Coastal Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ucmg20

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To cite this article: Douglas W. Bell, Suzanne B. Bricker, Christopher Kinkade & Elizabeth S. Darrow (2022) Bivalve Shellfish Aquaculture in the National Estuarine Research Reserves: Assessing Current Activities, Relevant Policy, and Engagement Approaches, Coastal Management, 50:5, 419-441, DOI: 10.1080/08920753.2022.2082857

To link to this article: https://doi.org/10.1080/08920753.2022.2082857

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COASTAL MANAGEMENT
2022, VOL. 50, NO. 5, 419–441
https://doi.org/10.1080/08920753.2022.2082857

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Bivalve Shellfish Aquaculture in the National Estuarine Research Reserves: Assessing Current Activities, Relevant Policy, and Engagement Approaches

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ABSTRACT

Expansion of shellfish aquaculture in the U.S. is currently being promoted for its demonstrated potential as an environmentally friendly and sustainable food production system. The National Estuarine Research Reserve System (NERRS), through its network of protected estuarine sites and research, education, and interpretation mandates, may provide an effective means for enhancing public awareness and management of shellfish aquaculture within the nation's estuarine areas. However, the NERRS's role regarding the presence of aquaculture within Reserve boundaries, for research or non-research purposes, is not broadly understood by NERRS stakeholders. The goals of this study were to broadly review and highlight the current activities, regulatory framework, and engagement approaches to aquaculture within the NERRS, and more specifically, to focus on the suitability and role(s) the NERRS may choose to seek or strengthen with respect to shellfish aquaculture. To accomplish this, a survey questionnaire was disseminated within the NERRS community. Twelve of the 29 Reserves within the NERRS held some type of aquaculture activity, while 17 Reserves believed their Reserve was suitable or potentially suitable for shellfish aquaculture. Reserve suitability was driven by a range of factors, including: water quality, NERRS regulations, character of Reserve land-managing entities, scope of protected areas, and preexisting or historical shellfish aquaculture and/or wild harvest activities. Overall, the Reserves' approach to shellfish aquaculture was locally focused, but with patterns that reflected a regional influence. Additionally, Reserves displayed key roles as coordinating entities and a trusted source of science. Particularly with establishing commercial aquaculture, it is critical to couple the goals of an aquaculture activity with the net positive and negative impacts to a specific geographic area. We recommend that the NERRS would benefit from developing best management practices for approaching shellfish aquaculture within Reserve boundaries, and educating and engaging with shellfish aquaculture stakeholders. One approach might be to develop a decision-support model for approaching and allowing each use of aquaculture (research, restoration, conservation, recreation, and commercial), in collaboration with regulatory agencies and other stakeholders.

KEYWORDS

aquaculture; National Estuarine Research Reserves; policy; shellfish

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Supplemental data for this article is available online at https://doi.org/10.1080/08920753.2022.2082857.

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Introduction

Growth of the U.S. aquaculture industry is recognized as a key objective to meet the global and domestic demand for sustainable seafood, while at the same time reducing the United States seafood deficit, currently calculated to be $16.8 billion (NMFS 2011, 2020). Aquaculture is generally defined in state and federal law as the controlled cultivation, propagation, rearing, harvest, and/or subsequent commerce of aquatic plants and animals in either an artificial (e.g., culture systems, tanks, submerged nets, or pens) or selected natural setting (O'Connell 2018). Bivalve shellfish aquaculture (often referenced as "mariculture", and hereafter referred to as simply shellfish aquaculture) represents an important subset of the growing U.S. commercial aquaculture industry, with an estimated annual value of $340 million, primarily from the production of oysters, clams, and mussels (NMFS 2020). An important feature of shellfish aquaculture is that in grow-out operations, shellfish feed and grow entirely on naturally occurring particulate material (primarily phytoplankton) in the water column with no external organic matter inputs (although typical hatchery practices use cultured phytoplankton during larval rearing and/or seed production). Well-managed shellfish aquaculture therefore is an environmentally friendly and sustainable food production system (Shumway et al. 2003; Hilborn et al. 2018).

Interest in shellfish aquaculture is also driven from its demonstrated provision of ecosystem services, including: habitat for important commercial, recreational, endangered, and threatened species (Dealteris, Kilpatrick, and Rheault 2004; Callier et al. 2018), species recovery (Brumbaugh et al. 2000), water filtration and nutrient removal (Bricker et al. 2018, Turner et al. 2019), and sustainable shoreline and erosion protection (Grabowski et al. 2012; Sutton-Grier, Wowk, and Bamford 2015). The National Oceanic and Atmospheric Administration (NOAA) National Shellfish Initiative, which aims to increase populations of bivalve shellfish in U.S. coastal waters, recognizes these benefits. The Initiative emphasizes furthering research of the environmental factors that affect shellfish populations, particularly factors exacerbated by climate change (e.g., temperature, salinity, carbonate chemistry, and pathogens), shellfish ecosystem services, and conservation practices (NMFS 2019).

However, without proper management controls, aquaculture can produce negative environmental consequences, such as water pollution, habitat destruction, disease exportation, and genetic pollution (Froehlich, Gentry, and Halpern 2017). Thus, the term "aquaculture" may elicit a range of attitudes, depending on the goals, approach, and interpretation of a specific aquaculture activity. To help mitigate this communication challenge, a recent report has attempted to synthesize and define a continuum of activities that balance socio-economic benefits to people, and the net ecological outcomes driven by an aquaculture activity (TNC, 2021). These terms, in no particular order are: restorative aquaculture, ecological aquaculture (and closely related "Ecosystem Approach to Aquaculture"), conservation aquaculture, stock enhancement, aquatic habitat restoration, and nature-based solutions. What is important to note is that each of these activities envelope aspects of another. For example, "restorative aquaculture occurs when commercial or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net positive environmental outcomes", while conservation aquaculture's "primary aim is focused on recovering or rebuilding

specific species", and does not typically include direct commercial sale (TNC, 2021). However, a term by itself also hides the nuance across typology, as conservation may ultimately have restorative elements, such as the increase in biodiversity or habitat provisioning following a targeted species' rebound; the same applies to commercial aquaculture. Thus, regardless of aquaculture terminology, the fundamental need to study and understand the balance between ecological impacts, ecosystem services, and socio-economic drivers and barriers is integral for determining the appropriateness of shellfish aquaculture in a given setting.

While progress continues toward understanding the direct and indirect environmental responses to bivalve shellfish cultivation (Forrest et al. 2009; Duball et al. 2019) and resolving its ecosystem services (Schatte Olivier et al. 2020; Bricker et al. 2020), the range of factors involved in farming (e.g., cultivation practices, gear types, siting, scale, and density of farms) requires continued assessment (Pacific Shellfish Institute 2015; Flimlin et al. 2010; Sea Grant Association 2016). Furthermore, expanding cultured shellfish production often relies on using submerged lands held in public trust. Thus, the potential for use conflicts and public objection raises several social, economic, and ecological considerations for natural resource management and legislation (Eichenberg and Vestal 1992; Silva et al. 2011; Bricker et al. 2016). For example, increased use of floating water column gear in North Carolina has led to public opposition to shellfish leases resulting from user conflicts associated mainly with perceived negative viewscape issues. These conflicts resulted in lawsuits and further development of leasing moratoria in counties that include part of the NCNERR (S.L. 2019-37 2019; North Carolina Division of Marine Fisheries (NC DMF) 2020). Whether enacted policy and/or promulgated rules permit or restrict shellfish aquaculture activities, their implementation will require monitoring and assessment of their impacts, and continued education and outreach for the impacted stakeholder community.

