APPENDIX A. SUPPLEMENTARY INFORMATION FOR METHODS

Table A.1. Search strings used for the discovery of relevant literature in the Web of Science (all results). Informal supplementary searches were also conducted for reports, theses and dissertations via Google Scholar and Open Access Theses and Dissertations (https://oatd.org). Searches were conducted in September 2020.

Search topic	**Search string**
Nutrient removal rates at seaweed farms (306 hits in WoS)	(aquacultur* OR farm* OR maricultur*) AND (seaweed OR alga* OR macroalga* OR kelp) AND (nutrient OR nitrogen OR phosphorus OR eutrophi*)AND (uptak* OR remov* OR bioextract* OR mitigat* OR bioremedia* OR remedia* OR denitrif*) AND (quantif* OR measur* OR assess* OR estimat* OR report* OR rate* OR efficien*) NOT (biofuel OR soil OR pond OR microalga* OR biofilm* OR dinoflag* OR cyanobacteri* OR hyacinth OR wetland OR freshwater)
Nutrient removal rates at bivalve farms (514 hits in WoS)	(aquaculture OR mariculture OR farm* OR cultur*) AND (shellfish OR bivalve* OR oyster* OR mussel* OR clam* OR geoduck* OR quahog* OR scallop*) AND (nutrient* OR nitrogen OR phosphorus) AND (bioextract* OR extract* OR remov* OR mitigat* OR filt* OR remedia*)
Denitrification rates at bivalve farms (71 hits in WoS)	(aquacultur* OR farm* OR cultur* OR maricultur*) AND (shellfish OR bivalve OR mussel* OR Aulacomya OR Choromytilus OR Mytilus OR Perna OR oyster* OR pearl OR Crassostrea OR Ostrea OR Saccostrea OR Pinctada OR Pteria OR scallop* OR Aequipecten OR Argopecten OR Chlamys OR Patinopecten OR Pecten OR Placopecten OR clam* OR cockle* OR geoduck OR quahog OR Anadara OR Scapharca OR Cerastoderma OR Tridacna OR Mactra OR Spisula OR Sinonovacula OR Corbicula OR Mercenaria OR Meretrix OR Paphia OR Protothaca OR Ruditapes OR Saxidomus OR Venerupis Mya OR Panopea) AND (denitrif*)
Habitat provision effects at bivalve and seaweed farms (1607 hits in WoS)	(aquacultur* OR farm* OR maricultur*) AND (seaweed OR alga* OR macroalga* OR kelp OR shellfish OR bivalve OR mussel* OR Aulacomya OR Choromytilus OR Mytilus OR Perna OR oyster* OR pearl OR Crassostrea OR Ostrea OR Saccostrea OR Pinctada OR Pteria OR scallop* OR Aequipecten OR Argopecten OR Chlamys OR Patinopecten OR Pecten OR Placopecten OR clam* OR cockle* OR geoduck OR quahog OR Anadara OR Scapharca OR Cerastoderma OR Tridacna OR Mactra OR Spisula OR Sinonovacula OR Corbicula OR Mercenaria OR Meretrix OR Paphia OR Protothaca OR Ruditapes OR Saxidomus OR Venerupis Mya OR Panopea) AND (habitat OR abund* OR "population density") NOT (soil OR pond) Note: Data were also included from four unpublished studies by Bridget Ferriss et al., Renee Mercaldo-Allen et al., James Foley and Jenny Shinn et al. (Appendix C).

Supplementary Text A.1. Full list of studies that met the criteria for inclusion.

Bivalve nutrient removal rates

1. Ajjabi LC, Abaab M, Segni R (2018) The red macroalga Gracilaria verrucosa in co-culture with the Mediterranean mussels Mytilus galloprovincialis: productivity and nutrient removal performance. Aquac Int 26:253–266

2. Bricker SB, Ferreira JG, Zhu C, Rose JM, Galimany E, Wikfors G, Saurel C, Miller RL, Wands J, Trowbridge P, Grizzle R, Wellman K, Rheault R, Steinberg J, Jacob A, Davenport ED, Ayvazian S, Chintala M, Tedesco MA (2018) Role of Shellfish Aquaculture in the Reduction of Eutrophication in an Urban Estuary. Environ Sci Technol 52:173–183

3. Bricker SB, Grizzle RE, Trowbridge P, Rose JM, Ferreira JG, Wellman K, Zhu C, Galimany E, Wikfors GH, Saurel C, Landeck Miller R, Wands J, Rheault R, Steinberg J, Jacob AP, Davenport ED, Ayvazian S, Chintala M, Tedesco MA (2020) Bioextractive Removal of Nitrogen by Oysters in Great Bay Piscataqua River Estuary, New Hampshire, USA. Estuaries and Coasts 43:23–38

4. Bricker SB, Rice KC, Bricker III OP (2014) From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River Estuary. Aquat Geochemistry 20:291–323

5. Brigolin D, Maschio GD, Rampazzo F, Giani M, Pastres R (2009) An individual-based population dynamic model for estimating biomass yield and nutrient fluxes through an off-shore mussel (Mytilus galloprovincialis) farm. Estuar Coast Shelf Sci 82:365–376

6. Buer AL, Maar M, Nepf M, Ritzenhofen L, Dahlke S, Friedland R, Krost P, Peine F, Schernewski G (2020) Potential and Feasibility of Mytilus spp. Farming Along a Salinity Gradient. Front Mar Sci 7:1–14

