the farming area for 55 of the 65 days of tracking. These results suggest that this species may use the structure of the oyster rafts for feeding and refuge and demonstrate site fidelity to farm areas. Authors note "black sea bream are highly dependent on, and reside among, the oyster farms in Hiroshima Bay" and that "results imply that oyster rafts function efficiently as artificial reefs and provide support for an abundant stock of black sea bream".

Tsuyuki. A. and T. Umino. 2018. Assessment of ichthyofauna at oyster rafts in Hiroshima Bay, Japan, using underwater video cameras. Aquacult. Sci. 66, 267–274.
This study investigated the ichthyofauna at oyster rafts supporting Crassostrea gigas in Hiroshima Bay, Japan, using underwater video cameras. Fish species around the rafts consisted of identified 18 species, with low similarities to the fish community in nearby coastal areas. Several commercial species, including black sea bream Acanthopagrus schlegelii, filefish Thamnaconus modestus, and surfperch Ditrema temmincki, aggregated at the oyster rafts throughout the year. The abundance of A. schlegelii (68%-85% relative abundance) accounted for most of the fish at the rafts, except in summer. Videos revealed that A. schlegelii, T. modestus, and D. temmincki preyed on the sessile organisms (probably mollusks, crustaceans and macroalgae) which had abundantly attached to the oyster wires. Authors note "that large and persistent aggregations of fishes suggests that the oyster rafts efficiently function as an artificial reef in the regional ecosystem".

Veggerby, K. B., M. D. Scheuerell, B. L. Sanderson, P. M. Kiffney, and B.E. Ferriss. 2024. Shellfish aquaculture farms as foraging habitat for nearshore fishes and crabs. Mar Coast Fish *16, e10282.*
This study used observations from underwater video to quantify how shellfish farms are used as foraging habitat for common nearshore species of fish and crabs in Puget Sound, Washington. A total of 393 crab observations, 431 demersal fish observations, and 1856 pelagic fish observations were made across all seven farm sites. Several common pelagic fish species foraged on aquaculture-growing gear more frequently than unfarmed areas, while Metacarcinus spp. crabs displayed higher foraging frequency in unfarmed mudflats. Benthic species including sculpins (Cottidae) and small flatfish (Pleuronectidae) used specific aquaculture-growing gear and mudflats at a similar frequency. Authors note that "our results suggest that shellfish farms within a larger nearshore habitat mosaic of eelgrass meadows, mudflats, bivalve aquaculture gear, and edge habitat can provide foraging habitat for several species of nearshore fish".

Further Reading:

Alleway, H. K., Waters, T. J., Brummett, R., Cai, J., Cao, L., Cayten, M. R., Costa-Pierce, B. A., Dong, Y.-W., Brandstrup Hansen, S. C., Liu, S., Liu, Q., Shelley, C., Theuerkauf, S. J., Tucker, L., Wang, Y., & Jones, R. C. (2023). Global principles for restorative aquaculture to foster aquaculture practices that benefit the environment [https://doi.org/10.1111/csp2.12982]. Conservation Science and Practice, n/a(n/a), e12982. https://doi.org/https://doi.org/10.1111/csp2.12982

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