One potential means to address information gaps and inform policy is through NOAA's National Estuarine Research System Reserve System (NERRS or Reserve System; Table 1). The NERRS, through its network of protected estuarine sites and research, education, and interpretation mandates (15 CFR §921.1(b)), may provide an effective means for enhancing public awareness and management of shellfish aquaculture within the nation's estuarine areas. However, the NERRS's role regarding aquaculture within Reserve boundaries, for research or non-research purposes, is not broadly understood by NERRS stakeholders.

Most pertinent to aquaculture, a use of a Reserve must comply with 15 CFR § 921.1(d), which prohibits habitat manipulation for resource management purposes unless it is: (1) a restoration activity that complies with other sections of National Estuarine Research Reserve System (NERRS), 15 C.F.R. § 921 (1993), (2) an activity necessary for the protection of public health or the preservation of other sensitive resource, or (3) an activity that is a "long term pre-existing use occurring in a buffer area". "Buffer" areas are designed to maintain "core" area integrity; while "core" areas are key land and water zones that are created to maintain long-term viability of the full suite of ecological processes unique to each Reserve. Habitat manipulation for research purposes is also allowed, as long as the activity is consistent with the Reserve's management plan, and is limited to the nature and extent necessary to complete research objectives (15 CFR §921.1(d)). Any use must also be designated within a Reserve's Management Plan. Ultimately, Reserve uses must also align with, and are subject to, the goals and

Table 1. National Estuarine Research Reserves.

Reserve	State	Biogeo region	Sub-region	Managing agency	Managing entity type	Designated	Size (acres)
Northeast[a]							
Great Bay	NH	Acadian	2	NH Fish and Game Department Marine Fisheries Division	DFW	1989	10,235
Narragansett Bay	RI	Virginian	3	RI Department of Environmental Management	DEP	1980	4,259
Waquoit Bay	MA	Virginian	3	MA Department of Conservation and Recreation	DNR	1988	2,804
Wells	ME	Acadian	2	Wells Reserve Management Authority	Collective	1984	2,250
Mid-Atlantic							
Chesapeake Bay Maryland	MD	Virginian	5	MD Department of Natural Resources	DNR	1985, 1990	6,249
Chesapeake Bay Virginia	VA	Virginian	5	Virginia Institute of Marine Science; College of William and Mary	Academic	1991	3,072
Hudson River	NY	Virginian	3	NY State Department of Environmental Conservation	DNR	1982	4,838
Delaware	DE	Virginian	4	DE Department of Natural Resources and Environmental Control	DNR	1993	6,206
Jacques Cousteau	NJ	Virginian	4	Rutgers University	Academic	1998	116,000
Southeast							
ACE Basin	SC	Carolinian	7	SC Department of Natural Resources	DNR	1992	99,308
Guana Tolomato Matanzas	FL	Carolinian	8	FL Department of Environmental Protection	DEP	1999	73,352
North Inlet-Winyah Bay	SC	Carolinian	7	Uni. of South Carolina Baruch Marine Field Laboratory	Academic	1992	18,916
Sapelo Island	GA	Carolinian	7	GA Department of Natural Resources	DNR	1976	6,110
Caribbean							
Jobos Bay	PR	West Indian	9	PR Department of Natural and Environmental Resources	DNR	1981	2,883
Gulf of Mexico							
Apalachicola Bay	FL	Louisianian	11	FL Department of Environmental Protection	DEP	1979	234,715
Grand Bay	MS	Louisianian	12	MS Department of Marine Resources	DNR	1999	18,049
Mission-Aransas	TX	Louisianian	13	Uni. of Texas, Marine Science Institute	Academic	2006	186,189
Rookery Bay	FL	West Indian	10	FL Department of Environmental Protection	DEP	1978	110,000
Weeks Bay	AL	Louisianian	11	AL Department of Conservation and Natural Resources	DNR	1986	9,317
West Coast							
Elkhorn Slough	CA	Californian	15	CA Department of Fish and Wildlife	DFW	1979	1,700
Kachemak	AK	Fjord	25	Uni. of Alaska Anchorage Alaska Center for Conservation Science	Academic	1999	372,000
Padilla Bay	WA	Columbian	19	Washington State Department of Ecology	DEP	1980	11,966
San Francisco Bay	CA	Californian	16	San Francisco State University	Academic	2003	3,710
South Slough	OR	Columbian	17	OR Department of State Lands	DNR/DEP	1974	4,711
Tijuana River	CA	Californian	14	CA State Parks; U.S. Fish and Wildlife Service	DFW; Federal	1982	2,293
Great Lakes							
Lake Superior	WI	Great Lakes	20	Uni. of Wisconsin-Madison, Division of Extension	Academic	2010	16,697
Old Woman Creek	OH	Great Lakes	22	OH Department of Natural Resources	DNR	1980	573
Kachemak Bay	AK	Fjord	25	Uni. of Alaska Anchorage Alaska Center for Conservation Science	Academic	1999	372,000
Pacific							
He'eia	HI	Insular	27	Uni. of Hawai'i Institute of Marine Biology	Academic	2017	1,385

Reserves are classified by NOAA to be representative of specific biogeographic regions with similar dominant plants, animals, and prevailing climate. There are 29 subregions within 11 biogeographic regions (Biogeo Region) that represent different types of estuaries. The managing agency, Reserve designation year, and Reserve size are also provided. The managing entity type is provided for reference and comparisons across management behavior, policy, and authority.

[a]Also note that the Connecticut NERR was undergoing the official Reserve designation process during this project and was not included in the analysis, although interviews were conducted with their staff. The CT NERR was officially designated January 14, 2022, during the review process of this manuscript.

regulations of any state, federal, and/or private entities that hold authority of a Reserve's open water, land, and submerged land. Most relevant to shellfish aquaculture is the use of submerged lands, which are held in trust under the Public Trust Doctrine and regulated and administered by state agencies (Tannenbaum 1985).

Thus, the mandates and structure of the Reserve system pose a few questions, such as to what degree is shellfish aquaculture considered as a manipulative activity, and how does shellfish aquaculture align with the management goals of a given Reserve, or Reserve System, as a whole? Determining what constitutes as a "manipulative" activity is beyond the scope of this study, instead, this study seeks to explore the alignment of aquaculture, predominantly shellfish aquaculture, with Reserve management goals. This was accomplished by reviewing and highlighting current activities, regulatory frameworks, and engagement approaches to aquaculture within the NERRS. In addition to reviewing applicable regulations, we distributed an optional survey to the NERRS' Research Coordinators. Questionnaire responses were assessed, and specific themes were identified for more detailed follow-up. The intended outcome of this synthesis is to provide information about shellfish aquaculture within and beyond the Reserve System that will enable further dialogue and collaborative opportunities for researchers, educators, federal and state regulatory coordinators, growers, other users of the coastal zone, and the general public.

Methodology

Survey questionnaire analysis

Reserve-specific information on aquaculture reported here comes from a voluntary survey questionnaire, shared on March 27, 2020 to the NERRS Research Coordinators (Appendix A). The questionnaire was developed following an initial set of individual email inquiries, sent between July and August 2017, which sought similar information on aquaculture activities in the Reserve or in waterbodies with a hydrologic connection to the Reserve (Appendix A). The questionnaire included both closed- and open-ended questions on presence, suitability, perceived effects of such shellfish aquaculture, and if Reserve staff engaged with these activities in any way. Questionnaire responses were submitted between March 27 and July 17, 2020 by a Reserve staff member, typically the Research Coordinator or aquaculture subject matter expert. Initial review of each Reserve's Management Plan found the plans to have relatively little information about shellfish aquaculture, and many were outdated (publishing years of current plans ranged from 2007 to 2020).