7. Carlsson MS, Engström P, Lindahl O, Ljungqvist L, Petersen JK, Svanberg L, Holmer M (2012) Effects of mussel farms on the benthic nitrogen cycle on the swedish west Coast. Aquac Environ Interact 2:177–191

8. Christensen PB, Glud RN, Dalsgaard T, Gillespie P (2003) Impacts of longline mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. Aquaculture 218:567–588

9. Cubillo AM, Ferreira JG, Pearce CM, Marshall R, Cheney D, Hudson B (2018) Ecosystem services of geoduck farming in South Puget Sound, USA: a modeling analysis. Aquac Int 26:1427–1443

10. Dedieu K, Rabouille C, Gilbert F, Soetaert K, Metzger E, Simonucci C, Jézéquel D, Prévot F, Anschutz P, Hulth S (2007) Coupling of carbon, nitrogen and oxygen cycles in sediments from a Mediterranean lagoon: a seasonal perspective. Mar Ecol Prog Ser 346:45–59

11. Dvarskas A, Bricker SB, Wikfors GH, Bohorquez JJ, Dixon MS, Rose JM (2020) Quantification and Valuation of Nitrogen Removal Services Provided by Commercial Shellfish Aquaculture at the Subwatershed Scale. Environ Sci Technol 54:16156–16165

12. Erler D V, Welsh DT, Bennet WW, Meziane T, Hubas C, Nizzoli D, Ferguson AJP (2017) The impact of suspended oyster farming on nitrogen cycling and nitrous oxide production in a sub-tropical Australian estuary. Estuar Coast Shelf Sci 192:117–127

13. Ferreira JG, Andersson HC, Corner RA, Desmit X, Fang Q, Goede ED De, Groom SB, Gu H, Gustafsson BG, Hawkins AJS (2008) Sustainable Options for People Catchment and Aquatic Resources: The SPEAR Project an International Collaboration on Integrated Coastal Zone Management.

14. Ferreira JG, Hawkins AJS, Monteiro P, Moore H, Edwards A, Goven R, Lourenco P, Mellor A, Nunes JP, Ramos L (2007) SMILE-sustainable mariculture in northern Irish lough ecosystems: assessment of carrying capacity for environmentally sustainable shellfish culture in Carlingford Lough, Strangford Lough, Belfast Lough, Larne Lough and Lough Foyle. Institute of Marine Research

15. Ferreira JG, Sequeira A, Hawkins AJS, Newton A, Nickell TD, Pastres R, Forte J, Bodoy A, Bricker SB (2009) Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species. Aquaculture 289:32–41

16. Ferreira JG, Saurel C, Nunes JP, Ramos L, Silva J, Vazquez F, Bergh Ø, Dewey W, Pacheco A, Pinchot M (2012) Framework for Ria Formosa water quality, aquaculture, and resource development.

17. Gibbs M, Ross A, Downes M (2002) Nutrient cycling and fluxes in Beatrix Bay, Pelorus Sound, New Zealand. New Zeal J Mar Freshw Res 36:675–697

18. Gifford S, Dunstan H, O’Connor W, Macfarlane GR (2005) Quantification of in situ nutrient and heavy metal remediation by a small pearl oyster (Pinctada imbricata) farm at Port Stephens, Australia. Mar Pollut Bull 50:417–422

19. Gifford S, Dunstan RH, O’Connor W, Roberts T, Toia R (2004) Pearl aquaculture - Profitable environmental remediation? Sci Total Environ 319:27–37

20. Gilbert F, Souchu P, Bianchi M, Bonin P (1997) Influence of shellfish farming activities on nitrification, nitrate reduction to ammonium and denitrification at the water-sediment interface of the Thau lagoon, France. Mar Ecol Prog Ser 151:143–153

21. Higgins CB, Stephenson K, Brown BL (2011) Nutrient Bioassimilation Capacity of Aquacultured Oysters: Quantification of an Ecosystem Service. J Environ Qual 40:271–277

22. Higgins CB, Tobias C, Piehler MF, Smyth AR, Dame RF, Stephenson K, Brown BL (2013) Effect of aquacultured oyster biodeposition on sediment N2 production in Chesapeake bay. Mar Ecol Prog Ser 473:7–27

23. Humphries AT, Ayvazian SG, Carey JC, Hancock BT, Grabbert S, Cobb D, Strobel CJ, Fulweiler RW (2016) Directly measured denitrification reveals oyster aquaculture and restored oyster reefs remove nitrogen at comparable high rates. Front Mar Sci 3:1–10

24. Jackson M (2019) Characterization of Oyster-Associated Biogeochemical Processes in Oyster Restoration and Aquaculture.

25. Kaspar HF, Gillespie PA, Boyer IC, MacKenzie AL (1985) Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. Mar Biol 85:127–136

26. Lindahl O, Hart R, Hernroth B, Kollberg S, Loo LO, Olrog L, Rehnstam-Holm AS, Svensson J, Svensson S, Syversen U (2005) Improving marine water quality by mussel farming: A profitable solution for Swedish society. Ambio 34:131–138

27. Lunstrum A, McGlathery K, Smyth A (2018) Oyster (Crassostrea virginica) Aquaculture Shifts Sediment Nitrogen Processes toward Mineralization over Denitrification. Estuaries and Coasts 41:1130–1146

28. McLaughlin SM, Leight AK, Spires JE, Bricker SB, Jacobs JM, Messick GA, Skelley S (2018) Coastal Ecological Assessment to Support NOAA's Choptank River Complex Habitat Focus Area: Tred Avon River.

29. Minjeaud L, Michotey VD, Garcia N, Bonin PC (2009) Seasonal variation in di-nitrogen fluxes and associated processes (denitrification, anammox and nitrogen fixation) in sediment subject to shellfish farming influences. Aquat Sci 71:425–435

30. Murphy AE, Anderson IC, Smyth AR, Song B, Luckenbach MW (2016) Microbial nitrogen processing in hard clam (Mercenaria mercenaria) aquaculture sediments: the relative importance of denitrification and dissimilatory nitrate reduction to ammonium (DNRA). Limnol Oceanogr 61:1589–1604

31. Nizzoli D, Bartoli M, Viaroli P (2006) Nitrogen and phosphorous budgets during a farming cycle of the Manila clam Ruditapes philippinarum: An in situ experiment. Aquaculture 261:98–108

32. Nizzoli D, Welsh DT, Fano EA, Viaroli P (2006) Impact of clam and mussel farming on benthic metabolism and nitrogen cycling, with emphasis on nitrate reduction pathways. Mar Ecol Prog Ser 315:151–165

33. Parker M, Bricker S (2020) Sustainable Oyster Aquaculture, Water Quality Improvement, and Ecosystem Service Value Potential in Maryland Chesapeake Bay. J Shellfish Res 39:269–281

34. Rawson Jr M V, Chen C, Ji R, Zhu M, Wang D, Wang L, Yarish C, Sullivan JB, Chopin T, Carmona R (2002) Understanding the interaction of extractive and fed aquaculture using ecosystem modeling. Responsible Mar Aquac CABI Publ Oxon:263–296

35. Ray NE, Al-Haj AN, Fulweiler RW (2020) Sediment biogeochemistry along an oyster aquaculture chronosequence. Mar Ecol Prog Ser 646:13–27

36. Reitsma J, Murphy DC, Archer AF, York RH (2017) Nitrogen extraction potential of wild and cultured bivalves harvested from nearshore waters of Cape Cod, USA. Mar Pollut Bull 116:175–181

37. Saurel C, Ferreira JG, Cheney D, Suhrbier A, Dewey B, Davis J, Cordell J (2014) Ecosystem goods and services from Manila clam culture in Puget Sound: a modelling analysis. Aquac Environ Interact 5:255–270

38. Sebastiano D, Levinton JS, 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. J Shellfish Res 34:573–583

39. Silva C, Ferreira JG, Bricker SB, DelValls TA, Martín-Díaz ML, Yáñez E (2011) Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. Aquaculture 318:444–457

40. Smyth AR, Murphy AE, Anderson IC, Song B (2018) Differential effects of bivalves on sediment nitrogen cycling in a shallow coastal bay. Estuaries and Coasts 41:1147–1163

41. Srisunont C, Babel S (2016) Estimating the carrying capacity of green mussel cultivation by using net nutrient removal model. Mar Pollut Bull 112:235–243

42. Testa JM, Brady DC, Cornwell JC, Owens MS, Sanford LP, Newell CR, Suttles SE, Newell RIE (2015) Modeling the impact of floating oyster (Crassostrea virginica) aquaculture on sediment-water nutrient and oxygen fluxes. Aquac Environ Interact 7:205–222

43. Turolla E, Castaldelli G, Fano EA, Tamburini E (2020) Life Cycle Assessment (LCA) Proves that Manila Clam Farming (Ruditapes philippinarum) is a Fully Sustainable Aquaculture Practice and a Carbon Sink. Sustainability 12:5252

44. Wei Z, Huo Y, Liu Q, Yang F, Long L, Bi H, Fan C, He P (2019) A field scale evaluation of Gracilaria lemaneiformis co-cultured with Crassostrea gigas as a nutrient bioextraction strategy in Yantian Bay, China. Algal Res 38:101407

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Seaweed nutrient removal rates

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2. Ajjabi LC, Abaab M, Segni R (2018) The red macroalga Gracilaria verrucosa in co-culture with the Mediterranean mussels Mytilus galloprovincialis: productivity and nutrient removal performance. Aquac Int 26:253–266

3. Augyte S, Yarish C, Redmond S, Kim JK (2017) Cultivation of a morphologically distinct strain of the sugar kelp, Saccharina latissima forma angustissima, from coastal Maine, USA, with implications for ecosystem services. J Appl Phycol 29:1967–1976

4. Duan Y, Yang N, Hu M, Wei Z, Bi H, Huo Y, He P (2019) Growth and nutrient uptake of Gracilaria lemaneiformis under different nutrient conditions with implications for ecosystem services: A case study in the laboratory and in an enclosed mariculture area in the East China Sea. Aquat Bot 153:73–80

5. Gao X, Endo H, Yamana M, Taniguchi K, Agatsuma Y (2013) Compensatory abilities depending on seasonal timing of thallus excision of the kelp Undaria pinnatifida cultivated in Matsushima Bay, northern Japan. J Appl Phycol 25:1331–1340

6. He P, Xu S, Zhang H, Wen S, Dai Y, Lin S, Yarish C (2008) Bioremediation efficiency in the removal of dissolved inorganic nutrients by the red seaweed, Porphyra yezoensis, cultivated in the open sea. WATER Res 42:1281–1289

7. Kim JK, Kraemer GP, Yarish C (2015) Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. Mar Ecol Prog Ser 531:155–166

8. Marinho GS, Holdt SL, Birkeland MJ, Angelidaki I (2015) Commercial cultivation and bioremediation potential of sugar kelp, Saccharina latissima, in Danish waters. J Appl Phycol 27:1963–1973