Responses to closed-ended questions pertaining to aquaculture presence within and neighboring to Reserves were possible to enumerate (Appendix B), but most questionnaire responses still required some level of qualitative analysis, which was performed using the Grounded Theory (Strauss and Corbin 1990). All responses were reviewed before codification.

To categorize the physical and geographical suitability of aquaculture (Question 3; Appendix C), responses were codified as:

- Suitable – Responses that explicitly confirmed suitability.
- Potentially – Responses that suggested promise or interest with limited barriers.

- Unlikely – Responses that indicated the possibility of aquaculture in or near the Reserve, but which noted considerable environmental or regulatory barriers.
- Not suitable – Statements explicitly indicated the Reserve was not suitable, due to factors such as limited area and physical conditions for potential leases or lack of commercial viability.

Questionnaire phrasing and responses did not allow "Suitability" to be discerned by the type of shellfish or goal(s) of aquaculture (e.g., commercial *vs*. restorative). Thus, in the context and scope of this study, we considered "Suitability" would primarily apply to commercial activities. The "Rationale" for "Suitability" was usually well-described by the respondent, but not always in response to the survey question. Thus, we used the entirety of responses and email correspondence for context and then codified them for meaningful categorization. In some cases, lack of suitability was due to multiple reasons (e.g., "Regulatory Protections" and "Impaired Water Quality"), in which case we selected the most fundamental barrier, such as environmental conditions, instead of regulatory protections.

- Appropriate Conditions – Statements that cited appropriate physical conditions, such as acceptable water quality.
- Impaired Water Quality – Water quality represents the primary defining barrier in preventing shellfish aquaculture. The degree of impairment was not considered in the association with suitability (i.e., "Not Suitable" or "Unlikely").
- Existing Local Activity – Nearby aquaculture farming indicates a degree of suitability for practice in Reserve boundaries.
- Not Explicitly Given – Rationale could not be discerned. Even if a Reserve holds aquaculture activities, but did not describe suitability, it was still coded as "Not Explicitly Given".
- Not Viable – Shellfish aquaculture would not be physically or commercially viable in the Reserve area.
- Recent Regulations – While the Reserve area is physically and geographically suitable, recent legislation was the defining factor in allowing aquaculture.
- Regulatory Protections – Statements that cited either a protected status or limited by state or federal regulations.

To assess if a Reserve had "observed negative or positive ecological or social effects due to aquaculture activities" (Question 6; Appendix A), responses to the 2017 email inquiries were also considered for qualitative analysis and cross-referenced with questionnaire responses to avoid double counting of similar or repeat statements. Final thematic categories were codified as: "Water Quality", "Non-Native Species", "Habitat", "Restoration", "Use Conflicts", "NIMBY", "Coastal Zone Protection", "Economic Support", and "Locally Sourced Food". Coding definitions are provided in Appendix D. The term "NIMBY", a colloquial sentiment that is an acronym for "Not In My Backyard" is used per Dear (1992), who describes the sentiment as "the protectionist attitudes of and oppositional tactics adopted by community groups facing an unwelcome development in their neighborhood". For coding purposes, this term applies to comments that referenced privacy, property value, and/or esthetic concerns, such as perceived impeded viewscape.

Lastly, questionnaire responses were assessed to gain a sense of observed environmental impacts from, and social opinion about shellfish aquaculture. Question 6, regarding "observed negative or positive ecological or social effects", was codified under the following schema: "Effect", "No Effect", "Unknown", "Not Specific", and "Not Applicable". Definitions used in codification are provided in Appendix D. Questions 6 and 11, which asked if aquaculture activities should be allowed in their Reserve, or generally within the Reserve System, and Question 12, which asked whether Reserve stakeholders may be impacted by aquaculture activities, were analyzed to assess Reserve and public support. A similar codification schema was used ("Concern", "Support", "Neutral", "Not Specific", and "Not Applicable") and defined in Appendix D.

Informational interviews

To obtain more context and understand specific cases of shellfish aquaculture within the NERRS, several Reserves were contacted for informational interviews. Staff, usually Reserve Research Coordinators, at the following Reserves agreed to provide additional information *via* interviews: Elkhorn Slough (CA), Guana Tolomato Matanzas ("GTM"; FL), Jacques Cousteau (NJ), Mission-Aransas (TX), and the proposed Connecticut NERR. Reserves were selected to provide regional representation and highlight specific issues or themes that were gleaned from questionnaire analysis (e.g., restoration, new aquaculture legislation, regulatory constraints, research engagement, Reserve establishment, and stakeholder coordination). Interviews were not standardized and were only used for clarification and expansion of questionnaire responses. Thus, no post-analysis was completed, and information obtained from interviews are referenced as personal correspondence.

Results

NERRS aquaculture activities and suitability

Notably, the questionnaire survey received full participation from all 29 Reserves. Participation rates for each specific question are shown within Appendix A. Of the 29 Reserves, 12 Reserves had existing aquaculture activities, while 17 did not (Figure 1; Table 2). On average, date of Reserve designation had no effect on presence or absence of aquaculture within Reserves (mean designation date for Reserves with Aquaculture: 1988; No Aquaculture: 1990; $t_{25} = -0.43$, $p = .67$), nor did the size of the Reserve (mean area for Reserves with Aquaculture: 51,640 acres; No Aquaculture: 41,692 acres; $t_{24} = 0.70$, $p = .49$). The predominant, specified aquaculture type was oyster culture (7), while three Reserves have clam aquaculture (Table 2). He'eia Reserve was the only Reserve to have non-shellfish aquaculture, while one other Reserve held unspecified shellfish aquaculture (Waquoit Bay, MA). He'eia (HI), GTM (FL), and Jacques Cousteau (NJ) also confirmed that aquaculture activities were established as long-term existing uses when these Reserves were designated. Management plan analysis was only able to clearly identify two Reserves that had commercial shellfish aquaculture uses prior to designation (Great Bay (NH) and South Slough (OR); Appendix E).