9. Sato Y, Hirano T, Niwa K, Suzuki T, Fukunishi N, Abe T, Kawano S (2016) Phenotypic differentiation in the morphology and nutrient uptake kinetics among Undaria pinnatifida cultivated at six sites in Japan. J Appl Phycol 28:3447–3458

10. Wei Z, Huo Y, Liu Q, Yang F, Long L, Bi H, Fan C, He P (2019) A field scale evaluation of Gracilaria lemaneiformis co-cultured with Crassostrea gigas as a nutrient bioextraction strategy in Yantian Bay, China. Algal Res - Biomass Biofuels Bioprod 38

11. Wu H, Huo Y, Hu M, Wei Z, He P (2015) Eutrophication assessment and bioremediation strategy using seaweeds co-cultured with aquatic animals in an enclosed bay in China. Mar Pollut Bull 95:342–349

12. Xiao X, Agusti S, Lin F, Li K, Pan Y, Yu Y, Zheng Y, Wu J, Duarte CM (2017) Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. Sci Rep 7

Nutrient valuation

1. Beseres Pollack J, Yoskowitz D, Kim H-C, Montagna PA (2013) Role and value of nitrogen regulation provided by oysters (Crassostrea virginica) in the Mission-Aransas Estuary, Texas, USA. PLoS One 8:e65314

2. Bricker SB, Rice KC, Bricker III OP (2014) From Headwaters to Coast: Influence of Human Activities on Water Quality of the Potomac River Estuary. Aquat Geochemistry 20:291–323

3. Buer AL, Maar M, Nepf M, Ritzenhofen L, Dahlke S, Friedland R, Krost P, Peine F, Schernewski G (2020) Potential and Feasibility of Mytilus spp. Farming Along a Salinity Gradient. Front Mar Sci 7:1–14

4. CT DEEP (2020) Report of the Nitrogen Credit Advisory Board for Calendar Year 2018 To the Joint Standing Environment Committee of the General Assembly. Hartford

5. DePiper GS, Lipton DW, Lipcius RN (2017) Valuing ecosystem services: Oysters, denitrification, and nutrient trading programs. Mar Resour Econ 32:1–20

6. Dvarskas A, Bricker SB, Wikfors GH, Bohorquez JJ, Dixon MS, Rose JM (2020) Quantification and Valuation of Nitrogen Removal Services Provided by Commercial Shellfish Aquaculture at the Subwatershed Scale. Environ Sci Technol 54:16156–16165

7. Gren IM (2019) The economic value of mussel farming for uncertain nutrient removal in the Baltic Sea. PLoS One 14:1–15

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9. Haamer J (1996) Improving water quality in a eutrophied fjord system with mussel farming. Ambio 25:356–362

10. Jones C, Branosky E, Selman M, Perez M (2010) How nutrient trading could help restore the Chesapeake Bay. World Resources Institute (WRI)

11. Kotta J, Futter M, Kaasik A, Liversage K, Rätsep M, Barboza FR, Bergström L, Bergström P, Bobsien I, Díaz E, Herkül K, Jonsson PR, Korpinen S, Kraufvelin P, Krost P, Lindahl O, Lindegarth M, Lyngsgaard MM, Mühl M, Sandman AN, Orav-Kotta H, Orlova M, Skov H, Rissanen J, Šiaulys A, Vidakovic A, Virtanen E (2020) Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. Sci Total Environ 709

12. Lai QT, Irwin ER, Zhang Y (2020) Estimating nitrogen removal services of eastern oyster (Crassostrea virginica) in Mobile Bay, Alabama. Ecol Indic 117:106541

13. Lindahl O, Hart R, Hernroth B, Kollberg S, Loo LO, Olrog L, Rehnstam-Holm AS, Svensson J, Svensson S, Syversen U (2005) Improving marine water quality by mussel farming: A profitable solution for Swedish society. Ambio 34:131–138

14. Melbourne Water (2019) Stormwater offsets explained.

15. NC DEQ (2021) Current Rate Schedules.

16. Newell RIE, Fisher TR, Holyoke RR, Cornwell JC (2005) Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay, USA. In: The comparative roles of suspension-feeders in ecosystems. Springer, p 93–120

17. Petersen JK, Hasler B, Timmermann K, Nielsen P, Tørring DB, Larsen MM, Holmer M (2014) Mussels as a tool for mitigation of nutrients in the marine environment. Mar Pollut Bull 82:137–143

18. Stephenson K, Aultman S, Metcalfe T, Miller A (2010) An evaluation of nutrient nonpoint offset trading in Virginia: A role for agricultural nonpoint sources? Water Resour Res 46:1–11

19. VA DEQ (2015) Annual report from the Virginia point source nutrient exchange.

20. Wheeler TB (2020) Oyster growers hope polluters will shell out for nutrient credits. Bay J

21. Wulff F, Humborg C, Andersen HE, Blicher-Mathiesen G, Czajkowski M, Elofsson K, Fonnesbech-Wulff A, Hasler B, Hong B, Jansons V, Mörth C-M, Smart JCR, Smedberg E, Stålnacke P, Swaney DP, Thodsen H, Was A, Żylicz T (2014) Reduction of Baltic Sea Nutrient Inputs and Allocation of Abatement Costs Within the Baltic Sea Catchment. Ambio 43:11–25

Fish habitat provision

1. Anyango JO, Mlewa CM, Mwaluma J (2017) Abundance, diversity and trophic status of wild fish around seaweed farms in Kibuyuni, South Coast Kenya. Int J Fish Aquat Stud 5:440–446

2. Bergman KC, Svensson S, Öhman MC (2001) Influence of algal farming on fish assemblages. Mar Pollut Bull 42:1379–1389

3. Bourdon R (2015) Interactions between fish communities and shellfish aquaculture in Baynes Sound, British Columbia. University of Victoria

4. Brown RA, Thuesen E V. (2011) Biodiversity of mobile benthic fauna in geoduck (Panopea generosa) aquaculture beds in southern Puget Sound, Washington. J Shellfish Res 30:771–776

5. Cartier LE, Carpenter KE (2014) The influence of pearl oyster farming on reef fish abundance and diversity in Ahe, French Polynesia. Mar Pollut Bull 78:43–50

6. Chesney EJ, Iglesias J (1979) Seasonal distribution, abundance and diversity of demersal fishes in the inner Ria de Arosa, Northwest Spain. Estuar Coast Mar Sci 8:227–239

7. Clarke LM (2017) Functional comparison of longline oyster aquaculture and eelgrass (Zostera marina L.) habitats among Pacific Northwest estuaries, USA. Oregon State University

8. Clynick BG, McKindsey CW, Archambault P (2008) Distribution and productivity of fish and macroinvertebrates in mussel aquaculture sites in the Magdalen islands (Quebec, Canada). Aquaculture 283:203–210

9. Collicut B (2016) The anthropogenic influence of shellfish aquaculture and microplastics on juvenile Pacific salmon on the east coast of Vancouver Island. University of Victoria

10. D'Amours O, Archambault P, McKindsey CW, Johnson LE (2008) Local enhancement of epibenthic macrofauna by aquaculture activities. Mar Ecol Prog Ser 371:73–84

11. Carvalho LL de, Souza EGA de, Mata Júnior MR da, Villaça RC (2017) Assessment of rocky reef fish assemblages close to seaweed farming. Aquac Res 48:481–493

12. DeAlteris JT, Kilpatrick BD, Rheault RB (2004) A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. J Shellfish Res 23:867–874

13. Drouin A, Archambault P, Clynick B, Richer K, McKindsey CW (2015) Influence of mussel aquaculture on the distribution of vagile benthic macrofauna in îles de la Madeleine, eastern Canada. Aquac Environ Interact 6:175–183

14. Dumbauld BR, Ruesink JL, Rumrill SS (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

15. Eklöf JS, la Torre-Castro M de, Nilsson C, Rönnbäck P, Eklof JS, la Torre-Castro M de, Nilsson C, Ronnback P (2006) How do seaweed farms influence local fishery catches in a seagrass-dominated setting in Chwaka Bay, Zanzibar? Aquat Living Resour 19:137–147

16. Foley J (2016) Baseline ecological monitoring report of Eucheuma and Gracilaria seaweed farms at Hatchet Caye and Little Water Caye near Placencia, Belize.

17. Hosack GR, Dumbauld BR, Ruesink JL, Armstrong DA (2006) Habitat associations of estuarine species: comparisons of intertidal mudflat, seagrass (Zostera marina), and oyster (Crassostrea gigas) habitats. Estuaries and Coasts 29:1150–1160

18. Iglesias J (1981) Spatial and temporal changes in the demersal fish community of the Ria de Arosa (NW Spain). Mar Biol 65:199–208

19. Murray LG, Seed R, Jones T (2007) Predicting the impacts of Carcinus maenas predation on cultivated Mytilus edulis beds. J Shellfish Res 26:1089–1098

20. Segvic-Bubic T, Grubisic L, Karaman N, Ticina V, Jelavic KM, Katavic I (2011) Damages on mussel farms potentially caused by fish predation - self service on the ropes? Aquaculture 319:497–504

21. Smith R, McDonald PS (2009) Examining the effects of predator exclusion structures associated with geoduck aquaculture on mobile benthic macrofauna in South Puget Sound, Washington. J Shellfish Res 28:730

22. Tallman JC, Forrester GE (2007) Oyster grow-out cages function as artificial reefs for temperate fishes. Trans Am Fish Soc 136:790–799

23. Taylor JC (2008) Evaluation of the ecological value of constructed intertidal oyster reefs and aquaculture structures in Delaware Bay: Habitat utilization by motile macrofauna. Rutgers University

24. Visch W, Kononets M, Hall POJ, Nylund GM, Pavia H (2020) Environmental impact of kelp (Saccharina latissima) aquaculture. Mar Pollut Bull 155

25. Wechsler JF (2004) Assessing the relationship between the ichthyofauna and oyster mariculture in a shallow coastal embayment, Drakes Estero, Point Reyes National Seashore. University of California, Davis

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2. Berrens R, Bergland O, Adams RM (1993) Valuation issues in an urban recreational fishery – spring chinook salmon in Portland, Oregon. J Leis Res 25:70–83

3. Cameron TA (1988) A new paradigm for valuing non-market goods using referendum data: maximum likelihood estimation by censored logistic regression. J Environ Econ Manage 15:355–379

4. Cantrell RN, Garcia M, Leung PS, Ziemann D (2004) Recreational anglers' willingness to pay for increased catch rates of Pacific threadfin (Polydactylus sexfilis) in Hawaii. Fish Res 68:149–158

5. Carson R, Hanemann M, Steinberg D (1990) A discrete choice contingent valuation estimate of the value of Kenai king salmon. J Behav Econ 19:53–68

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9. Hicks RL, Gautam AB, Voorhees D Van, Osborn M, Gentner B (1999) An introduction to the NMFS Marine Recreational Fisheries Statistics Survey with an emphasis on economic valuation. Mar Resour Econ 14:375–385

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12. Kroeger T, Guannel G (2014) Fishery enhancement and coastal protection services provided by two restored Gulf of Mexico oyster reefs. In: Valuing Ecosystem Services. Edward Elgar Publishing

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14. Loomis JB (1988) Contingent valuation using dichotomous choice models. J Leis Res 20:46–56

15. McConnell KE, Strand IE (1994) The economic value of Mid and South Atlantic sportfishing. University of Maryland

16. Milon JW, Thunberg EM, Adams CM, Lin CT (1994) Recreational anglers' valuation of near-shore marine fisheries in Florida.