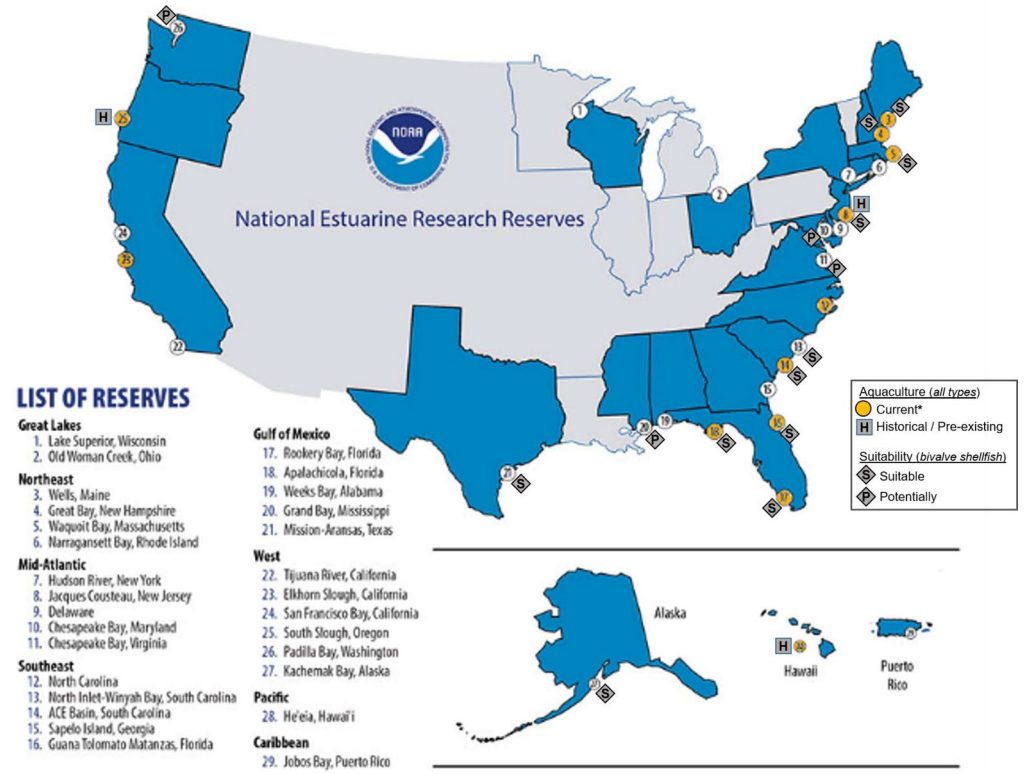

Figure 1. Aquaculture activities (of all types) and suitability for bivalve shellfish aquaculture across the National Estuarine Research Reserve (NERR) System. Orange circles indicate the current* presence of aquaculture within Reserve boundaries, as of the information collection (*May 2020). Reserves with aquaculture activities as a historical or preexisting use are demarcated with a boxed "H". Suitability is indicated by diamonds, with the letter "S" indicating "Suitable" conditions, and "P" indicating "Potentially" suitable conditions. Note that three Reserves have current aquaculture activities, but without "Suitable" designations. This is due to the either: the discontinuation of existing shellfish leases and establishment of leasing moratoriums within several NC counties, despite current permitted activities (North Carolina NERR); the Reserve is a state-designated marine protected area, although select preexisting aquaculture activities were allowed to remain upon Reserve designation (South Slough NERR); the Reserve is a state-designated marine protected area with impaired water quality conditions, and thus the application of aquaculture is specifically for conservation purposes (Elkhorn Slough NERR).

Existence of aquaculture operations was primarily attributed to appropriate water quality and geophysical characteristics within the Reserve (6 of the 13; Table 2; Figure 2(A)). Four Reserves with aquaculture did not explicitly cite a reason for suitability. Elkhorn Slough Reserve (CA) was stated to be "Not Suitable" for aquaculture, although the Reserve is actively conducting conservation aquaculture. South Slough (OR) has commercial leases, but given state protections, the activity is "Unlikely" to expand within boundaries. Similarly, the North Carolina Reserve had aquaculture leases at the time of the survey, but cited recent legislation that would prevent existing lease renewals and future activities.

In total, 13 Reserves were reported to exhibit "Suitable" conditions, including the 9 Reserves stated above (Table 2 and Figure 2(B)). Six Reserves did not cite any

Table 2. Shellfish aquaculture activities within or neighboring to each of the National Estuarine Research Reserves.

Reserve	State	Aquaculture	Suitability	Rationale	Neighbor	Engage
Northeast						
Great Bay	NH	Oyster[a]	Suitable	Appropriate Conditions	Yes	No
Narragansett Bay	RI	–	Suitable	Not Explicitly Given	Yes	No
Waquoit Bay	MA	Shellfish	Suitable	Not Explicitly Given	No	
Wells	ME	Oyster	Suitable	Appropriate Conditions	Yes	No
Mid-Atlantic						
Chesapeake Bay Maryland	MD	–	Potentially	Existing Local Activity	Yes	No
Chesapeake Bay Virginia	VA	–	Potentially	Existing Local Activity	Yes	Yes
Delaware	DE	–	Unlikely	Impaired Water Quality	No	–
Hudson River	NY	–	Not Suitable	Not Explicitly Given	No	–
Jacques Cousteau	NJ	Clam, Oyster[a]	Suitable	Appropriate Conditions	Yes	Yes
Southeast						
ACE Basin	SC	Oyster	Suitable	Appropriate Conditions	Yes	–
Guana Tolomato Matanzas	FL	Clam	Suitable	Appropriate Conditions	No	–
North Carolina	NC	Shellfish[c]	Unlikely	Regulatory Protections	Yes	No
North Inlet-Winyah Bay	SC	–	Suitable	Appropriate Conditions	No	–
Sapelo Island	GA	–	Not Suitable	Impaired Water Quality	Yes	No
Carribean						
Jobos Bay	PR	–	Unlikely	Regulatory Protections	No	–
Gulf of Mexcio						
Apalachicola Bay	FL	Oyster	Suitable	Not Explicitly Given	Yes	Yes
Grand Bay	MS	–	Potentially	Impaired Water Quality	No	–
Mission-Aransas	TX	–	Suitable	Recent Regulations	Yes	No
Rookery Bay	FL	Clam	Suitable	Not Explicitly Given	No	–
Weeks Bay	AL	–	Not Suitable	Not Explicitly Given	No	–
West Coast						
Elkhorn Slough	CA	Oyster[b]	Not Suitable	Impaired Water Quality	No	–
Kachemak Bay	AK	–	Suitable	Not Explicitly Given	Yes	Yes
Padilla Bay	WA	–	Potentially	Not Explicitly Given	Yes	No
San Francisco Bay	CA	–	Not Suitable	Impaired Water Quality	No	–
South Slough	OR	Oyster[a]	Unlikely	Regulatory Protections	Yes	Yes
Tijuana River	CA	–	Not Suitable	Impaired Water Quality	No	–
Great Lakes						
Lake Superior	WI	–	Not Suitable	Not Viable	No	–
Old Woman Creek	OH	–	Not Suitable	Regulatory Protections	No	–
Pacific						
He'eia	HI	Crab (Mud), Finfish (Mullet, Threadfin Moi)[a]	Suitable	Not Explicitly Given	No	–

Reserve suitability and rationale are also provided. Neighboring activities, considered to have a shared hydrologic connection, and Reserves engagement are also listed. See Appendix C for raw responses used to codify Suitability and Rationale.

[a]Identified as a long-term preexisting use from either the questionnaire or management plan analysis (Appendix D).

[b]Restoration/conservation focused aquaculture.

[c]Current activity, although existing leases will expire in 2021, and will not be renewed.