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Supplementary Text A.1. Treatment of fish population data and simulation of production enhancement.

For cases where there was zero abundance in one habitat, we conservatively assumed a relative abundance of 10:1 in the observed direction. Where a study provided abundance data for several qualitatively different farm or reference habitat types (e.g. presence/absence of gear or habitat structure), we calculated effect sizes for each. We aggregated a mean value across all timepoints at which farming was taking place, improving our ability to compare habitat effects across studies and regions, but at the cost of flattening seasonal patterns.

Representative sampling of the farm footprint requires that all microhabitats within the farm boundary are surveyed with the same detection rate of individuals present in that macrohabitat. This is rarely the case. For example, randomly-placed visual census transects spanning gear and the seabed between may sample relatively large, non-cryptic fish representatively but miss those within baskets or cages, while bagging or lift-netting oyster cages will effectively sample individuals closely associated with the aquaculture gear, but miss any large individuals that flee rather than hiding within the structure. For conservatism, we only corrected downwards, by reducing reported densities for studies that selectively sampled aquaculture gear, but not increasing reported densities for studies that sampled between gear and therefore may have missed higher densities of fish associated with gear.

Most fish survey methods only sample a subset of the species and size classes present at a site, with the result the reported density is both (i) an underestimate of the true density, and (ii) reflective of a biased subset of individuals. For example, lift nets may sample the majority of small fish present, while almost all larger or more mobile fishes will evade capture. Conversely, visual census is most effective at sampling relatively large, bold fishes, while the size-selectivity of seine and trawl methods depends on a range of factors including mesh size, net width, speed, turbidity and habitat complexity.

Obtaining starting values for juvenile density required two broad assumptions to be made: First, nearly half of the species comparisons in our dataset were provided as catch-per-unit-effort or another relative abundance unit. We converted these to density units based on defensible estimates of the effective area sampled by each method. These values are given in the supplementary data file (Appendix C), and we report the effect of omitting such cases from the analysis in-text (also see Figure A.1). Second, very few studies in our dataset presented size- or age-frequency distributions of the individuals sampled. We therefore implemented a standardised protocol for estimation of age 0+ juvenile density (D_{juv}). For each comparison, we first defined the size range that was likely to be effectively sampled by the survey methods used, based on variables such as mesh size or trap entrance dimensions relative to body size (Appendix B). Habitat- and species-specific production was then simulated as follows:

Surviving density-at-age D_t was estimated using the equation

(Eqn A.1) $D_{t+1} = D_t \cdot e\string^(-M_t)$

where Dt is the surviving density at age t (calculated at increments up to the species maximum age, t_{max}), M_t is the instantaneous natural mortality rate at age t (mean of several M-estimation methods, detailed below). Age-specific mortality (M_t) was based on a species-level estimate for M adjusted according to (Lorenzen 2000)

(A.2) $M_t = M \cdot (L_c/L_t)$

where L_c is the value for length at recruitment to the fishery (here assumed to occur at 40% of maximum length) and L_t is length-at-age according to the von Bertalanffy growth function (Von Bertalanffy 1938)

(A.3) $L_t = L_{inf}(1 - e^{(-K(t-t_0))})$

where L_{inf} is the length in cm at an infinitely high age, and K is a growth coefficient. t_0 is the theoretical age at length zero predicted by the growth rate function, assumed to be equal to zero. Using the simulated size-frequency distribution (D_t at age), we measured the size-frequency kernel over two length ranges: the range effectively sampled ($K_{sampled}$), and the range from length-at-recruitment to length-at-age-1 (K_{juv}). D_{juv} is then taken to be equal to the sampled density multiplied by $K_{juv}/K_{sampled}$. The estimated value for D_{juv} was, on average, equal to 66% of $D_{sampled}$ (Figure A.2). With an estimate of D_{juv} as a starting cohort density, surviving density-at-age was integrated from the assumed mean age of the D_{juv} cohort (0.5 years) to the species maximum age t_{max} (Eqn A.1). We did not attempt to model production below 0.5 years of age. Mean length at age (L_t) was fitted using Eqn A.3, and converted to mean weight at age (W_t) using the weight-at-length equation (Le Cren 1951)

(A.4) $W_t = a \cdot L_t^{b}$

where W_t is the weight at age in grams and a and b are species-specific constants. Multiplying L_t and W_t then gave surviving biomass at age (B_t). Integrating B_t and D_t from age 0.5 to t_{max} (Figure A.3, Figure A.4) gave values that we took to represent the theoretical steady state annual production (zu Ermgassen et al. 2016). Annual production of landable fish was estimated by integrating above the age at which fish were expected to reach landable size. Landable sizes were assigned according to regulatory size limits or else set at 40% of the species maximum length, with a universal minimum of 20 cm for fishes unless the species is known to be harvested at smaller sizes.

An analysis by (Then et al. 2015) found that t_{max}-based methods performed best, and particularly a nonlinear least squares variation on (Hoenig 1983) method, parameterised as

(A.6) $M_{nls} = 4.889 \cdot t_{max}^{(-0.916)}$

We also computed production estimates using three alternative M-estimation methods re-parameterised by (Then et al. 2015), namely a simplified version of (Pauly 1980) growth-based method (Eqn A.7), and one- and two-parameter growth-based methods (Eqns A.8, A.9) (Jensen 1996, 2001).

(A.7) $M_{Pauly} = 4.118 \cdot K^{0.73} \cdot L_{inf}^{(-0.33)}$

(A.8) $M_K = 1.692 \cdot K$

(A.9) $M_{K2} = 0.098 + 1.55 \cdot K$

We use these methods to estimate M for both fishes and invertebrates, using carapace width or length in place of total length for the M_{Pauly} method. We primarily report production estimates based on the mean of M_{nls}, M_{Pauly}, M_K and M_{K2}.

Our method does not require prior evidence of habitat use for inclusion of species, but instead takes observed population densities at farm and reference sites as indicators of relative habitat value. This means that while we impose a stricter test of the measured enhancement effect by subtracting production at reference habitats from production at farms, we also allow more species to contribute to assemblage-level production than previous applications of this method. Despite this, we likely still underestimate the assemblage-level density, as only species that were effectively sampled (minimum 10 individuals sampled within at least one habitat type) were included.

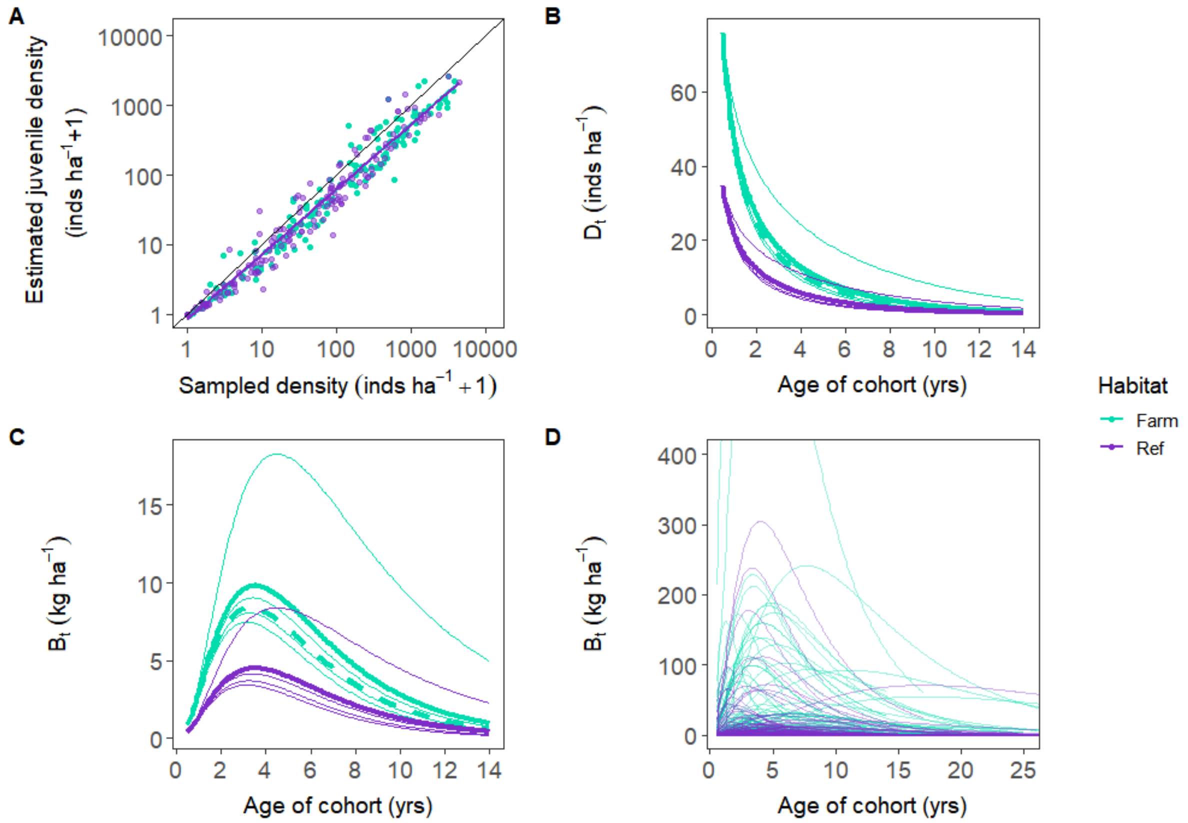

Figure A.1. Representations of projected fish production. **Panel A** shows the comparison of sampled fish density ($D_{sampled}$) and estimated age 0+ juvenile density (D_{juv}). On average, D_{juv} is equal to 64% and 66% of $D_{sampled}$ for farm and reference habitats, respectively. **Panels B and C** show production of an example cohort from 0.5 years to maximum age, in terms of (panel B) surviving density-at-age, D_t, and (panel C) surviving biomass-at-age, B_t. Production in this case is higher at farm sites and will yield a positive value for additional fish produced at farm habitats. Thick lines show production trajectories according to the mean natural mortality estimate M, while thin lines show the range of trajectories according to M_{nls}, M_{Pauly}, M_K and M_{K2} methods. The thick dashed line shows the effect of increasing mean M by 10% at farm sites only. **Panel D** Shows all lifetime production trajectories considered in the analysis.