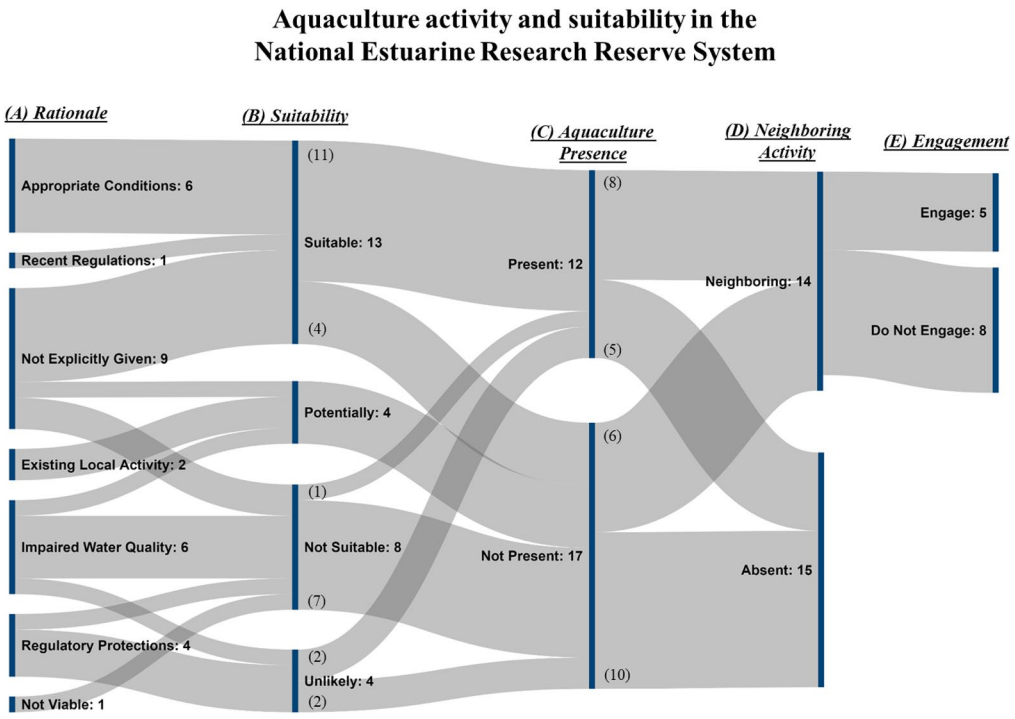

Figure 2. Sankey plot of aquaculture activities and their presence in Reserves. Each column synthesizes survey responses (see Table 2). For the presence of aquaculture within the Reserve (Colum C) and whether or not aquaculture is currently suitable within a reserve (Column B). The primary reason for suitability, or lack there-of, is provided in Column A. Questionnaire phrasing and responses, did not allow "Suitability" to be discerned by the type (e.g., bivalve shellfish *vs.* shellfish) or purpose of aquaculture (e.g., commercial *vs.* restorative). Thus, in the context and scope of this study, we considered "Suitability" would primarily apply to commercial activities. Neighboring aquaculture activities, which were considered to have a shared hydrologic connection with the Reserve, and Reserve engagement is synthesized in Column D and E, respectively. Note that the potential for category alignment at each node does not reference the same Reserve. For example the "Recent Regulations" category does not necessitate that aquaculture is "Suitable" or "Present" despite the seemingly uninterrupted flow between nodes.

specific rationale for why shellfish aquaculture was considered "Suitable". Mission-Aransas (TX) cited the recent state legislature that has enabled the initial scoping of shellfish aquaculture within Reserve boundaries. Of the Reserves with "Suitable" conditions, four did not have existing aquaculture activities (Kachemak Bay (AK), Narragansett Bay (RI), North Inlet-Winyah Bay (SC), and Mission-Aransas (TX)). Four Reserves were identified to have "Potentially" suitable conditions, two of which are due to nearby existing operations (Chesapeake Bay Maryland and Virginia). Grand Bay (MS) is evaluating a potential site within the Reserve, but the area is challenged by elevated fecal coliforms levels. The one other Reserve (Padilla Bay, WA) did not explicitly cite rationale for "Potentially" suitable aquaculture conditions.

Out of the 16 Reserves that do not hold shellfish aquaculture, 11 Reserves stated that aquaculture was "Not Suitable" (8) or "Unlikely" (4), most often citing poor water quality (6), or regulatory protection (4). Tijuana River (CA) and Elkhorn

Slough (CA) were reported to have both impaired waters and regulatory protection (Table 2).

A total of 14 Reserves reported neighboring aquaculture activities (Table 2; Figure 2(D)), with eight of those Reserves holding aquaculture within their own boundaries. The type of neighboring aquaculture was not always specified (Appendix F; Table F), but did represent a slightly broader range of aquaculture types, such as steelhead trout (Great Bay, NH), kelp (Great Bay, NH), and shrimp (Mission-Aransas, TX) (Appendix F). Reserve respondents were asked to identify all aquaculture, harvesting, and fishing activities, both commercial and recreational, and those tabulated responses are provided in Appendix F; Table F. Appropriate water quality or geophysical conditions within, but not external to Reserves, was the most common reason for the absence of neighboring aquaculture, despite presence of within-Reserve aquaculture. For Reserves that did have neighboring aquaculture activities, five Reserves were engaged with growers in some manner, by providing data and research capacity, advisory and hatchery services, general awareness on shellfish aquaculture issues, and/or cooperating with regulatory approval (Figure 2(E)). Notably, Mission-Aransas (TX) had been turned away from engagement by a neighboring shrimp farm (Appendix D; Table D).

Regional trends in the presence of aquaculture in Reserves were apparent: other than Hawaii (one Reserve with traditional fish culture), the Northeast region of the US had the highest proportion of Reserves with aquaculture (3 out of 4; see https://coast.noaa.gov/nerrs for regional boundaries, accessed Sept 2020). The Southeast, Mid-Atlantic, and Gulf of Mexico regions all held aquaculture activities in approximately half of their Reserves. The West Coast had two out of four Reserves with aquaculture, where one was dedicated for restoration purposes only. The Great Lakes region reported no aquaculture activities.

Socio-economic and ecological issues within the NERRS

The NERRS respondents were asked to provide observations and opinions of relevant socio-economic issues that may be related to the presence or nearby activity of shellfish aquaculture. This analysis was conducted to obtain a sense of issue prevalence and is not meant to represent the most important issue to an individual Reserve or across the NERRS. From individual correspondence and survey responses, socio-economic and ecological issues were discernibly described and able to be coded 28 times (Figure 3). The response rate to this specific inquiry, considering both initial email correspondence and questionnaire responses that were evaluated, was about 80%. Twelve Reserves did not contribute to the coded 28 issues. Additionally, a number of respondents alluded to the broader relevance of these issues within the state, not necessarily within their Reserve. The most predominant topic mentioned was Water Quality (25%), followed by Use Conflicts (18%), Restoration (14%), NIMBY and Locally Sourced Food (both 11%), and Economic Support and Habitat, and Non-Native Species and Coastal Resilience (both 4%).

Questionnaire respondents cited few observable socio-economic or ecological impacts that could be discerned from within-Reserve or neighboring aquaculture activities. Out of the 12 Reserves that held shellfish aquaculture, nine did not specify any impacts or indicated that impacts were currently unknown. Two Reserves cited no observed

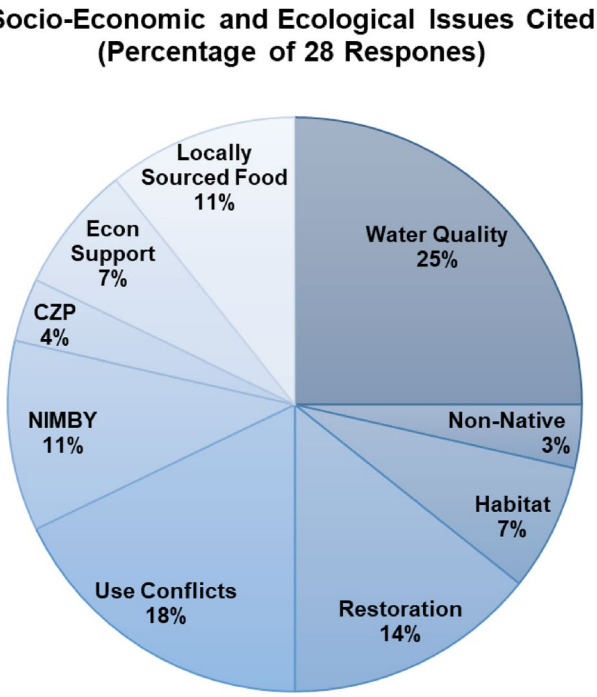

Figure 3. (A) Percentage of socio-economic and ecological topics that were able to be categorized from survey responses and personal correspondence (see Methodology) in relation to aquaculture activities within or neighboring to the Reserve. There is no discrimination between positive or negative connotations within each topic. CZP: Coastal Zone Protection; Econ Support: Economic Support; Non-Native: Non-Native Species; NIMBY: Not In My Backyard.

effects (Wells (ME)) and Mission-Aransas (TX)), while one Reserve cited observable effects from the presence of shellfish aquaculture, in which abandoned infrastructure had led to marine debris after storm events (Rookery Bay, FL). Questionnaire responses were able to provide a general sense of NERRS and public opinion on aquaculture although eighteen Reserves did not specify any opinion, or indicated that it was not applicable (no aquaculture activities). Five Reserves felt that public opinion was supportive of activities, while four cited both concern and support (i.e., equivocal). Two Reserves cited only concern, specifically "Use Conflicts" and "NIMBY".

Discussion

Regulatory influence on shellfish aquaculture within the NERRS

In light of this study's regulatory overview of the NERRS, any aquaculture use (i.e., research, restoration, conservation, recreation, and/or commercial) is technically allowable within a Reserve's boundaries, per National Estuarine Research Reserve System (NERRS), 15 C.F.R. § 921 (1993), but the use would be subject to numerous layers of scrutiny with respect to a Reserve's management goals and any applicable regulations. While the NERRS regulations provide an overarching template for the allowability of aquaculture, a commercial activity is also subject to any applicable federal, state,

and/or local regulation that is specific to the type of aquaculture, such as shellfish aquaculture.

Based on the applied coding schema, the predominant inhibiting factor for shellfish aquaculture (i.e., "Not Suitable" or "Unlikely") was "Impaired Water Quality". The causes and risks of impairment were not sought in the questionnaire, although based upon interviews and Reserve Management Plans, the primary causes were sewage or proximity to sewage sources (Appendix C), and pesticides and sedimentation (Wasson 2010). However, the variety of land ownership held within Reserve boundaries and interests of abutting entities also made "Regulatory Protections" a consistent driver in shaping the present and future possibility of aquaculture activities.

In total, six Reserves cited some type of "Regulatory Protection" with respect to shellfish aquaculture. In North Carolina, the state's Natural Heritage Program determined that aquaculture activities in the Masonboro Island Reserve violated the state's Nature Preserves Act (§143B–135.250. –§143B–135.272), despite the Reserve area's physical suitability. Jobos Bay (PR) was also reported to have appropriate physical conditions and interest from local fishermen in seeking to supplement their fishing practices. However, scoping of aquaculture within Reserve boundaries was eventually halted due to concerns over the potential impact to a local population of West Indian manatees, which are protected under both the Endangered Species Act (ESA) and the Marine Mammal Protection Act. The four other Reserves with reported "Regulatory Protections" were due to a type of protected area (Elkhorn Slough, CA; Old Woman Creek, OH; South Slough, OR, Tijuana River, CA). The specific definition and rules of a "Protected" area vary, so the general definition applied here is an area that restricts commercial or recreational uses in some manner. Four Reserves (GTM, FL; Jacques Cousteau, NJ; Rookery Bay, FL; Waquoit Bay, MA) were among charter members of the national network of marine protected areas (MPAs), although as of 2008, 25 MPA units existed with the Reserve System (Zinn et al. 2007). All four of the Reserves with inaugural MPAs hold aquaculture within their boundaries, so MPA status did not preclude aquaculture. South Slough (OR) is a unique example of a protected NERR, which has allowed several existing plots of oyster culture to continue in operation (100 acres total); although following state designation as a MPA (South Slough Estuary, Oregon revised statutes (ORS) §§ 273.553 - 273.554 2019), no future aquaculture activities have been allowed by current state statute (South Slough Estuary, Oregon revised statutes (ORS) §§ 273.553 - 273.554 2019; Yednock, B.; personal communication). Mission Aransas (TX) is a good example of a Reserve with numerous unique land units, one of which is part of the Aransas National Wildlife Refuge (University of Texas Marine Science Institute 2015). The Refuge is home to an endangered Whooping Crane population, which is anticipated to shape where shellfish mariculture leases will be positioned as Texas rolls out recently promulgated mariculture rules (House Bill (TX HB) 1300 2019; Buskey, E.; personal communication).

While not necessarily a regulatory protection, private land in a Reserve may be held by non-governmental organizations or individuals, who may have inherited land parcels through "King's" or "Crown Grants", and may complicate the determination or initiative for aquaculture within a Reserve's boundaries. For example, much of the North Inlet-Winyah Bay (NI-WB) NERR (SC) consists of the Hobcaw Barony, a

16,000-acre property dedicated to research and education. The property is managed by a private foundation (Belle W. Baruch Foundation), which owns the intertidal flats as a holdover from the original King's Grant. Thus, while the South Carolina Department of Natural Resources owns the waters and subtidal land with the Reserve (NI-WB NERR, 2011), the Baruch Foundation would also exert significant influence in determining the possibility of activities in NI-WB (Table 2).

Not all protected areas discourage shellfish aquaculture activities. Florida applies a unique protected status to Reserves which are modeled after federal anti-degradation statutes (Antidegradation Policy and Implementation Methods, 40 C.F.R § 131.12, 2015). Waters within Florida's estuarine reserves are designated as "Outstanding Florida Waters", which receive the highest level of protection against any activity that would potentially enable degradation of existing high-quality waters (Surface Water Quality Standards. Florida Administrative Code (FAC), 62–302 2016). Under these statutes, commercial aquaculture activities are considered to be in favor of public interest within these protected boundaries (Section 258.42, F.S.). Regulations for Florida Aquatic Preserves, which include estuarine reserves, also maintain several statutes similar in language with NERR policy. For example, Florida Aquatic Preserves, Intent Florida Administrative Code (FAC), 18-20.001 (1997)(2)(a) F.A.C. states that Preserves are "established for the purpose of being preserved in an essentially natural or existing condition" and meant to "preserve, protect, and enhance these exceptional areas of sovereignty submerged lands by reasonable regulation of human activity". Rookery Bay NERR (FL) is one of three Reserves that clearly noted establishment of shellfish aquaculture activities post-NERR designation. In 2004, leases in Rookery Bay (FL) (designated 1978; Table 1) were established on sovereign submerged lands within Reserve boundaries (FL DEP 2013), which is allowable due to state legislation stating "that aquaculture shall be recognized as a practicable resource management alternative to produce marine aquaculture products, to protect and conserve natural resources, to reduce competition for natural stocks, and to augment and restore natural populations" (Public Lands and Properties, Fla. Stat. Title XVIII 253.68 2019(2)(a), F.S.).

The recognition of water quality-related suitability for aquaculture within Florida Aquatic Preserves appears to be a common theme across the Reserve System, as several questionnaire responses indicated that limited anthropogenic development of upland areas and desirable estuarine water quality were drivers for the presence of shellfish aquaculture. This demonstrates the overlapping requirements of aquaculture with the goals of Reserve conservation, such as the use and protection of clean water.