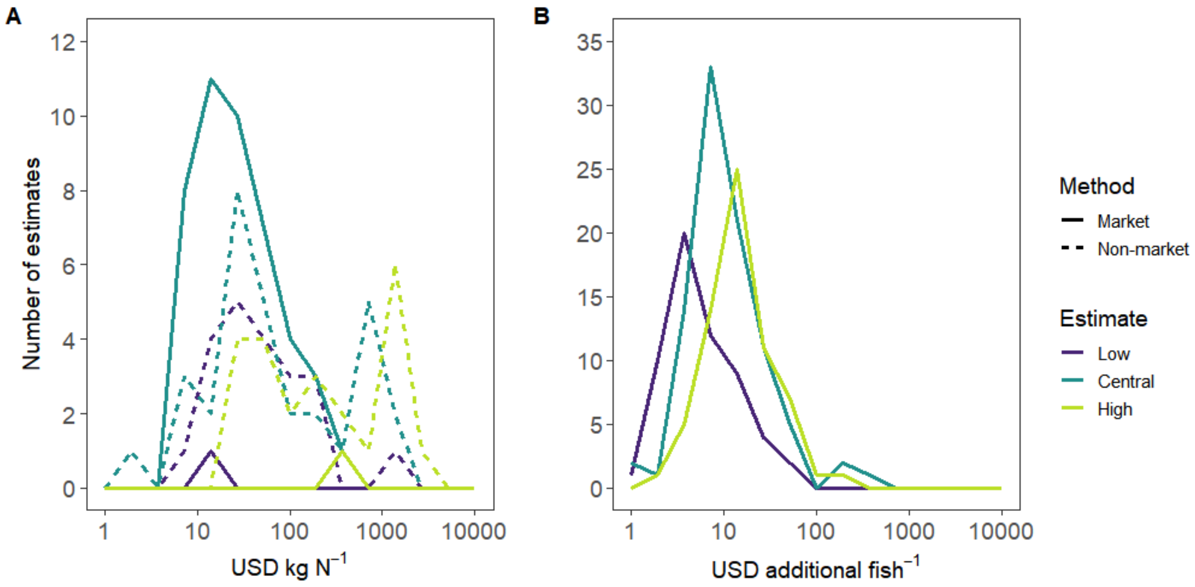

Figure A.2. Frequency polygon of monetary values for nitrogen removal (**Panel A**) and recreational fish capture (**Panel B**) returned by the literature review, standardised to 2020 USD and grouped into low, central or high estimates as identified by the primary source. In most cases, studies contributed both a low and high estimate to the plotted dataset, or else only a central estimate. Where only low and high estimates were reported, we used the midpoint of the reported range as an approximate central estimate. For nitrogen removal estimates, we also distinguish between market and non-market valuation methods.

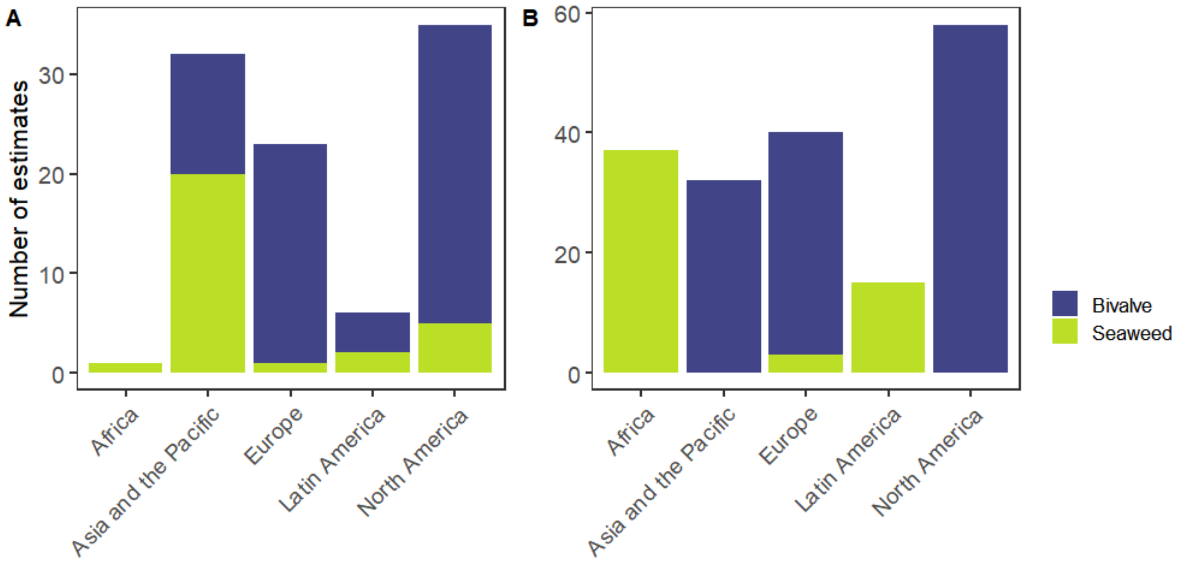

Figure A.3. Geographic representation of (**Panel A**) nutrient removal estimates at the level of sites (or studies, if sites were not given separately) and (**Panel B**) fish abundance estimates at the level of species within studies. Panel A omits 5 non-region-specific estimates for nitrogen content of seaweeds (Kim et al. 2017). In 2018, regional bivalve and seaweed production volumes were: Africa: 4 and 113 kt; Asia and the Pacific: 15581 and 32176 kt; Europe: 680 and 5 kt; Latin America: 405 and 21 kt; North America: 234 and ~0 kt (values obtained using FishStatJ software: FAO Fisheries and Aquaculture, 2020).

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