Aquaculture engagement across the NERRS

While the NERRS highlights "Research" within its title, the System is also mandated to serve broader education and interpretation roles, within and external to Reserve boundaries, in the conservation and management of coastal resources. Of the 19 Reserves either neighboring or holding aquaculture activities, five Reserves reported engagement with commercial aquaculture practitioners. When described, reported engagement took the shape of collaborative research projects with local aquaculture growers, sharing of water quality data, and advisory roles. One such example is an application targeted for Pacific coast shellfish growers. Developed by Padilla Bay (WA),

South Slough (OR), Hudson River (NY), Jacques Cousteau (NY), and Chesapeake Bay Virginia (VA) Reserves (Helms, A and DeLuca, M.; personal communication), the application is currently hosted on the Northwest Association of Networked Ocean Observing Systems (NANOOS) Visualization System and utilizes real-time NERRS System-Wide Monitoring Program water quality data. The most defining and consistent form of engagement, learned from in-depth interviews with multiple Reserves, involved establishing and/or coordinating advisory and other regional stakeholder groups. Such groups were dedicated to a range of activities including restoration, water quality research and monitoring, education and outreach, and conflict resolution surrounding shellfish aquaculture. We also note that this study's questionnaire likely underestimates Reserve engagement, as those involved with the NANOOS Visualization System did not necessarily affirm engagement *via* the questionnaire. This is due to the structure of the survey question (Appendix A – Q2), which sought engagement with local activities of each Reserve.

The GTM NERR (FL; Table 1) provides a leadership role with the area's Oyster and Water Quality Task Force of the GTM Rivers, which was initiated in the late 1980s following shellfish harvest closures due to bacteria (GTM OWQTF, n.d.). The Task Force provides a community for collaboration and strategic direction that engages state agencies, local government, academic research and extension, residents, and shellfish harvesters. While the Reserve includes clam aquaculture leases, the Task Force is particularly focused on oyster restoration and sustainability for commercial and recreational harvest. Currently funded projects that have been initiated from their efforts include quantifying nutrient removal and ecosystem services of bivalves, oyster population modeling, and impacts of sea level rise to stormwater and septic systems (Dix, N.; personal communication). Much of GTM waters are designated as Class II or Outstanding Florida Waters, which are both protected for shellfish propagation or harvesting (Surface Water Quality Standards. Florida Administrative Code (FAC), 62–302 2016), although the spatial extent of the quality of such waters is decreasing (Dix, N.; personal communication). Despite broad stakeholder participation, grant funding is still the critical mechanism in driving efforts to understand and improve the health of GTM waters (Dix, N; personal communication), and it was clear that GTM leadership creates momentum for this task force.

Staff of the Elkhorn Slough NERR (CA; Table 1) also provides a key leadership role in sustaining the Native Olympia Oyster Collaborative (NCOC, n.d.). Similar to the GTM task force, the collaborative itself does not receive funding support, but given the large physical distances between west coast estuaries that are native to this species, the Collaborative provides a necessary community of practice focused on native oyster restoration. Elkhorn Slough not only suffers from eutrophication, but high levels of pesticides, sedimentation, and non-native species, significantly threatening the viability of the native Olympia oyster (*Ostrea lurida*) population (Wasson 2010). Due in part to many decades of culturing of the non-native Pacific oyster (*Crassostrea gigas*) as well as other non-native oysters, the dominant cover on hard substrates in the estuary is comprised almost entirely of non-native species (Wasson et al. 2001; Wasson et al. 2005). In order to stave off local extinction, Dr. Kerstin Wasson, Elkhorn Slough's research coordinator, led California's first conservation aquaculture project to restore the native Olympia population. Following several years

of modifying approaches for successful, sustainable recruitment, efforts in the Reserve have formulated a scientific framework for conservation aquaculture (Wasson et al. 2020). This ongoing work has also provided a unique opportunity to engage and educate the local community.

Staff at the Jacques Cousteau NERR (JCNERR; Table 1), which hold additional leadership and coordinating roles within Rutgers University's Aquaculture Innovation Center, play an integral advisory role in resolving the use conflict between the migratory red knot shorebird (*Calidris canutus rufa*) and oyster growers within the Delaware Bay ecosystem. The red knot utilizes the southern Delaware Bay as one of its migratory stopover locations where the shorebirds fatten on nutrient-rich horseshoe crab eggs. This is also the location of existing oyster leases authorized under a Corps General Permit, with conditions specific to NJ (Janasie et al. 2019a, 2019b). After a decade of public petitioning, red knots were listed as "Threatened" under the ESA in 2015. While a biological opinion, required by formal consultation under ESA Section 7, did not find that the Corps permit conditions would jeopardize the red knot or its habitat, several conservation measures were established affecting farm operations, such as limiting gear placement, farm work hours, and access to farms (Janasie et al. 2019a, 2019b). While lingering concerns exist, a catalyst in addressing these conflicts was the formation of a stakeholder committee, which involved two JCNERR staff members (DeLuca, M.; personal communication). Notably, the stakeholder committee was without participation from regulatory agencies, which may have introduced a source of friction and/or bias to committee deliberations. One of the first steps in creating goodwill was through a scientific symposium resulting in recognition that sustainable environmental practices were of primary interest to growers. With the conservation measures in place, the Corps and FWS are now required to meet at least annually to review any new science, providing a recurring opportunity for adaptive management (Janasie et al. 2019a, 2019b). Given the potential for more conflicts, the Reserve is developing a spatial plan for mapping existing uses and lease siting (DeLuca, M.; personal correspondence).

As intended with the creation of the NERRS, the activities of each Reserve are directed in response to the local environmental conditions and most pressing coastal management issues. Not surprisingly, water quality was the most frequently cited issue and the fundamental ecological driver for the presence or absence of shellfish aquaculture activities (Figure 2(A)). Shellfish aquaculture activities were most frequently present in northeastern Reserves (Table 2), potentially reflecting the region's mature commercial shellfish aquaculture industry and public acceptance of these activities. The northeast region's history of shellfish aquaculture and NERRS may contribute to a broader, shared recognition of potential ecosystem services of shellfish aquaculture. For example, the town of Mashpee (MA) has recently finished a demonstration study evaluating nutrient reduction *via* oyster grow-out in several of the area's estuarine systems, many of which were impaired by excess nitrogen. Results indicated that shellfish seeding had a positive localized effect on water quality, and suggest that expansion of seeding and harvesting could reduce the nitrogen equivalent to 15% of the nitrogen load to the Mashpee River (Howes et al. 2020; Fisher, A., personal communication). The designation and intent of Florida's Aquatic Preserves also demonstrate regional recognition of ecosystem services as a result of shellfish aquaculture. Virginia's

Chesapeake Bay Reserve expressed significant engagement with shellfish aquaculture activities, which again may be due to a state's mature commercial industry (Goelz 2020). In the Gulf of Mexico, the oyster industry traditionally has relied on wild set for a primarily shucked-product market. In recent years, investment in hatcheries and research and promotion by government and university extension agencies (e.g., Mississippi-Alabama and Louisiana Sea Grant, Auburn University Shellfish Lab) have fostered development of more controlled farming, which has established a market for premium half-shell products and expansion of a successful regional off-bottom industry (Walton, W. personal communication). On the west coast, shellfish aquaculture faces a unique scenario in which aquaculture of the non-native Pacific oyster may potentially conflict with restoration of wild native Olympia oysters (Ridlon et al. 2021a), but opportunities for conservation aquaculture activities that support species recovery, including partnerships with commercial shellfish growers, are underway (Ridlon et al. 2021b). West Coast-based Shellfish Initiatives (NMFS 2019) mostly recognize this balance. For Reserves that hold high-quality water bodies, expansion of shellfish aquaculture into relatively undisturbed areas likely poses the potential for use concerns. Masonboro Island's (NC) NIMBY concerns may demonstrate an example of this. At the time of questionnaire response, only three Reserves without aquaculture indicated active consideration. States with mature industries can perhaps provide blueprints and would serve as an excellent resource regarding the siting, planning, permitting, consensus-building, and research.

Recommendations for addressing shellfish aquaculture by the NERRS

With the U.S. shellfish aquaculture industry currently expanding, management issues will continue to evolve and require applied research and varying forms of information exchange and sharing. If they have not already, Reserves will likely experience external pressure regarding aquaculture activities within Reserve boundaries and be called upon for their expertise in resolving management issues.

As described, Reserves in Texas, North Carolina, and South Carolina have different stages of state-wide shellfish aquaculture development and could benefit from increased awareness of approaches of other Reserves and states. Questionnaire responses provided awareness that South Carolina, in light of North Carolina's recent actions to expand aquaculture, was scoping the expansion of shellfish aquaculture within state waters. Such an expansion is likely to affect both the NI-WB and ACE Basin NERRs. Therefore, we recommended the NERRS establish best management practices for studying shellfish aquaculture, educating, and engaging with its relevant stakeholders. Given that only 17 out of 29 Reserves contributed to the 28 identified socio-economic and ecological issues in this study, increased participation from all Reserves would likely strengthen the consideration and selection of best-management practices. Examples of information exchange and sharing could involve Reserve management plan design, coastal spatial planning design, and materials which evaluate impacts (or the potential of impacts) between an aquaculture activity and any relevant permitting consideration: such as ESA-listed species and their critical habitat designations, Essential Fish Habitat, Treaty Rights, and historical properties or areas of cultural significance.

For example, as the recently designated Connecticut Reserve develops their approach to Reserve management with regards to existing aquaculture leases in core and buffer areas, the He'eia Reserve's management plan may provide a useful template, as the plan thoroughly incorporates traditional aquaculture practices and permitting in the state of Hawaii (Hawai'i Office of Planning 2016). Connecticut's and New York's Long Island Sound Blue Plan may be a useful resource in helping JCNERR staff help shape New Jersey's spatial plan research and implementation as well. Issues surrounding aquaculture decisions shared by multiple Reserves and identified by this survey may help Reserves approach these issues more efficiently by providing opportunities for broader and more structured sharing of information across the NERR System.

Beyond aquaculture activities within a Reserve, this assessment demonstrates how NERRS staff are also uniquely positioned to serve in key coordination roles, and as neutral, trusted sources of science. Conversations with Elkhorn Slough and GTM Reserves show that communities of practice, with varying degrees of strategic direction, are ideal in shaping and implementing solutions for coastal management. As stated by Karl, Susskind, and Wallace (2007), "Collaborative approaches to policy making can generate the civil discourse necessary to produce creative and durable solutions to complex and contentious environmental dilemmas." This approach is also followed in the East Coast Shellfish Growers BMPs, which state that one of the highest priorities for BMP development is shaping their role in improving public perception of the industry's environmental stewardship (Flimlin et al. 2010). There is a growing body of work showing that when properly sited, operated, and maintained, environmental impacts of commercial shellfish aquaculture are positive (Gallardi 2014; Turner et al. 2019). However, there is still a need for studies on aquaculture carrying capacity to understand the scale of environmental impacts and benefits. Reserves with active advisory boards or stakeholder groups, such as local advisory committees, may provide catalysts for growth in this area. Additionally, Reserve staff can play key roles in advisory roles as demonstrated with the red knot conflict as a particular example (DeLuca, M.; personal correspondence).

In review of the NERRS and shellfish aquaculture regulatory frameworks, the Reserve System is relatively well-aligned to address shellfish aquaculture within its mandated goals and expertise in estuarine and coastal science, education, and interpretation. The underlying theme of this connection is water quality as demonstrated by the GTM's Oyster and Water Quality Task Force and Florida Aquatic Preserves' statutes. While restoration water quality goals may be of greater importance to the Reserves, monitoring and maintenance of water quality is not only a goal of the NERRS, but a requirement for commercial-focused activities.

With respect to aquaculture, we recommend that the NERRS as a whole considers developing a decision-support model, to allow individual Reserves to prioritize specific considerations for approaching and allowing each use of aquaculture (research, restoration, conservation, recreation, and commercial), by type or species (e.g., oyster mariculture *vs.* finfish). Existing decision support tools could be used as a guide, such as those developed for oyster restoration siting (Puckett et al. 2018; Theuerkauf et al. 2019; Ridlon et al. 2021b). One critical consideration to include in the framework would be the degree of manipulation and interpretation of the activity in preserving Reserve resources and natural ecosystem function (see 15 CFR § 921.1(d)). As described

by Froehlich, Gentry, and Halpern (2017), it is essential to couple the goals of an aquaculture activity with the net benefits to a specific area, considering scale and carrying capacity. While the primary goal of aquaculture is human consumption, other benefits and impacts to society and the environment may best be considered through a stakeholder-driven approach led by trusted NERRS staff familiar with local regulatory issues and environmental threats and embedded in the local community.

Conclusion

The overall goal of this study was to review and highlight the current activities, regulatory framework, and engagement approaches to aquaculture within the NERRS, and more specifically to focus on the suitability and role(s) the NERRS may strengthen or seek with respect to shellfish aquaculture siting. We found that individual Reserves' approaches were locally focused, but that patterns reflected a regional influence, due to factors of state and regional geographic setting, historical shellfish populations, use of the coastal landscape, and shellfish aquaculture regulations and management. In light of national and state Shellfish Initiatives in the U.S., the expansion of shellfish aquaculture will likely press into more estuarine systems. The NERRS principal research foci: environmental change, water quality, and habitat protection, are all central for managing the growth of shellfish aquaculture in viable U.S. estuaries. As such, and when appropriate, Reserves have demonstrated that they can play an integral role in shaping science-based management of shellfish aquaculture through research, education, and interpretation and it is expected that they will continue to do so. As demonstrated here, shellfish aquaculture covers a wide and complex set of issues. Thus, dissemination of emerging tools, science, and BMPs is essential for discussion of the potential for advancing sustainable aquaculture throughout coastal regions represented by the NERRS. The information synthesized responds to this need and provides stakeholders of the Reserve System (researchers, educators, federal and state regulatory coordinators, growers, and the general public) with a useful resource to better understand the mechanisms which have shaped, and will continue to influence, aquaculture activities in the NERRS.

Acknowledgments

The authors are extremely appreciative of the NERRS staff willingness to engage in this assessment. We particularly thank E. Buskey, M. DeLuca, N. Dix, J. Vaudrey, and K. Wasson for their time, expertise, and insight during informational interviews. Special thanks to M. DeLuca and K. Wasson for their insightful reviews of this manuscript. Additional thanks to A. Freitag in making sure our qualitative analysis design was appropriated, and to N. Garber, M. Rath, L. Swann, and C. Weirich for their feedback on this effort and manuscript.

Funding

This project arose from conversations during stakeholder meetings from the "ShARES Project" funded by the NOAA NERRS Science Collaborative (University of Michigan Subaward 3004278672, collaborators T. Alphin, M. Posey, S. Brander, B. Puckett).

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